



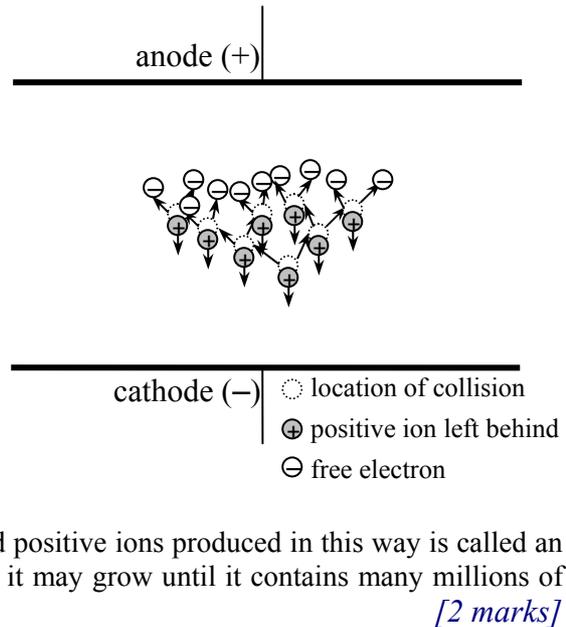
EE 427 – High Voltage Breakdown & Testing – Model Answers

[Answers given may be more than what would be expected from one candidate within the examination duration]

Level 4 Semester 2 Examination - August 2005

1. (a) The avalanche process is one of the processes which occur in the breakdown of gaseous dielectrics and is based on the generation of successive ionising collisions leading to an avalanche.

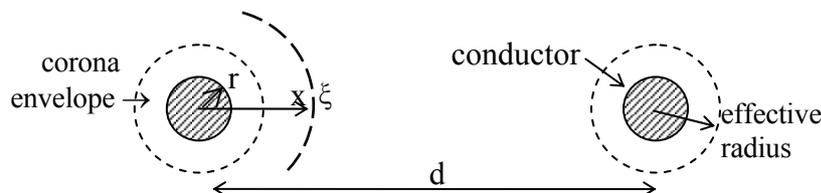
Suppose a free electron exists (caused by some external effect such as radio-activity or cosmic radiation) in a gas where an electric field exists. If the field strength is sufficiently high, then it is likely to ionize a gas molecule by simple collision resulting in 2 free electrons and a positive ion. These 2 electrons will be able to cause further ionization by collision leading in general to 4 electrons and 3 positive ions. The process is cumulative, and the number of free electrons will go on increasing as they continue to move under the action of the electric field. The swarm of electrons and positive ions produced in this way is called an electron avalanche. In the space of a few millimetres, it may grow until it contains many millions of electrons.



[2 marks]

- (b) When a voltage is applied, the stress surrounding a conductor is a maximum at the conductor surface itself, and decreases rapidly as the distance from the conductor increases. Thus when the stress has been raised to critical value immediately surrounding the conductor, ionisation would commence only in this region and the air in this region would become conducting. The effect is to increase the effective conductor diameter while the voltage remains constant. This results in two effects. Firstly, an increase in the effective sharpness of the conductor would reduce the stress outside this region, and secondly, this would cause a reduction of the effective spacing between the conductors leading to an increase in stress. Depending on which effect is stronger, the stress at increasing distance can either increase or decrease. If the stress is made to increase, further ionisation would occur and flashover is inevitable.

The condition for stable corona can be analysed as follows.



The electric stress ξ at a distance x from a conductor of radius r , and separated from the return conductor by a distance d is given by $\xi = \frac{l}{\epsilon_0} \cdot \frac{q}{2 \pi x l}$, where q is the charge on each conductor in length l .

$$\xi = \frac{l}{\epsilon_0} \cdot \frac{q}{2 \pi x l}$$

Thus the potential V can be determined from $V = \int \xi dx = \int_r^{d-r} \frac{q}{2 \pi x \epsilon_0} \cdot dx$

Since both charges (+ q and - q) produce equal potential differences, the total potential difference between the two conductors is double this value. Thus the conductor to neutral voltage, which is half the difference would be equal to this value is given by

$$V = \frac{q}{2 \pi \epsilon_0} \cdot \log_e \left(\frac{d-r}{r} \right)$$

Therefore the electric stress at distance x is given by $\xi_x = \frac{V}{x \log_e \frac{d-r}{r}}$, $\xi_x = \frac{V}{x \log_e \frac{d}{r}}$ if $d \ll r$

[Note; ξ_x and V can both be peak values or both rms values]

Under ordinary conditions, the breakdown strength of air, and hence the inception of corona ξ_{max} can be taken as 30 kV/cm (peak value) or $\xi_{rms} = 30/\sqrt{2} = 21.2$ kV/cm.

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 Since there is no electric stress within the conductor, the maximum stress will occur when x is a minimum, that is at $x = r$.

Thus if $E_{0,rms}$ is the rms value of the disruptive critical voltage to neutral, $\xi_{rms} = 21.2 = \frac{E_{0,rms}}{r \log_e \frac{d}{r}}$

When the surface of the conductor is irregular, it is more liable to corona. Thus an irregularity factor m_0 is introduced to account for this reduction. Typical values of this factor range from 0.98 for a roughened conductor down to about 0.85 for a 7 strand cable.

Corona will of course be affected by the physical state of the atmosphere, and hence by the air density. An air density correction factor δ is introduced, given by the usual expression, with p being the pressure expressed in **torr** and t being the temperature expressed in $^{\circ}\text{C}$.

$$\delta = \frac{p}{760} \cdot \frac{273 + 20}{273 + t} = \frac{0.386 p}{273 + t}$$

The disruptive critical voltage can then be written as in the following equation.

$$E_{0,rms} = \frac{21.2 \delta m_0 r \log_e (d/r)}{\text{kV to neutral}} \quad [3 \text{ marks}]$$

- (c) Impurities, which lead to the breakdown of commercial liquids below their intrinsic strength, can be divided into the following 3 categories.

(i) **Breakdown due to gaseous inclusions**

Gas or vapour bubbles may exist in impure liquid dielectrics, either formed from dissolved gasses, temperature and pressure variations, or other causes.

The electric field E_b in a gas bubble which is immersed in a liquid of permittivity ϵ_1 is given by

$$E_b = \frac{3 \epsilon_1}{2 \epsilon_1 + 1} E_0 \quad \text{where } E_0 \text{ is the field in the liquid in the absence of the bubble.}$$

The electrostatic forces on the bubble cause it to get elongated in the direction of the electric field. The elongation continues, when sufficient electric field is applied, and at a critical length the gas inside the bubble (which has a lower breakdown strength) breaks down. This discharge causes decomposition of the liquid molecules and leads to total breakdown.

(ii) **Breakdown due to liquid globules**

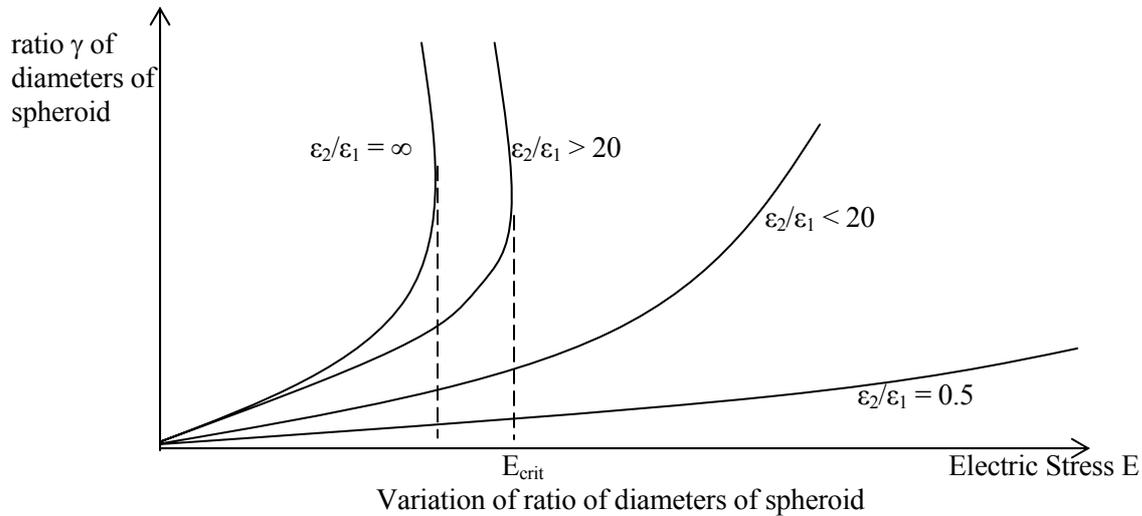
If an insulating liquid contains in suspension a globule of another liquid, then breakdown can result from instability of the globule in the electric field.

Consider a spherical globule of liquid of permittivity ϵ_2 immersed in a liquid dielectric of permittivity ϵ_1 . When it is subjected to an electric field between parallel electrodes, the field inside the globule would be given by $E = \frac{3 \epsilon_1}{2 \epsilon_1 + \epsilon_2} E_0$, where E_0 is the field in the liquid in the absence of the globule.

The electrostatic forces cause the globule to elongate and take the shape of a prolate spheroid (i.e. an elongated spheroid). As the field is increased, the globule elongates so that the ratio γ of the longer to the shorter diameter of the spheroid increases. For the same field E , the ratio γ is a function of ϵ_2/ϵ_1 .

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When $\epsilon_2 \gg \epsilon_1$ (generally when $\epsilon_2/\epsilon_1 > 20$), and the field exceeds a critical value, no stable shape exists, and the globule keeps on elongating eventually causing bridging of the electrodes, and breakdown of the gap. When $\epsilon_2/\epsilon_1 \gg 20$, the critical field at which the globule becomes unstable no longer depends on the ratio, and is given by E_{crit} .

$$E_{crit} = 1.542 \left(\frac{\sigma}{R \epsilon_1} \right)^{1/2} \text{ kV/cm}$$

where σ = surface tension of the globule (N/m)
 ϵ_1 = relative permittivity of the insulating liquid
 R = initial radius of globule (m).

Even a droplet of water even as small as $1 \mu\text{m}$ in radius (quite unobservable) can greatly reduce the breakdown strength of the liquid dielectric. Thus even submicroscopic sources of water, such as condensed breakdown products, or hygroscopic solid impurities, may greatly influence breakdown conditions. A globule which is unstable at an applied value of field elongates rapidly, and then electrode gap breakdown channels develop at the end of the globule. Propagation of the channels result in total breakdown.

(iii) Breakdown due to solid particles

In commercial liquids, solid impurities cannot be avoided and will be present as fibres or as dispersed solid particles. If the impurity is considered to be a spherical particle of permittivity ϵ_2 and is present in a

liquid dielectric of permittivity ϵ_1 , it will experience a force $F = \frac{1}{2} r^3 \epsilon_0 \frac{(\epsilon_2 - \epsilon_1)}{\epsilon_2 + 2 \epsilon_1} \Delta E^2$

where E = applied field, r = radius of particle.

Generally $\epsilon_2 > \epsilon_1$, so that the force would move the particle towards the regions of stronger field. Particles will continue to move in this way and will line up in the direction of the field. A stable chain of particles would be produced, which at a critical length may cause breakdown.

Because of the tendency to become contaminated, liquids are seldom used alone above 100 kV/cm in continuously energised equipment. However they may be used up to 1 MV/cm in conjunction with solids which can be made to act as barriers, preventing the line-up of solid impurities and localising bubbles which may form. [3 marks]

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(d) Surface Breakdown**Surface flashover**

Surface flashover is a breakdown of the medium in which the solid is surrounded, such as gas. The role of the solid dielectric in this flashover is to distort the field so that the electric strength of the medium is exceeded.

If a piece of solid insulation is inserted in a medium such that the solid surface is perpendicular to the equipotentials at all points, then the voltage gradient is not affected by the solid insulation.

An example of this is a cylindrical insulator placed in air in the direction of a uniform field. Field intensification will result when the solid insulation departs from the cylindrical shape. An air gap exists next to the electrode, and the stress can reach up to ϵ_r [dielectric constant of the cylinder] times the mean stress in the gap. Discharge may therefore occur at a voltage approaching $1/\epsilon_r$ times the breakdown voltage in the absence of the cylinder, and these discharges can precipitate a breakdown.

The three essential components of the surface flashover phenomena in a medium are

- (i) the presence of a conducting film across the surface of the insulation
- (ii) a mechanism whereby the leakage current through the conducting film is interrupted with the production of sparks,
- (iii) degradation of the insulation caused by the sparks.

The conducting film is usually moisture from the atmosphere absorbed by some form of contamination. Moisture is not essential, as a conducting path can also arise from metal dust due to wear and tear of moving parts. Sparks are drawn between moisture films, separated by drying of the surface due to heating effect of leakage current, which act as extensions to the electrodes. [For a discharge to occur, there must be a voltage at least equal to the Paschen minimum for the particular state of the gas. For example, Paschen minimum in air at N.T.P it is 380 V, whereas tracking can occur at well below 100 V. It does not depend on the gaseous breakdown.]

Degradation of the insulation is almost exclusively the result of heat from the sparks, and this heat either carbonises if tracking is to occur, or volatilises if erosion is to occur.

Tracking

Carbonization results in a permanent extension of the electrodes and usually takes the form of a dendritic growth, known as **Tracking**. Tracking is the formation of a permanent conducting path across a surface of the insulation, and in most cases the conduction (carbon path) results from degradation of the insulation itself leading to a bridge between the electrodes. The insulating material must be organic in nature for tracking to occur. Increase of creepage path during design will prevent tracking, but in most practical cases, moisture films can eliminate the designed creepage path.

Erosion

In a surface discharge, if the products of decomposition are volatile and there is no residual conducting carbon on the surface, the process is simply one of pitting. This is known as **Erosion**, which again occurs in organic materials.

If surface discharges are likely to occur, it is preferable to use materials with erosion properties rather than tracking properties, as tracking makes insulation immediately completely ineffective, whereas erosion only weakens the material but allows operation until replacement can be made later. [2 marks]

- (e) Maximum stress = 25 kV/mm, spacing = 4 mm. Assume safety factor already included.

therefore assuming uniform field, maximum permissible voltage = $25 \times 4 = 100$ kV (no safety factor)

or, maximum permissible voltage = $100/2 = \underline{50 \text{ kV}}$ (with a safety factor of 2) [1 mark]



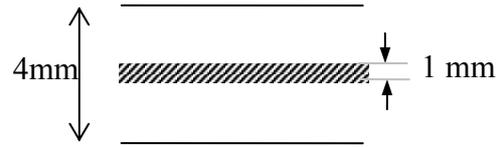
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(f) $V = V_{oil} + V_{solid}$

Since the same electric flux flows in both material on the application of a voltage, the charges are the same.

Thus using $q = CV$, gives the ratio of voltages across the oil and the solid as



$$\frac{V_{oil}}{V_{solid}} = \frac{C_{solid}}{C_{oil}} = \frac{\left(\frac{A\epsilon_o\epsilon_{solid}}{1 \times 10^{-3}}\right)}{\left(\frac{A\epsilon_o\epsilon_{oil}}{3 \times 10^{-3}}\right)} = \frac{3 \times 4.5}{1} = 4.5, \text{ giving } \frac{\xi_{oil}}{\xi_{solid}} = \frac{\left(\frac{V_{oil}}{d_{oil}}\right)}{\left(\frac{V_{solid}}{d_{solid}}\right)} = \left(\frac{V_{oil}}{V_{solid}}\right) \times \left(\frac{d_{solid}}{d_{oil}}\right)$$

$$\frac{\xi_{oil}}{\xi_{solid}} = 4.5 \times \frac{1}{3} = 1.5$$

Thus a higher stress will occur in the oil than in the solid and hence the maximum voltage will be when stress in the oil is exceeded.

$$\therefore V_{oil} = 25 \times 3 = 75 \text{ kV, and } V_{solid} = \frac{V_{oil}}{4.5} = \frac{75}{4.5} = 16.67 \text{ kV}$$

Thus maximum applicable voltage = $75 + 16.67 = 91.67 \text{ kV}$ (no safety factor) [2½ marks]
 = 45.8 kV (with a safety factor of 2)

The introduction of the solid does not improve the breakdown voltage but may reduce the migration of charge in non-linear fields. [½ mark]

2. (a) **Cascade arrangement of transformers**

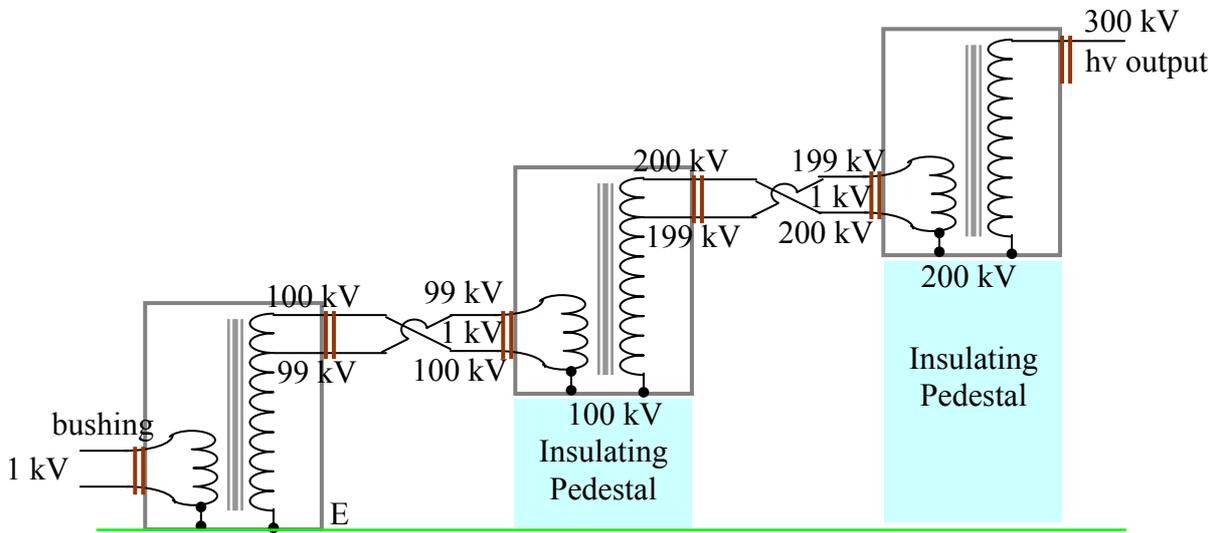


Figure shows a typical cascade arrangement of transformers used to obtain up to 300 kV from three units each rated at 100 kV insulation. The low voltage winding is connected to the primary of the first transformer, and this is connected to the transformer tank which is earthed. One end of the high voltage winding is also earthed through the tank. The high voltage end and a tapping near this end is taken out at the top of the transformer through a bushing, and forms the primary of the second transformer.

One end of this winding is connected to the tank of the second transformer to maintain the tank at high voltage. The secondary of this transformer too has one end connected to the tank and at the other end the next cascaded transformer is fed.

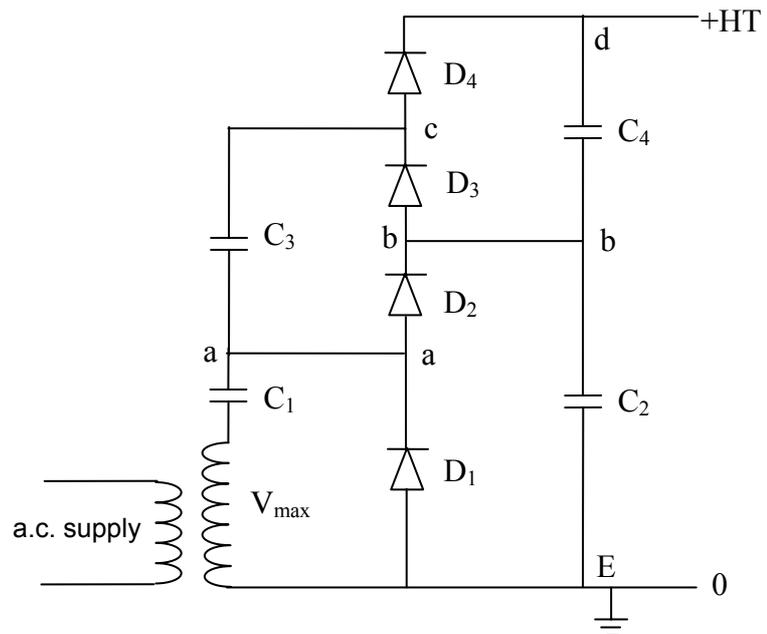
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This cascade arrangement can be continued further if a still higher voltage is required. In the cascade arrangement shown, each transformer needs only to be insulated for 100 kV, and hence the transformer can be relatively small. If a 300 kV transformer had to be used instead, the size would be massive. High voltage transformers for testing purposes are designed purposely to have a poor regulation. This is to ensure that when the secondary of the transformer is short circuited (as will commonly happen in flash-over tests of insulation), the current would not increase to too high a value and to reduce the cost. In practice, an additional series resistance (commonly a water resistance) is also used in such cases to limit the current and prevent possible damage to the transformer. [3 marks]

(b) Cockroft-Walton Voltage Multiplier Circuit

The Cockroft-Walton voltage multiplier circuit is commonly used to obtain high direct voltages for testing purposes, and is shown .

Let V_{\max} be the peak value of the secondary voltage of the high voltage transformer. To analyze the behaviour, consider that charging of capacitors actually takes place stage by stage rather than somewhat simultaneously, to make analysis easier to follow. Consider the first part of the circuit containing the diode D_1 , the capacitor C_1 , and the secondary winding. During the first negative half cycle of the applied voltage, the capacitor C_1 charge up to voltage V_{\max} . Since during the positive half cycle which follows, the diode D_1 is reverse biased, the capacitor C_1 will not discharge (or will not charge up in the other direction) and the peak of this half cycle, the point **a** will be at $2 V_{\max}$. During the following cycles, the potential at **a** will vary between 0 and $2 V_{\max}$, depending on whether the secondary voltage and the capacitor voltage are opposing or assisting.



Initially, capacitor C_2 would be uncharged, and the voltage at **b** would be zero. Thus as the voltage at **a** varies between 0 and $2 V_{\max}$, the diode D_2 is forward biased, and the capacitor C_2 would charge to $2 V_{\max}$. Once the voltage at **b** has reached $2 V_{\max}$, the voltage at **a** would be less than or equal to the voltage at **b**. Thus once C_2 has charged up, this diode too would be reverse biased and the capacitor C_2 would not discharge. The voltage at **b** would now remain constant at $2 V_{\max}$. C_3 is also initially assumed uncharged. Since the voltage at **a** varies between 0 and $2 V_{\max}$, the diode D_3 would initially be forward biased for almost the whole cycle. Thus the capacitor C_3 charges until it reaches $2 V_{\max}$ when **b** is $2 V_{\max}$ and **a** is 0 . As the voltage at **a** again increases to $2 V_{\max}$, the voltage at **c** increases, and thus the diode D_3 is reverse biased and C_3 would not discharge. Now as **a** reaches $2 V_{\max}$ the voltage at **c** rises to $4 V_{\max}$, as C_3 has not discharged.

Thus after charging up has taken place, the voltage at **c** varies between $2 V_{\max}$ and $4 V_{\max}$. Assuming C_4 also to be initially uncharged, since the voltage at **b** is a constant at $2 V_{\max}$ and the voltage at **c** varies between $2 V_{\max}$ and $4 V_{\max}$ initially, during most of the cycle, the diode D_4 is forward biased and C_4 charges up to the maximum difference between **d** and **b** (i.e. to $2 V_{\max}$). This occurs when the voltage at **c** is $4 V_{\max}$ and the voltage at **d** would now be $4 V_{\max}$. As the voltage at **c** falls from $4 V_{\max}$ to $2 V_{\max}$, since the capacitor C_4 has charged up it would not discharge, since there is no discharge path. Thus once the capacitors are charged up the voltage at **d** remains constant at $4 V_{\max}$.

This sequence of voltages gained is shown in the Table.



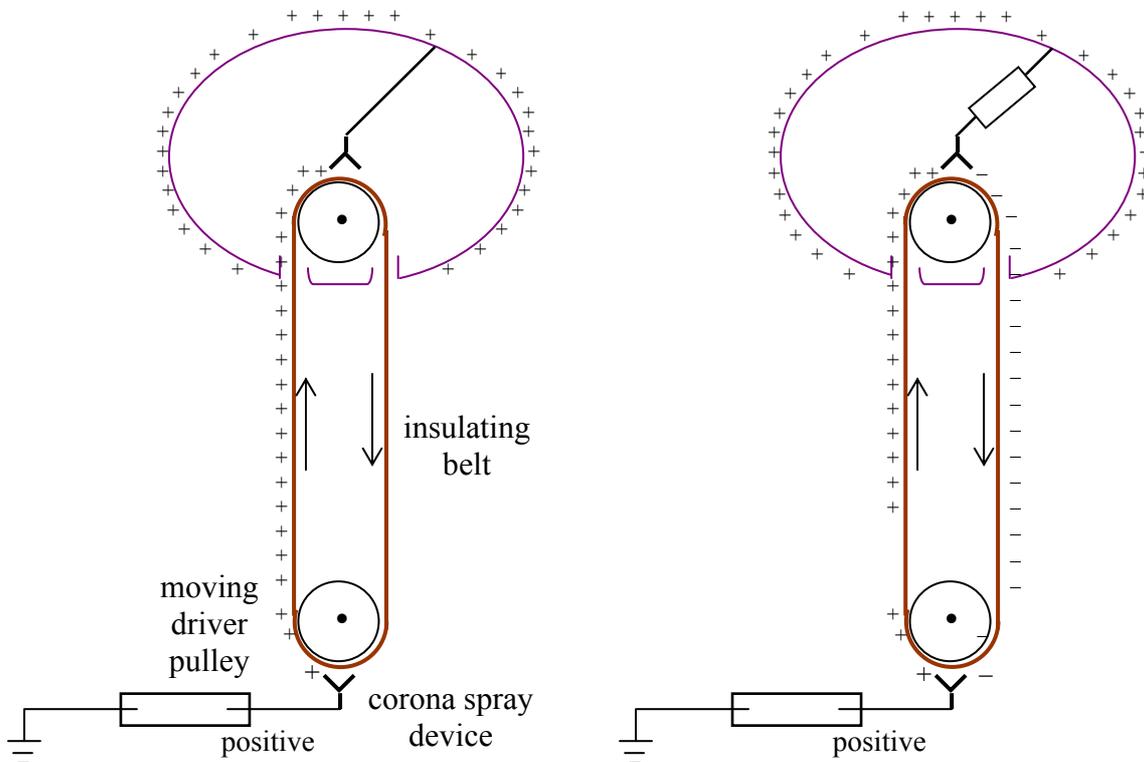
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Cycle \ Location	0	T/2	T	3T/2	2T	5T/2	3T	7T/2	4T
	-	+	-	+	-	+	-	+	-
a	0	2 Vm	0	2 Vm	0	2 Vm	0	2 Vm	0
b	0	2 Vm							
c	0	0	2 Vm	4 Vm	2 Vm	4 Vm	2 Vm	4 Vm	2 Vm
d	0	0	0	4 Vm					

When the generator is used for a test, or when it is loaded, a current is drawn from the generator, and the capacitors lose some of their charge to the load, and the voltage falls depending on the load. As the voltage across any of the capacitors drops, then at some point in the applied alternating voltage cycle, the corresponding diode would become forward biased and charging up of the capacitor would once again result. Thus when a load is connected, there would be a small ripple in the output voltage. [4 marks]

(c) **Van de Graeff generator**



The Van de Graeff generator is an electrostatic generator used to obtain very high direct voltages. However it cannot supply much current and the power output is restricted to a few kilowatt, and its use is restricted to low current applications.

The Van de Graeff generator uses an insulating belt as the carrier of charge. The generator consists of a low direct voltage source, with corona discharge taking place at the positive end of the source. The corona formation (spray) is caused by a core like structure with sharp points (corona spray device). Charge is sprayed onto the belt at the bottom by corona discharges at a potential of 10 to 100 kV above earth and carried to the top of the column and deposited at a collector. The upper electrode at which the charge is collected has a high radius of curvature and the edges should be curved so as to have no loss. The generator is usually enclosed in an earthed metallic cylindrical vessel and is operated under pressure or in vacuum.



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$$V = \frac{Q}{C}$$

The higher voltage of the upper electrode arises from the fact that for the same charge, a smaller capacitance gives a larger voltage. The upper electrode has a smaller capacitance to earth on account of the larger spacing involved.

The potential of the high voltage electrode rises at a rate of $\frac{dV}{dt} = \frac{I}{C} \frac{dQ}{dt} = \frac{I}{C}$

where I is the net charging current.

A steady potential will be reached by the high voltage electrode when the leakage currents and the load current are equal to the charging current. The edges of the upper electrode are so rounded as to avoid corona and other local discharges.

With a single source at the lower end, the belt moves upwards with a positive charge and returns uncharged. Charging can be made more effective by having an additional charge of opposite polarity sprayed onto the belt by a self inducing arrangement (negative corona spray). using an ingenious method. this arrangement effectively doubles the charging rate. [3 marks]

(d) Resonant Transformers

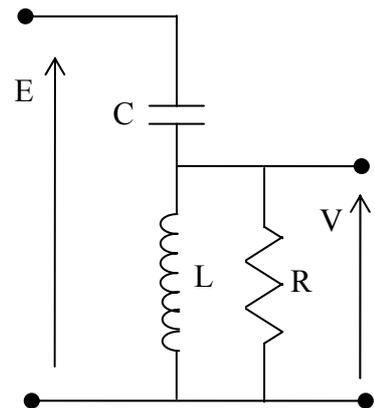
The resonance principle of a series tuned L-C circuit can be made use of to obtain a higher voltage with a given transformer.

Let **R** represent the equivalent parallel resistance across the coil and the device under test. The current **i** would be given by

$$i = \frac{E}{\frac{1}{j\omega C} + \frac{j\omega L R}{R + j\omega L}}$$

so that $v = i \cdot \frac{j\omega L R}{R + j\omega L}$

i.e. $v = \frac{-\omega^2 L C R \cdot E}{R + j\omega L - \omega^2 L C R} = -\frac{E \cdot R}{j\omega L}$ at resonance

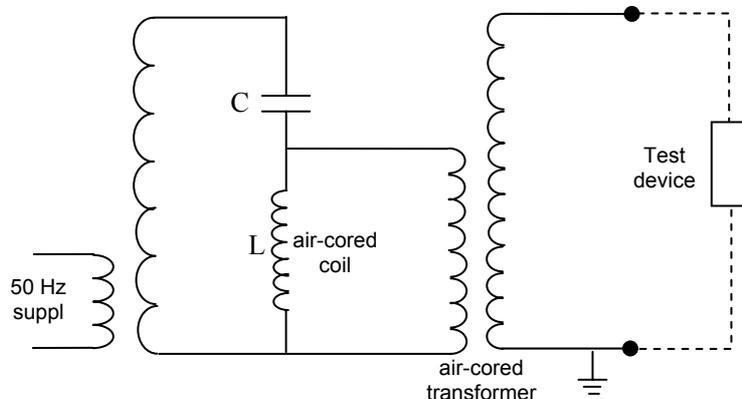


Since **R** is usually very large, the **Q** factor of the circuit ($Q = R/L\omega$) would be very large, and the output voltage would be given by $|v| = E \cdot \frac{R}{L\omega} = E \cdot Q$, at resonance $\omega = 2\pi f = \frac{1}{\sqrt{LC}}$

It can thus be seen that a much larger value than the input can be obtained across the device under test in the resonant principle.

Figure shows the application of the resonance principle at power frequency.

For certain applications, particularly when the final requirement is a direct voltage, it is an advantage to select a frequency higher than power frequency (50 Hz). This would result in a smaller transformer having fewer turns, and also simplifies the smoothing after rectification. Air-cored coils are used to simplify the construction and the insulation.



[3 marks]

The Q-factor drops to below unity when power is drawn, and hence high voltages will not be obtained. Thus the resonance method is not suitable for power transmission. [1 mark]

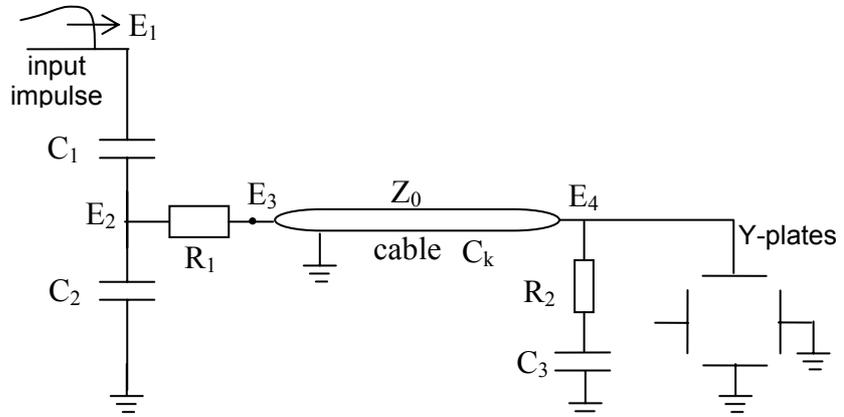


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3. (a) The cable used to connect the test waveform to the oscilloscope will necessarily have reflections occurring both at the potential divider end and the oscilloscope end. Further, the effective capacitance of the lower arm of the divider would change after the capacitance of the cable gets charged. Thus matching needs to be done. [½ mark]

Matching the cable at the sending end would require the effective impedance seen at E_2 from the cable side to match the cable. Since for a surge, the capacitance is almost like a short-circuit compared to a resistance, this would give $R_1 = Z_0$. Similarly for matching at oscilloscope end, $R_2 = Z_0$.



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.

Initially $E_2 = E_1 \cdot \frac{C_1}{C_1 + C_2}$, also $E_3 = E_2 \cdot \frac{Z_0}{R_1 + Z_0} = \frac{1}{2} E_2$, $\because R_1 = Z_0$ for matching

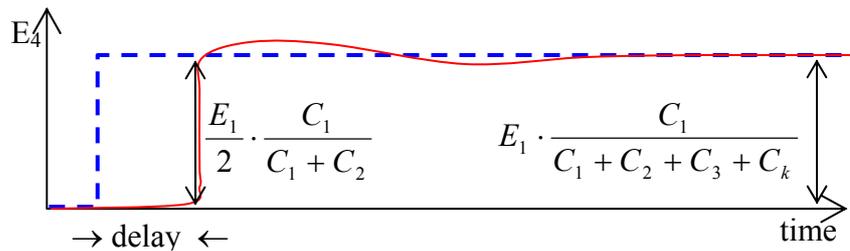
Due to perfect matching at the receiving end, the voltage wave is transmitted without any reflection.

Therefore the observed voltage is given by $E_r = E_3 = \frac{1}{2} E_2 = \frac{E_1}{2} \cdot \frac{C_1}{C_1 + C_2}$

After very long 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, $E_2 = E_1 \cdot \frac{C_1}{C_1 + C_2 + C_3 + C_k}$

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



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

i.e. $C_1 + C_2 = C_3 + C_k$

[3½ marks]

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(b) Dielectric loss measurement using Oscilloscope

In an oscilloscope, if two alternating voltages of the same frequency are applied to the x-plate and y-plate, 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 difference increases, the area increases and reaches a maximum when the phase angle difference is 90° .

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.

The use of the standard capacitor C ensures that the voltage across it is 90° 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 $v_1 = V_{1m} \sin(\omega t - \delta)$ and the x-deflection is proportional to $v_2 = V_{2m} \sin \omega t$ which is taken as the reference.

$$\text{i.e. } y = a \cdot V_{1m} \sin(\omega t - \delta)$$

$$= a \cdot (I_{sm}/\omega C) \sin(\omega t - \delta)$$

$$\text{and } x = b \cdot V_{2m} \sin \omega t$$

where a, b are constants.

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

$$\begin{aligned} A &= \int y \cdot dx = \int_0^T a \cdot \frac{I_{sm}}{\omega C} \cdot \sin(\omega t - \delta) \cdot b \cdot V_{2m} \cdot \omega \cdot \cos \omega t \cdot dt \\ &= \frac{a \cdot b}{C} \cdot \frac{2\pi}{\omega} \cdot I_s V_2 \sin \delta \end{aligned}$$

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

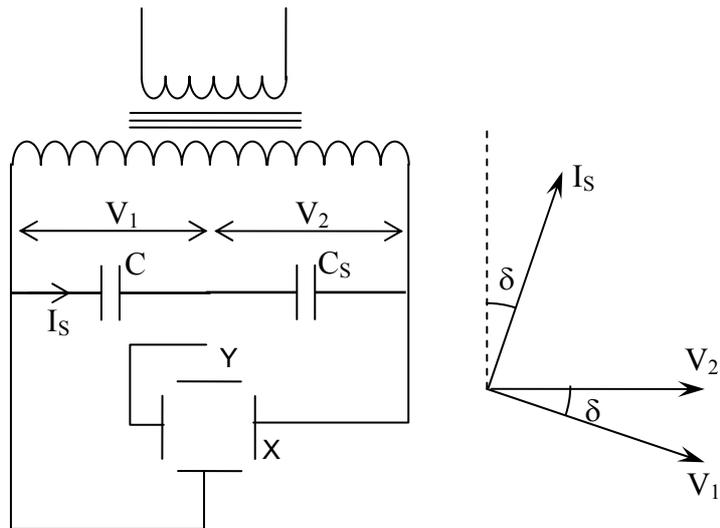
[4 marks]

- (c) The tests on insulators can be divided into three groups. These are the type tests, sample tests and the routine tests.

Type tests

These tests are done to determine whether the particular design is suitable for the purpose. A sample of two type tests for an insulator is described below.

Withstand Test: The insulator should be mounted so as to simulate practical conditions. A $1.2/50 \mu s$ wave of the specified voltage (corrected for humidity, air density etc.) is applied. Flashover or puncture should not occur. [If puncture occurs, the insulator is permanently damaged]. The test is repeated five times for each polarity.



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One-minute Rain test: The insulator is sprayed throughout the test with artificial rain drawn from a source of supply at a temperature within 10°C of the ambient temperature of the neighbourhood of the insulator. The rain is sprayed at an angle of 45° on the insulator at the prescribed rate of 3 mm/minute. The resistivity of the water should be $100\text{ ohm}\cdot\text{m} \pm 10\%$. The prescribed voltage is maintained for one minute.

Sample Tests

The sample is tested fully, up to and including the point of breakdown. These are done only on a few samples. Two examples for an insulator is given below.

Temperature cycle test: The complete test shall consist of five transfers (hot-cold-hot-....), each transfer not exceeding 30 s.

Electro-mechanical test: The insulator is simultaneously subjected to electrical and mechanical stress. (i.e. it shall be subjected to a power frequency voltage and a tensile force simultaneously. The voltage shall be 75% of dry flash-over voltage of the unit. There should be no damage caused.

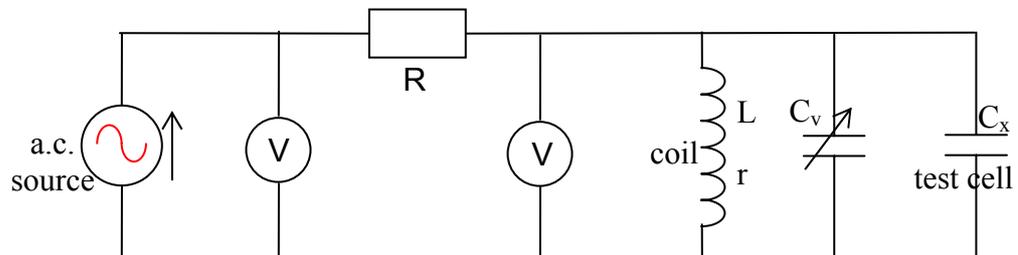
Routine Tests

These are to be applied routinely on all units to ensure a minimum level of performance.

Power frequency withstand test: In the case of insulators, testing shall be commenced at a low voltage and shall be increased rapidly until flash-over occurs every few seconds. The voltage shall be maintained at this value for a minimum of five minutes, or if failures occur, for five minutes after the last punctured piece has been removed. At the conclusion of the test the voltage shall be reduced to about one-third of the test voltage before switching off.

Mechanical Routine Test: A mechanical load of 20% in excess of the maximum working load of the insulator is applied after suspending the insulator for one minute. There should be no mechanical failure of the insulator. [3 marks]

- (d) The capacitance and loss tangent of a test cell containing liquid can be measured using a resonance circuit as shown.



The circuit is first tuned for resonance without connecting the test cell and the value of the variable capacitor C_{v0} determined. The capacitance of the circuit at resonance $C = C_{v0}$.

The circuit is then de-tuned to the half-power points (voltage corresponding to $1/\sqrt{2}$) from which the value of the effective Q-factor is determined. If C_+ and C_- are the values at the half power points, then it can be shown that the Q factor Q_0 can be obtained from

$$Q = \frac{C_+ + C_-}{C_+ - C_-} = \frac{2C + (\Delta C_+ - \Delta C_-)}{\Delta C_+ + \Delta C_-}, \text{ where } \Delta C_+ \text{ and } \Delta C_- \text{ are the variations at the half-power}$$

points. Usually Q is high, and $\Delta C_+ = \Delta C_- = \Delta C$, so that $Q_0 = \frac{C}{\Delta C_{v0}}$

Next the test cell is added, and the resonance value C_{v1} and the detuned variation ΔC_{v1} obtained.

$$Q_1 = \frac{C}{\Delta C_{v1}}. \text{ Since total capacitance is unchanged, } C_x = C_{v0} - C_{v1}$$

also, $\tan \delta = \frac{1}{Q_1} - \frac{1}{Q_0} = \frac{\Delta C_{v1} - \Delta C_{v0}}{C_{v0}}$ since the loss tangent is inversely proportional to the Q-factor.

[3 marks]

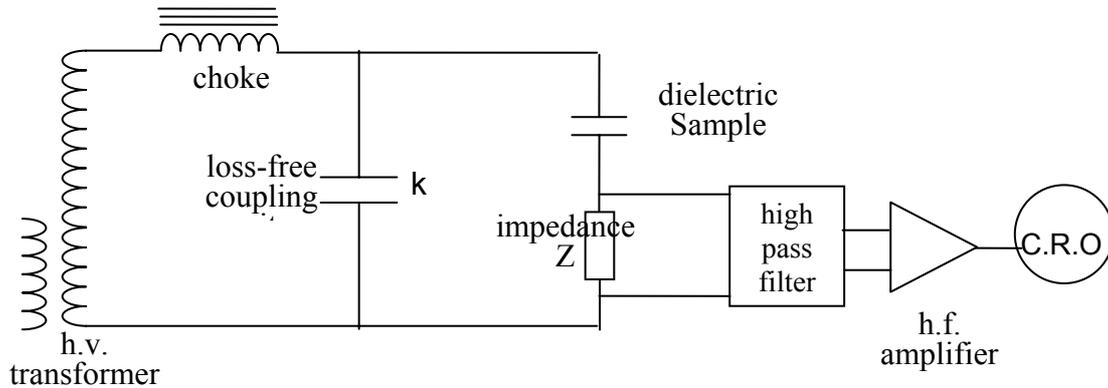


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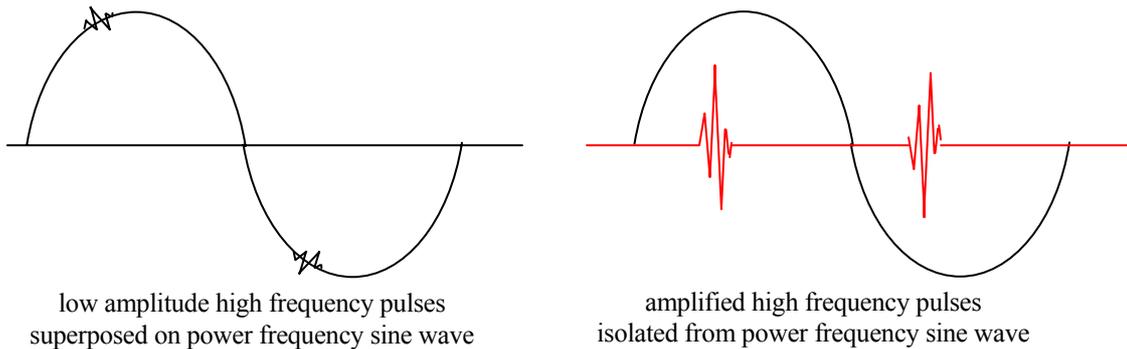
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4. (a) Using the oscilloscope with filtration and amplification

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

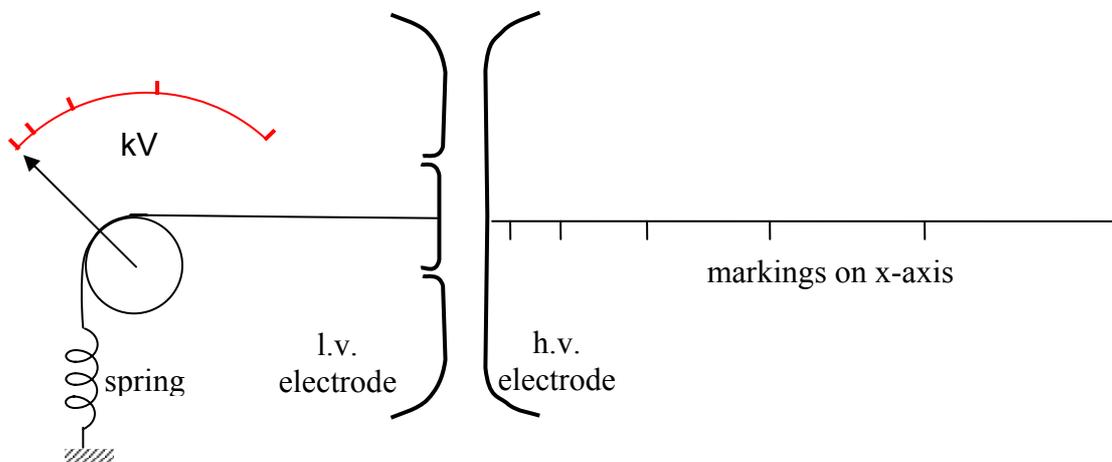


The apparatus used in the observation (namely the coupling capacitor and the impedance) should be discharge free, so that all the discharges caused is due to the sample. The discharges occurring in the transformer and the choke do not affect the measurement as they are short circuited through the coupling capacitor. The internal discharge pulses caused in the sample are of high frequency, so that the low frequency components are bypassed and the high frequency components are amplified in the measurement circuit.



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. [4 marks]

(b) Abraham Voltmeter



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.

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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 pair of plates is given by

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

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

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

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

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).

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.

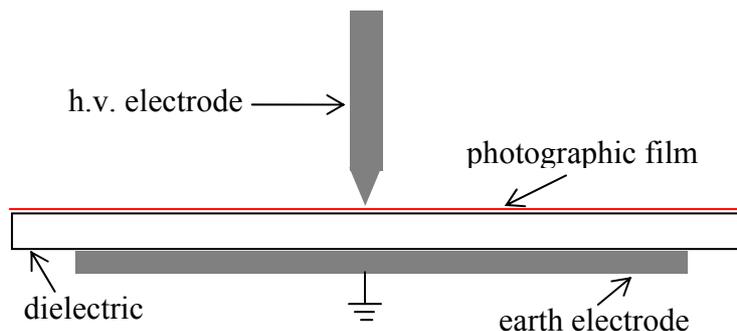
As shown in the figure the right hand electrode forms the high voltage plate, while the centre portion of the left hand disc is cut away and encloses a small disc which is movable and is geared to the pointer of the instrument. The range of the instrument can be altered by setting the right hand disc 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, without the use of any potential divider or other reduction method. [These electrostatic instruments can be used to measure both a.c. and d.c. voltages]. [3 marks]

(c) 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 Lichtenberg patterns obtained by using a Klydonograph.

The Klydonograph shown 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.



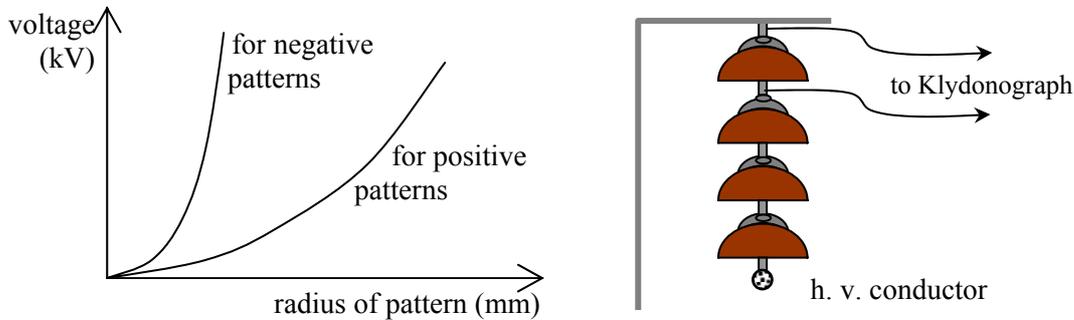
The photographic film can be made to rotate continuously by a clockwork mechanism. The apparatus is enclosed in a blackened box so as not to expose the photographic film. When an impulse voltage is applied to the high voltage electrode, the resultant photograph shows the growth of filamentary streamers 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 Lichtenberg patterns. When a positive high voltage is applied to the upper electrode, clearly defined streamers 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.



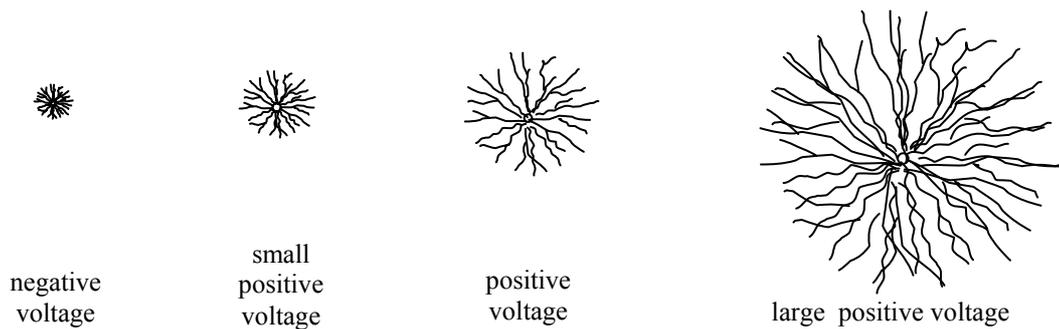
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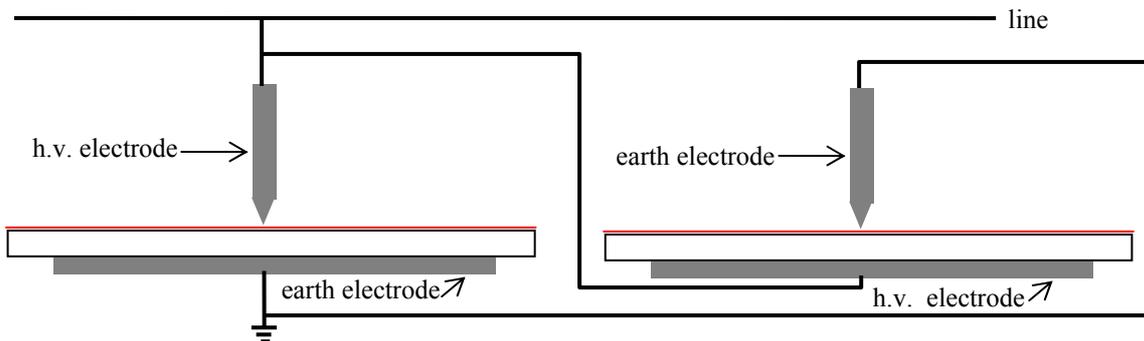
For a given apparatus with a fixed thickness of dielectric, the radius of the pattern obtained, as shown, is a definite function of the voltage applied, and thus by calibrating the Klydonograph using a high voltage oscilloscope and known surge voltages, it is possible to use this apparatus to record 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 occurring in transmission lines, an insulator string potential divider is used.



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 it is usually preferable to use the positive pattern for the measurement of high voltage surges. The applied voltage versus radius of pattern characteristics of the Lichtenberg pattern is as shown.



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, the following modification is made.



In the modification shown, there are two such instruments, with the electrode connections made in opposite directions, so that the positive pattern is always available for accurate measurement from one or the other. 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. [3 marks]

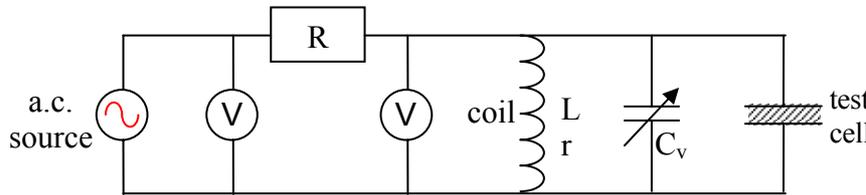
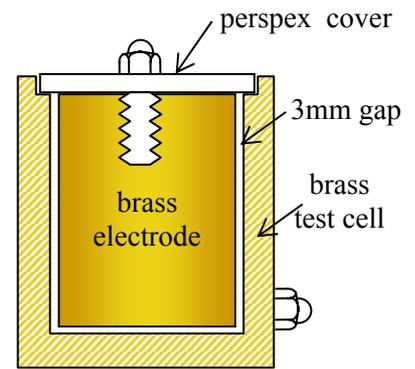


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(d) Measurement of dielectric constant and dissipation factor of a liquid dielectric

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, the stray capacitance must be considered.



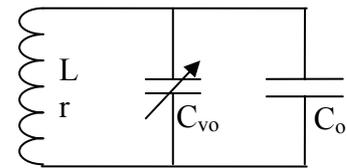
The test cell is connected in parallel with a variable capacitor and made part of a resonant circuit. In the circuit, R is a high series resistance used to keep the total current in the circuit very nearly constant.

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

$$\text{then } \omega^2 L (C_v + C_{test}) = 1$$

The stray capacitance can be eliminated using the following procedure at the selected frequency (say 1 MHz). For resonance, $C_v + C_{test}$ must be a constant.

(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 $C_{v0} + C_0$.



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 $1/\sqrt{2}$) are reached. If C_+ and C_- are the values at the half power points, then it can be shown that the Q factor is given by

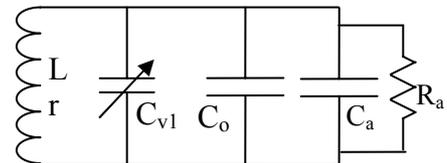
$$Q = \frac{C_+ + C_-}{C_+ - C_-} = \frac{2C + (\Delta C_+ - \Delta C_-)}{\Delta C_+ + \Delta C_-}$$

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

If Q is high, $\Delta C_+ = \Delta C_- = \Delta C$, 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 $C_{v0} + C_0 = C_{v1} + C_0 + C_a$
 $\therefore C_a = C_{v0} - C_{v1}$

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

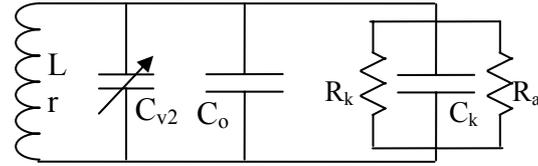
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(iii) The liquid is now introduced into the test cell.

[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 ϵ_r is the relative permittivity of the liquid dielectric, then the capacitance of the active portion of the test cell with the liquid would be $\epsilon_r C_a$.

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

$$C_{v0} + C_0 = C_{v2} + C_0 + \epsilon_r C_a \text{ giving } \epsilon_r C_a = C_{v0} - C_{v2}$$

$$\therefore \text{dielectric constant } \epsilon_r = \frac{C_{v0} - C_{v2}}{C_{v0} - C_{v1}}$$

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

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

The loss factor of the dielectric is given by

$$\text{loss factor} = \frac{1}{\omega C_k R_k} = \frac{1}{\omega C R_k} \cdot \frac{C}{C_k} = \frac{C}{k C_a} \cdot \left[\frac{1}{Q_k} - \frac{1}{Q_a} \right] = \frac{C}{k C_a} \cdot \frac{[\Delta C_k - \Delta C_a]}{C} = \frac{1}{k C_a} \cdot [\Delta C_k - \Delta C_a]$$

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

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.

$$\begin{aligned} \text{loss factor} &= \frac{1}{\omega C_k R_k} = \frac{1}{\omega C R_k} \cdot \frac{C}{C_k} \\ &= \frac{C}{k C_a} \cdot \left[\frac{1}{Q_k} - \frac{1}{Q_a} \right] = \frac{C}{k C_a} \cdot \frac{[\Delta C_k - \Delta C_a]}{C} \\ \text{i.e. loss tangent} &= \frac{1}{k C_a} \cdot [\Delta C_k - \Delta C_a] \end{aligned}$$

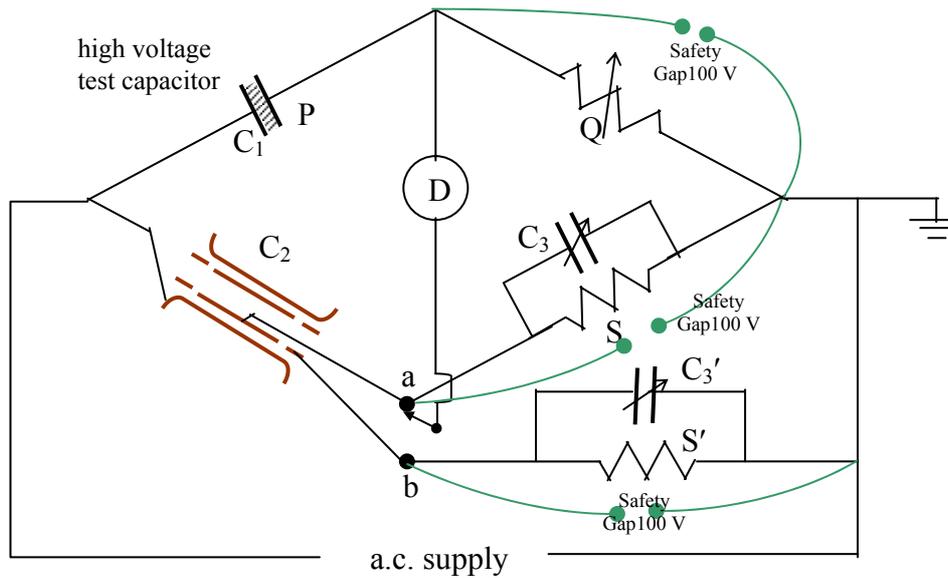
[4 marks]



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5. (a)



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 , 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.

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 its design. This guard is kept at the same potential as the main electrode without a direct connection, as shown, through another balance arm. 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 (being the 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. [4 marks]

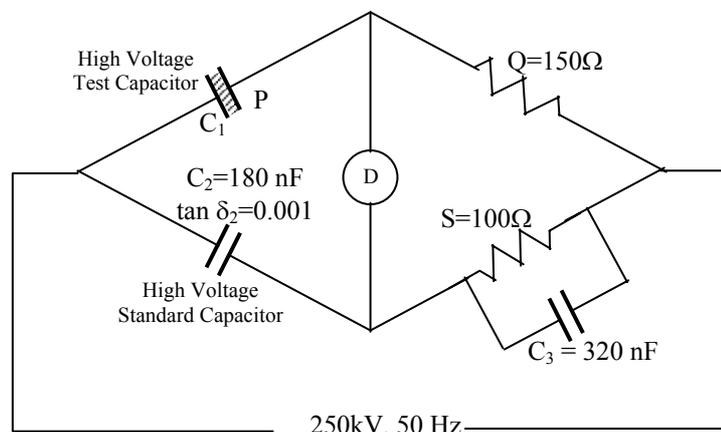
- (b) Since the losses in the high voltage standard capacitor and in the high voltage test capacitor are extremely low, the balance condition may be obtained without considering losses.

Thus

$$\frac{C_2}{C_1} = \frac{Q}{S} \text{ giving } C_1 = \frac{S}{Q} C_2$$

for balance of an a.c. bridge, the phase angles must also balance.

[3 marks]



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impedance angle = $-\varphi$, loss angle = $\pi/2 - \varphi = \delta$

Thus

$$\frac{Z_1 \angle (-\pi/2 + \delta_1)}{Z_2 \angle (-\pi/2 + \delta_2)} = \frac{Z_4 \angle 0}{Z_3 \angle -\theta_3} \text{ giving } (-\pi/2 + \delta_1) - (-\pi/2 + \delta_2) = 0 - (-\theta_3)$$

i.e. $\delta_1 - \delta_2 = \theta_3, \delta_1 = \delta_2 + \theta_3$

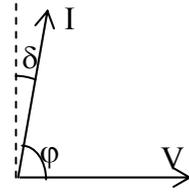
$$\tan \delta_1 \approx \tan \delta_2 + \tan \theta = \tan \delta_2 + \omega C_3 S$$

at balance

$$\frac{C_1}{180} = \frac{100}{150} \text{ giving unknown capacitor } C_1 = \underline{\underline{120 \text{ nF}}} \quad [2 \text{ marks}]$$

$$\tan \delta_1 \approx \tan \delta_2 + \omega C_3 S = 0.001 + 2\pi \times 50 \times 320 \times 10^{-9} \times 100$$

$$\text{loss tangent} = \underline{\underline{0.01105}} \quad [2 \text{ marks}]$$



[3 marks]