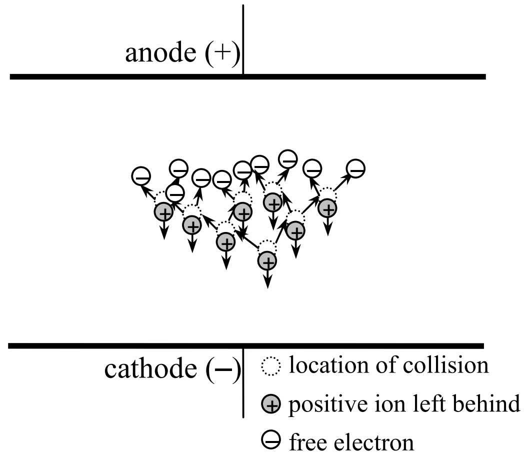
EE 427 – High Voltage Breakdown & Testing – Model Answers

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

Level 4 Semester 2 Examination - June 2006

Answer 1

(a) The avalanche process is one that occurs 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, which is the avalanche. *2 marks*

(b) Let n_0 = number of electrons/second emitted from the cathode,

n_x = number of electrons/second moving at a distance x from the cathode

α = number of ionising collisions, on average, made by one electron per unit drift in the direction of the field. [Townsend's first ionisation coefficient]

Consider a laminar of thickness dx at a distance x from the cathode.

The n_x electrons entering the laminar will traverse it in the presence of the applied field E.

The ionising collisions generated in the gas gap will be proportional to both dx and to n_x.

Thus $dn_x \propto n_x . dx$

Therefore $dn_x = \alpha . n_x . dx$ (from definition of α)

$$\int_{n_0}^{n_x} \frac{d\, n_x}{n_x} = \alpha \int_0^x dx$$

Rearranging and integrating gives $$\log_e (n_x / n_0) = \alpha . x$$

$$n_x = n_0 \cdot e^{\alpha x}$$

If the anode is at a distance x = d from the cathode,

then the number of electrons n_d striking the anode per second is given by

$$n_d = n_0 . e^{\alpha d}$$

$\therefore$ on average, each electron leaving cathode produces $(n_d - n_0)/n_0$ new electrons (and corresponding positive ions) in the gap.

In the **steady state**, the number of positive ions arriving at the cathode/second must be exactly equal to the number of newly formed electrons arriving at the anode. Thus the circuit current will be given by

$I = I_0 . e^{\alpha d}$, where I_0 is the initial photo-electric current at the cathode.

Consider now the current growth equations with the secondary mechanism also present.

Let γ = number of secondary electrons (on average) produced at the cathode per ionising collision in the gap. [Townsend's second ionisation coefficient]

n_0 = number of primary photo-electrons/second emitted from the cathode

n_0' = number of secondary electrons/second produced at the cathode

n_0'' = total number of electrons/second leaving the cathode

Then $n_0' = n_0 + n_0''$

On the average, each electron leaving the cathode produces $[e^{\alpha d} - 1]$ collisions in the gap, giving the number of ionising collisions/second in the gap as $n_0''(e^{\alpha d} - 1)$.

Thus by definition $$\gamma = \frac{n_0'}{n_0''(e^{\alpha d} - 1)}$$

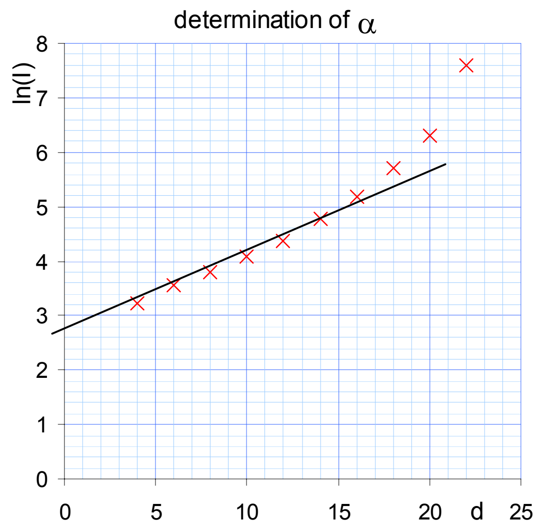
giving $n_{0'} = \gamma\, n_0''(e^{\alpha d} - 1)$

but $n_0'' = n_0 + n_0'$

so that $n_0'' = n_0 + n_0''(e^{\alpha d} - 1).\gamma$

This gives the result

$$n_0'' = \frac{n_0}{1 - \gamma(e^{\alpha d} - 1)}$$



Similar to the case of the primary process (with α only),

we have $$n_d = n_0''\, e^{\alpha d} = \frac{n_0\, e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)}$$

In steady state, the circuit current I will be given by

$$I = \frac{I_0\, e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)}$$ **4 marks**

When αd is very small, $I \cong I_o e^{\alpha d}$, so that $\ln I = \alpha d + \ln I_o$

d (mm)	4	6	8	10	12	14	16	18	20	22
I (pA)	25	35	45	60	80	120	180	300	550	2000
ln (I)	3.22	3.56	3.81	4.09	4.38	4.79	5.19	5.70	6.31	7.60

from graph, gradient = α = (5.58 – 2.64)/20 = 0.147 mm^{-1} , **2 marks**

intercept = $\ln I_o$ = 2.64, I_o = 14.0 pA

substituting for high value of d, $2000 = \dfrac{14.0e^{0.147\times 22}}{1-\gamma(e^{0.147\times 22}-1)} = \dfrac{355.3}{1-24.38\gamma}$, gives $\gamma = 0.034$ **2 marks**

(c) On the application of an impulse voltage, a certain time elapses before actual breakdown occurs even though the applied voltage may be much more than sufficient to cause breakdown under static conditions.

In considering the time lag observed between the application of a voltage sufficient to cause breakdown and the actual breakdown the two basic processes of concern are (i) the appearance of avalanche initiating electrons and (ii) the temporal growth of current after the criterion for static breakdown is satisfied.

(i) Statistical Time lag t_s

The statistical time lag is the average time required for an electron to appear in the gap in order that breakdown may be initiated.

If β = rate at which electrons are produced in the gap by external irradiation
P_1 = probability of an electron appearing in a region of the gap where it can lead to a spark
P_2 = probability that such an electron appearing in the gap will lead to a spark

then, the average time lag $$t_s = \frac{1}{\beta P_1 P_2}$$

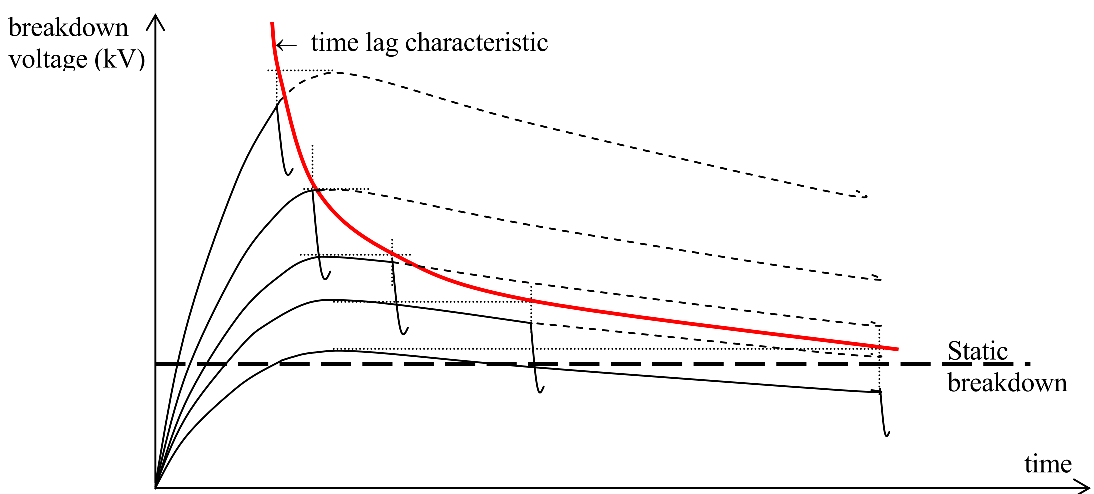
If the level of irradiation is increased, β increases and therefore t_s decreases. Also, with clean cathodes of higher work function β will be smaller for a given level of illumination producing longer time lags.
The type of irradiation used will be an important factor controlling P_1, the probability of an electron appearing in a favourable position to produce breakdown.

If the gap is overvolted, then the probability of producing a current sufficient to cause breakdown rapidly increases. P_2 therefore increases with overvoltage and may tend to unity when the overvoltage is about 10%. As $P_2 \rightarrow 1$ with increasing overvoltage, $t_s \rightarrow 1/\beta P_1$. **1 mark**

(ii) Formative time lag

After the statistical time lag, it can be assumed that the initiatory electron is available which will eventually lead to breakdown. The additional time lag required for the breakdown process to form is the formative time lag. An uninterrupted series of avalanches is necessary to produce the requisite gap current (μA) which leads to breakdown, and the time rate of development of ionisation will depend on the particular secondary process operative. The value of the formative time lag will depend on the various secondary ionisation processes. Here again, an increase of the voltage above the static breakdown voltage will cause a decrease of the formative time lag tf. **1 mark**

(d) **Time lag characteristic**



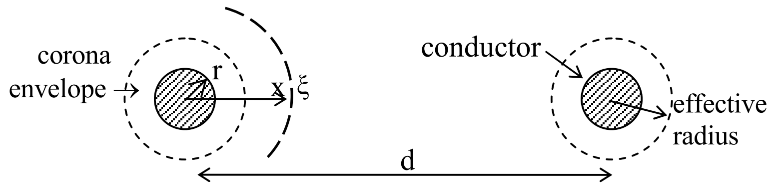
The time lag characteristic is the variation of the breakdown voltage with time of breakdown, and can be defined for a particular waveshape. The time lag characteristic based on the impulse waveform is shown.

For different amplitudes of the same waveform, the instant of breakdown and the peak amplitude of the prospective waveform is taken and joined to give the characteristic. **2 marks**

Answer 2

(a) 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 $\xi = \frac{1}{\varepsilon_0} . \frac{q}{2\pi x l}$, where q is the charge on each conductor in length *l*.

Thus the potential V can be determined from $V = \int \xi dx = \int_r^{d-r} \frac{q}{2\pi x \varepsilon_0} . dx$

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 $V = \frac{q}{2\pi \varepsilon_0} . \log_e\left(\frac{d-r}{r}\right)$

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 « r

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.

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 ^{0}C.

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

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

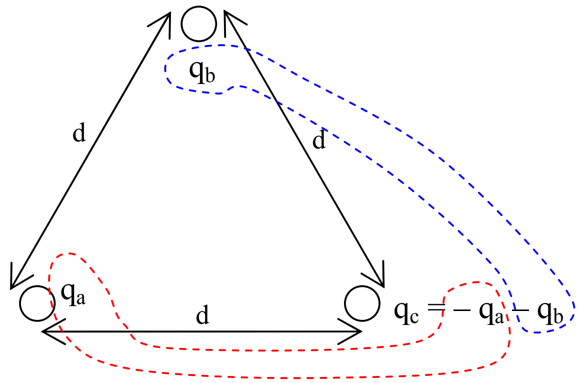
$E_{0,rms} = 21.2\, \delta\, m_0\, r \log_e (d/r)$ kV to neutral

3 marks

Total charge is zero, so that $q_c = -q_a - q_b$

q_a and $-q_a$ are a pair similar to the two conductor case. Similarly is q_b and $-q_b$.

These give the solution to the three phase case with equilateral spacing as the same as the single phase solution. **1 mark**



Corona inception occurs at 80 kV at NTP

$$\delta = \frac{765}{760} \times \frac{273+20}{273+35} = 0.9576$$

actual corona inception voltage = 80 × 0.9576 = 76.6 kV **1 mark**

(b) 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

$$E_b = \frac{3\,\varepsilon_1}{2\,\varepsilon_1 + 1} E_0$$ where E_0 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. **1 mark**

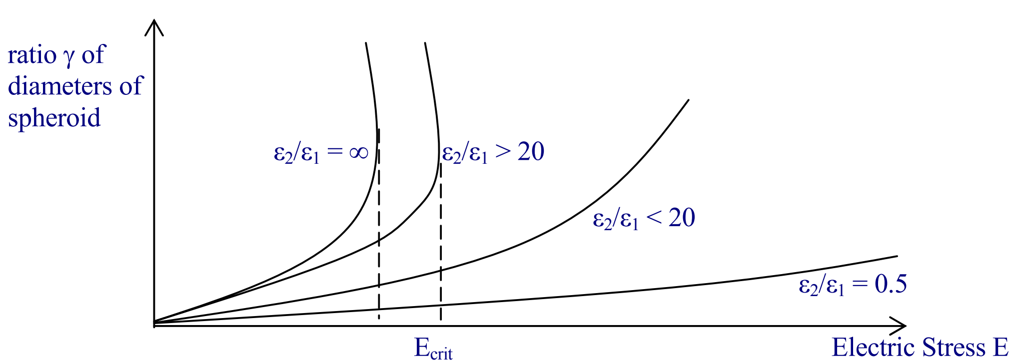
(ii) Breakdown due to liquid globules

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.

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

$$E = \frac{3\,\varepsilon_1}{2\,\varepsilon_1 + \varepsilon_2} E_0,$$ 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 $\varepsilon_2/\varepsilon_1$.



When $\varepsilon_2 >> \varepsilon_1$ (generally when $\varepsilon_2/\varepsilon_1 > 20$), 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 $\varepsilon_2/\varepsilon_1 >> 20$, the critical field at which the globule becomes unstable no longer depends on the ratio, and is given by $E_{crit.}$

$$E_{crit} = 1.542\left(\frac{\sigma}{R\,\varepsilon_1}\right)^{1/2} \; kV/cm$$

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 μm 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. **1 mark**

(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 $F = \frac{1}{2} r^3 \varepsilon_0 \frac{(\varepsilon_2 - \varepsilon_1)}{\varepsilon_2 + 2\,\varepsilon_1} \Delta E^2$

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

Generally $\varepsilon_2 > \varepsilon_1$, 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. **1 mark**

(c) Four processes which cause breakdown of solid insulation below their intrinsic strength are

(i) Surface Breakdown

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.

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

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

The conducting film is usually moisture from the atmosphere absorbed by some form of contamination. 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.

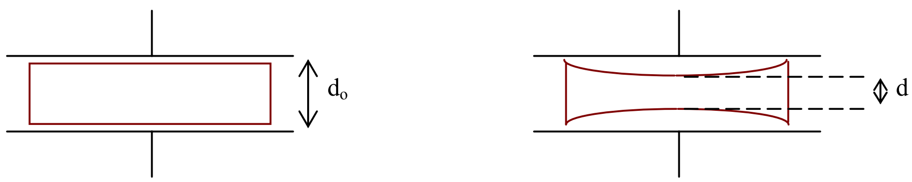
Carbonization results in a permanent extension of the electrodes and usually takes the form of a dendritic growth, known as **Tracking**. Tracking is the formation of a permanent conducting path across a surface of the insulation, and in most cases the conduction (carbon path) results from degradation 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.

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 material but allows operation until replacement can be made later. **1.5 marks**

(ii) Electromechanical Breakdown

When an electric field is applied to a dielectric between two electrodes, a mechanical force will be exerted on the dielectric due to the force of attraction between the surface charges. This compression decreases the dielectric thickness thus increasing the effective stress.



In the absence of field — With applied field

Compressive force $P_c = \frac{1}{2} D E = \frac{1}{2} \varepsilon_o \varepsilon_r V^2/d^2$,

and From Hooke's Law for large strains, $P_c = Y \ln (d_o/d)$

At equilibrium, equating forces gives the equation,

$$V^2 = \frac{2Y}{\varepsilon_o \varepsilon_r} d^2 \ln\frac{d_o}{d}$$

By differentiating with respect to d, it is seen that the system becomes unstable when $\ln (d_o/d) > \frac{1}{2}$ or $d < 0.6\, d_o$.

Thus when the field is increased, the thickness of the material decreases. At the field when $d < 0.6\, d_o$, any further increase in the field would cause the mechanical collapse of the dielectric.

The apparent reduced stress (V/d_o) at which this collapse occurs is thus given by the equation

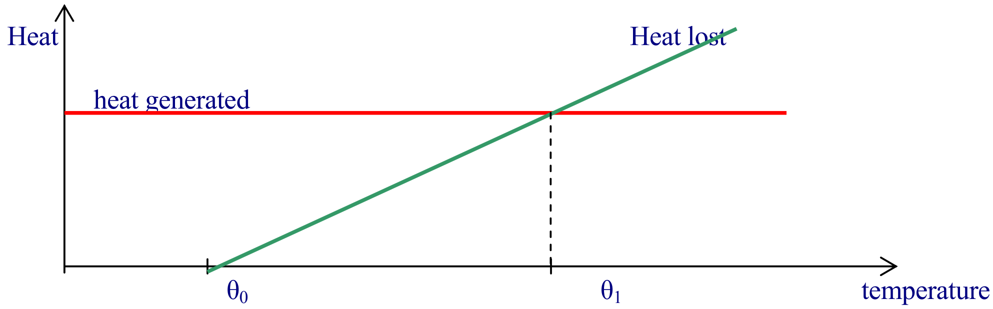
$$E_a = 0.6 \left[\frac{Y}{\varepsilon_o \varepsilon_r} \right]^{\frac{1}{2}}$$

1.5 marks

(iii) Thermal Breakdown

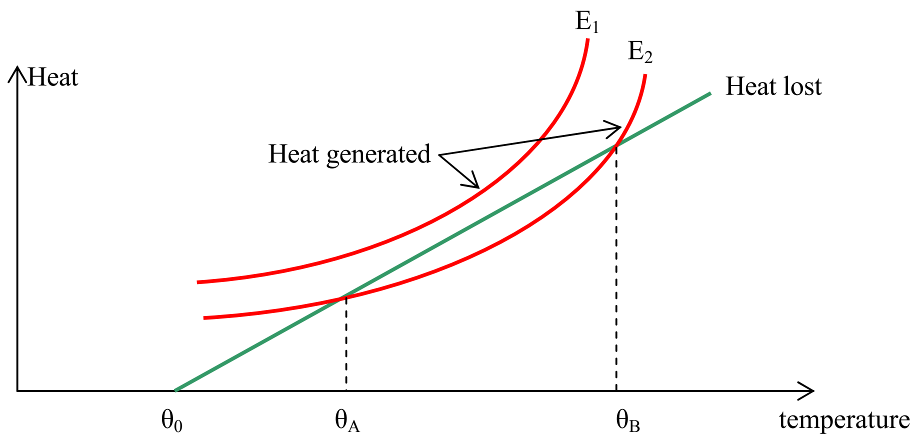
Heat is generated continuously in electrically stressed insulation by dielectric losses, which is transferred to the surrounding medium by conduction through the solid dielectric and by radiation from its outer surfaces. If the heat generated exceeds the heat lost to the surroundings, the temperature of the insulation increases.

The simplest case is where the loss of heat by cooling is linearly related to the temperature rise above surroundings, and the heat generated is independent of temperature. (i.e. the resistivity and the loss angle do not vary with temperature).



Heat lost = k (θ - θ_0), where θ = ambient temperature

Equilibrium will be reached at a temperature θ_1 where the heat generated is equal to the heat lost to the surroundings, as shown.



In practice, although the heat lost may be considered somewhat linear, the heat generated increases rapidly with temperature, and at certain values of electric field no stable state exists where the heat lost is equal to the heat generated so that the material breaks down thermally. The rapid increase is due to the fact that with rise in temperature, the loss angle of the dielectric increases in accordance with an exponential law (loss $\propto e^{-A/T}$, where T is the absolute temperature).

Figure shows the variation of heat generated by a device for 2 different applied fields and the heat lost from the device with temperature.

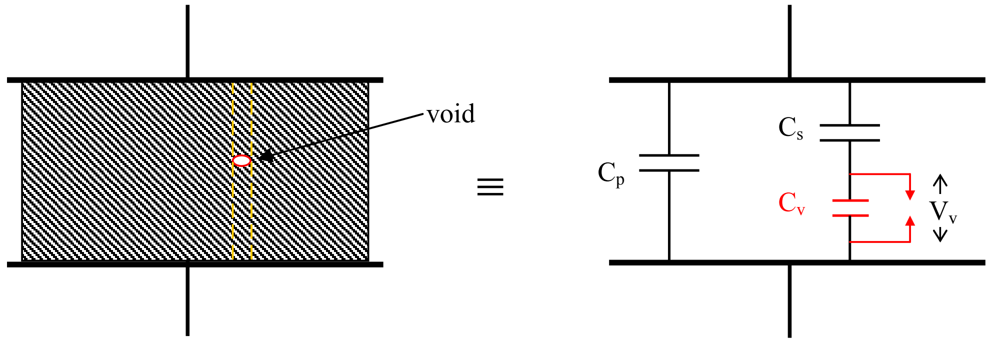
For the field E_2, a stable temperature θ_A exists (provided the temperature is not allowed to reach θ_B). For the field E_1, the heat generated is always greater than the heat lost so that the temperature would keep increasing until breakdown occurs.

The maximum voltage a given insulating material can withstand cannot be increased indefinitely simply by increasing its thickness. Owing to thermal effects, there is an upper limit of voltage V_θ, beyond which it is not possible to go without thermal instability. This is because with thick insulation, the internal temperature is little affected by the surface conditions. Usually, in the practical use of insulating materials, V_θ is a limiting factor only for high-temperature operation, or at high frequency failures.

1.5 marks

(iv) Breakdown due to internal discharges

Solid insulating materials sometimes contain voids or cavities in the medium or boundaries between the dielectric and the electrodes. These voids have a dielectric constant of unity and a lower dielectric strength. Hence the electric field strength in the voids is higher than that across the dielectric. Thus even under normal working voltages, the field in the voids may exceed their breakdown value and breakdown may occur. The mechanism can be explained by considering the following equivalent circuit of the dielectric with the void shown.



Equivalent circuit of dielectric with void

When the voltage V_v across the void exceeds the critical voltage V_c, a discharge is initiated and the voltage collapses. The discharge extinguishes very rapidly (say 0.1 μs). The voltage across the void again builds up and the discharges recur. The number and frequency of the discharges will depend on the applied voltage. The voltage and current waveforms (exaggerated for clarity) are shown in figure.

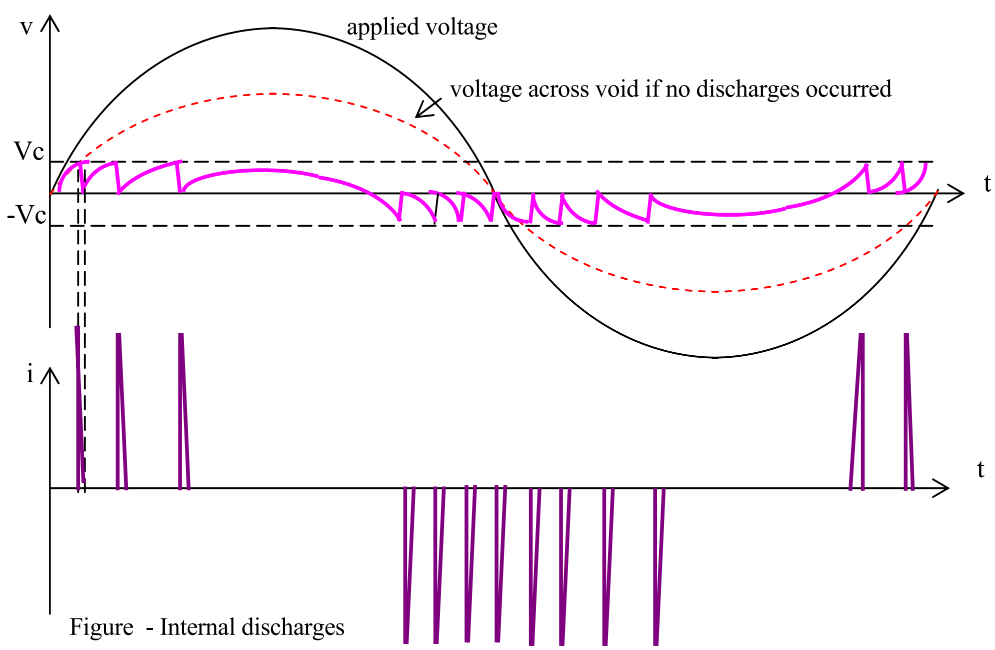


Figure - Internal discharges

In each of the discharges, there will be heat dissipated in the voids which will cause carbonization of the surface of the voids and erosion of the material. The gradual erosion of the material and consequent reduction in the thickness of the insulating material eventually leads to breakdown. **1.5 marks**

Other alternate processes that may be described instead

Electrochemical Breakdown

or Chemical deterioration

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

Answer 3

(a) **Cascade arrangement of transformers**

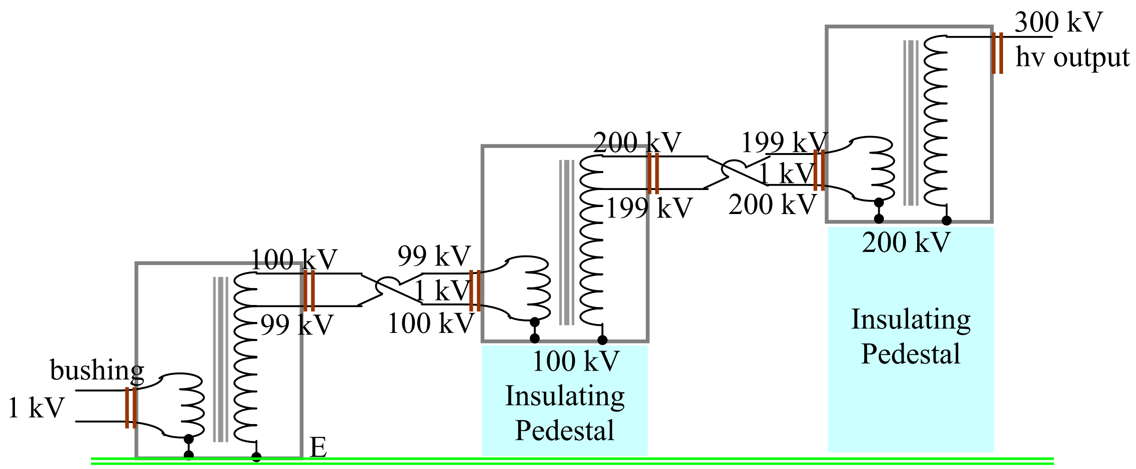
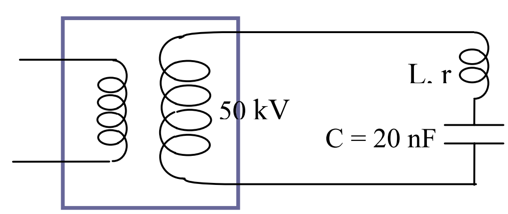


Figure shows a typical cascade arrangement of transformers used to obtain up to 300 kV from three units each rated at 100 kV insulation. The low voltage winding is connected to the primary of the first transformer, and this is connected to the transformer tank which is earthed. One end of the high voltage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

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) 200 kVA, 230V/50 kV, 50 Hz testing transformer, 8% leakage reactance, 2% winding resistance, Q =15



Base Z = $\frac{V^2}{V.A} = \frac{(50\times10^3)^2}{200\times10^3}$ = 12,500 Ω

x_t = 8 % = 12,500×0.08 = 1000 Ω, $L_t = \frac{1000}{100\pi}$ =3.183 H

r_t = 2 % = 12,500×0.02 = 250 Ω

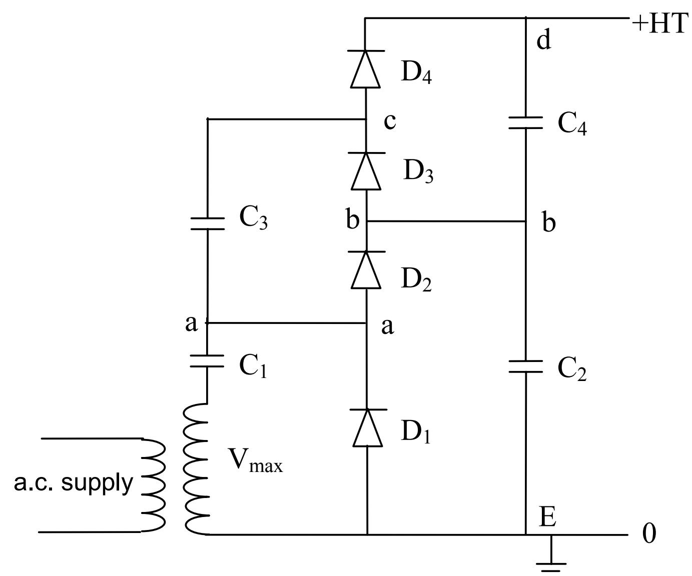
for resonance, $\omega_0^2 = \frac{1}{L_{eq}C}$, L + L_t = $\frac{1}{(2\pi\times50)^2\times20\times10^{-9}}$ = 506.6 H → L = 506.6 – 3.18 = 503.4 H

5 marks

Q = 15 = $\frac{L\omega}{r}$ → r = $\frac{503.4\times100\pi}{15}$ = 10,544 Ω, I = 300×10^3×20×10^{-9}×100π = 1.885 A

V_{in} (hv) = 1.885×(10544+250) = 20,347 V → V_{in} (lv) = 20,347×$\frac{230}{50000}$ = 93.6 kV **2 marks**

(c) **Cockroft-Walton Voltage Multiplier Circuit**



Let $\mathbf{V_{max}}$ be peak value of secondary of high voltage transformer.

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 $\mathbf{D_1}$, the capacitor $\mathbf{C_1}$, and the secondary winding. During the first negative half cycle of the applied voltage, the capacitor $\mathbf{C_1}$ charges up to voltage $\mathbf{V_{max}}$. Since during the positive half cycle which follows, the diode $\mathbf{D_1}$ is reverse biased, the capacitor $\mathbf{C_1}$ 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 $\mathbf{2\ V_{max}}$. During the following cycles, the potential at a will vary between **0** and $\mathbf{2\ V_{max}}$, 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 biassed, 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 biassed 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 biassed 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 biassed 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 biassed 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.

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	2 Vm	2 Vm	2 Vm	2 Vm	2 Vm	2 Vm	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	4 Vm	4 Vm	4 Vm	4 Vm	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

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]

Answer 4

(a) 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

$$\text{Energy stored } W = \tfrac{1}{2} C V^2$$

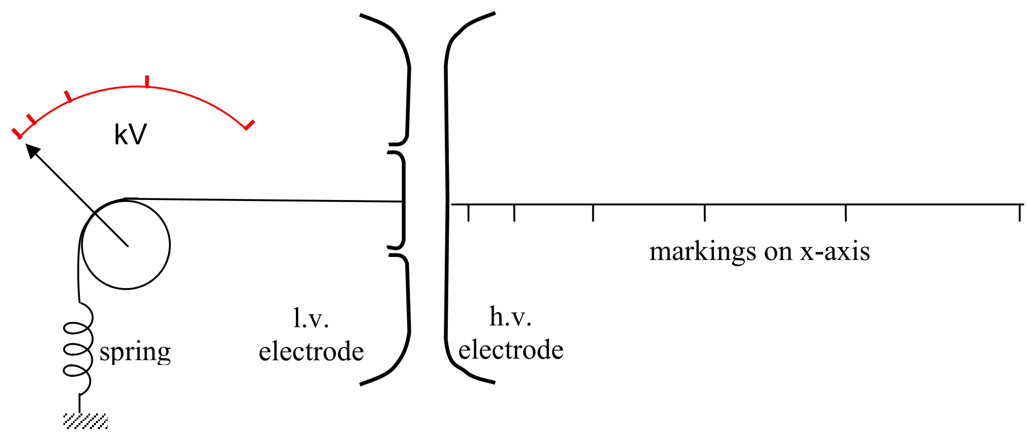
$$\text{so that } \quad dW = \tfrac{1}{2} V^2 dC = F\,dx$$

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

Thus the deflecting torque of an electrostatic voltmeter is proportional to the product of the square of the applied voltage and the rate of change of capacitance. **3 marks**

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

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

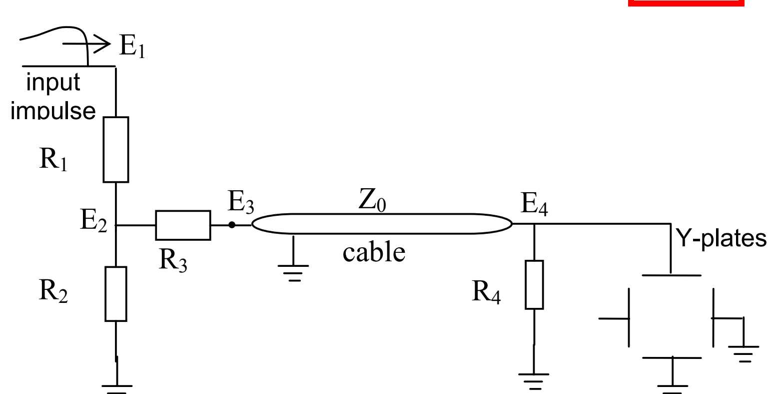


The force of attraction is proportional to the square of the potential difference applied, provided the variation in x is small, so that the meter reads the square value (or can be marked to read the rms value). In this meter, the electrostatic force is balanced by a spring force as shown.

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 purpose of this is to keep the field roughly constant as movement occurs only on a small section.

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 electrostatic instruments can be used to measure both a.c. and d.c. voltages. **2 marks**

(b) 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. Thus matching needs to be done. **1 mark**



In this case, the cable is matched at both ends, so that there is no reflection at either end.

This arrangement reduces to a minimum the irregularities produced by the cable circuit.
Matching the cable at the receiving end would require the impedance seen by the surge at E_4 to be equal to the cable surge impedance Z_o. Also the sending end would require the effective impedance seen at E_2 from the cable side to match the cable.

Thus for perfect matching at receiving end, $R_4 = Z_0$
and for perfect matching at sending end, $R_3 + R_1 // R_2 = Z_0$
since $R_1 >> R_2$, this gives $R_3 + R_2 = Z_0$
Thus
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.

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

Thus an undistorted waveform is obtained with ratio $\frac{R_2}{2 (R_1 + Z_1)}$ **4 marks**

(c) **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^o.

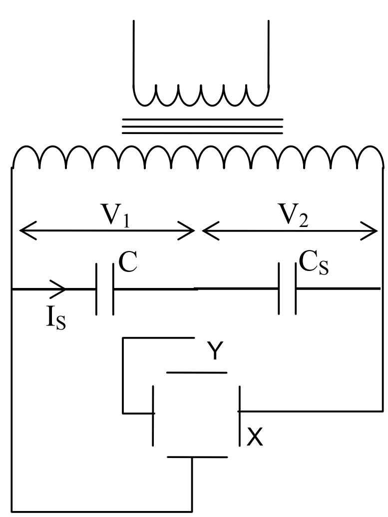
This property is made use of in dielectric loss measurements. A potential difference proportional to the applied voltage is applied to one pair of plates and a potential difference proportional to the integral of the current through the dielectric is applied to the other pair. Since the loss is to be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

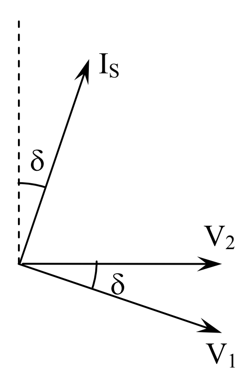
The voltages across the capacitor and across the sample are applied across the two plates. The area of the ellipse thus formed is proportional to the power loss in the dielectric. If the power loss in the dielectric is zero, the figure traced out on the oscilloscope would be a straight line.

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.

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

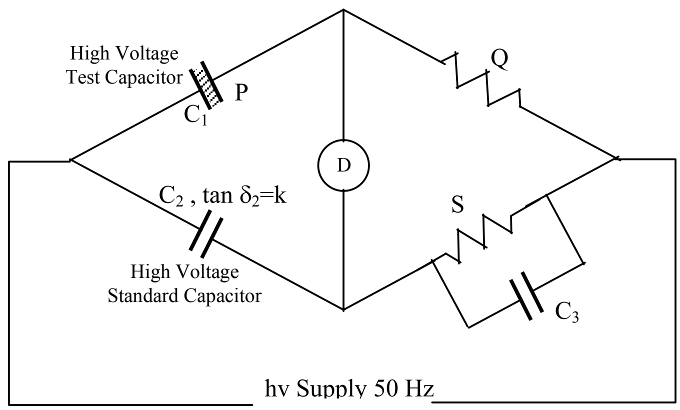
$$A = \int y \,.\, dx = \int_0^T a \,.\, \frac{I_{sm}}{\omega C} \,.\, \sin(\omega t - \delta) \,.\, b \,.\, V_{2m} \,.\, \omega \,.\, \cos \omega t \,.\, dt$$

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

It is thus seen that the area of the ellipse is proportional to the power loss. **5 marks**

Answer 5

(a) 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

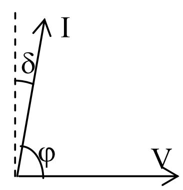
$$\frac{C_2}{C_1} = \frac{Q}{S} \quad \text{giving} \quad C_1 = \frac{S}{Q} C_1$$

2 marks

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

impedance angle = – φ,

loss angle = π/2 – φ = δ



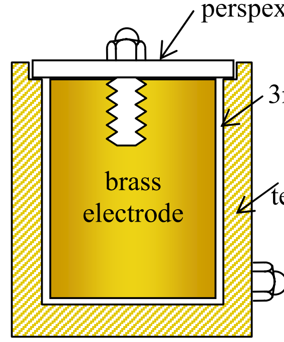
Thus

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

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

$\tan \delta_1 \approx \tan \delta_2 + \tan \theta = k + \omega C_3 S$ **2 marks**

(b) **Test Cell used in the Measurement of dielectric constant and loss tangent of an insulating liquid**



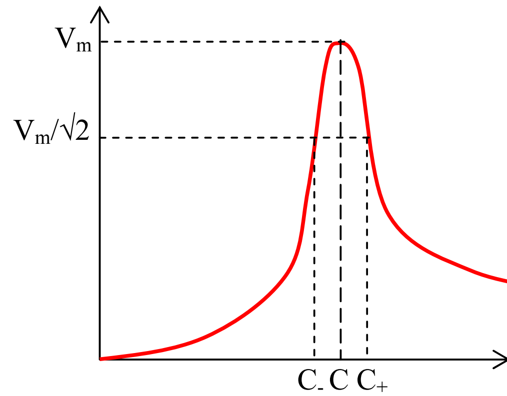
The test cell used in the measurement consists of a brass cell inside which is suspended a brass electrode from a perspex cover. The outer cell is the earthed electrode, and there is a gap of 3 mm all round between this and the inner brass electrode. Since the electrodes are near each other, the stray capacitance must be considered.

The test cell is connected in parallel with a variable capacitor and made part of a constant current resonant circuit.

The inner brass electrode of the test cell can be removed to obtain and eliminate the stray capacitance.

The test cell permits replacement of the 3 mm air gap by the insulating liquid permitting comparison of capacitances to determine the dielectric constant through the measurement of capacitance change at resonance.

The circuit is then de-tuned to the half-power points (voltage corresponding to 1/√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 at resonance can be obtained from

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

where ΔC_+ and ΔC_- are the variations at the half-power points.

Usually Q is high, and $\Delta C_+ = \Delta C_- = \Delta C$, so that $Q = \frac{C}{\Delta C_v}$

The following can be determined from the values of resonant Q for the cases with and without insulating oil. Thus

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

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

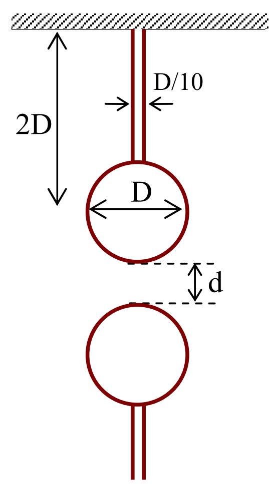
The loss factor may thus be calculated from

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

2 marks

(c) **Use of sphere gaps in the measurement of high voltages**

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. A sphere 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 breakdown strength of a gas depends on the size of the spheres (diameter D), their distance apart (spacing d) and a number of other factors such as clearance from adjacent objects. As such minimum clearances are specified.

Also, the density of the surrounding air affects the spark-over voltage for a given gap setting. Thus the correction for any air density change must be made using the air density correction factor δ .

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

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 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.

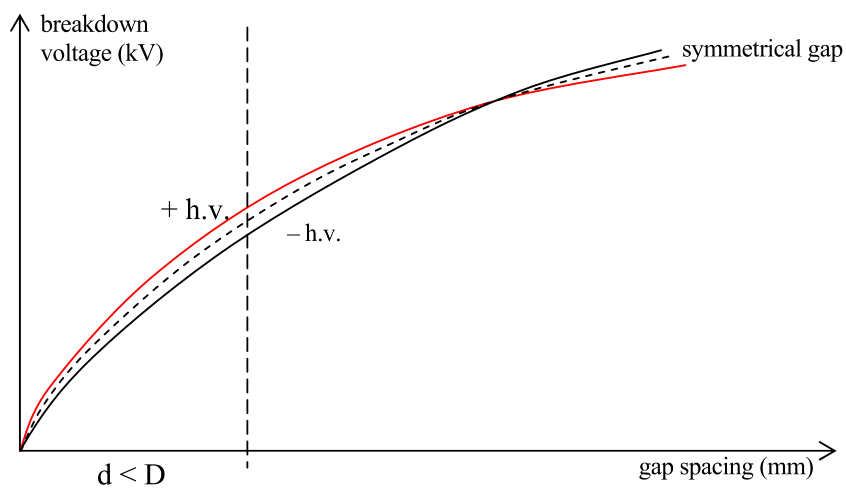
By precise experiments, the breakdown voltage variation with gap spacing, for different diameters (62.5 mm, 125 mm, 250 mm, 500 mm, 1 m and 2 m) and distances, have been calculated and represented in charts. These are used in the measurements.

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.



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.

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).

When 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.

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.

3 marks

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

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

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^o C of the ambient temperature of the neighbourhood of the insulator. The rain is sprayed at an angle of 45 ^{o} on the insulator at the prescribed rate of 3 mm/minute. The resistivity of the water should be 100 ohm-m ± 10%. The prescribed voltage is maintained for one minute.

Sample Tests test the sample fully, up to and including the point of breakdown. These are done only on a few samples. An example for an insulator is given below.

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 are to be applied routinely on all units to ensure a minimum level of performance. A typical test is given below.

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.

3 marks