Measurement of High Voltage

6.0 High Voltage Measurement

High voltages can be measured in a variety of ways. Direct measurement of high voltages is possible up to about 200 kV, and several forms of voltmeters have been devised which can be connected directly across the test circuit. High Voltages are also measured by stepping down the voltage by using transformers and potential dividers. The sparkover of sphere gaps and other gaps are also used, especially in the calibration of meters in high voltage measurements. Transient voltages may be recorded through potential dividers and oscilloscopes. Lightning surges may be recorded using the Klydonograph.

6.1 Direct Measurement of High Voltages

6.1.1 Electrostatic Voltmeters

One of the direct methods of measuring high voltages is by means of electro-static voltmeters. For voltages above 10 kV, generally the attracted disc type of electrostatic voltmeter is used.
When two parallel conducting plates (cross section area **A** and spacing **x**) are charged **q** and have a potential difference **V**, then the energy stored in the is given by

$$\text{Energy stored } W = \tfrac{1}{2} C V^2 \text{ so that change } dW = \tfrac{1}{2} V^2 \, dC = F \, dx$$

$$\therefore \text{ Force } F = \tfrac{1}{2} V^2 \frac{dC}{dx} \text{ N}$$

$$\text{for uniform field Capacitance } C = \frac{A\varepsilon}{x} \text{ so that } \frac{dC}{dx} = -\frac{A\varepsilon}{x^2}$$

$$\therefore F = -\tfrac{1}{2} A \varepsilon \frac{V^2}{x^2} \text{ N}$$

It is thus seen that the force of attraction is proportional to the square of the potential difference applied, so that the meter reads the square value (or can be marked to read the rms value).

Electrostatic voltmeters of the attracted disc type may be connected across the high voltage circuit directly to measure up to about 200 kV, without the use of any potential divider or other reduction method. [The force in these electrostatic instruments can be used to measure both a.c. and d.c. voltages].

Abraham Voltmeter

The Abraham voltmeter is the most commonly used electrostatic meter in high voltage testing equipment. In this instrument, there are two mushroom shaped hollow metal discs.

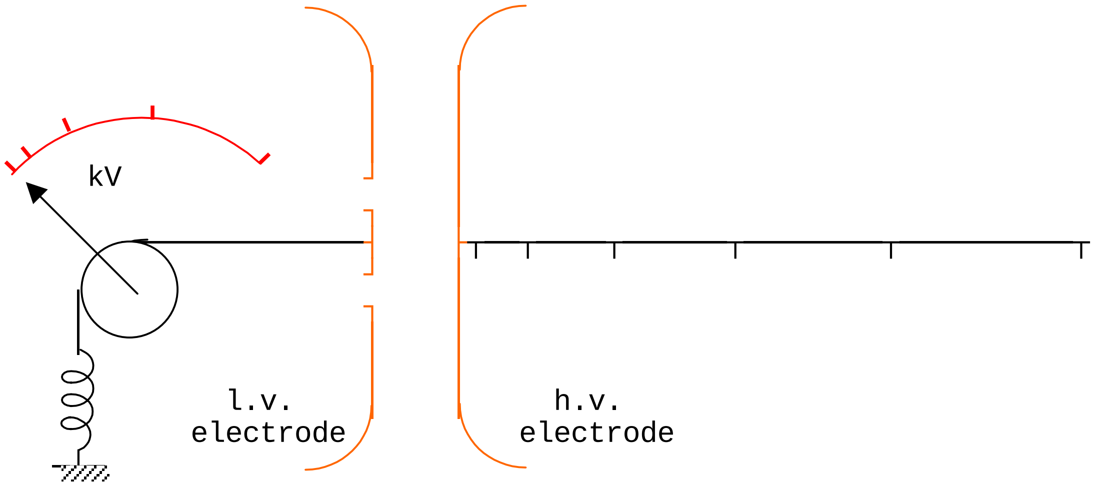


Figure 6.1 - Abraham electrostatic voltmeter

As shown in figure 6.1 the right hand electrode forms the high voltage plate, while the centre portion of the left hand disc is cut away and encloses a small disc which is movable and is geared to the pointer of the instrument. The range of the instrument can be altered by setting the right hand disc at pre-marked distances. The two large discs form adequate protection for the working parts of the instrument against external electrostatic disturbances. These instruments are made to cover ranges from 3 kV to 500 kV. Owing to the difficulty of designing electrostatic voltmeters for the measurement of extra high voltages which will be free from errors due to corona effects, within the instrument, and to the external electrostatic fields, a number of special methods have been devised for the purpose.

6.1.2 Sphere gaps

The sphere gap method of measuring high voltage is the most reliable and is used as the standard for calibration purposes.

The breakdown strength of a gas depends on the ionisation of the gas molecules, and on the density of the gas. As such, the breakdown voltage varies with the gap spacing; and for a uniform field gap, a high consistency could be obtained, so that the sphere gap is very useful as a measuring device.

By precise experiments, the breakdown voltage variation with gap spacing, for different diameters and distances, have been calculated and represented in charts.

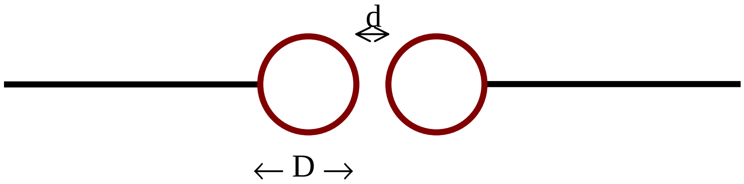
In the measuring device, two metal spheres are used, separated by a gas-gap. The potential difference between the spheres is raised until a spark passes between them. The breakdown strength of a gas depends on the size of the spheres, their distance apart and a number of other factors. A spark gap may be used for the determination of the peak value of a voltage wave, and for the checking and calibrating of voltmeters and other voltage measuring devices.

The density of the gas (generally air) affects the spark-over voltage for a given gap setting. Thus the correction for any air density change must be made. The air density correction factor δ must be used.

$$\delta = \frac{P}{760} x \frac{273+20}{273+t} = 0.386\left[\frac{P}{273+t}\right]$$

The spark over voltage for a given gap setting under the standard conditions (760 torr pressure and at 20°C) must be multiplied by the correction factor to obtain the actual spark-over voltage.

The breakdown voltage of the sphere gap (figure 6.2) is almost independent of humidity of the atmosphere, but the presence of dew on the surface lowers the breakdown voltage and hence invalidates the calibrations.



where d = gap spacing, D = sphere diameter

Figure 6.2 - Measuring spheres

The breakdown voltage characteristic (figure 6.3) has been determined for similar pairs of spheres (diameters 62.5 mm, 125 mm, 250 mm, 500 mm, 1 m and 2 m)

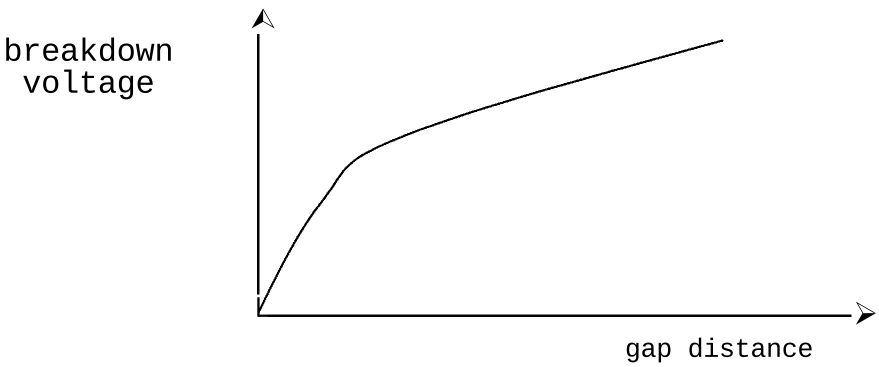


Figure 6.3 - Breakdown voltage characteristic of sphere gaps

When the gap distance is increased, the uniform field between the spheres becomes distorted, and accuracy falls. The limits of accuracy are dependant on the ratio of the spacing **d** to the sphere diameter **D**, as follows.

d	< 0.5 D,	accuracy = ± 3 %
0.75 D > d	> 0.5 D,	accuracy = ± 5 %

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

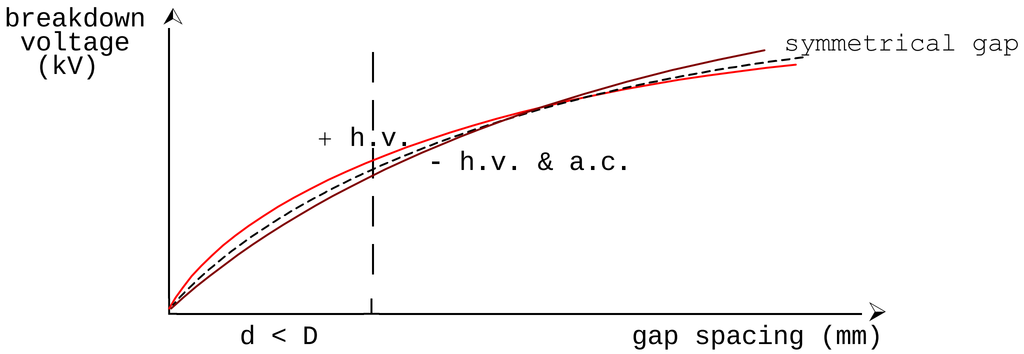


Figure 6.4 - Breakdown voltage characteristics

The breakdown voltage characteristic is also dependant on the polarity of the high voltage sphere in the case of asymmetrical gaps (i.e. gaps where one electrode is at high voltage and the other at a low voltage or earth potential). If both electrodes are at equal high voltage of opposite polarity (i.e. + ½ V and - ½ V), as in a symmetrical gap, then the polarity has no effect. Figure 6.4 shows these breakdown voltage variations.

In the case of the asymmetrical gap, there are two breakdown characteristics; one for the positive high voltage and the other for the negative high voltage. Since the breakdown is caused by the flow of electrons, when the high voltage electrode is positive, a higher voltage is generally necessary for breakdown than when the high voltage electrode is negative. However, when the gaps are very far apart, then the positive and the negative characteristics cross over due to various space charge effects. But this occurs well beyond the useful operating region. Under alternating voltage conditions, breakdown will occur corresponding to the lower curve (i.e. in the negative half cycle under normal gap spacings). Thus under normal conditions, the a.c. characteristic is the same as the negative characteristic.

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

"The length of any diameter shall not differ from the correct value by more than 1% for spheres of diameter up to 100 cm or more than 2% for larger spheres".

Peak values of voltages may be measured from 2 kV up to about 2500 kV by means of spheres. One sphere may be earthed with the other being the high voltage electrode, or both may be supplied with equal positive and negative voltages with respect to earth (symmetrical gap).

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

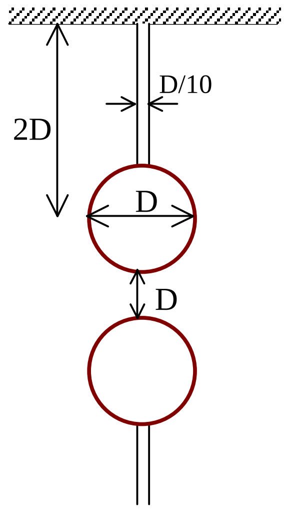


Figure 6.5 - sphere gap

Needle gaps may also be used in the measurement of voltages up to about 50 kV, but errors are caused by the variation of the sharpness of the needle gaps, and by the corona forming at the points before the gap actually sparks over. Also the effect ~~of~~ the variation of the humidity of the atmosphere on such gaps is much greater.

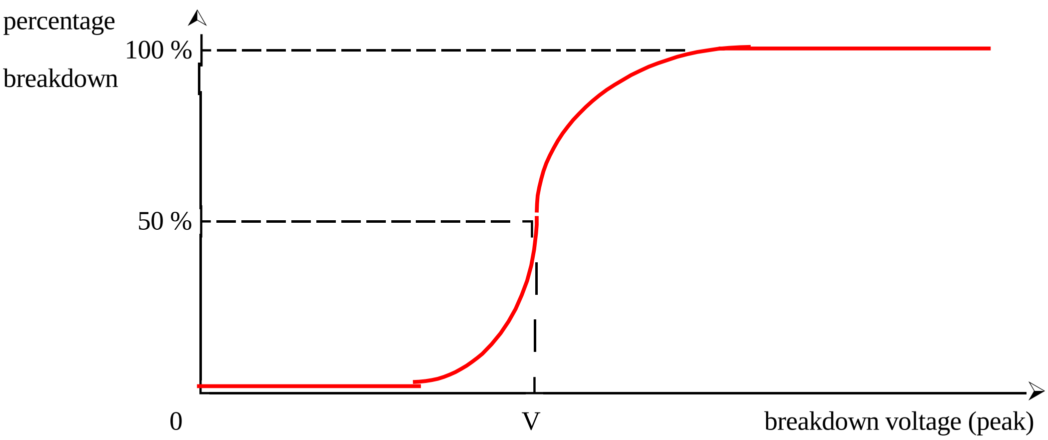


Figure 6.6 - Breakdown voltage characteristic for impulses

Usually, a resistance is used in series with the sphere gap, of about 1 Ω/V so as to limit the current under sparkover conditions to about a maximum of 1 A.

However for impulse measurements, a series resistance must not be used since this causes a large drop across the resistance. In measuring impulse voltages, since the breakdown does not occur at exactly the same value of voltage each time, what is generally specified is the 50 % breakdown value. A number of impulses of the same value is applied and a record is kept of the number of times breakdown occurs, and a histogram is plotted with the peak value of the impulse voltage and the percentage of breakdown (figure 6.6).

6.2 Transformer and potential divider methods of measurement

6.2.1 Transformer ratio method

The use of the primary voltage to estimate the secondary voltage is a fairly rough method of measurement, but is satisfactory enough for most ac tests. In this method (figure 6.7), the voltage on the low voltage side of the high-tension transformer is measured. The actual voltage across the load is not measured.

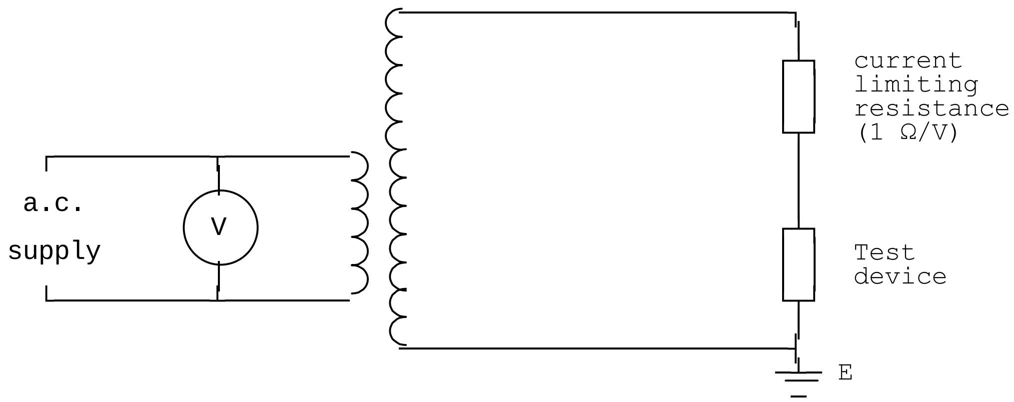


Figure 6.7 - transformer ratio method

Since the current taken by the device under test is usually very small, currents such as due to corona may cause considerable error in the measured voltage. This method measures the rms voltage. In order to determine the peak value it is necessary to determine the wave form of the secondary voltage.

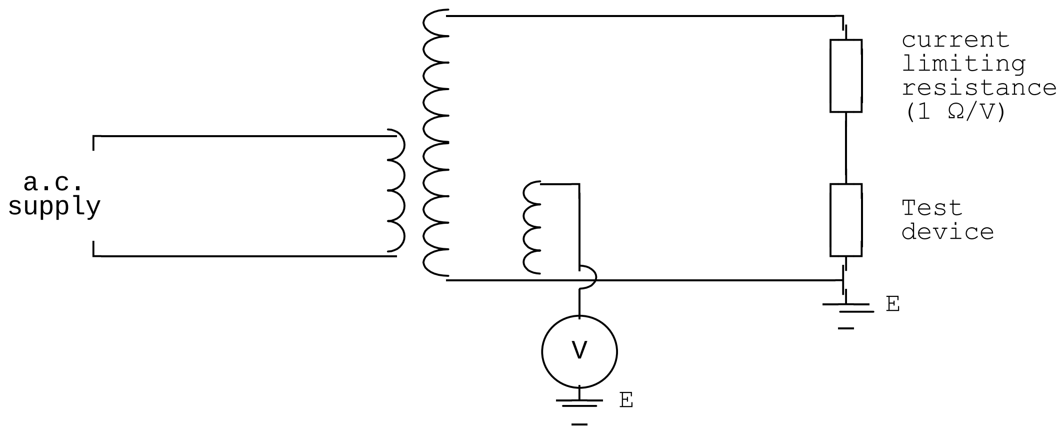


Figure 6.8 - with additional potential winding

Some high voltage transformers (figure 6.8) carry a separate voltmeter-coil having a number of turns which is a definite fraction of the secondary turns. This method cannot be used with the cascade arrangement of the transformers.

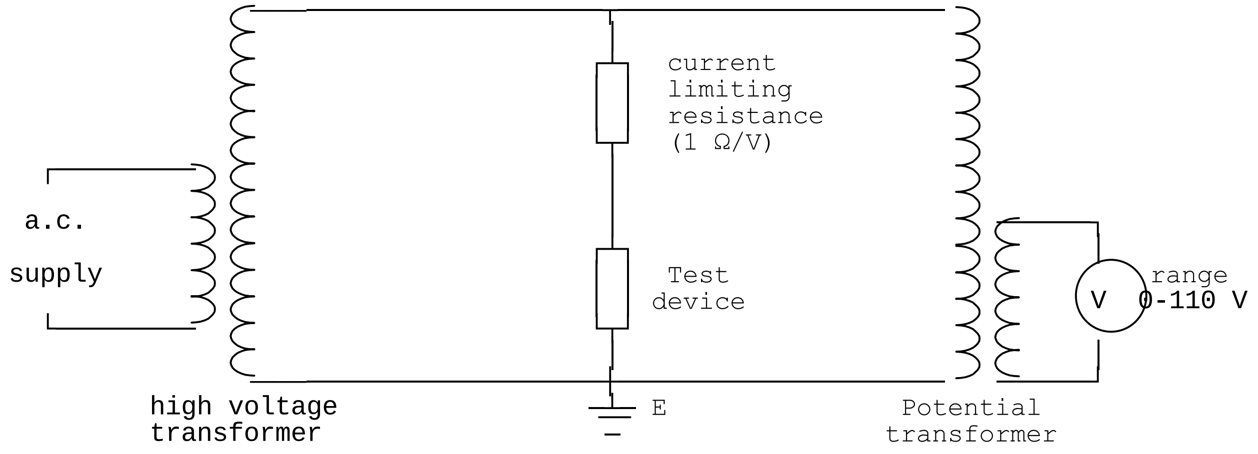


Figure 6.9 - with potential transformer

It may also be possible to have a potential transformer connected across the test device and the voltage measured, however this is an expensive arrangement.

Even this method may not be very satisfactory under very high voltage conditions and the series resistance method of measurement may be used.

Series resistance method of measurement

In the series resistance method a high series resistance (specially designed to withstand high voltage) and resistance of 20 kΩ/V, is used with micro-ammeter (having a 50 μA movement). This method is applicable for both ac and dc. A number of resistances would be necessary in series, and to prevent leakage current, we would have to have the whole system in a insulated container, which is earthed for shielding purposes. As a safety measure, a safety gap or neon lamp is connected across the micro-ammeter. If we use a stable supply (of accuracy 0.10%) we would finally end up with an accuracy of 1%.

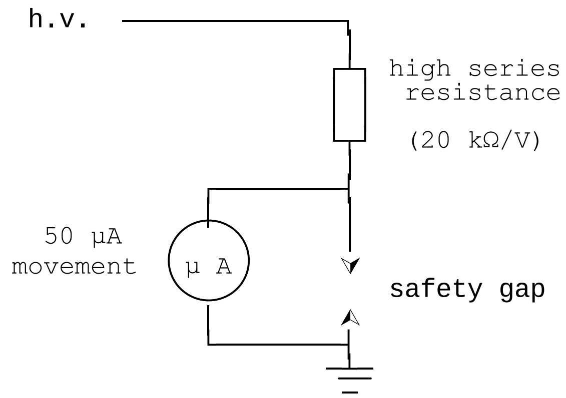


Figure 6.10 - Series resistor microammeter

When the above method is used for alternating voltages, there would be the effect of the distributed capacitances as well. The capacitive effects can be reduced by providing a suitable screen, or by balancing the capacitance.

6.2.2 Resistive potential divider method

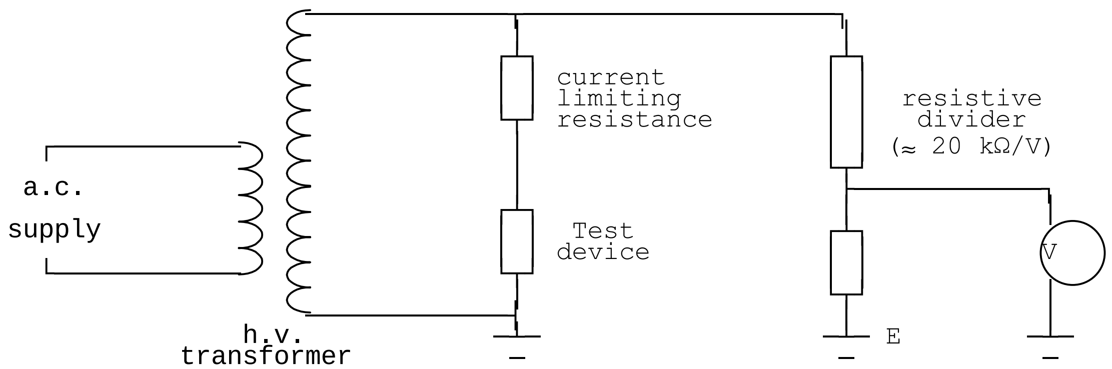


Figure 6.11 - Resistive potential divider method

In this method, a high resistance potential divider is connected across the high-voltage winding, and a definite fraction of the total voltage is measured by means of a low voltage voltmeter.

Under alternating conditions there would be distributed capacitances. One method of eliminating this would be to have a distributed screen of many sections and using an auxiliary potential divider to give fixed potential to the screens.

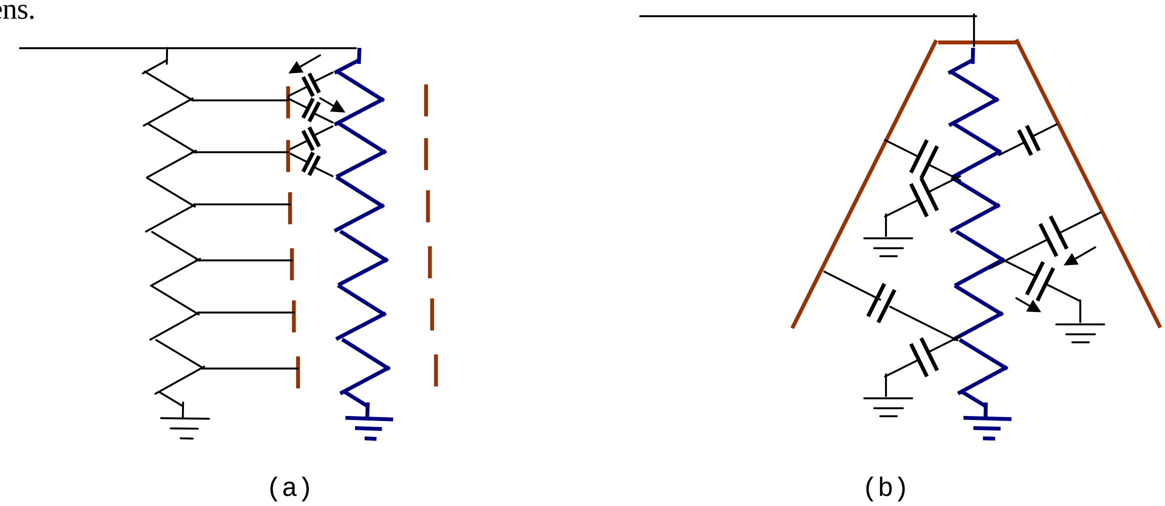


Figure 6.12 - Screening of resistive dividers

The currents flowing in the capacitances would be opposite in directions at each half of the screen so that there would be no net capacitive current (Figure 6.12 (a)).

It also possible to have a metal conical screen (Figure 6.12 (b)). The design has to be done by trial and error. There would be capacitances to the conical screen as well as capacitances to earth, so that if at any point the capacitive current from conical screen to the point is equal to that from the point to the earth, then the capacitances would have no net effect.

6.2.3 Capacitive potential divider method

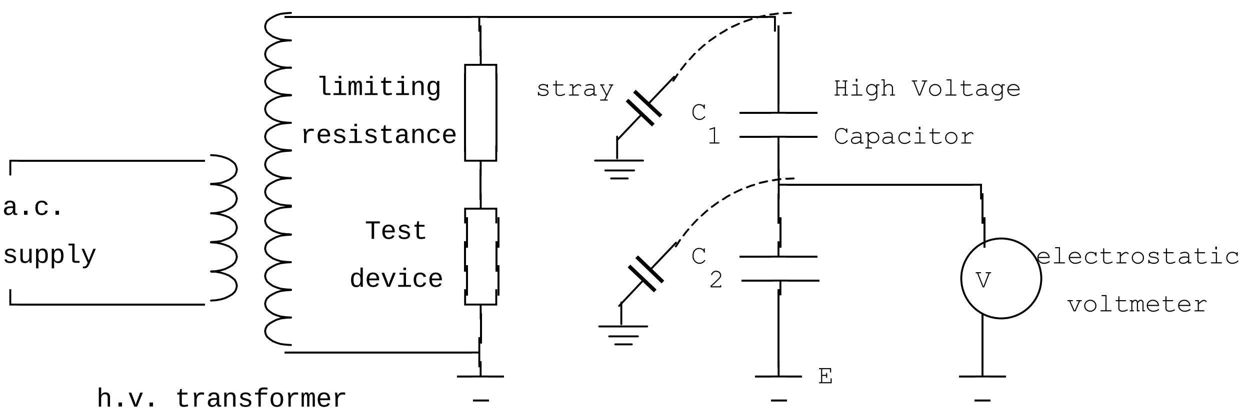


Figure 6.13 - Capacitive potential divider method

For alternating work, instead of using a resistive potential divider, we could use a capacitive potential divider. In this two capacitances C_1 and C_2 are used in series, the electrostatic voltmeter being connected across the lower capacitor.

If the system is kept at a fixed position, we can make corrections for the fixed stray capacitances. Or if screens are used, the capacitance to the screen would be a constant,and we could lump them up with the capacitances of the arms.

Neglecting the capacitance of the voltmeter (or lumping the electrostatic voltmeter capacitance with C_2) the effective capacitance of C_1 and C_2 in series is $C_1C_2/(C_1+C_2)$, and since the charge is the same,

$$\text{Voltage across } C_2 = \frac{1/C_2}{(C_1 + C_2)/C_1 C_2} . V = \frac{C_1}{C_1 + C_2} . V$$

The capacitance of h.v. standard capacitor must be accurately known, and the capacitance must be free from dielectric losses.For this reason, air capacitances are always used for this purpose.This method also measures the r.m.s. value.

It is sometimes more useful to have a measure of the peak value of the alternating voltage rather than the r.m.s. value,since it is the peak value of the applied voltage which produces the actual breakdown stress in the material under test.

If the shape of the voltage waveform is known, the peak voltage may be obtained from the r.m.s. voltage.It is often more satisfactory however, to use some method of voltage measurement which gives the peak value of the voltage directly.

6.2.4 Matching of Potential dividers

When waveforms are observed on the oscilloscope, through a potential divider, a cable is necessary to connect the test waveform to the oscilloscope, and also to cause a small delay between the arrival of the trigger pulse and the waveform (Figure 6.14).

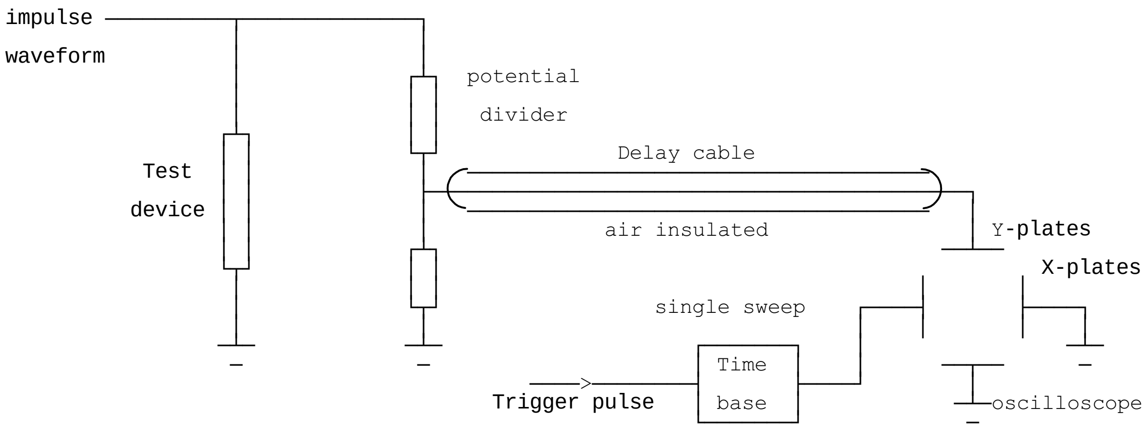


Figure 6.14 - Observation of impulse waveform through potential divider

If the delay cable is lossless , then it may be represented by purely inductances and capacitors, so that the surge impedance of cable or delay network = Zo = $[z/y]^{1/2}$. In a lossless cable , Zo is purely resistive.

$$\text{Velocity of the wave in cable } = \frac{1}{\sqrt{LC}} \approx \frac{1}{\sqrt{\mu_0 \varepsilon}} = \frac{3 \times 10^8}{\sqrt{\varepsilon_r}}$$

The oscilloscope can display a maximum of about 50 V to 100 V and thus the impulse voltage must be reduced by a suitable potential divider. The requirement of the potential divider used are that it reduces the applied voltage without producing any distortion (i.e: the ratio of the potential divider does not vary with time or frequency). The potential divider can be of two types.

(i) Resistive
and (ii)Capacitive.

In practice , neither case is obtained in the pure form, but a mixture of both.The capacitive effect in the resistive divider is much more than the resistive effect on the capacitive divider.

In the case of the resistive divider , the lower arm of the divider has its resistance fixed by the surge impedance of the cable used (for matching) and by the wave-tail requirements of the impulse generator circuit (if any impulse generator is used).The ratio of the divider is determined by the sensitivity of the C.R.O and the voltage.

The capacitive divider is generally bulkier than the resistive divider , but has several advantages. It can be used as part of the wavefront forming circuit. The self capacitance of the cable connecting the device to the C.R.O adds to the capacitance of the cable connecting the divider to the oscilloscope adds to the capacitance of the lower arm.

When the initial part of the surge enters the cable, it acts as a transmission line and presents its surge impedance to the surge, but when the line becomes charged, it behaves as a capacitor.

When using potential dividers, it is necessary to suitably terminate the cable at the two ends so as to have perfect matching of the cables at two ends.

Resistive potential dividers

There are three ways in which they may be matched to delay cables.

(1) Matching at potential divider end only:

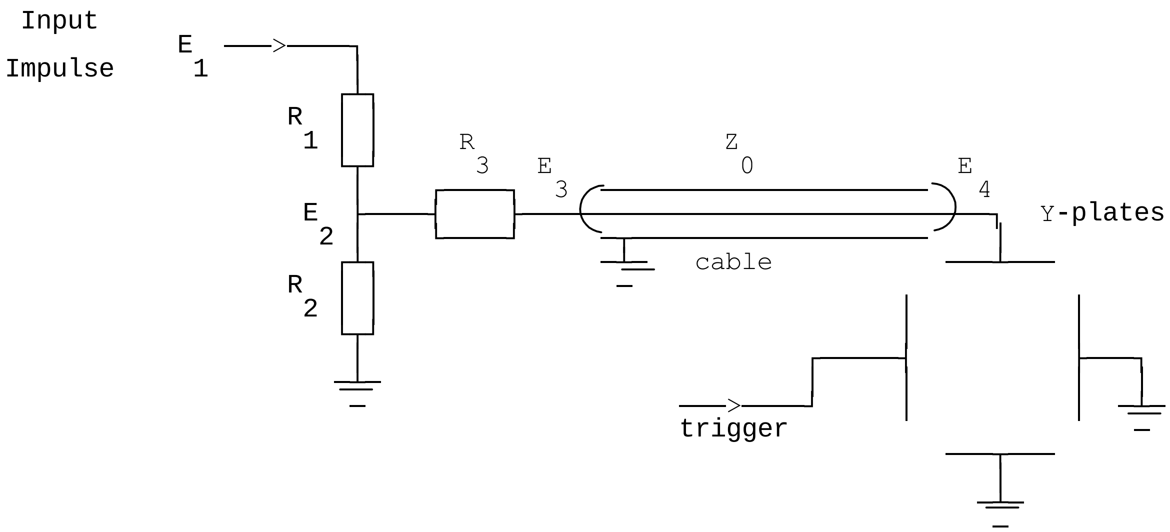


Figure 6.15 - Matching of resistive divider at sending end only

In this arrangement, the receiving (ie: the end connected across the CRO Y-plates) is kept on open circuit, and we try to obtain perfect matching at the sending end, so that there is no reflection, and perfect reflection at the receiving end.

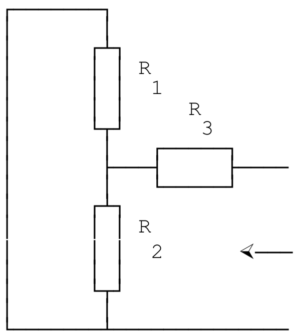


Figure 6.16

For perfect matching at the sending end, the equivalent impedance of the section before the cable must be Z_O

Impedance $= R_3 + R_1//R_2$

$= R_3 + R_1.R_2/(R_1 + R_2)$

$= Z_O$ for perfect matching at s.e

If $R_1 >> R_2$ as usually is, then we have $R1//R2 \approx R2$, $\therefore Z_O = R_2 + R_3$

At the junction of the divider $\mathbf{E_2}$, the equivalent impedance to earth Z_1 is given by

$$Z_1 = R_2 // (R_3 + Z_0) = \frac{R_2 (R_3 + Z_0)}{(R_2 + R_3 + Z_0)} = \frac{R_2 (R_3 + Z_0)}{2 Z_0}, \because Z_0 = R_2 + R_3$$

$$\therefore \text{ voltage at junction } E_2 = \frac{Z_1}{Z_1 + R_1} . E_1 = \frac{R_2 (R_3 + Z_0)}{2 Z_0 (Z_1 + R_1)} . E_1$$

$$\text{so that } E_3 = \frac{Z_0}{R_3 + Z_0} . E_2 = \frac{Z_0}{(R_3 + Z_0)} . \frac{R_2 (R_3 + Z_0)}{2 Z_0 (Z_1 + R_1)} . E_1 = \frac{R_2}{2 (Z_1 + R_1)} . E_1$$

This voltage waveform E_3 travels towards the receiving end and is reflected at the open end without change of sign, so that the voltage transmitted to the CRO is 2 E_3.

$$\therefore E_r = E_4 = \frac{R_2}{Z_1 + R_1} . E_1, \quad \text{where } Z_1 = \frac{R_2 (R_3 + Z_0)}{2 Z_0}$$

OR If the lower arm itself is balanced, that is $R_2 = Z_0$, then $R_3 = 0$ and the voltage transmitted to the oscilloscope is given by

$$E_r = \frac{Z_0}{R_1 + \frac{1}{2} Z_0} . E_1$$

(2) Matching the cable at the oscilloscope end only:

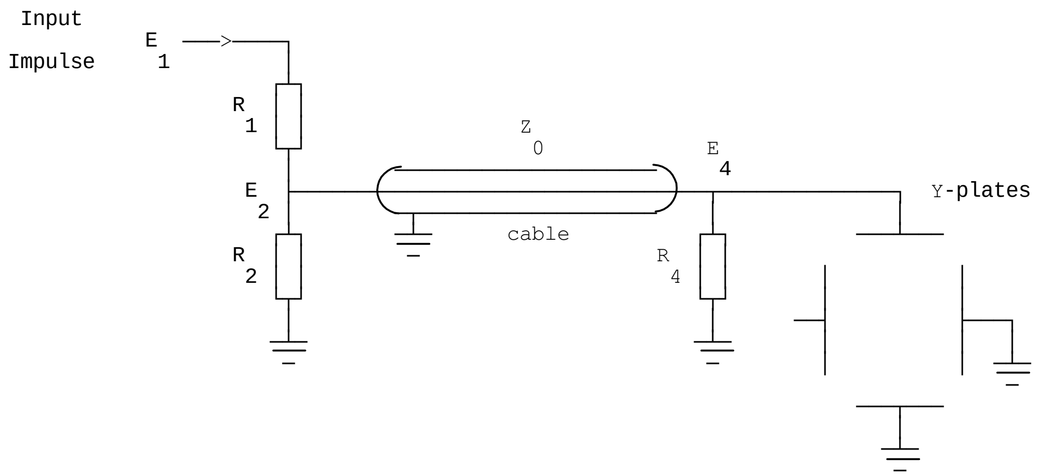


Figure 6.17 - Matching of resistive divider at receiving end only

In this arrangement, the cable is matched only at the receiving end so that there will no reflection at this end.

$$\text{Equivalent impedance at E 2} = Z_1 = R_2 // Z_0 = \frac{R_2 Z_0}{R_2 + Z_0}$$

$$\therefore E_2 = \frac{Z_1}{Z_1 + R_1} . E_1$$

Since the cable is properly matched at the receiving end, $R_4 = Z_0$

The voltage wave E_2 travels along the cable , and since there is proper matching at the receiving end, it is transmitted with out any reflection.

$$\therefore\ E_4 = E_2 = \frac{Z_1}{Z_1 + R_1} \cdot E_1 = \frac{R_2\, Z_0}{R_2\, Z_0 + + (R_2 + Z_0)\, R_1} \cdot E_1 = \frac{R_2\, Z_0}{(R_1 + R_2)\, Z_0 + R_1\, R_2} \cdot E_1$$

For given values of R_1, R_2 and E_1 this arrangement gives smaller voltages at the C.R.O than when only the divider end is matched.

If the point E_2 is not connected to earth through the resistance R_2, (ie. if $R_2 = \infty$), then we have

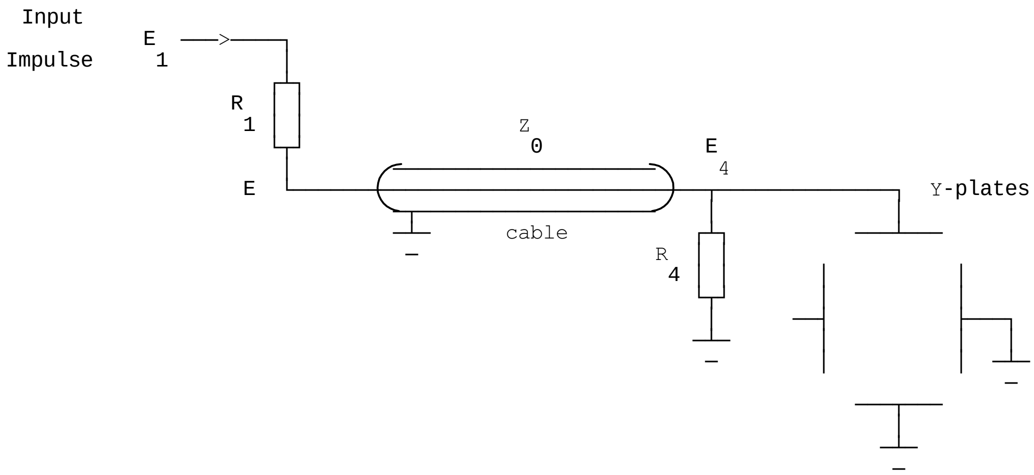


Figure 6.18 - Matching of resistive divider at receiving end (with $R_2 = \infty$)

For this case the voltage at the oscilloscope is given by

$$E_4 = \underset{R_2 \to \infty}{Lt} \frac{R_2\, Z_0}{(R_1 + R_2)\, Z_0 + R_1\, R_2} \cdot E_1 = \frac{Z_0}{Z_0 + R_1} \cdot E_1$$

(3) Matching at both ends of the cable :

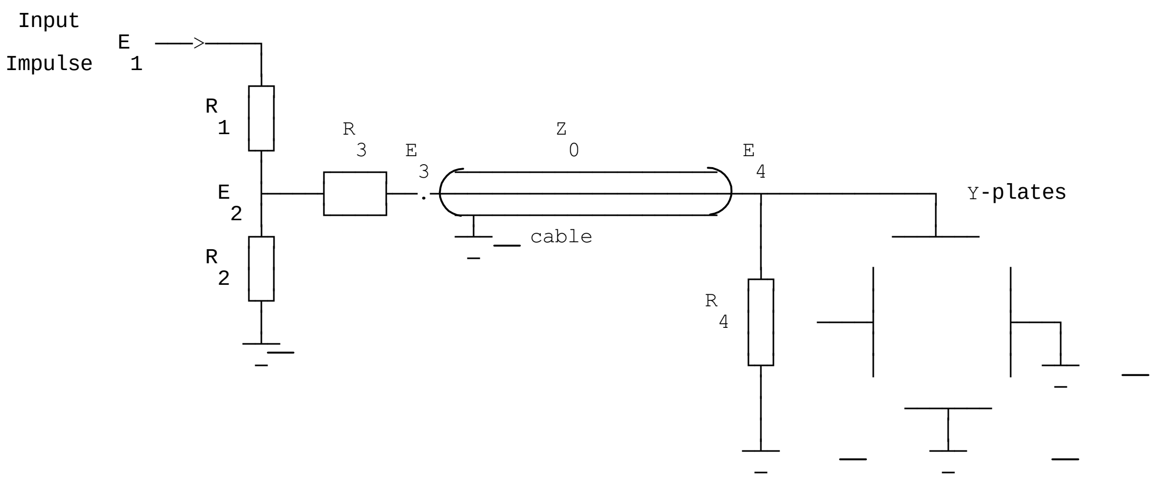


Figure 6.19 - Matching of resistive divider at both ends

In this case, the cable is matched at both ends . With this termination there is no reflection at either end. This arrangement is used when it is necessary to reduce to a minimum the irregularities produced in the delay cable circuit.

As before, for perfect matching at receiving end, $R_4 = Z_0$
and for perfect matching at sending end, $R_2 + R_3 = Z_0$.

Also, at E_2, the equivalent impedance Z_1 to earth is given by

$$Z_1 = R_2 // (R_3 + Z_0) = \frac{R_2 (R_3 + Z_0)}{(R_2 + R_3 + Z_0)} = \frac{R_2 (R_3 + Z_0)}{2 Z_0}, \because Z_0 = R_2 + R_3$$

$$\therefore \text{ voltage at junction } E_2 = \frac{Z_1}{Z_1 + R_1} . E_1 = \frac{R_2 (R_3 + Z_0)}{2 Z_0 (Z_1 + R_1)} . E_1$$

$$\text{so that } E_3 = \frac{Z_0}{R_3 + Z_0} . E_2 = \frac{Z_0}{(R_3 + Z_0)} . \frac{R_2 (R_3 + Z_0)}{2 Z_0 (Z_1 + R_1)} . E_1 = \frac{R_2}{2 (Z_1 + R_1)} . E_1$$

Due to perfect matching at the receiving end, this is transmitted without any reflections.

$$\therefore E_4 = E_3 = \frac{R_2}{2 (R_1 + Z_1)} . E_1$$

The stray capacitances present between the turns of the resistances would make the current distribution along the resistance non-uniform. When the rate of change of voltage is high, then the errors due to the capacitances are large (especially in waves such as chopped waves).

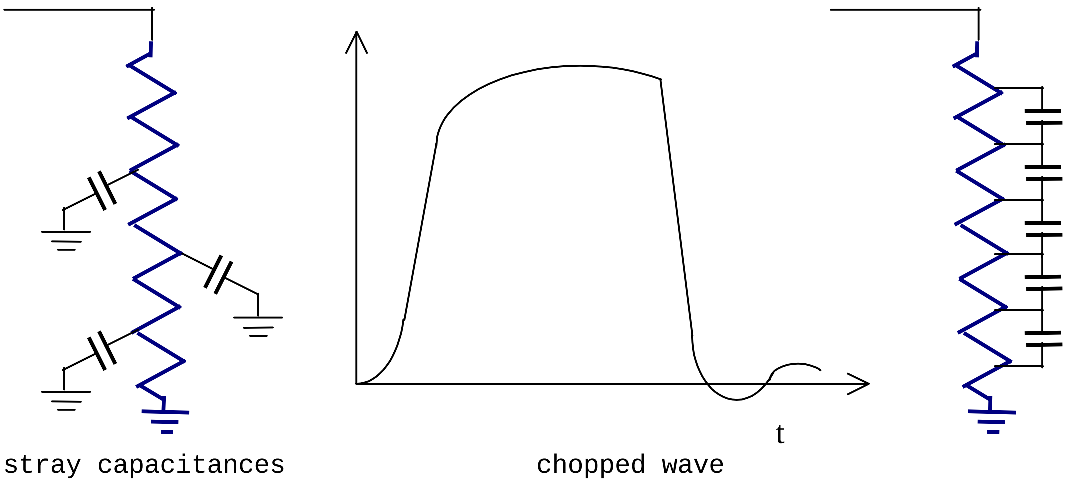


Figure 6.20 - Stray capacitances and chopped wave

By having a distributed capacitance along the resistance which are larger than the stray capacitances, the effect of the stray capacitance may be eliminated.

An easier way to compensate for the stray capacitances is by having capacitive potential divider instead of the resistive divider.

Capacitive potential dividers

The effect of stray capacitance may be made constant, in a capacitive divider, by shielding the potential, divider; and hence make an allowance for it. The disadvantage of the capacitive potential divider is that proper termination cannot be done.

There are two methods used to couple capacitive dividers to delay cables.

(1) Simple capacitor connection

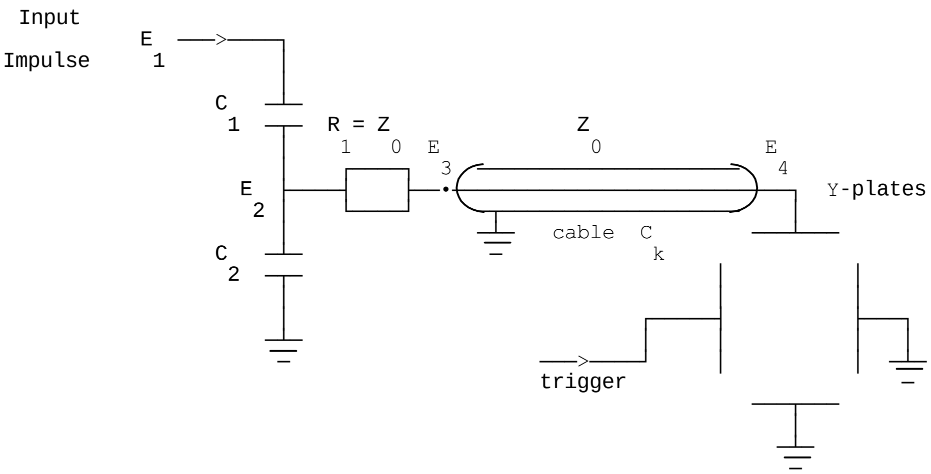


Figure 6.21 - Matching of capacitive divider (simple capacitor connection)

In the simple capacitor connection, we attempt to prevent reflections at sending end.

The sending end is terminated with a resistance $R_1 = Z_o$ in series with the cable. Initially the cable capacitance would not have charged up, and only C_1 and C_2 would be present.

Initially,

$$E_2 = E_1 \cdot \frac{C_1}{C_1 + C_2}$$

$$E_3 = E_2 \cdot \frac{Z_0}{Z_0 + R_1} = \tfrac{1}{2} E_2 , \because \textit{for matching } R_1 = Z_0$$

Due to perfect reflection at the receiving end, E_3 travelling towards it would be reflected and hence the voltage transmitted to the CRO would be doubled.

$$\text{i.e. } E_r = 2\,E_3 = 2 \times \tfrac{1}{2} E_2 = E_2 = E_1 \cdot \frac{C_1}{C_1 + C_2}$$

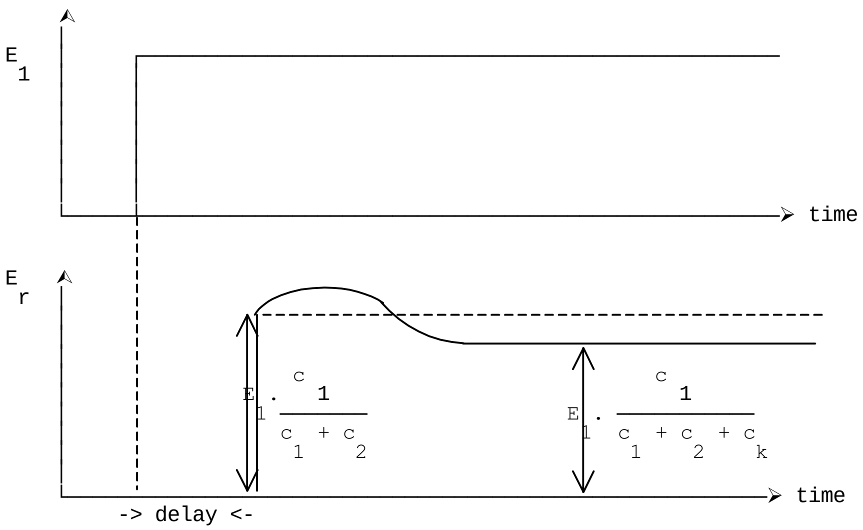


Figure 6.22 - Waveforms for simple capacitor connection

This gives the amplitude of the voltage wave as it reaches the Y-plates. As time goes on, the cable capacitance charges up and behaves as a capacitance in parallel with the lower arm.

Therefore, after infinite time, voltage at Y-plates would be given by

$$E_r = E_1 \cdot \frac{C_1}{C_1 + C_2 + C_k}$$

Thus the ratio of the input voltage to the output voltage of the capacitive divider varies with time and we get a distorted output waveform displayed on the oscilloscope. Thus the capacitive potential divider introduces distortion. The difference between the initial and final ratios will be appreciable unless C_2 is at least 10 times that of the cable capacitance C_k, in which case the error would be about 10%.

This error can be reduced by transferring part of the low voltage capacitor to the C.R.O. end of the delay cable and connecting it in series with a resistance equal to the cable surge impedance Z_0 (resistive if cable is lossless).

(2) Split capacitor connection

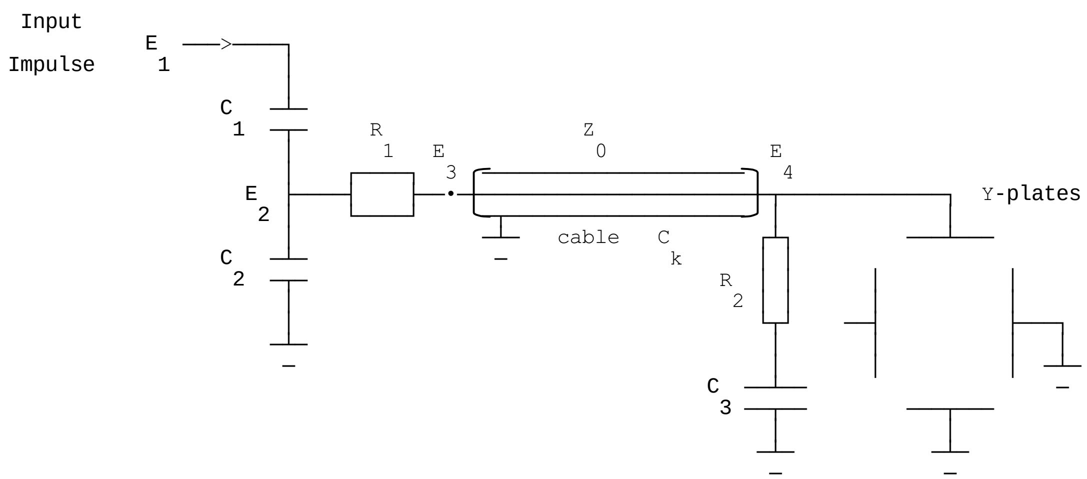


Figure 6.23 - Matching of capacitive divider (simple capacitor connection)

In this connection, in addition to matching the cable at the sending end ($R_1 = Z_0$), it is also matched at the oscilloscope end ($R_2 = Z_0$). Further to ensure that the long term ratio remains the same as the initial ratio, the lower end capacitor is split into C_2 and C_3.

Initially the capacitances C_k and C_3 would not have charged, and only the capacitances C_1 and C_2 would be effective in the voltage ratio.

$$\text{Initially} \quad E_2 = E_1 \cdot \frac{C_1}{C_1 + C_2}$$

$$\text{also} \quad E_3 = E_2 \cdot \frac{Z_0}{R_1 + Z_0} = \tfrac{1}{2} E_2, \quad \because R_1 = Z_0 \text{ for matching}$$

Due to perfect matching at the receiving end, the voltage wave is transmitted without any reflection. Therefore the observed voltage is given by

$$\therefore \; E_r = E_3 = \tfrac{1}{2} E_2 = \frac{E_1}{2} \cdot \frac{C_1}{C_1 + C_2}$$

After infinite time, the capacitances C_k and C_3 would have completely charged up, and the receiving end in effect would be on open circuit, since C_3 would no longer be conducting.

Since all the capacitors C_2, C_3 and C_k are in parallel,

$$E_2 = E_1 \cdot \frac{C_1}{C_1 + C_2 + C_3 + C_k}$$

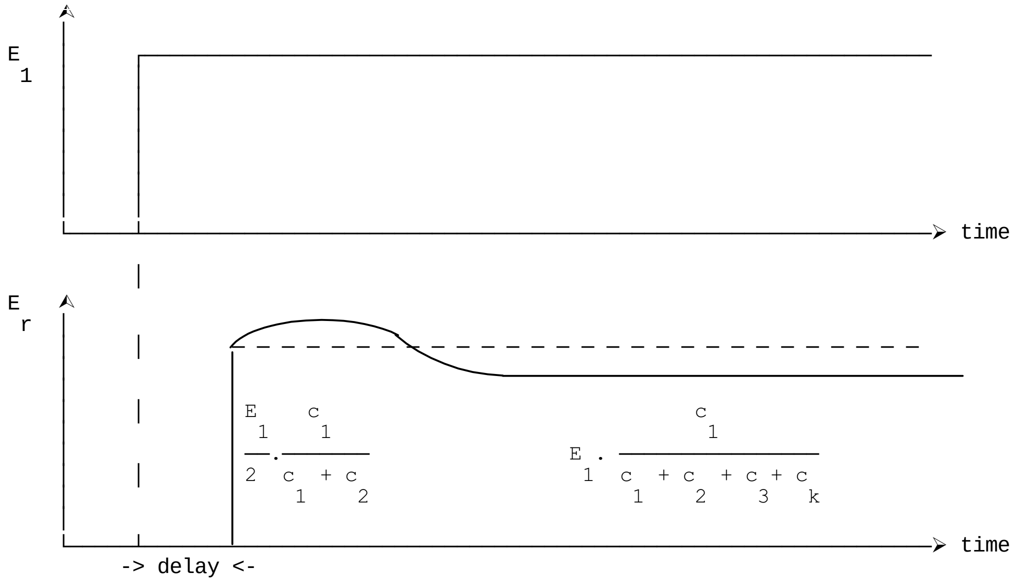


Figure 6.24 - Waveforms for split capacitor connection

If the initial and the final values of the ratio are made equal, then the distortion is reduced to a great degree.

$$\frac{E_1}{2} \cdot \frac{C_1}{C_1 + C_2} = E_1 \cdot \frac{C_1}{C_1 + C_2 + C_3 + C_k}$$

$$\text{i.e. } C_1 + C_2 = C_3 + C_k$$

If this condition is satisfied, then the distortion is low and near faithful reproduction can be expected as shown in figure 6.25.

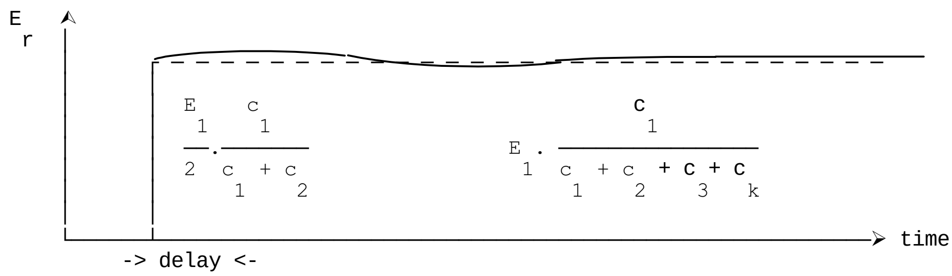


Figure 6.25 - Waveforms for split capacitor connection (low distortion)

6.3 Measurement of Surges

6.3.1 Klydonograph

Lightning is probably the most spectacular of the high voltage phenomena. Very little is known about lightning, as it is not possible to create lightning or to obtain a lightning strike when and where we please. Also very little is known of its effects and the voltages of the surges that appear in the transmission lines due to it.

The phenomena of the lightning could be studied to a certain extent by the surges it produces on the transmission lines. The frequency of occurrence of surge voltages and the magnitude of the surge it produces on the transmission lines could be studied using Litchenberg patterns obtained by using a Klydonograph.

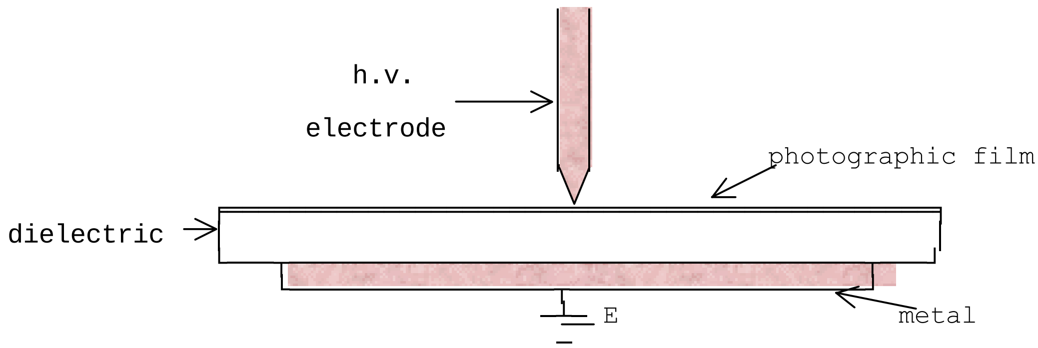


Figure 6.26 - Klydonograph

The Klydonograph (Figure 6.26) has a dielectric sheet, on the surface of which is placed a photographic film. The insulator material separates a plane electrode on one side, and a pointed electrode which is just in contact with the photographic film. The high voltage is applied to the pointed electrode and the other electrode is generally earthed. The photographic film can be made to rotate continuously by a clockwork mechanism. The apparatus is enclosed in a blackened box so as not to expose the photographic film. When an impulse voltage is applied to the high voltage electrode, the resultant photograph shows the growth of filamentary streamers which develop outwards from the electrode.

This imprint on the photographic plate is not due to normal photographic action, and occurs even through there is no visible discharge between the electrodes. If flashover of the insulator or a visible discharge occurs, then the film would become exposed and no patterns would be obtained. These patterns obtained on the photographic film are known as Litchenberg patterns. When a positive high voltage is applied to the upper electrode, clearly defined steamers which lie almost within a definite circle is obtained. If the voltage applied is negative, then the observed pattern is blurred and the radius of the pattern is much smaller. For both types of surges, the radius of the pattern obtained increases with increase in voltage.

For a given apparatus with a fixed thickness of dielectric, the radius of the pattern obtained (Figure 6.27a) is a definite function of the voltage applied, and thus by calibrating the Klydonograph using a high voltage oscilloscope and known surge voltages, it is possible to use this apparatus to record surges that occur. If the positive voltage applied is increased beyond a certain value, branching may occur along the branches coming out from the electrode. The maximum voltage that can be measured using a Klydonograph is dependant on the thickness of the dielectric material. Thus to measure voltages beyond this value,such as occuring in transmission lines, an insulator string potential divider is used. (Figure 6.27b)

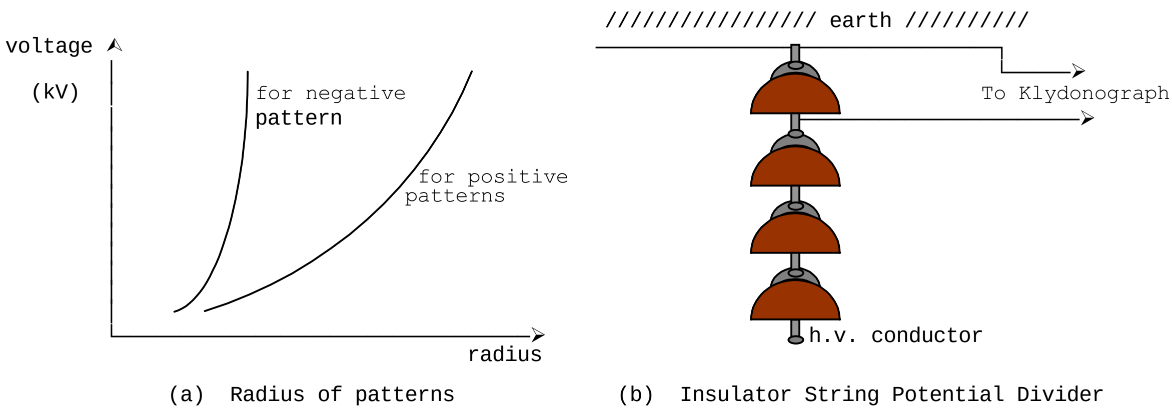


Figure 6.27 - Klydonograph

For a fixed apparatus, for a positive high voltage applied as the top electrode, the variation of the applied voltage with radius of the pattern obtained is quite definite and the radius is quite large. In the case of the negative high voltages, the characteristics is much more variable and the radius is much smaller.

Thus usually it is preferable to use the positive pattern for the measurement of high voltage surges. The applied voltage versus radius of pattern characteristics of the Litchenberg pattern is shown in figure 6.28.

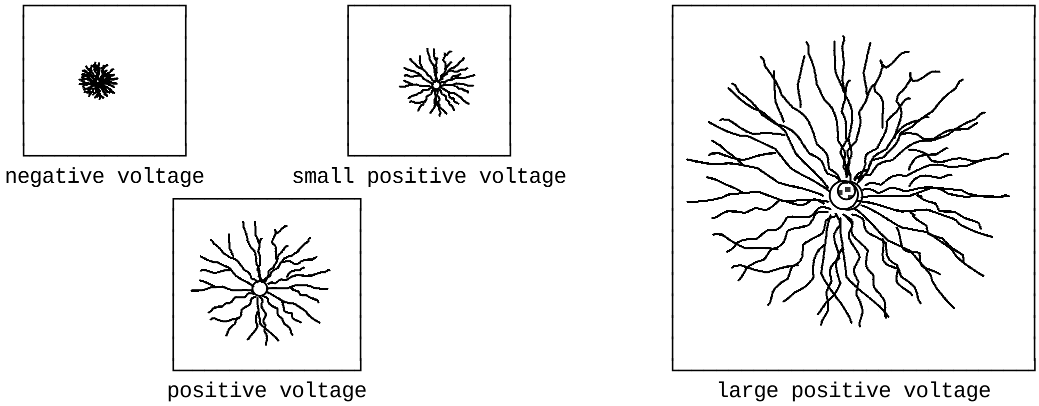


Figure 6.28 - Litchenberg patterns

Since the surges due to lightning may be either positive or negative, and since it is preferable to observe the positive pattern in either case, we make a modification to the apparatus.

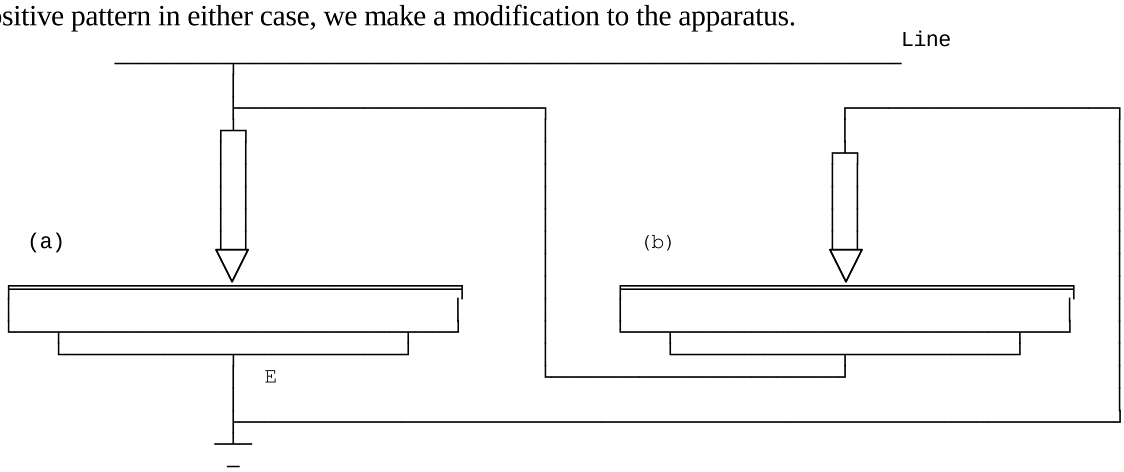


Figure 6.29 - Klydonograph for measurement of both polarities

In the modification shown in figure 6.29, there are two such instruments, with the electrode connections made in opposite directions. Thus in the modification, if a positive surge comes, then a positive pattern would be recorded in (a) and a negative pattern in (b), of which the pattern on (b) can be used for the measurement of the positive surge.

In the case of a negative surge, the opposite would happen, and the pattern on (b) could be used for the measurement. Thus the magnitude of the surge as well as the polarity could be determined from the Litchenberg patterns on (a) and (b). Since the photographic film is continuously moving, it is possible in some elaborate apparatus to record the date and time occurrence of the surge as well.

6.4 General measurements

6.4.1 Peak reading voltmeters

(i) Capacitor charging method

In the positive half cycle, the capacitor charges up to the peak value, and when the voltage falls it discharges (very slightly) through the milliammeter, and so that the voltage across the capacitor is very nearly a constant at the peak value and the current is thus proportional to the peak value. (The time constant RC of the above circuit must be very high in comparison to the period of the applied voltage).

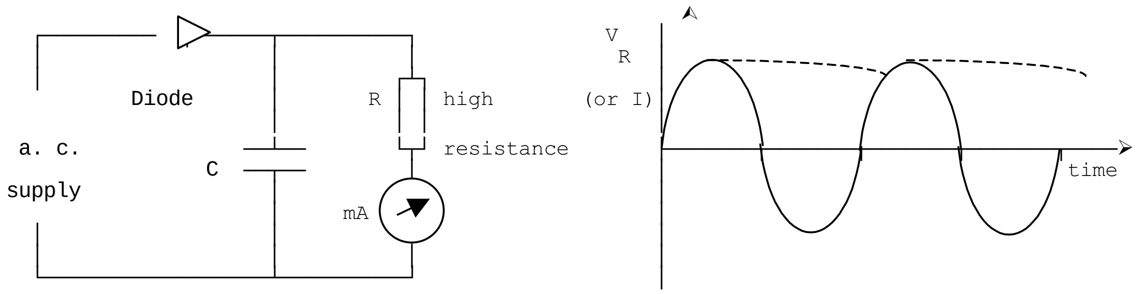


Figure 6.30 - Capacitor charging method

(ii) Using neon lamp

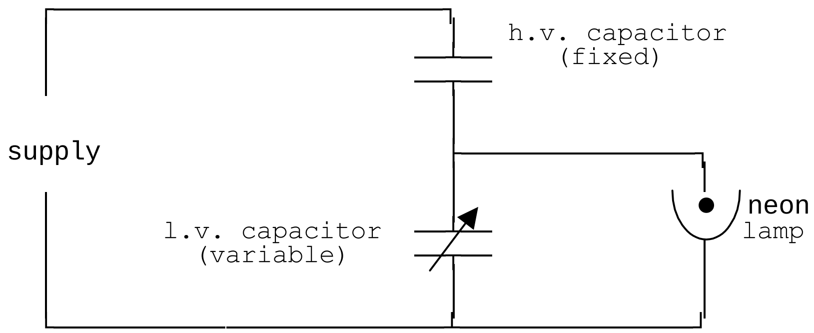


Figure 6.31 - Using neon lamp

A neon tube (if the voltage at which the lamp strikes is known) can be used with a capacitive potential divider to obtain the peak value of an applied voltage waveform. The low voltage variable capacitor is varied until the neon lamp strikes.

From the ratio of the capacitances, the supply voltage can be calculated. Since the extinction voltage is more constant than the striking voltage, the extinction voltage could be used as the standard. An accuracy of ± ½ % could be obtained with the striking voltage and an accuracy of ± ¼ % could be obtained with extinction voltage.

(iii) Rectifier-Capacitor current method

The best known and the most usual method of measuring the peak value is the rectified capacitor current method. A high voltage capacitor is connected to the hv supply with a rectifier ammeter in the earth connection. The indicated value will correspond to the peak value of the positive or negative half cycle. The diode used in series with the milliammeter should have a low forward resistance and a high reverse resistance a ratio of $1:10^5$ is desirable. Silicon diodes provide an ideal rectifier for the purpose.

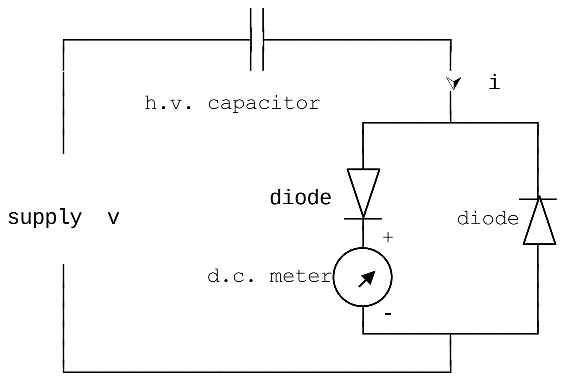


Figure 6.32 - Rectifier-capacitor current method

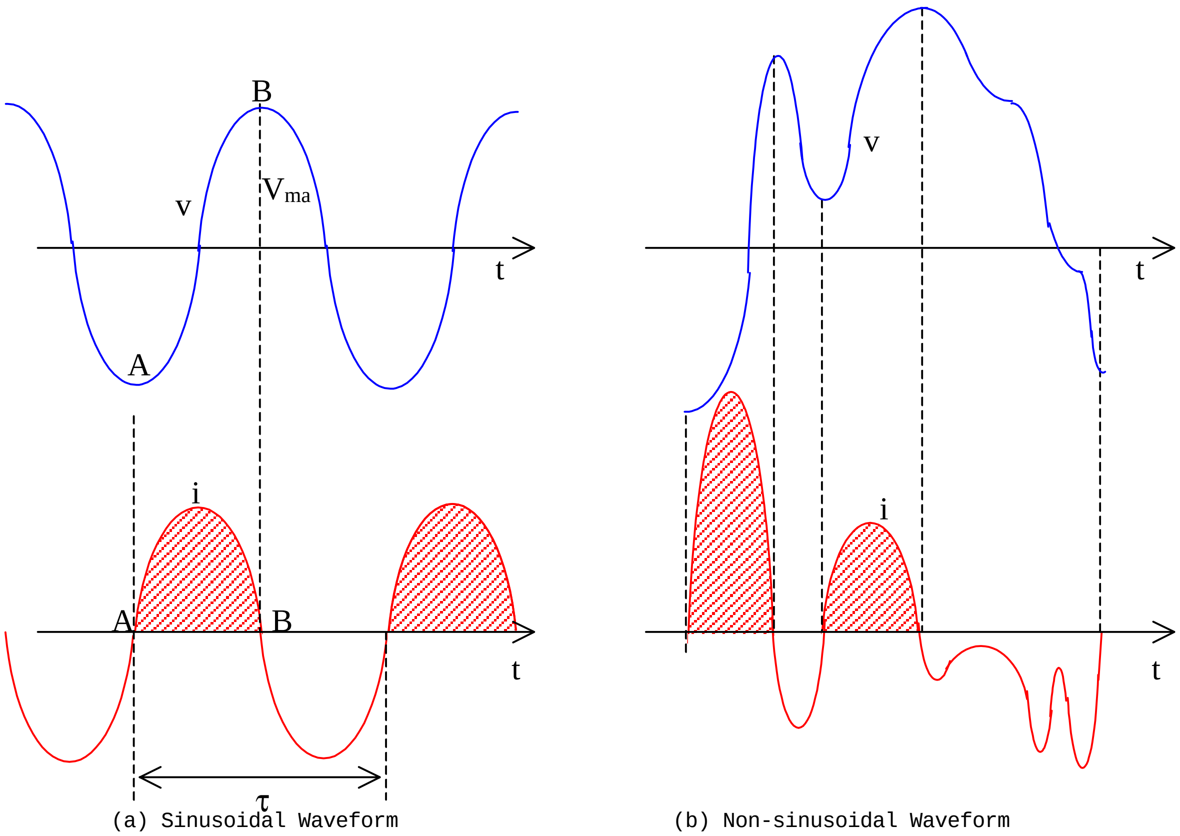


Figure 6.33 - Waveforms for peak measurement

For the circuit shown in figure 6.32, and the corresponding waveforms in figure 6.33 (a),

$$i = C \frac{dv}{dt}, \quad \text{so that} \quad \int_A^B i \, . \, dt = \int_A^B C \, . \, dV$$

$$\therefore \; I_{av} \, . \, \tau = C \, . \, 2\, V_{max}, \quad \text{giving} \quad V_{max} = \frac{\tau \, . \, I_{av}}{2\,C} = \frac{I_{av}}{2\,C\,f}$$

Since a d.c meter is used it would read I_{av}, and hence would correspond to the maximum value of voltage, independent of the waveform, except in the case when there is more than one maxima and minima per cycle. In such a case the meter reading would no longer corresponds to the actual maxima (Figure 6.33(b)), but an addition of successive peak-to-peaks.

Instead of using a half wave rectifying unit as in figure 6.32, we could also used a full wave rectifying unit as shown in figure 6.34.

In this case, the reading of the meter would effectively be double giving the result

$$V_{max} = \frac{I_{av}}{4\,C\,f}$$

Thus using either half wave or full wave rectifying units, we can obtain the peak value of the voltage independent of the wave form, if the capacitance and frequency are known from the reading of the d.c meter.

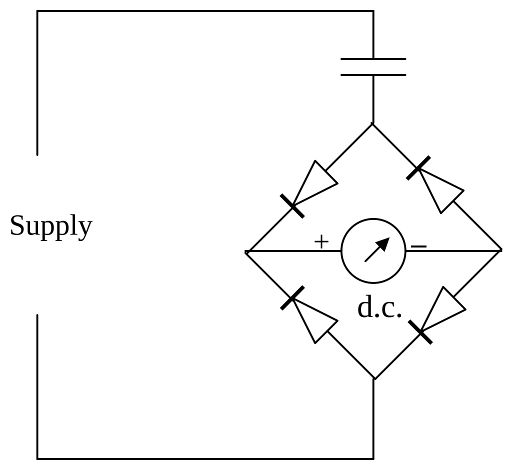


Figure 6.34 - Full wave circuit

6.4.2 Oscilloscope for measurement of fast transients

High voltage oscilloscopes are used for the study of fast transient phenomena, particularly in the work on high-voltage and on spark breakdown in small gaps.These have a high sweep speed. Since the speed is high, the intensity is lowered and hence a higher intensity is required. In these the beam should not come on till the transient comes in because;

(a) if it is stationary, the spot of high intensity would fog the photograph before the transient comes on, and

(b) if it is moving, the beam may have swept before the transient comes.

Thus the beam should be brought on just before the transient comes on, by being triggered by the transient. The transient should come on the Y-plate only shortly after the beam, so that the whole transient is clearly seen. For this a delay cable is used.

The delay cable ensures that the transient appears slightly after the beam comes on.

Such a scope can have a maximum of 50 V to 100 V applied across Y plate so that we would have to use a potential divider. For high writing speed,the anode - cathode voltage should be high (50 - 100 kV). The sweep generator should produce a single sweep (not repetitive) , as transients are not repetitive, and triggered by the signal. The delay cable causes the signal to appear at the Y-plates a fraction of a micro second after the sweep generator is triggered (100m length of cable may cause a delay of about 0.3 μs.

6.5 Measurements of capacitance and loss tangent

6.5.1 High Voltage Schering Bridge

The high voltage Schering bridge is the method most widely used for measuring capacitance and loss tangent (or

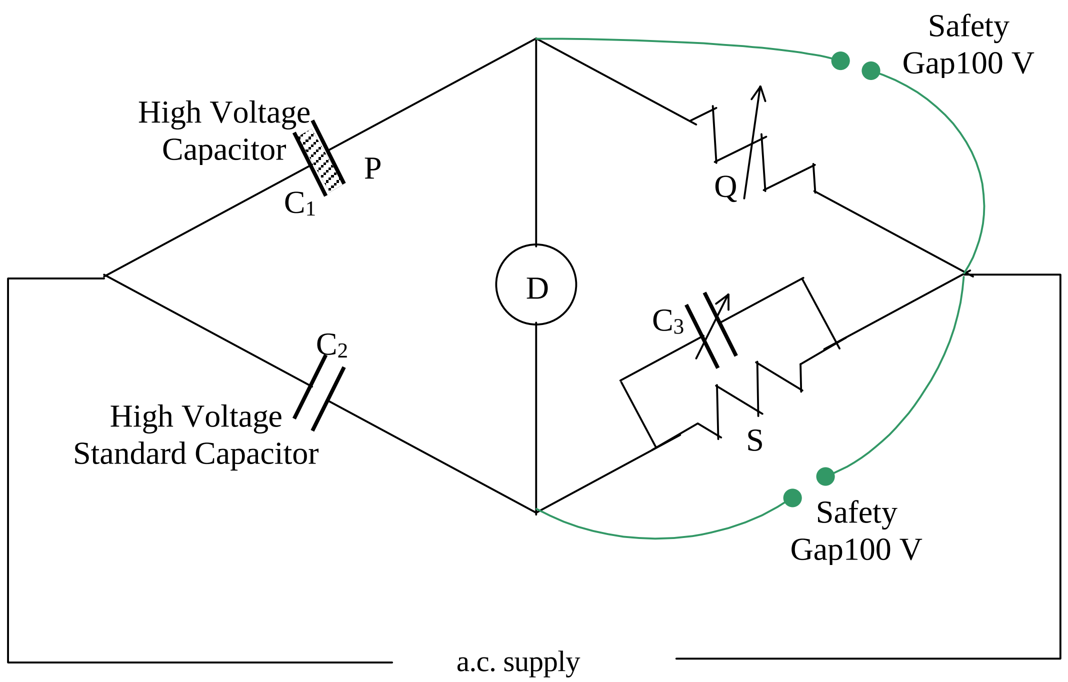


Figure 6.35 - High Voltage Schering Bridge

power factor) in dielectrics. Figure 6.35 shows the arrangement.

One arm of the bridge is the high voltage test capacitor (assumed to be represented by a series combination of capacitance C_1 and resistance P). The other three arms are a standard high voltage capacitor C_2 (generally a loss free air capacitor of value 100 to 500 pF) a variable low resistance Q, and a parallel combination of a standard low resistance S and a variable capacitance C_3.

The high voltage supply for the bridge is obtained through a high voltage transformer. For reasons of safety, only the high voltage test capacitor and the high voltage standard capacitor will be at high voltage. The other components are at low voltage and are not allowed to have voltages greater than about 100 V applied across them by means of safety gaps connected across them (The safety gaps are either gas discharge gaps or paper gaps). The impedance of these arms must thus necessarily be of values much less than that of the high voltage capacitors. For measurements at power frequencies, the detector used is a vibration galvanometer, usually of the moving magnet type (If the moving coil type is used, it has to be tuned). The arms Q and C_3 are varied to obtain balance.

It can be shown that this bridge is frequency independent, and that at balance

$$\frac{C_2}{C_1} = \frac{Q}{S}, \quad \text{also} \quad \frac{P}{Q} = \frac{C_3}{C_2}$$

power factor angle = φ, loss angle = $\pi/2 - \varphi = \theta$

$$\theta \approx \tan\theta = \omega P C_1 = \omega C_3 S$$

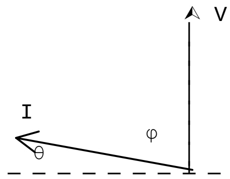


Figure 6.36

The low voltage end of the bridge is usually earthed, and since the voltages across Q and S are limited to about 100 V, the detector would also be near earth potential. Thus all the variable arms and the detector can be safely handled by the operator.

It should be noted that the bridge is an unequal arm bridge, so that the relative sensitivity will be small. However, since the applied voltage is high, this is not a practical disadvantage and a reasonable variation can be obtained across the detector.

Since the value of the standard capacitor must be accurately known, there should be no distortion of the field in it. Thus a high voltage guard is provided in it design. This guard is earthed directly (which causes a small error), or kept at the same potential as the main electrode without a direct connection as shown in figure 6.37.

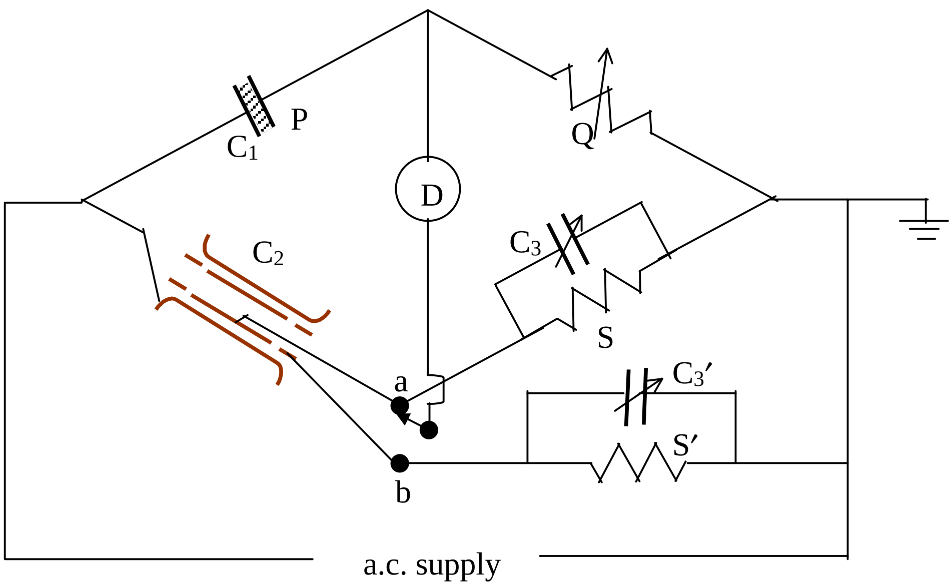


Figure 6.37 - Bridge with guarded standard capacitor

The following procedure is used to have the guard electrode at the same potential as the main electrode. The bridge is adjusted for balance with the switch in position (a) - the normal Schering Bridge. Then with the switch in position (b) the bridge is again balanced using only S' and C_3'. This ensures that finally **a** and **b** are at the same potential (same potential as the other end of the detector). Successive balance is carried out in positions **a** and **b** alternately until final balance is obtained. This connection can be used for capacitances up to 2000 pF.

When it is required to obtain higher value unknown capacitances (such as in the case of a very long cable), the circuit is modified in the following manner so that high current variable resistance standards would not be required. In this case we have a high current fixed value resistor shunted by a low current variable high resistance which acts similar to a potential divider. The expression at balance is obtained by converting the mesh consisting of r, p and Q into star form, thus obtaining the normal schering bridge arrangement.

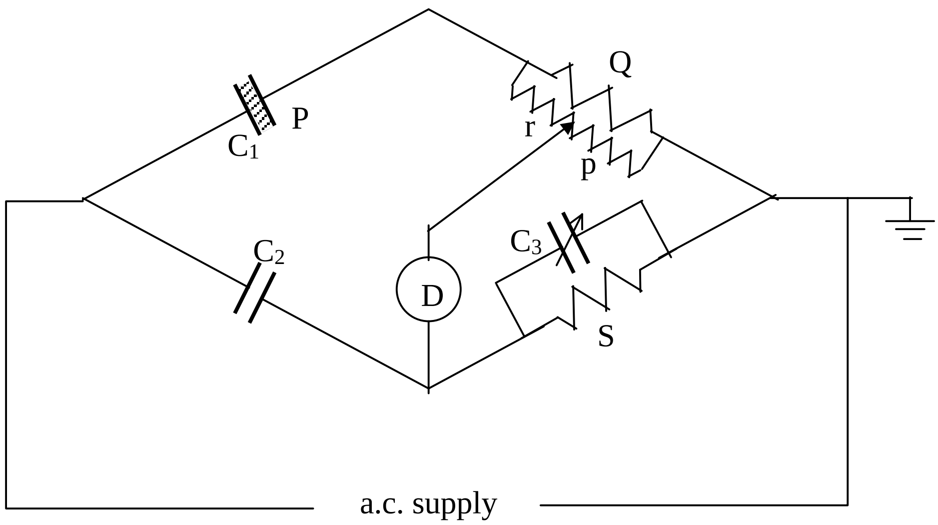


Figure 6.38 - Schering Bridge for high capacitances

At balance, it can be shown that

$$C_1 = C_2 \frac{S}{Q} \frac{Q + r + p}{p}, \quad \text{also} \quad P =$$

$$\text{so that} \quad \tan\theta = \omega C_3 S \left[1 - \frac{C_2 r}{C_3 p} \right]$$

In the case of a cable already buried or earthed, then we would have to earth the end of the source near the test capacitor. Then all the equipment, and hence the operator would have to be at a high voltage to earth. The operator can either operate the instruments using long insulated rods, or get into a Faraday cage (A cage which is raised to the same potential as the high voltage electrode so that there is no difference in potential). The earthing of the test capacitor near the detector end instead of the source end would bring the instruments near earth potential, but is not used due to the introduction of stray capacitances by this means which would cause measuring errors.

6.5.2 Dielectric loss measurement using Oscilloscope

In an oscilloscope, if two alternating voltages of the same frequency are applied to the x and y plates, the resulting figure will be an ellipse. When the two voltages are in phase, the figure will be a straight line with an enclosed area of zero. As the phase angle increases, the area increases and reaches a maximum when the phase angle difference is 90^o.

This property is made use of in dielectric loss measurements. A potential difference proportional to the applied voltage is applied to one pair of plates and a potential difference proportional to the integral of the current through the dielectric is applied to the other pair. Since the loss is to be measured in a dielectric sample, a lossless large capacitor is connected in series with the sample.

The voltages across the capacitor and across the sample are applied across the two plates. The area of the ellipse thus formed is proportional to the power loss in the dielectric. If the power loss in the dielectric is zero, the figure traced out on the oscilloscope would be a straight line.

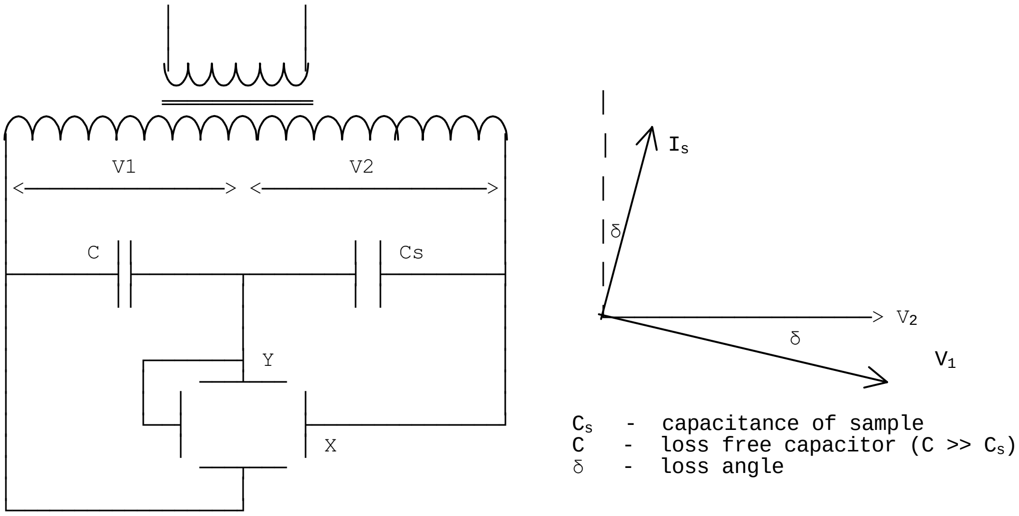


Figure 6.39 - Dielectric loss measurement using oscilloscope

The use of the standard capacitor C ensures that the voltage across it is 90^o out of phase with the current. Hence the angle on which the area of the ellipse depends is not the power factor angle but the loss angle.

$$\text{Power loss in } C_s = V_2 I_s \sin\delta$$

The **y**-deflection on the oscilloscope is proportion to $\mathbf{v_1 = V_{1m} \sin(\omega t - \delta)}$ and the **x**-deflection is proportional to $\mathbf{v_2 = V_{2m} \sin \omega t}$ which is taken as the reference.

i.e. $$y = a \,.\, V_{1m} \sin(\omega t - \delta) = a \,.\, (I_{sm}/\omega C) \sin(\omega t - \delta)$$

and $$x = b \,.\, V_{2m} \sin \omega t$$

where a, b are constants.

The area of the ellipse traced out on the oscilloscope screen is given by

$$A = \int y\,.\,dx = \int_0^T a\,.\frac{I_{sm}}{\omega C}.\sin(\omega t - \delta).b.V_{2m}.\omega.\cos\omega t.dt$$

$$= \frac{a.b}{C}.\frac{2\pi}{\omega}.I_s V_2 \sin\delta$$

It is thus seen that the area of the ellipse is proportional to the power loss.

6.5.3 Detection of internal discharges

Detection of internal discharges can be carried out by various methods. It can be done by (a) visual methods - in transparent insulation the sparks can be detected by either direct observation or by using a photo-electric cell; (b) audible methods - the audible clicks given out by the discharges may be detected by using a microphone, an ultrasonic detector or other transducer; and (c) electrical methods - these will be detailed out in the following sections.

Electrical Methods of discharge detection

(a) Using a corona detector

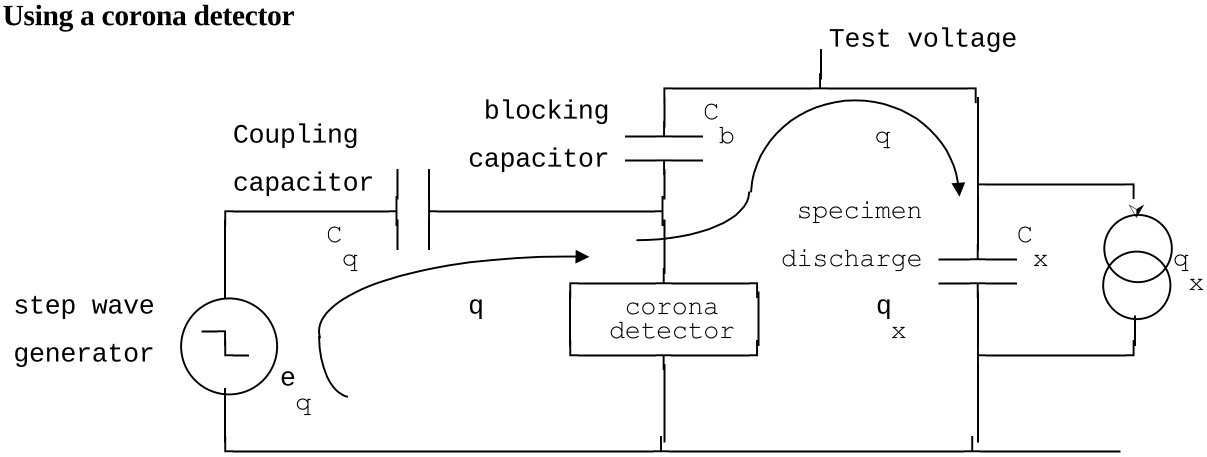


Figure 6.40 - Discharge detection using corona detector

The discharge detector shown in the figure 6.40, is basically a wide band amplifier with a gain of 10^6 and a bandwidth of 10 kHz to 150 kHz. The lossy dielectric sample may be represented by a capacitance C_x in parallel with its discharge q_x. For the charge flow, it may be assumed that the high voltage supply circuit provides almost infinite impedance, and that the step wave generator has a negligible internal impedance. Thus the discharge flow path is as shown on the diagram. When the corona detector shows no discharge across it, the voltage drop caused by the coupling capacitor C_q must equal the voltage produced by the step wave generator, and the voltage across the blocking capacitor C_b and by the specimen must must be zero. Since the specimen has its own discharge in the opposite direction to **q**, the total discharge through the specimen in the direction of **q**, must be **q - q**$_x$.

Since no drop occurs across the detector at balance,

$$e_q - \frac{q}{C_q} = 0, \quad \text{i.e. } q = e_q\, C_q$$

$$\text{also} \quad \frac{q}{C_b} + (q - q_x)/C_x = 0$$

$$\text{i.e.} \quad q\left(\frac{1}{C_b} + \frac{1}{C_x}\right) = \frac{q_x}{C_x}$$

$$q_x = e_q\, C_q \left(1 + \frac{C_x}{C_b}\right)$$

Substituting for **q**, we have

The energy dissipated in the void is given by

$$w = \tfrac{1}{2}\, q_x\, V_0$$

where V_0 = peak voltage across specimen at inception voltage

(b) Using the oscilloscope with filtration and amplification

Internal discharges occurring within dielectric samples can be observed by measuring the electrical pulses in the circuit where such discharges occur.

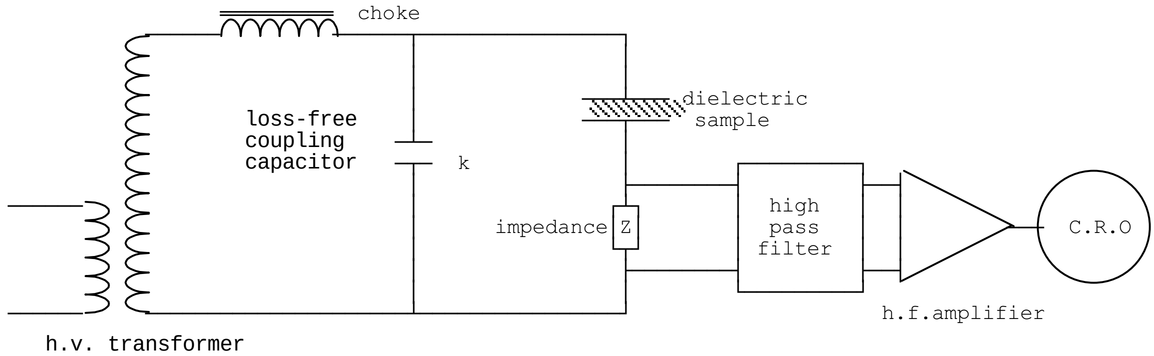
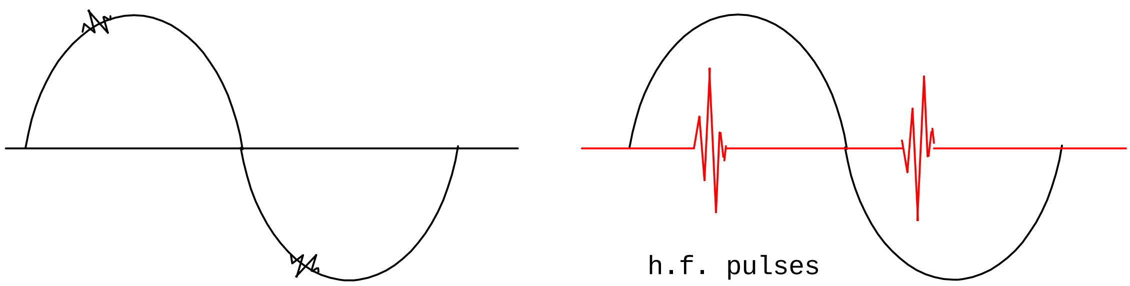


Figure 6.41 - Circuit for discharge detection

The apparatus used in the observation (namely the coupling capacitor and the impedance) should be discharge tree, so that all the discharges caused is due to the sample. However, discharges occurring in the transformer and the choke are short circuited through the coupling capacitor and do not affect the measurement. The discharge pulses caused in the sample are of high frequency, so that we bypass the low frequency and amplify the high frequency in the measurement circuit.



low amplitude high frequency pulses
superposed on sine wave (power freq)

Figure 6.42 - Output waveforms

The coupling capacitor k is provided so that the high frequency components would be provided with a low impedance path. In the absence of this low impedance path, the path is highly inductive so that these would act as high impedance to the high frequency.

(c) Using oscilloscope with elliptical time base

In many instances, the detector cannot be used close to equipment, and matching units are employed which permit the use of about 30 m of co-axial lead between detector and the source of discharge. Calibration is done by injection of a known step voltage into the system. This gives direct calibration of discharge amplitude and takes into account the response of the amplifier. The discharge detector input circuit is shown in figure 6.43. The output of the amplifier is displayed on a oscilloscope having an elliptical time base. The time base is produced from a phase shifting R-C network. It is possible to distinguish between several types of discharges from the nature of the output displayed on the oscilloscope.

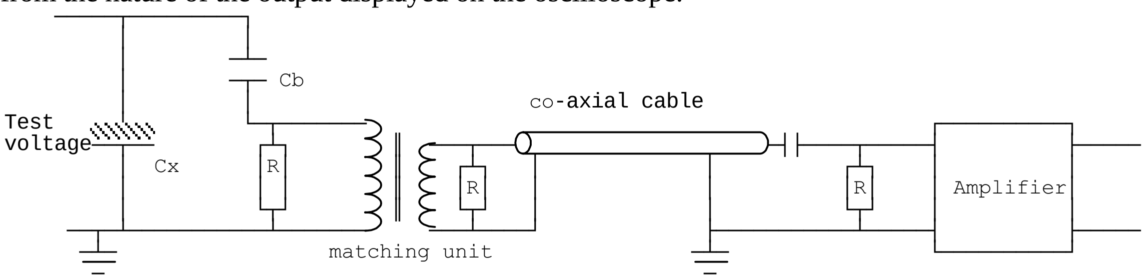


Figure 6.43 - Discharge detector input circuit

Displays on the oscilloscope for some typical discharges are shown in figure 6. together with corresponding waveforms arising out of external discharges as well as from contact noise.

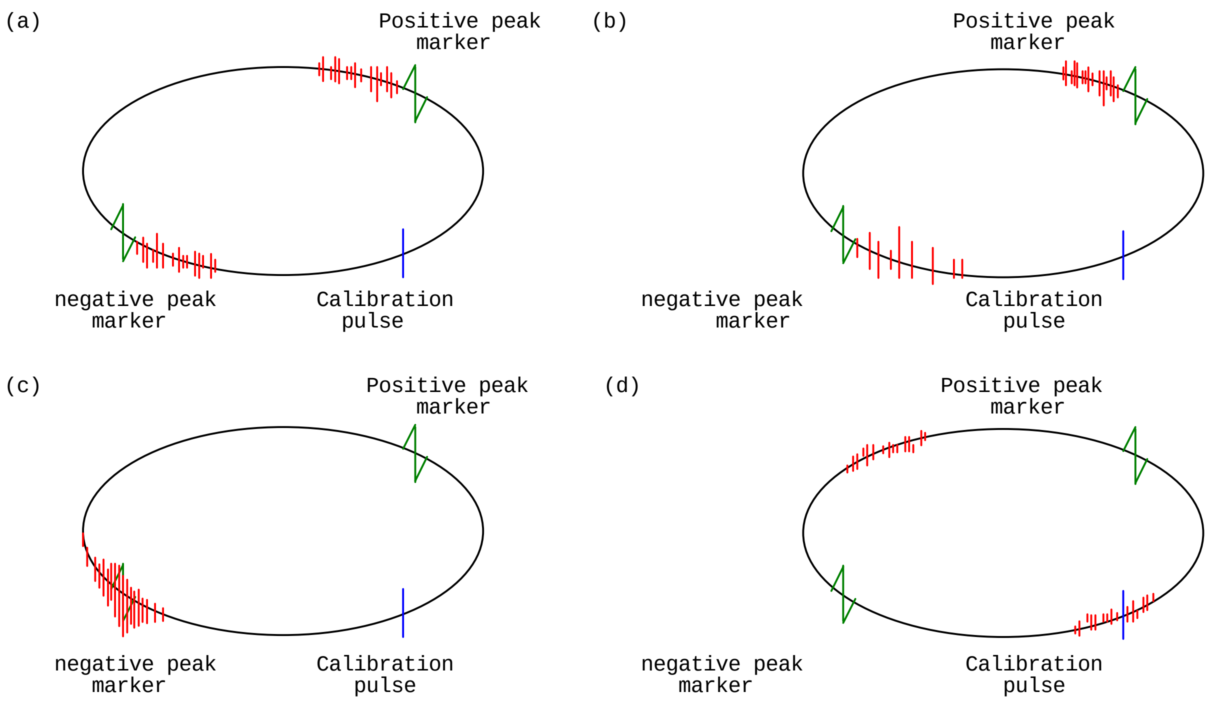


Figure 6.44 - Displays for typical discharges

(a) For a typical oil-impregnated paper capacitor: The discharges are approximately equal in magnitude and number in the two half cycles, but have opposite polarity.

(b) For a polythene insulated cable: The discharges show the asymmetry typical of discharges between a conductor and the solid insulation for a polythene insulated cable.

(c) External discharges: Corona produces a very symmetrical display about the negative voltage peak and as the voltage increases the discharges spread over a larger part of the ellipse but remain symmetrical.

(d) Contact noise: Bad contacts in the system produce many small discharges at the current peaks.

Oscilloscope connections for elliptical time base

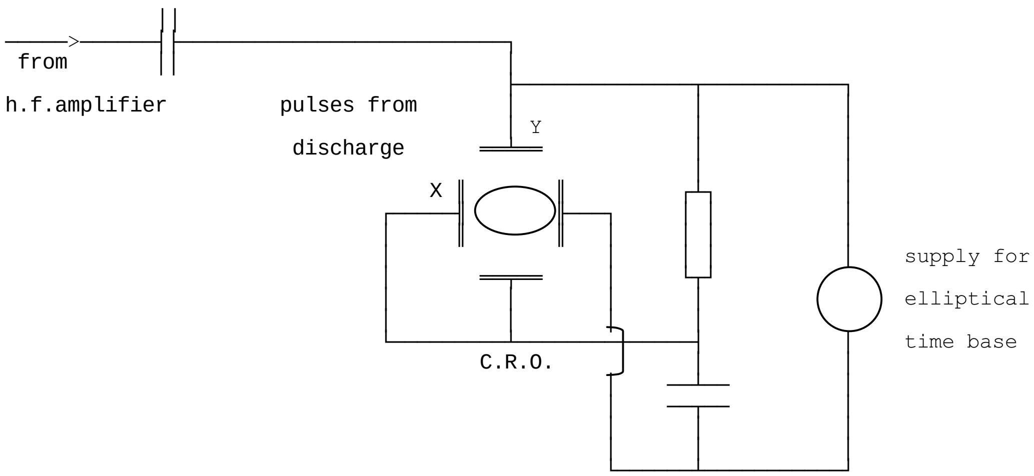


Figure 6.45 - Generation of elliptical time base

The oscilloscope X and Y plates are supplied from a separate source so as to form an ellipse on the screen. By applying the output from the high frequency amplifier to the Y-plates, we can obtain the high frequency pulse superposed on the ellipse. The height of the pulse can be measured.

Knowing the voltage sensitivity of the scope, we can find the magnitude. Knowing the characteristics of the amplifier we can calculate the output from the circuit. Then deriving a relation between the discharge from the sample and the output across the impedance we can know the discharge from the sample.

Calculation of internal discharge from measurements

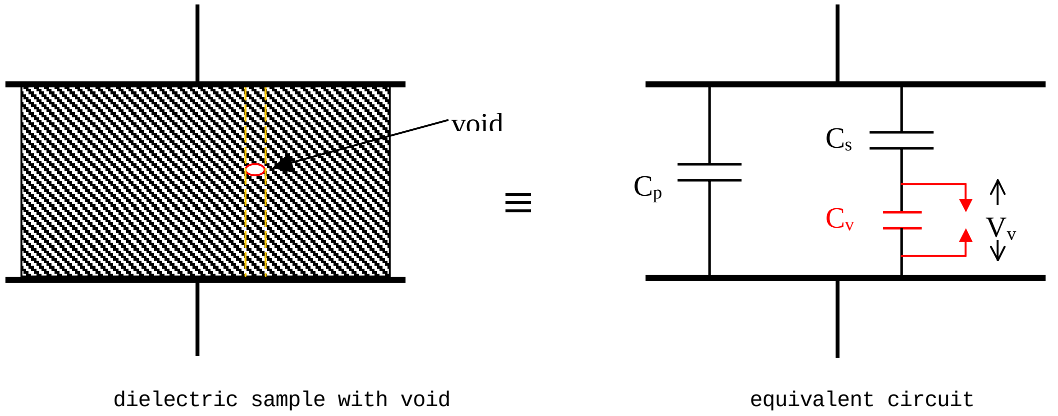


Figure 6.46 - Equivalent circuit of dielectric with void

The internal discharges can be analysed by considering a single flaw in the dielectric as shown in figure 6.46.

The dielectric can be considered as being composed of a number of capacitances. Between the two electrodes (other than in the strip containing the flaw), the material is homogeneous and can be represented by a single capacitance between the electrodes. The strip containing the flaw can also be considered as made up of three capacitances in series; one representing the capacitance of the flaw and the other two representing the capacitance on either side of the flaw.

The series capacitance on either side can be combined together to form a single capacitance as shown in figure 6.47.

a - capacity of rest of dielectric
b - capacity of section of dielectric in series with cavity
c - capacity of cavity

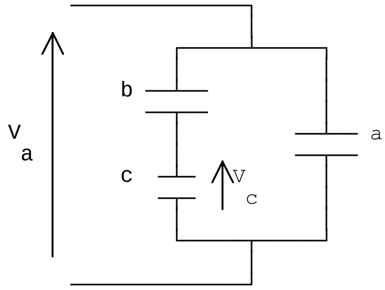


Figure 6.47 - Equivalent circuit

If the voltage across the cavity is greater than a certain critical value, then the cavity would breakdown, the cavity capacitor discharges instantly, and the voltage across the cavity would fall to zero.

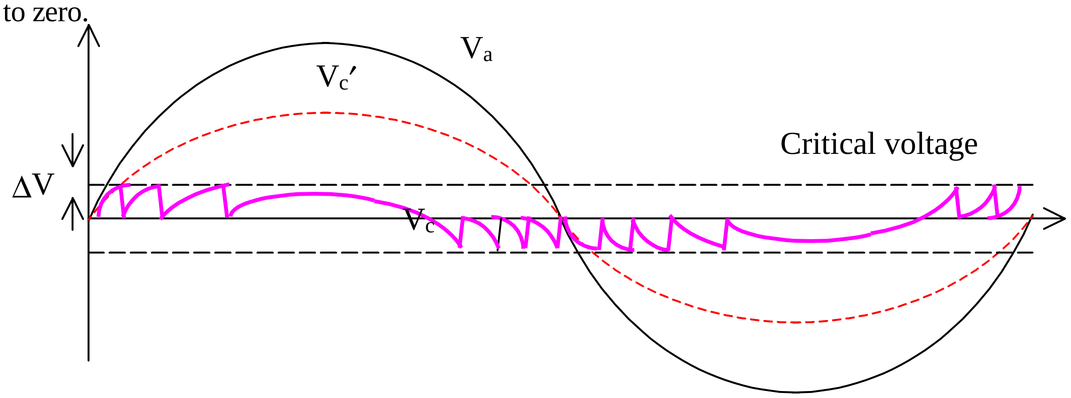
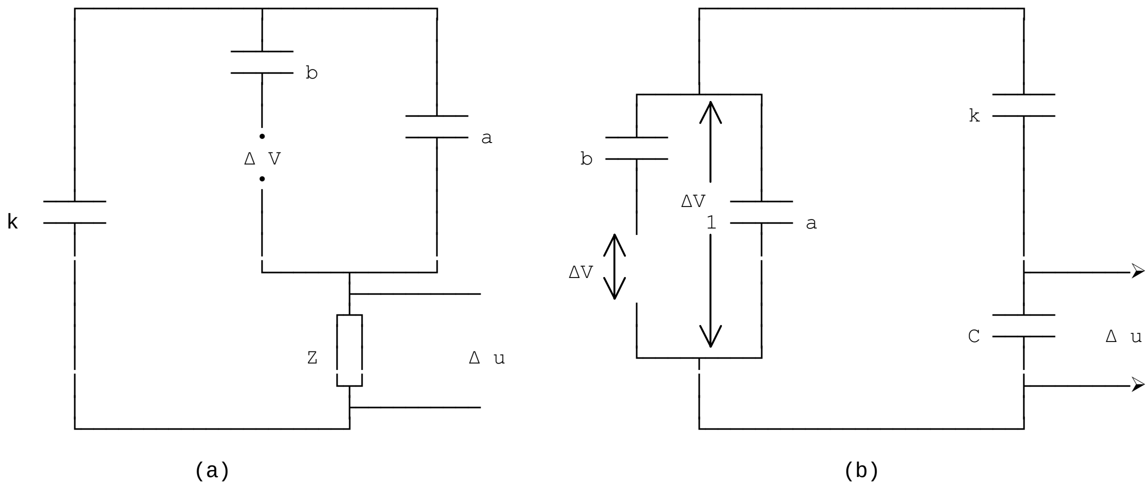


Figure 6.48 - Discharge waveforms across void

The cavity capacity again charges up within a very short period, and again collapses discharging the charge.



where Δu - measured voltage across impedance Z

ΔV - critical voltage across cavity

ΔV_1 - Voltage across sample

Figure 6.49 - Circuit for analysis

This process repeats itself until the voltage across the cavity falls below the critical value. This gives rise to a series of high frequency pulses (each of duration of the order of 100 ns). Figure 6.49 shows the actual circuit with the sample replaced by its equivalent circuit.

Consider the case of the impedance Z being a capacitor C. The voltage ΔV_1 would also be the voltage across the series combination of C and k.

Thus

$$\frac{\Delta V_1}{\Delta V} = \frac{b}{b + a + \frac{C\,k}{C+k}}, \quad \text{so that} \quad \frac{\Delta u}{\Delta V_1} = \frac{k}{k+C}$$

$$\therefore \quad \Delta u = \frac{\Delta V\,.\,b}{b + a + \frac{C\,k}{k+C}} \cdot \frac{k}{k+C}$$

$$= \frac{b\,.\,\Delta V}{(b+a)\,(1 + C/k) + C}$$

In this expression **b.ΔV** is the charge dissipated in the discharge. Also, since the cavity is small, its capacity has negligible effect on the total capacitance.

$$\Delta u = \frac{q}{(\text{apparatus capacitance})\,(1 + C/k) + C}$$

If the impedance across which the voltage is measured is a parallel combination of a capacitance C and a resistance R, then the above calculated value of voltage would correspond to the value before the capacitor C discharges through the resistance R exponentially, and the actual expression would be

$$\Delta u = \frac{q \cdot e^{-\frac{t}{CR}}}{(\text{apparatus capacitance})\,(1 + C/k) + C}$$

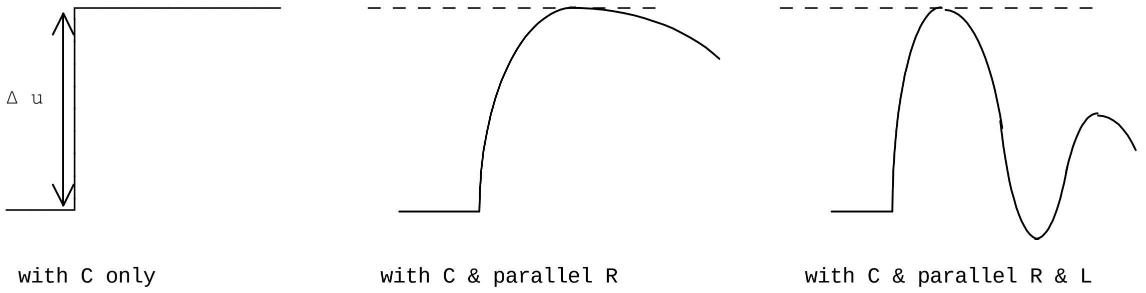


Figure 6.50 - Output waveform

All the apparatus other than the sample should be as discharge free as possible. If there are external discharges other than from the sample, the value of Δu would be due to the total discharge and the calculations would be in error. A method of avoiding external discharges is by having a bridge type of circuit as shown in figure 6.51.

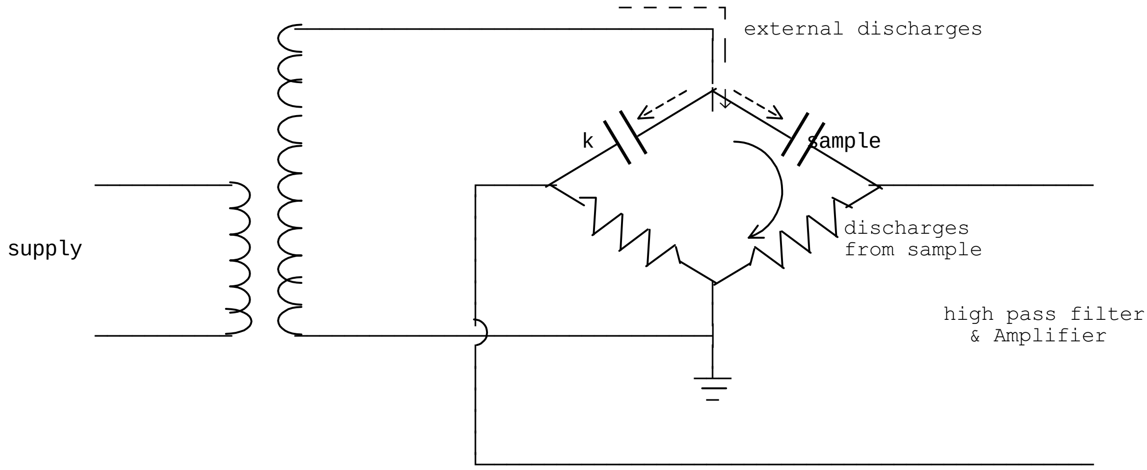


Figure 6.51 - Circuit to avoid effects of external discharges

In this circuit, external discharges would affect both the resistances equally, so that if the detection is done across the two resistances, it would measure only the discharges due to the internal flaws in the sample.

6.5.4 Measurement of dielectric constant and dissipation factor of a liquid dielectric at high frequencies using a resonance method

The test cell used in the measurement consists of a brass cell inside which is suspended a brass electrode from a perspex cover. The outer cell is the earthed electrode, and there is a gap of 3 mm all round between this and the inner brass electrode. Since the electrodes are near each other, we have to take into account the stray capacitance as well.

The test cell is connected in parallel with a variable capacitor and made part of a resonant circuit as shown in figure 6. . In the circuit, R is a high series resistance used to keep the total current in the circuit very nearly constant. The stray capacitance C_0 of the test cell can be obtained by removing the inner electrode of the test cell and with the empty cell resonance obtained.

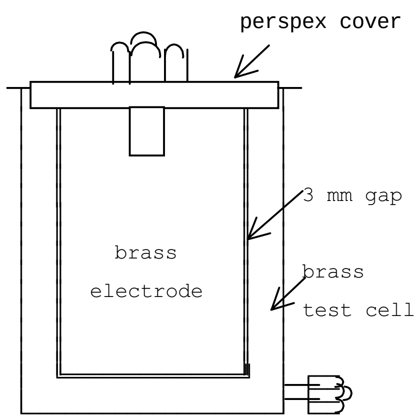


Figure 6.52 - Test Cell

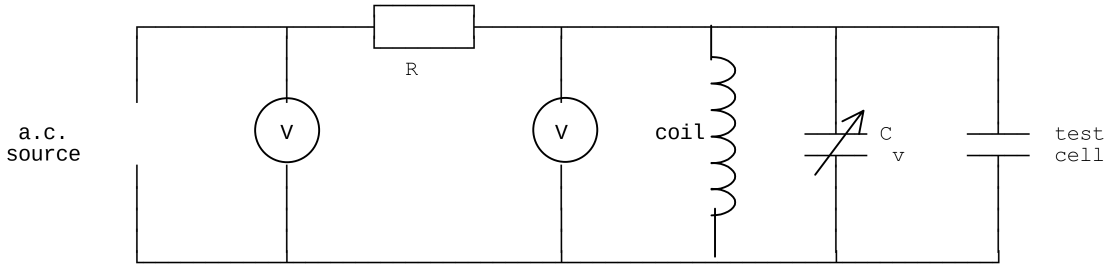


Figure 6.53 - Test Circuit

If C_v is the value of the variable capacitor at resonance, at the angular frequency ω, then

$$\omega^2 L(C_v + C_0) = 1$$

The above calculation is required only if the stray capacitance value is actually required. Otherwise the stray capacitance can be eliminated using the following procedure at the selected frequency (say 1 MHz).

(i) With the outer cell and with only the brass screw and the perspex cover of the inner cell in position, the variable capacitor C_{v0} is varied until resonance is obtained. Under this condition, only the stray capacitance C_0 is present, and the total capacitance will be at resonance with the coil inductance L. The effective capacitance, in this case, is $C_{v0} + C_0$.

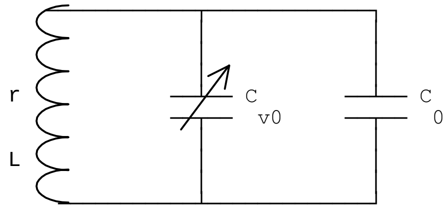


Figure 6.54 - Equivalent circuit for case (i)

The Q-factor of the circuit will be dependant on the resistance r of the coil. The Q-factor can be determined from the half-power points. The variable capacitance is varied in either direction from resonance until the half-power points (voltage corresponding to 1/√2) are reached. If C_+ and C_- are the values at the half power points,

$$Q = \frac{C_+ + C_-}{C_+ - C_-} = \frac{2C + (\Delta C_+ - \Delta C_-)}{\Delta C_+ + \Delta C_-}$$

where ΔC_+, ΔC_- are the variations at the half-power points

then it can be shown that the Q factor is given by
If Q is high,

$$\Delta C_+ = \Delta C_- = \Delta C, \text{ so that } Q = \frac{C}{\Delta C}$$

(ii) The inner electrode is now screwed in, and the circuit is again adjusted for resonance at the same frequency.

If C_a is the capacitance of the active portion of the test cell with air as dielectric, and R_a is the equivalent shunt resistance of the circuit with air as dielectric, then the total value of the capacitance required must remain the same. This is true for all cases.
Thus we have

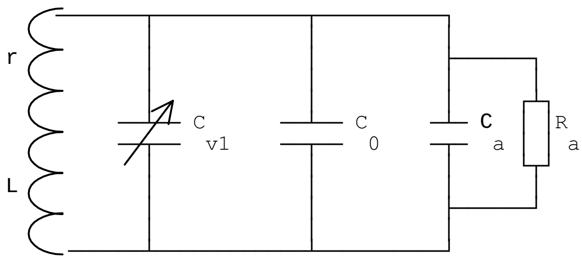


Figure 6.55 - Equivalent circuit for case (ii)

$$C_{v0} + C_0 = C_{v1} + C_0 + C_a$$

$$\therefore C_a = C_{v0} - C_{v1}$$

The Q-factor of the circuit however will be different from the earlier value, due to the additional parallel resistance. If the parallel equivalent resistance of the inductor is considered, then it is seen that the overall Q factor Q_a is given as the parallel equivalent of the Q-factors of the coil resistance and the resistance R_a. The Q-factor corresponding to the resistance R_a is $\omega C R_a$, so that

$$\frac{1}{Q_a} = \frac{1}{Q_L} + \frac{1}{\omega C R_a}$$

(iii) The liquid is now introduced into the test cell. [The liquid level should be slightly below the perspex cover, so that the surface condition of the perspex is not changed.] If R_k is the equivalent shunt resistance of the liquid, and k is the relative permittivity of the liquid dielectric, then the capacitance of the active portion of the test cell with the liquid would be kC_a.

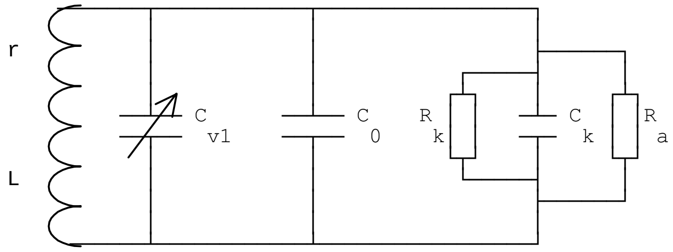


Figure 6.56 - Equivalent circuit for case (iii)

If C_{v2} is the value of the variable capacitor at resonance, then

$$C_{v0} + C_0 = C_{v2} + C_0 + k\,C_a$$

$$\text{giving} \quad k\,C_a = C_{v0} - C_{v2}$$

$$\therefore \; k = \frac{C_{v0} - C_{v2}}{C_{v0} - C_{v1}}$$

Also we have the equivalent Q factor Q_k equivalent to the parallel equivalent. Thus

$$\frac{1}{Q_k} = \frac{1}{Q_L} + \frac{1}{\omega C R_a} + \frac{1}{\omega C R_k}$$

Thus the inverse of $\omega C R_k$ can be determined from

$$\frac{1}{\omega C R_k} = \frac{1}{Q_k} - \frac{1}{Q_a}$$

$$\frac{1}{Q_k}, \frac{1}{Q_a} \text{ can be calculated using } \frac{1}{Q_k} = \frac{(\Delta C)_k}{C}, \; \frac{1}{Q_a} = \frac{(\Delta C)_a}{C}$$

$$\text{loss factor} = \frac{1}{\omega C_k R_k} = \frac{1}{\omega C R_k} \cdot \frac{C}{C_k}$$

$$= \frac{C}{k\,C_a} \cdot \left[\frac{1}{Q_k} - \frac{1}{Q_a}\right] = \frac{C}{k\,C_a} \cdot \frac{[\Delta C_k - \Delta C_a]}{C}$$

$$= \frac{1}{k\,C_a} \cdot [\Delta C_k - \Delta C_a]$$

The loss factor of the dielectric is given by

$$\text{i.e. loss factor} = \frac{\Delta C_k - \Delta C_a}{C_{v0} - C_{v2}}$$

Note: in making connections it is essential that care is taken to minimise stray capacitances by using short leads, and the components should not be disturbed during the experiment.

6.5.5 Ionic Wind Voltmeter

When a highly charged point is situated in air or other gas, a movement of the air around the point is observed. This is referred to as the electric wind and is brought about by the repulsion of ions from the surface of the point by the intense electro-static field. These ions colliding with uncharged molecules of air carry them with it setting up the electric wind. A similar wind is observed also at the earth electrode. In the ionic wind voltmeter, a hot wire, of platinum-gold alloy, included in one arm of a Wheatstone bridge network is used as the earthed electrode of high-tension gap. Before the high voltage is applied, the bridge is balanced. When the voltage of the gap exceeds the "threshold voltage" (voltage required before the potential gradient is sufficient for ionization to commence), the electric wind cools the hot wire and hence reduces the resistance. This reduction causes an appreciable out-of-balance voltage in the bridge. The voltage waveform influences the instrument reading, and the instrument is calibrated for a sine wave.

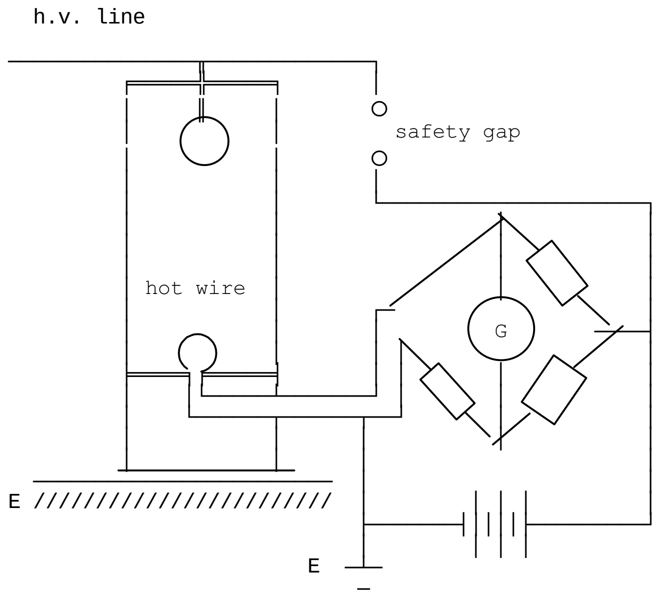


Figure 6.57 - Ionic Wind Voltmeter

The voltmeter can be used to determine either the peak value or the r.m.s. value of alternating voltages and direct voltages. The principle advantages are that the h.v. may be measured by an observer at some distance from the charged conductors, and the robust construction and freedom from disturbances by temperature and weather conditions which make it suitable for outdoor use.

6.5.6 Dumb-bell Voltmeter

A rather specialized way of measuring r.m.s. voltage was developed by F.M.Bruce in which the period of oscillation of a conducting spheroid in an electro-static field was determined. This enabled the voltage to be determined in terms of length and time, with an accuracy of 0.05%.

The instrument is shown on figure 6.58.

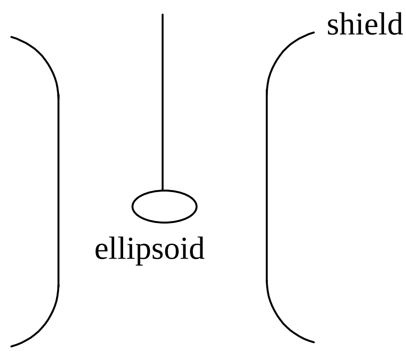


Figure 6.58 - Dumb-bell voltmeter