4.1 CAPACITOR VOLTAGE TRANSFORMER

The capacitive voltage transformer step-down the high voltage input signals and provide the low voltage signals which can easily measure through the measuring instrument. The Capacitive voltage transformer (CVT) is also called capacitive potential transformer.

Capacitance voltage transformer are more complex than the resistance type. For measurement of impulse voltages not exceeding 1 MV capacitance dividers can be both portable and transportable. In general, for measurement of 1 MV and over, the capacitance divider is a laboratory fixture. The capacitance dividers are usually made of capacitor units mounted one above the other and bolted together. It is this failure which makes the small dividers portable. A screening box similar to that described earlier can be used for housing both the low voltage capacitor unit C_2 and the matching resistor if required.

The low voltage capacitor C_2 should be non-inductive. A form of capacitor which has given excellent results is of mica and tin foil plate, construction, each foil having connecting tags coming out at opposite corners. This ensures that the current cannot pass from the high voltage circuit to the delay cable without actually going through the foil electrodes. It is also important that the coupling between the high and low voltage arms of the divider be purely capacitive.

Hence, the low voltage arm should contain one capacitor only; two or more capacitors in parallel must be avoided because of appreciable inductance that would thus be introduced. Further, the tappings to the delay cable must be taken off as close as possible to the terminals of C_2. Figure shows variants of capacitance potential dividers.

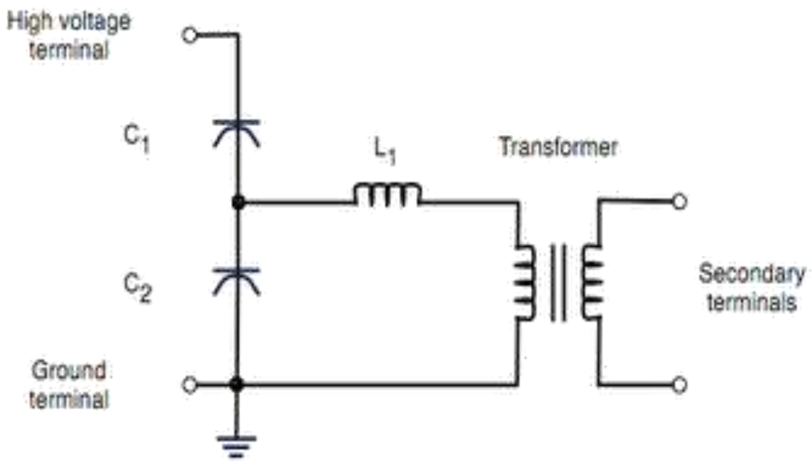


Figure 4.1.1 Capacitive Voltage Transformer

A low Resistor in parallel to C_2 would load the low voltage arm of the divider too heavily and decrease the output voltage with time. Since R and Z form a potential divider and R = Z, the voltage input to the cable will be half of the voltage across the capacitor C_2. This halved voltages travels towards the open end of the cable (CRO end) and gets doubled after reflection. That is, the voltage recorded by the CRO is equal to the voltage across the capacitor C_2. The reflected wave charges the cable to its final voltage magnitude and is absorbed by R (i.e. reflection takes place at R and since R = Z, the wave is completely absorbed as coefficient of voltage reflection is zero) as the capacitor C2 acts as a short circuit for high frequency waves. The transformation ratio, therefore, changes from the value:

However, the capacitance of the delay cable Cd is usually small as compared with C2.For capacitive divider an additional damping resistance is usually connected in the lead on the High voltage side as shown in figure. The performance of the divider can be improved if damping resistor which corresponds to the a periodic limiting case is inserted in series with the individual element of capacitor divider. This kind of damped capacitive divider acts for high frequencies as a resistive divider and for low frequencies as a capacitive divider. It can, therefore, be used over a wide range of frequencies i.e. for impulse voltages of very different duration and also for alternating voltages.

4.5 DIGITAL TECHNIQUES IN HIGH VOLTAGE MEASUREMENT

Resistance Potential Dividers

The resistance potential dividers are the first to appear because of their simplicity of construction, less space requirements, less weight and easy portability. These can be placed near the test object which might not always be confined to one location. The length of the divider depends upon two or three factors. The maximum voltage to be measured is the first and if height is a limitation, the length can be based on a surface flash over gradient in the order of 3–4 kV/cm irrespective of whether the resistance R1 is of liquid or wire wound construction. The length also depends upon the resistance value but this is implicitly bound up with the stray capacitance of the resistance column, the product of the two (RC) giving a time constant the value of which must not exceed the duration of the wave front it is required to record. It is to be noted with caution that the resistance of the potential divider should be matched to the equivalent resistance of a given generator to obtain a given wave shape.

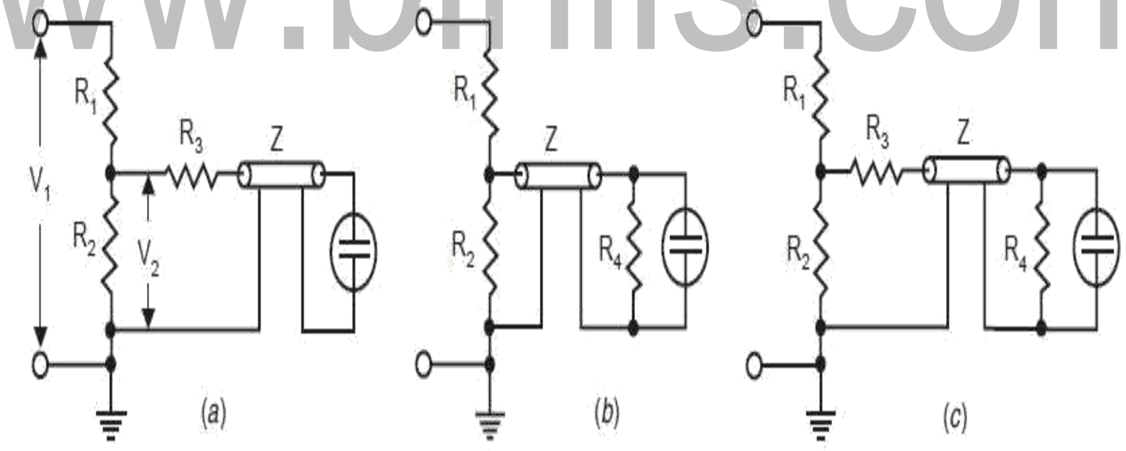


Figure 4.5.1 various forms of resistance potential dividers recording circuits

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 438]

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., $R2 < Z$. In fact, sometimes the condition for matching is given as

$$Z = R3 + \frac{R1R2}{R1+R2}$$

But, since usually $R_1 >> R_2$, the above relation reduces to $Z = R_3 + R_2$.

$$V2 = \frac{Z1}{Z1+R1}V1$$

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.

$$Z1 = \frac{(Z+R3)R2}{R2+Z+R3} = \frac{(Z+R3)R2}{2Z}$$

Therefore,

$$V2 = \frac{(Z+R3)R2}{2Z}\frac{V1}{Z1+R1}$$

$$V3 = \frac{V2}{Z+R3}Z = \frac{Z}{Z+R3}\frac{(Z+R3)R2}{2Z}.\frac{V1}{Z1+R1} = V1\frac{R2}{2(Z1+R1)}$$

However, the voltage entering the delay cable is

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 The reflected wave, however, as it reaches the low voltage arm of the potential divider does not suffer any reflection as $Z = R_2 + R_3$ and is totally absorbed by $(R_2 + R_3)$. Since R_2 is smaller than Z and Z_1 is a parallel combination of R_2 and $(R_3 + Z)$, Z_1 is going to be smaller than R_2 and since $R_1 >> R_2$, R_1 will be much greater than Z_1 and, therefore to a first approximation $Z_1 + R_1 \approx R_1$.

Therefore,

$$V_3' = \frac{R2}{R1} V1 \approx \frac{R2}{R1+R2} V1 \text{ as } R2 << R1$$

cable Matching is done by a pure ohmic resistance R_4 = Z at the end of the delay cable and, therefore, the voltage reflection coefficient is zero i.e. the voltage at the end of the cable is transmitted completely into R4 and hence appears across the CRO plates without being reflected. As the input impedance of the delay cable is R_4 = Z, this resistance is a parallel to R2 and forms an integral part of the divider's low voltage arm. The voltage of such a divider is, therefore, calculated as follows: Equivalent impedance

$$R1 + \frac{R2Z}{RZ+Z} = \frac{R1(R2+Z)+R2Z}{(R2+Z)}$$

$$I = \frac{V1(R2+Z)}{R1(R2+Z)+R2Z}$$

Therefore, Current

$$V2 = \frac{IR2Z}{R2+Z} = \frac{V1(R2+Z)}{R1(R2+Z)+R2Z}\frac{R2Z}{R2+Z}$$

$$= \frac{R2Z}{R1(R2+Z)+R2Z} V1$$

$$\frac{V2}{V1} = \frac{R2Z}{R1(R2+Z)+R2Z}$$

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

$$V2 = \frac{R2}{2R1+R2} V1$$

For a given applied voltage V_1 this arrangement will produce a smaller deflection on the CRO Plates as compared to the one in Figure. The arrangement of Figure) provides for matching at both ends of the delay cable and is to be recommended where it is felt necessary to reduce to the minimum irregularities produced in the delay cable circuit. Since matching is provided at the CRO end of the delay cable, therefore, there is no reflection of the voltage at that end and the voltage recorded will be half of that recorded in the arrangement of ,

$$V2 = \frac{R2}{2(R1+R2)} V1$$

It is desirable to enclose the low voltage resistance (s) of the potential dividers in a metal screening box. Steel sheet is a suitable material for this box which could be provided with a detachable closefitting lid for easy access. If there are two low voltage resistors at the divider position as in Figure they should be contained in the screening box, as close together as possible, with a removable metallic partition between them. The partition serves two purposes (i) it acts as an electrostatic shield between the two resistors (ii) it facilitates the changing of the resistors. The lengths of the leads should be short so

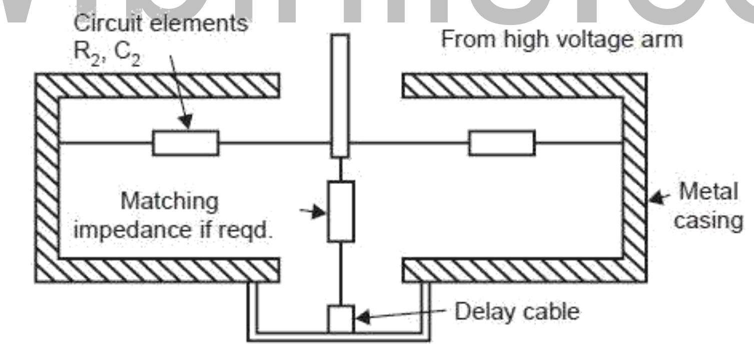


Figure 4.5.2 shows a sketched cross-section of possible layout for the low voltage arm of voltage divider.

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 445]

Capacitance Potential Dividers

Capacitance potential dividers are more complex than the resistance type. For measurement of impulse voltages not exceeding 1 MV capacitance dividers can be both portable and transportable. In general, for measurement of 1 MV and over, the capacitance divider is a laboratory fixture. The capacitance dividers are usually made of capacitor units mounted one above the other and bolted together. It is this failure which makes the small dividers portable. A screening box similar to that described earlier can be used for housing both the low voltage capacitor unit C_2 and the matching resistor if required.

The low voltage capacitor C_2 should be non-inductive. A form of capacitor which has given excellent results is of mica and tin foil plate, construction, each foil having connecting tags coming out at opposite corners. This ensures that the current cannot pass from the high voltage circuit to the delay cable without actually going through the foil electrodes. It is also important that the coupling between the high and low voltage arms of the divider be purely capacitive. Hence, the low voltage arm should contain one capacitor only; two or more capacitors in parallel must be avoided because of appreciable inductance that would thus be introduced.

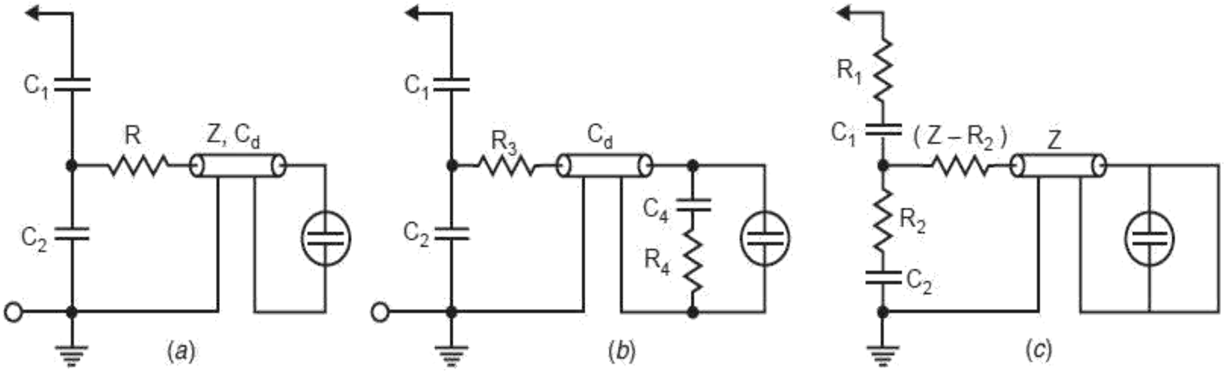


Figure 4.5.3 Capacitor divider

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 451]

A low Resistor in parallel to C_2 would load the low voltage arm of the divider too heavily and decrease the output voltage with time. Since R and Z form a potential divider and R = Z, the voltage input to the cable will be half of the voltage across the capacitor C_2. This halved voltages travels towards the open end of the cable (CRO end) and gets doubled after reflection. That is, the voltage recorded by the CRO is equal to the voltage across the capacitor C_2. The reflected wave charges the cable to its final voltage magnitude and is absorbed by R (i.e. reflection takes place at R and since R = Z, the wave is completely absorbed as coefficient of voltage reflection is zero) as the capacitor C2 acts as a short circuit for high frequency waves. The transformation ratio, therefore, changes from the value:

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

for very high frequencies to the value

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

However, the capacitance of the delay cable Cd is usually small as compared with C2. For capacitive divider an additional damping resistance is usually connected in the lead on the High voltage side. The performance of the divider can be improved if damping resistor which corresponds to the a periodic limiting case is inserted in series with the individual element of capacitor divider. This kind of damped capacitive divider acts for high frequencies as a resistive divider and for low frequencies as a capacitive divider. It can, therefore, be used over a wide range of frequencies i.e. for impulse voltages of very different duration and also for alternating voltages.

4.2 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. It is possible to have uniform electric field between the plates with suitable arrangement of 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,

$$w_d = \frac{1}{2} \in E^2$$

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 i

$$dw = w_d A dx = \frac{1}{2} \in E^2 A dx$$

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

$$F = \frac{dw}{dx} = \frac{1}{2} \in E^2 A$$

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

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

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 Electrostatic voltmeters measure the force based on the above equations and are arranged such that one of the plates is rigidly fixed whereas the

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

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 millimeter to a few millimeters 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.

The force developed between the plates is sufficient to be used to measure the voltage. Various designs of the voltmeter have been developed which differ in the construction of electrode arrangement and in the use of different methods of restoring forces required to balance the electrostatic force of attraction. Some of the methods are

- Suspension of moving electrode on one arm of a balance. Suspension of the moving electrode on a spring.
- Pendulous suspension of the moving electrode. Torsional suspension of moving electrode.

The small movement is generally transmitted and amplified by electrical or optical methods. If the electrode movement is minimized and the field distribution can exactly be calculated, the meter can be used for absolute voltage measurement as the calibration can be made in terms of the fundamental quantities of length and force. From the expression for the force, it is clear that for a given voltage to be measured, the higher the force, the greater is the precision that can be obtained with the meter. In order to achieve higher force for a given voltage, the area of the plates should be large, the spacing between the plates (d) should be small and some dielectric medium other than air should be used in between the plates.

If uniformity of electric field is to be maintained an increase in area A must be accompanied by an increase in the area of the surrounding guard ring and of the opposing plate and the electrode may, therefore, become unduly large especially for higher voltages. Similarly the gap length cannot be made very small as this is limited by the breakdown strength of the dielectric medium between the plates. If air is used as the medium, gradients upto5 kV/cm has been found satisfactory. For higher gradients vacuum or SF6 gas has been used. The greatest advantage of the electrostatic voltmeter is its extremely low loading effect as only electric fields are required to be set up. Because of high resistance of the medium between the plates, the active power loss is negligibly small. The voltage source loading is, therefore, limited only to their active power required to charge the instrument capacitance which can be as low as a few pico farads for low voltage voltmeters.

The measuring system as such does not put any upper limit on the frequency of supply to be measured. However, as the load inductance and the measuring system capacitance form a series resonance circuit, a limit is imposed on the frequency range. For low range voltmeters, the upper frequency is generally limited to a few MHz. 4.shows a schematic diagram of an absolute electrostatic voltmeter. 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 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 range10 to 100 kV are measured, the accuracy is of the order of 0.01 per cent. Hueter has used a pair of spheres of 100 cms diameter for the measurement of high voltages utilizing the electrostatic attractive force between them. The spheres are arranged with a vertical axis and at spacing slightly greater than the sparking distance for the particular voltage to be measured. The upper high voltage sphere is supported on a spring and the extension of spring caused by the electrostatic force is magnified by a lamp-mirror scale arrangement. An accuracy of 0.5 per cent has been achieved by the arrangement.

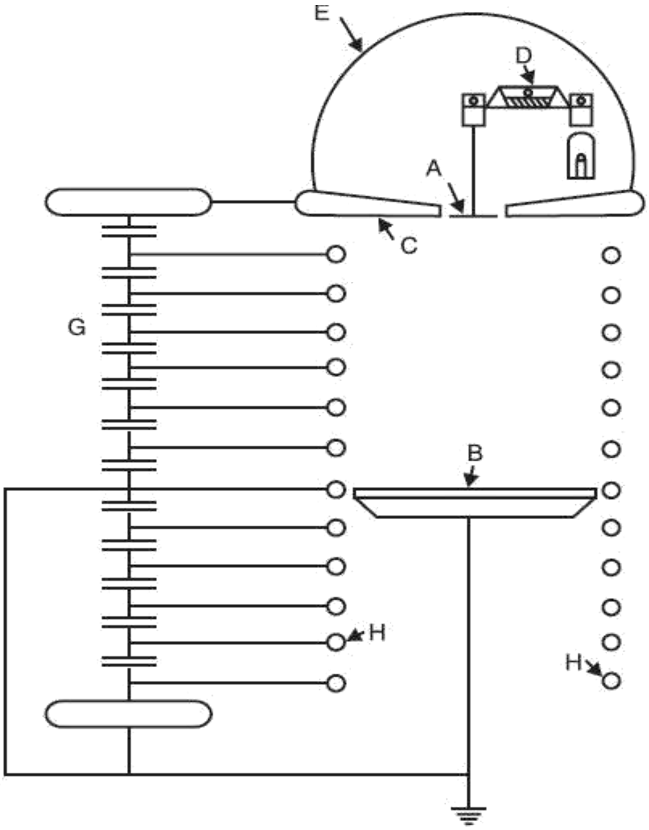


Figure 4.2.1 Schematic diagram of electrostatic voltmeter

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 487]

Electrostatic voltmeters using compressed gas as the insulating medium have been developed. Here for a given voltage the shorter gap length enables the required uniformity of the field to be maintained with electrodes of smaller size and a more compact system can be evolved. 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%. The high voltage electrode and earthed plane provide uniform electric field within the region of a 5 cm diameter disc set in a 65 cm diameter guard plane. A weighing balance arrangement is used to allow a large damping mass. The gap length can be varied between 2.5, 5 and10 cms and due to maximum working electric stress of 100 kV/cm, the voltage ranges can be selected to 250 kV, 500 kV and 100 kV. With 100 kV/cm as gradient, the average force on the disc is found to be0.8681 N equivalent to 88.52 gm wt. The disc movements are kept as small as 1 μm by the weighing balance arrangement. The voltmeters are used for the measurement of high a.c. and d.c voltages.

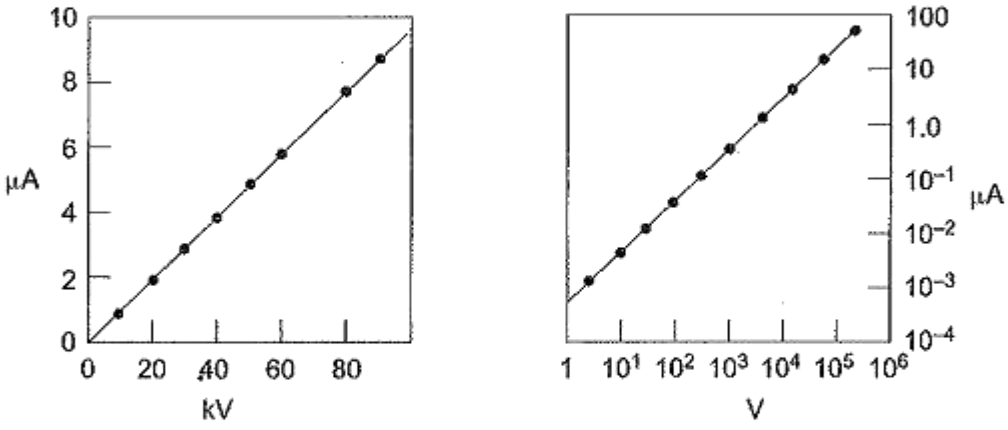
4.3 GENERATING VOLTMETERS

Direct connection to high-voltage source is avoided in Generating Voltmeters. Generating voltmeter is a variable capacitor electrostatic voltage generator which generates current proportional to the applied external voltage.(driven by external synchronous or constant speed motor and does not absorb power or energy from the voltage measuring source).

Principle of operation

The charge stored in a capacitor of capacitance C is given by q = CV. If the capacitance of the capacitor varies with time when connected to a voltage source of voltage V, the current through the capacitor is given by For a constant angular frequency ω, the current is proportional to the applied voltage V. The generated current is rectified and measured by a moving coil meter. Generating voltmeter can be used for a.c voltage measurements also provided that angular frequency ω is the same or equal to half that of the supply frequency.

Generating voltmeters employ rotating sectors for variation of capacitance. Figure gives the schematic diagram of a generating voltmeter. The high voltage source is connected to a disc electrode S_3 which is kept at a fixed distance on the axis of the other low voltage electrodes S_0,S_1 and S_2.The rotor S_0 is driven at a constant speed by a synchronous motor at a suitable speed(1500,1800, 3000, or 3600 rpm).The rotor vanes of S_0 cause periodic change in capacitance between the insulated disc S_2 and the hv electrode S_3.The shape and number of the vanes of S_0 and S_1 are so designed that they produce sinusoidal variation in the capacitance.



(a) Rotating cylinder type

(b) Rotating vane type

Figure 4.3.1Calibration curve for generating voltmeter

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 586]

- **Advantages**
  - ☐ No source loading by the meter
  - ☐ No direct connection to high voltage electrode
  - ☐ Scale is linear and extension of range is easy
  - ☐ a very convenient instrument for electrostatic devices such as Van de Graaff generator and particle accelerators.
- **Limitations**
  - ☐ Require calibration
  - ☐ Careful construction is needed and is a cumbersome instrument requiring an auxiliary drive.
  - ☐ Disturbance in position and mounting of the electrodes make the calibration invalid.

4.4 PEAK VOLTMETERS

Passive circuits are not very frequently used these days for measurement of the peak value of a.c. or impulse voltages. The development of fully integrated operational amplifiers and other electronic circuits has made it possible to sample and hold such voltages and thus make measurements and, therefore, have replaced the conventional passive circuits. However, it is to be noted that if the passive circuits are designed properly, they provide simplicity and adequate accuracy and hence a small description ofthese circuits is in order. Passive circuits are cheap, reliable and have a high order of electromagnetic compatibility. However, in contrast, the most sophisticated electronic instruments are costlier and their electromagnetic compatibility (EMC) is low. The passive circuits cannot measure high voltages directly and use potential dividers preferably of the capacitance type. Fig. 4.4.1 shows a simple peak voltmeter circuit consisting of a capacitor voltage divider which reduces the voltage V to be measured to a low voltage Vm.

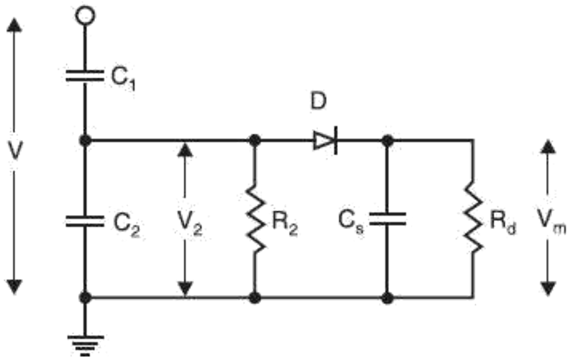


Figure 4.4.1 Peak voltmeter

Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 603]

Suppose R_2 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 C_2 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. If the reverse current through the diode is very small and the discharge time constant of the storage capacitor very large, the storage capacitor will not discharge significantly for a long time and hence it will hold the voltage to its value for a long time. If now, V is decreased, the voltage V_2 decreases proportionately and since now the voltage across C_2 is smaller than the voltage across Cs to which it is already charged, therefore, the diode does not conduct and the voltage across Cs does not follow the voltage across C_2. Hence, a discharge resistor R_d must be introduced into the circuit so that the voltage across Cs follows the voltage across C_2. From measurement point of view it is desirable that the quantity to be measured should be indicated by the meter within a few seconds and hence Rd is so chosen that $R_dC_s \approx 1$ sec. As a result of this, following errors are introduced. With the connection of R_d, the voltage across Cs will decrease continuously even when the input voltage is kept constant. Also, it will discharge the capacitor C_2 and the mean potential of V_2 (t) will gain a negative d.c component. Hence a leakage resistor R_2 must be inserted in parallel with C_2 to equalize these unipolar discharge currents.

The second error corresponds to the voltage shape across the storage capacitor which contains ripple and is due to the discharge of the capacitor Cs. If the input impedance of the measuring device is very high, the ripple is independent of the meter being used. The error is approximately proportional to the ripple factor and is thus frequency dependent as the discharge time constant cannot be changed. If RdCs = 1 sec, the discharge error amounts to 1% for 50 Hz and 0.33% for
150 Hz. The third source of error is related to this discharge error. During the conduction time (when the voltage across Cs is lower than that across C_2 because of discharge of Cs through Rd) of the diode the storage capacitor Cs is recharged to the peak value and thus Cs becomes parallel with C_2. If discharge error is ed, recharge error er is given by

Hence Cs should be small as compared withC_2 to keep down the recharge error. It has also been observed that in order to keep the overall error to a low value, it is desirable to have a high value of R_2. The same effect can be obtained by providing an equalizing arm to the low voltage arm of the voltage divider as shown in Fig. 4.4.2 This is accomplished by the addition of a second network comprising diode, Cs and Rd for negative polarity currents to the circuit shown in Fig.4.4.3 With this, the d.c currents in both branches are opposite in polarity and equalize each other. The errors due to R2 are thus eliminated. Rabus developed another circuit shown in Figure to reduce errors due to resistances. Two storage capacitors are connected by a resistor Rs within every
branch and both are discharged by only one resistance Rd.

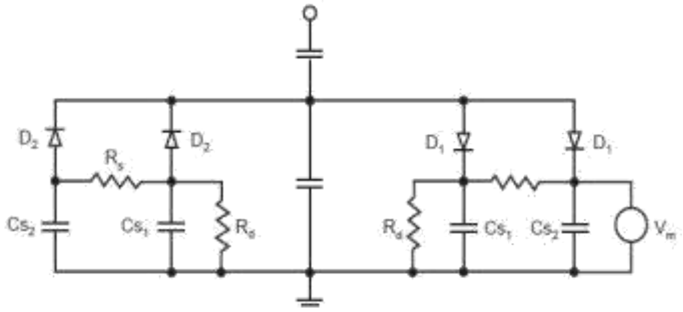


Figure 4.4.2 Two-way booster circuit designed by Rabus

Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 610]

Here because of the presence of Rs, the discharge of the storage capacitor Cs_2 is delayed and hence the inherent discharge error is reduced. However, since these are two storage capacitors within one branch, they would draw more charge from the capacitor C_2 and hence the recharge error would increase. It is, therefore, a matter of designing various elements in the circuit so that the total sum of all the errors is a minimum. It has been observed that with the commonly used circuit elements in the voltage dividers, the error can be kept to well within about 1% even for frequencies below 20 Hz. The capacitor C_1 has to withstand high voltage to be measured and is always placed within the test area whereas the low voltage arm C_2 including the peak circuit and instrument form a measuring unit located in the control area. Hence a coaxial cable is always required to connect the two areas. The cable capacitance comes parallel with the capacitance C_2 which is usually changed in steps if the voltage to be measured is changed. A change of the length of the cable would, thus, also require recalibration of the system. The sheath of the coaxial cable picks up the electrostatic fields and thus prevents the penetration of this field to the core of the conductor. Also, even though transient magnetic fields will penetrate into the core of the cable, no appreciable voltage (extraneous of noise) is induced due to the symmetrical arrangement and hence a coaxial cable provides a good connection between the two areas. Whenever, a discharge takes place at the high voltage end of capacitor C_1 to the cable connection where the current looks into a change in impedance a high voltage of short duration may be built up at the low voltage end of the capacitor C_1 which must be limited by using an over voltage protection device (protection gap).

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