EE 427 – High Voltage Breakdown & Testing – Model Answers

Level 2 Semester 2 Examination - March 2008

1 (a) The basic ionisation processes are

(i) Ionisation by simple collision

When the kinetic energy of an electron (½ mu²), in collision with a neutral gas molecule exceeds the ionisation energy ($E_i = eV_i$) of the molecule, then ionisation can occur.

$M + e^- (½ mu^2) \rightarrow M^+ + 2e^-$ (i.e. $½ mu^2 > Ei$) *[½ mark]*

(ii) Ionisation by Double electron impact

In the case of simple collision, the neutral gas molecule does not always gets ionised on electron impact. In such cases, the molecule will be left in an excited state M*, with energy E_e.

$M + e^- (½ mu^2) \rightarrow M^* + e^-$

This excited molecule can subsequently give out a photon of frequency ν with energy emitted hν. The energy can be given out when the electron jumps from one orbit to the next.

$M^* \rightarrow M + h\nu$

If a gas molecule is already raised to an excited state (with energy E_e) by a previous collision, then ionisation of this excited molecule can occur by a collision with a relatively slow electron. This electron would need less energy than the ionisation energy, but the energy must exceed the additional energy required to attain the ionisation energy.

$M^* + e^- (½ mu^2) \rightarrow M^+ + 2e^-$ (i.e. $½ mu^2 > E_i - E_e$) *[½ mark]*

(iii) Photo-ionisation

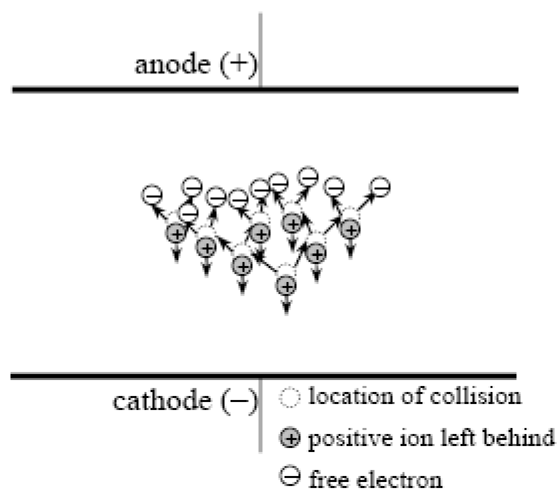
A molecule in the ground state can be ionised by a photon of frequency ν provided that the quantum of energy emitted h ν (by an electron jumping from one orbit to another), is greater than the ionisation energy of the molecule.

$M + h\nu \rightarrow M^+ + e^-$ (i.e. $h\nu > E_i$, where h = Plank's constant)

[½ mark]

The ***avalanche mechanism*** in the breakdown of gaseous dielectrics is based on the generation of successive ionizing collisions leading to an avalanche.

If a free electron exists (caused by some external effect such as radio-activity) in a gas where an electric field exists, then if the field strength is sufficiently high, 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 millions of electrons.



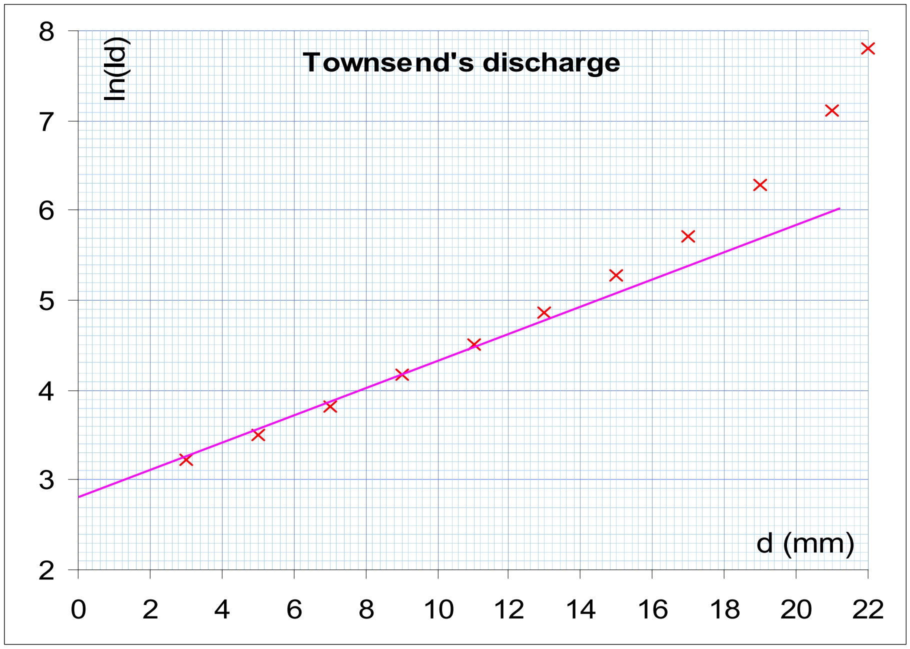
[½ mark]

(b) Derivation of $I_d = I_o e^{\alpha d}$ without considering secondary effects *[2 marks]*

$ln(I_d) = \alpha\, d + ln(I_o)$, where α is the Townsend's first ionization coefficient *[1 mark]*

d (mm)	3	5	7	9	11	13	15	17	19	21	22
I_d (pA)	25	33	45	65	90	130	195	300	540	1220	2470
$\ln(I_d)$	3.219	3.497	3.807	4.174	4.5	4.868	5.273	5.704	6.292	7.107	7.812

[1 mark]



Graph *[2 marks]*

Intercept = 2.8 not required

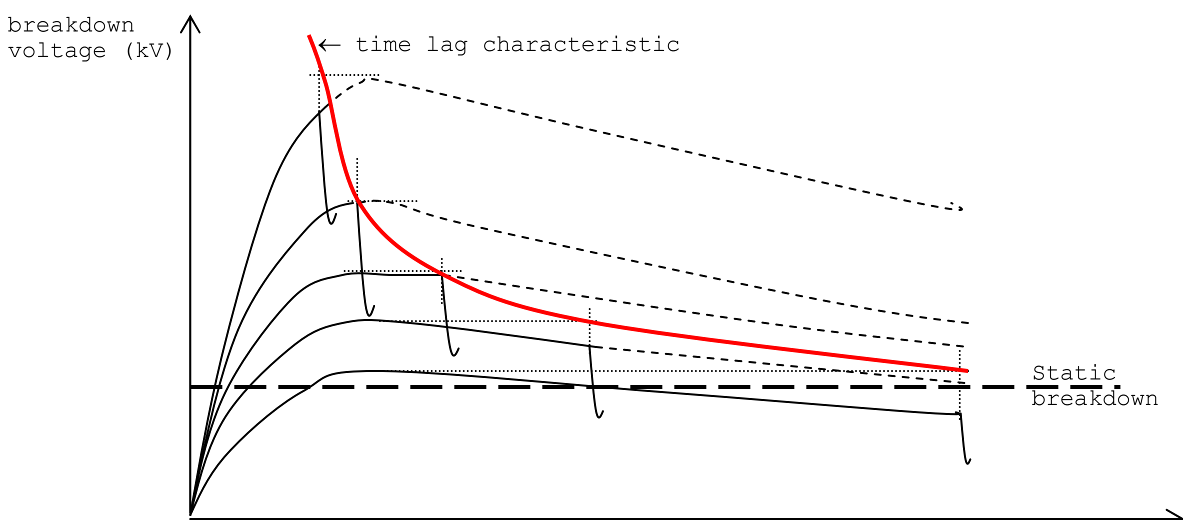
i.e. $\ln(I_{do}) = 2.8$ not required

$I_{do} = 16.44$ pA not required

$$\text{Gradient} = \frac{4.26 - 2.8}{10} = 0.146$$

i.e. $\alpha = 0.146\ \text{mm}^{-1}$ *[1 mark]*

(c) **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. The peak value of the prospective standard impulse voltage (1.2/50μs) is obtained and plotted against the breakdown time. This characteristic is used in the co-ordination of insulation. *[2 marks]*

(d) The impurities which lead to the breakdown of commercial liquids below their intrinsic strength, can be divided into the following 3 categories.

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]*

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.

If a spherical globule of liquid of permittivity ε_2 immersed in a liquid dielectric of permittivity ε_1, and 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 $\varepsilon_2/\varepsilon_1$. 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. *[1 mark]*

Breakdown due to solid particles

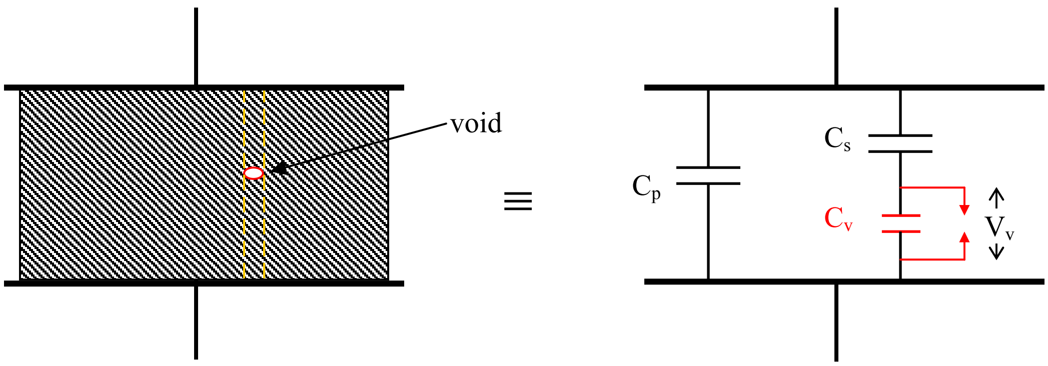
In commercial liquids, solid impurities cannot be avoided and will be present as fibres or as dispersed solid particles. If the impurity is considered to be a spherical particle of permittivity ε_2 and is present in a liquid dielectric of permittivity ε_1, it will experience a force

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

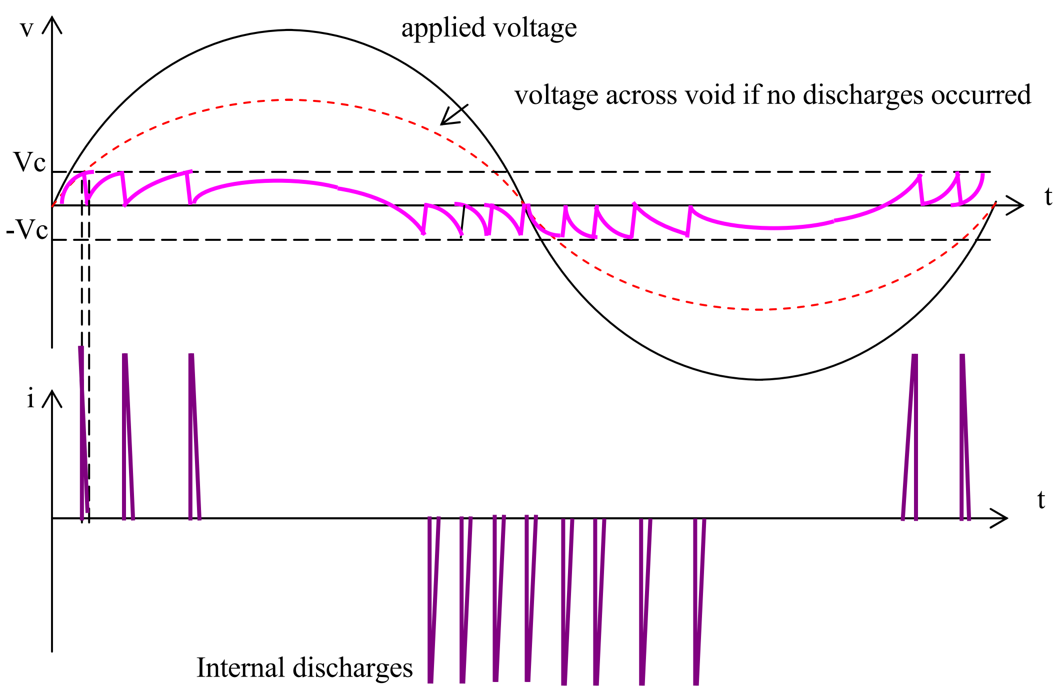
2 (a) **Breakdown due to internal discharges**

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 may breakdown. The mechanism can be explained by considering the equivalent circuit of the dielectric with the void



Dielectric — 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 the figure.

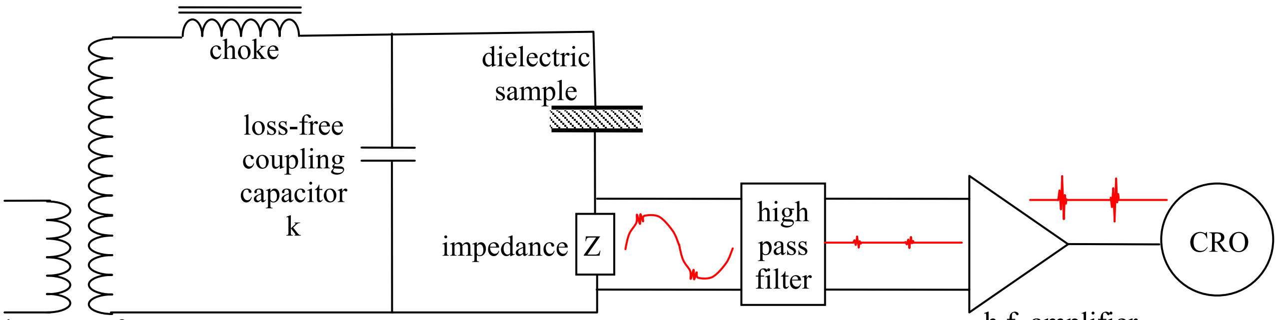


In each of the discharges, there will be heat dissipated in the voids which will cause carbonization of the surface of the voids and erosion of the material. The gradual erosion of the material and consequent reduction in the thickness of the insulating material eventually leads to breakdown.

Breakdown by this process is slow and may occur in a few days or may take a few years. *[2 marks]*

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. However, discharges occurring in the transformer and the choke are short circuited through the coupling capacitor and do not affect the measurement. The discharge pulses caused in the sample are of high frequency, so that we bypass the low frequency and amplify the high frequency in the measurement circuit. *[1 mark]*

(b) at 20 ^{o}C, 760 torr, corona inception = 90 kV, $m_o = 1$, fair weather

at 40 ^{o}C, 765 torr, assuming $m_o = 0.95$ for roughening (usual range 0.98 to 0.93) *[½ mark]*

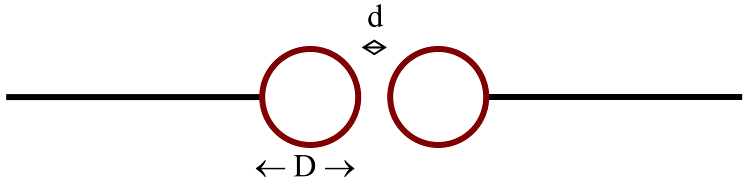
$$\delta = \frac{273+20}{273+40} \times \frac{765}{760} = 0.9423$$ *[1 mark]*

Thus corona inception

Under fair weather conditions = $90 \times 0.9423 \times 0.95 = \underline{\underline{80.6 \text{ kV}}}$ *[1 mark]*

Under stormy weather conditions = 0.8×80.567 = $\underline{\underline{64.5 \text{ kV}}}$ (assuming 80%) *[½ mark]*

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



where d = gap spacing, D = sphere diameter

In the measuring device, two metal spheres are used, separated by a gas-gap. The potential difference between the spheres is raised until a spark passes between them. The breakdown strength of a gas depends on the size of the spheres, their distance apart and a number of other factors. *[½ mark]*

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

$$\delta = \frac{P}{760} x \frac{273+20}{273+t} = 0.386 \left[\frac{P}{273+t} \right]$$ *[½ mark]*

The spark over voltage for a given gap setting under the standard conditions (760 torr pressure and at 20^{o}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 and distances, have been calculated and represented in charts for standard atmospheric conditions for similar pairs of spheres (diameters 62.5 mm, 125 mm, 250 mm, 500 mm, 1 m and 2 m)
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 $= \pm 3\,\%$
$0.75\,D > d > 0.5\,D$, accuracy $= \pm 5\,\%$ *[½ mark]*

For accurate measurement purposes, gap distances in excess of 0.75D are not used.
In sphere gaps used in measurement, to obtain high accuracy, the minimum clearance to be maintained between the spheres and the neighbouring bodies and the diameter of shafts are also specified, since these also affect the accuracy. There is also a tolerance specified for the radius of curvature of the spheres.
The breakdown voltage characteristic is also dependant on the polarity of the high voltage sphere in the case of asymmetrical gaps. Peak values of voltages may be measured from 2 kV up to about 2500 kV by means of spheres. One sphere may be earthed with the other being the high voltage electrode, or both may be supplied with equal positive and negative voltages with respect to earth (symmetrical gap). *[½ mark]*

(d) When two parallel conducting plates (cross section area **A** and spacing **x**) are charged **q** and have a potential difference **V**, then the energy stored in the is given by

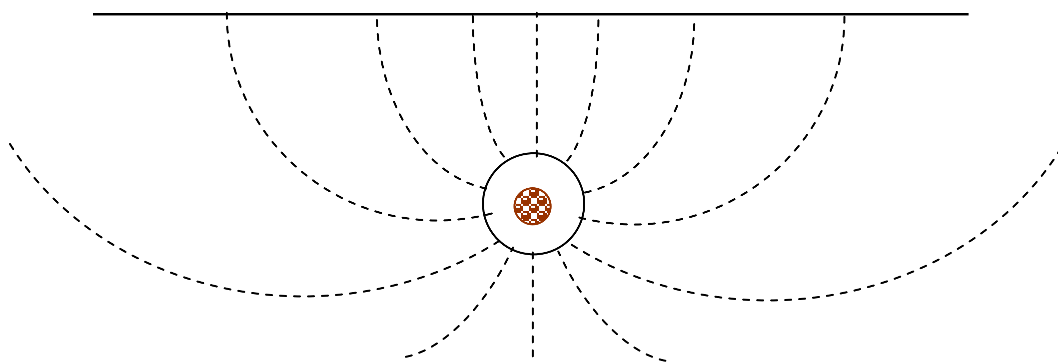
$$\text{Energy stored } W = \tfrac{1}{2} C V^2 \text{ so that change } dW = \tfrac{1}{2} V^2 dC = F\,dx$$ *[1 mark]*

$$\therefore \text{ Force } F = \tfrac{1}{2} V^2 \frac{dC}{dx} \text{ N}$$ *[½ mark]*

$$\text{for uniform field Capacitance } C = \frac{A\,\varepsilon}{x} \text{ so that } \frac{dC}{dx} = -\frac{A\,\varepsilon}{x^2}$$ *[1 mark]*

$$\therefore F = -\tfrac{1}{2} A\,\varepsilon \frac{V^2}{x^2} \text{ N}$$ *[½ mark]*

(e) Consider a cable buried under the surface of the earth.



Heat flow lines from buried cable

If	θ	=	maximum allowable difference in temperature between the core and surroundings (^{o}C)
	R_θ	=	Effective Resistance of conductor (including effects of sheath loss)
	I	=	Current carried by conductor
	H	=	Heat produced in the core (W)
	S'	=	Thermal resistance of dielectric
	S"	=	Thermal resistance of cable outside dielectric
	S	=	S' + S" = Total thermal resistance of cable
	G	=	Thermal resistance of ground from cable to surroundings

$$\therefore \quad H = \frac{\theta}{S+G} = W_d + I^2 R_\theta$$

[1 mark]

$$\text{i.e.} \quad \theta = (W_d + I^2 R_\theta)(S+G)$$

The total temperature rise between the conductor and the surroundings is given by

$$\theta = H(S+G)$$

Total power loss = dielectric loss (W_d) + ohmic loss ($I^2 R_\theta$) *[1 mark]*

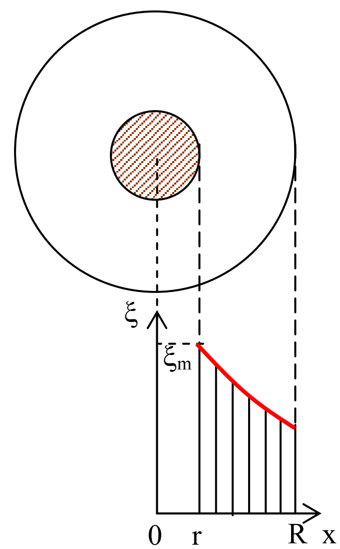
At equilibrium, the total power loss must equal to the heat produced.

This gives the current rating of the cable as

$$I = \sqrt{\frac{\theta - W_d(S+G)}{R_\theta(S+G)}}$$

[1 mark]

3 (a) The voltage difference across the conductor and the sheath of a single core cable is given by



$$v = \frac{q}{2\pi\varepsilon}\log_e\frac{R}{r}, \quad \text{also,} \quad \xi_x = \frac{q}{2\pi\varepsilon x}$$

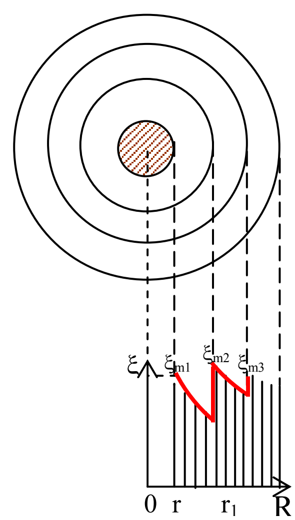
$$\text{so that} \quad \xi_x = \frac{v}{x\log_e\frac{R}{r}}$$

It is seen that since **x** is the only variable, the stress is not uniform and that the maximum stress in the dielectric occurs at the minimum value of the radius **x** (i.e. x = r). *[3 marks]*

(b) The electric stress in the dielectric may be more equally distributed by (i) Capacitance grading, and (ii) Intersheath grading

Capacitance Grading

In this method of grading, the insulation material consists of various layers having different permittivities.



$$V_1 = \xi_{max}\, r \log_e\frac{r_1}{r}$$

similarly V_2, V_3 can be determined

Consider a cable graded by means of 3 layers of insulation having permittivities ε_1, ε_2, ε_3, respectively. In order to secure the same value of maximum stress in each layer, the maximum stresses in the layers are equated.

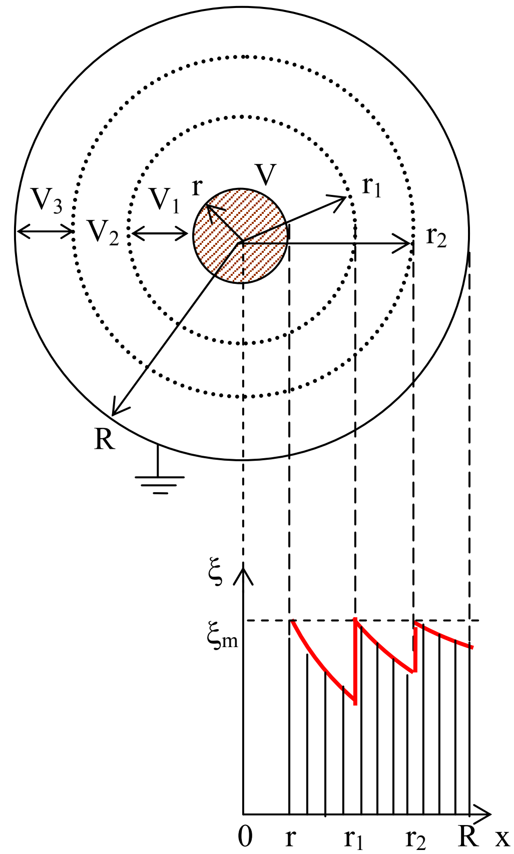
$$\frac{q}{2\pi\varepsilon_0\varepsilon_1 r} = \frac{q}{2\pi\varepsilon_0\varepsilon_2 r_1} = \frac{q}{2\pi\varepsilon_0\varepsilon_3 r_2}$$

$$\therefore \quad \varepsilon_1 r = \varepsilon_2 r_1 = \varepsilon_3 r_2$$

Hence by grading the insulation, without increasing the overall diameter of the cable, the operating voltage can be raised. In the above analysis, it has been assumed that the maximum permissible stress is the same for all three dielectrics used. If the maximum stress in the three sections are different, and are ξ_1, ξ_2, ξ_3 respectively, then the maximum stresses should be reached at the same time for the most economical operation of the insulation. This condition gives us the result *[2 marks]*

Intersheath Grading

In this method of grading, the same insulating material is used throughout the cable, but is divided into two or more layers by means of cylindrical screens or intersheaths. These intersheaths are connected to tappings from the supply transformer, and the potentials are maintained at such values that each layer of insulation takes its proper share of the total voltage. The intersheaths are relatively flimsy, and are meant to carry only the charging current.



Since there is a definite potential difference between the inner and outer radii of each sheath, we can treat each section separately as a single core cable.

If **V_1, V_2, V_3, ...** are the potential differences across the sections of insulation, then

$$\xi_{\max} = \frac{V_1}{r \log_e \frac{r_1}{r}} = \frac{V_2}{r_1 \log_e \frac{r_2}{r_1}} = ...$$

Since the cable insulation now consists of a number of capacitors in series, formed by the respective intersheaths, all potential differences **V_1, V_2, V_3, ...** are in phase. Thus, if **V** is the phase to neutral voltage, we can also write

$$V = V_1 + V_2 + V_3 + \dots\dots\dots + V_n$$

Solving, the voltage to be applied to the intersheaths can be determined. *[2 marks]*

(c) line to ground voltage = 132/√3 = 76.21 kV *[½ mark]*

additional voltage = 40 kV = V_2 (voltage across outer insulation) *[½ mark]*

thus voltage across inner insulation = 76.21 – 40 = 36.21 kV = V_1 *[½ mark]*

rms breakdown stress = 240/√2 = 169.71 kV/cm *[½ mark]*

rms maximum allowable stress = 169.21/2.5 = 67.88 kV/cm *[½ mark]*

Thus

$$\xi_{\max,rms} = 67.88 = \frac{36.21}{0.95 \log_e \frac{r_1}{0.95}} = \frac{40}{r_1 \log_e \frac{R}{r_1}}$$ *[2½ mark]*

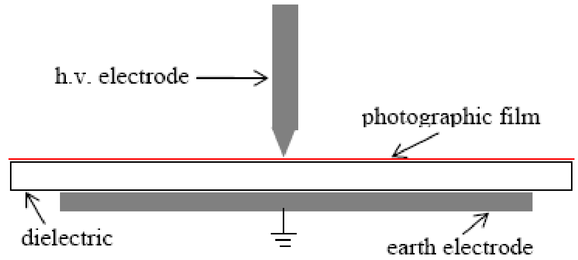
$$\log_e \frac{r_1}{0.95} = \frac{36.21}{0.95 \times 67.88} = 0.5615$$ *[1 mark]*

Giving r_1 = 1.6656 cm = 16.7 mm *[½ mark]*

$$\log_e \frac{R}{1.6656} = \frac{40}{1.6656 \times 67.88} = 0.3538$$ *[1 mark]*

Giving r_1 = 2.3725 cm = 23.7 mm *[½ mark]*

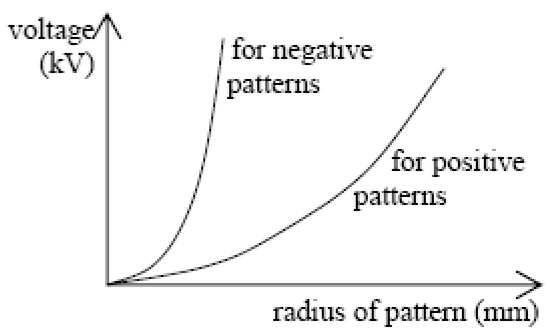
4 (a) The frequency of occurrence of surge voltages and the magnitude of the surge, lightning produces on the transmission lines could be studied using Litchenberg patterns obtained by using a Klydonograph.

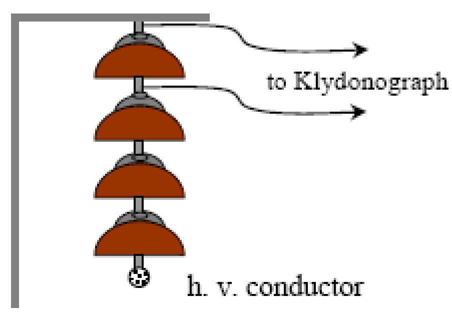


The Klydonograph has a dielectric sheet, on the surface of which is placed a photographic film. The insulator material separates a plane electrode on one side, and a pointed electrode which is just in contact with the photographic film. The high voltage is applied to the pointed electrode and the other 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. *[1 mark]*

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

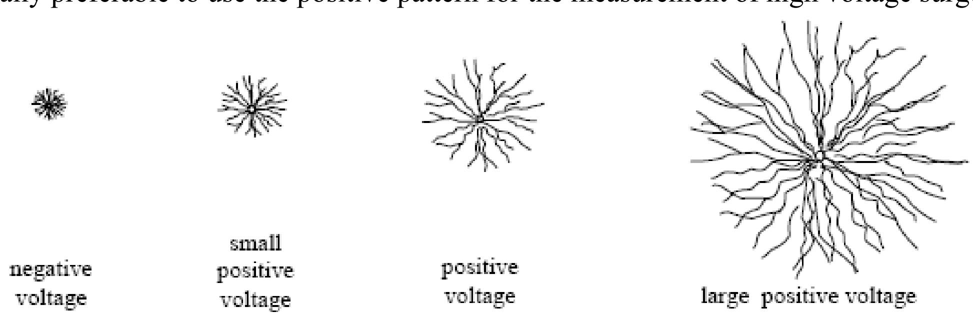
For a given apparatus with a fixed thickness of dielectric, the radius of the pattern obtained is a definite function of the voltage applied, and thus by calibrating the Klydonograph using a high voltage oscilloscope and known surge voltages, it is possible to use this apparatus to record surges that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





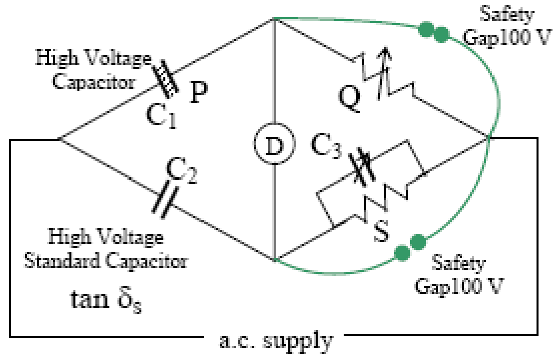
[½ mark]

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.



[½ mark]

(b) $C_2 = 100$ nF, $\tan\delta_2 = 0.001$, $Q = 210\ \Omega$
$C_3 = 140$ nF, $S = 100\ \Omega$
Diagram *[1 mark]*



Also at balance

$$\frac{Z_1\angle -90^o + \delta_1}{Z_1\angle -90^o + \delta_2} = \frac{Q}{Z_3\angle -\theta_3}$$ *[1 marks]*

Schering Bridge is frequency independent (assumption) *[½ mark]*

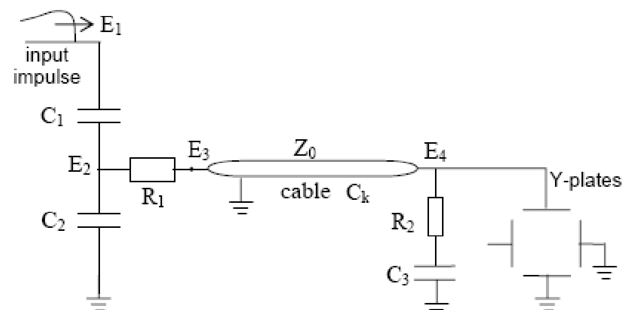
thus at balance, at high frequencies

$$\frac{C_1}{C_2} = \frac{S}{Q},\quad \text{gives } C_1 = \frac{100}{210}\times 100 = \underline{\underline{47.62\ \text{nF}}}$$ *[1 mark]*

also at balance, equating phase angles
$\delta_1 - \delta_2 = \theta_3$ *[1 mark]*
assuming losses to be very small, $\tan\delta \approx \delta$ *[½ mark]*
so that $\tan\delta_1 - \tan\delta_2 = \tan\theta_3$
i.e. $\tan\delta_1 - 0.001 = \omega C_3 S = 100\pi \times 140\times10^{-9}\times100 = 0.004398$

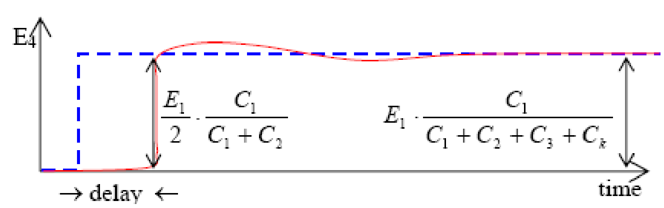
$\tan\delta_1 = \underline{\underline{0.0054}}$ *[1 mark]*

(c) 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 to avoid distortion. *[1 mark]*

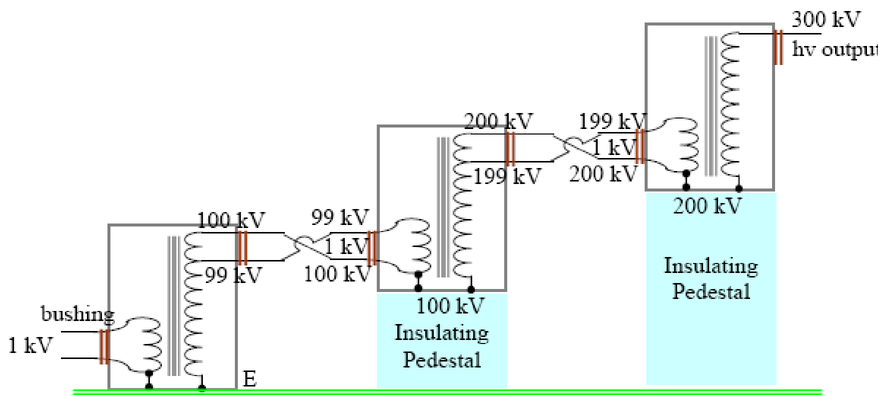


Matching the cable at the sending end would require the effective impedance seen at E_2 from the cable side to match the cable. Since for a surge, the capacitance is almost like a short-circuit compared to a resistance, this would give $R_1 = Z_0$. Similarly for matching at oscilloscope end, $R_2 = Z_0$. *[2 mark]*

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. 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. If the initial and the final values of the ratio are made equal, then the distortion is reduced to a great degree. *[1 mark]*



(d) 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.

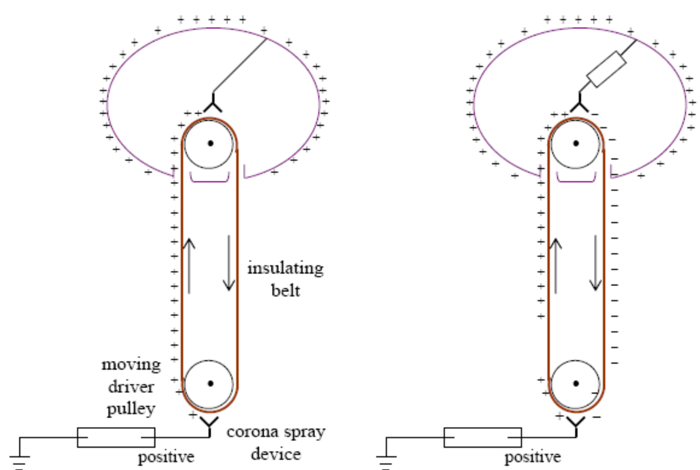


One end of the high voltage winding is also earthed through the tank. The high voltage end and a tapping near this end is taken out at the top of the transformer through a bushing, and forms the primary of the second transformer. One end of this winding is connected to the tank of the second transformer 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. *[1½ marks]*

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. These restrictions are not suitable for power transformers. *[½ marks]*

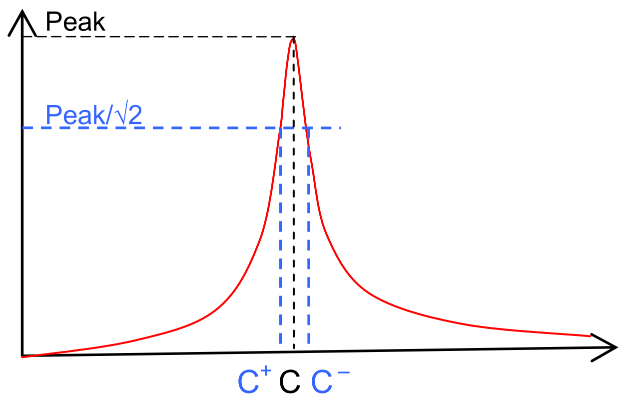
5 (a) The Van de Graeff generator is an electrostatic generator used to obtain very high direct voltages. However it cannot supply much current and the power output is restricted to a few kilowatt, and its use is restricted to low current applications.

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. *[2 marks]*

(b) C_{v0} = 100 nF, half-power points 98 nF and 102 nF



Assumed Q-factor $= \dfrac{2\times C}{C^{+}-C^{-}}$ *[1 mark]*

$$\text{Q-factor} = \frac{C^{+}{}_{v0}+C^{-}{}_{v0}}{C^{+}{}_{v0}-C^{-}{}_{v0}} = \frac{102+98}{102-98} = 50,$$

giving tan δ_0 = 1/50 = 0.02 *[2 marks]*

C_{v1} = 40 nF,

half-power points 33.3 nF and 47.7 nF

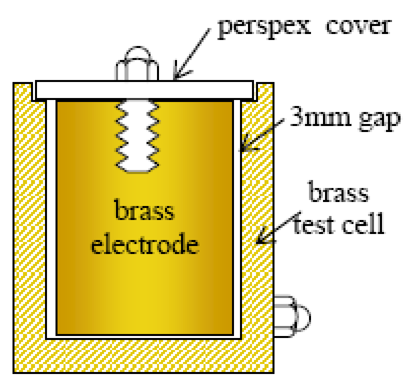
∴ value of unknown capacitor = $C_{v0} - C_{v1}$

= 100 – 40 = <u>60 nF</u> *[1 mark]*

$$\text{Q-factor} = \frac{(60+47.7)+(60+33.3)}{(60+47.7)-(60+33.3)} = 13.958,$$ giving tan δ_1 = 1/50 = 0.0716 *[2 marks]*

Thus the loss-factor of the unknown is = 0.0716 – 0.02 = <u>0.0516</u> *[1 mark]*

(c) 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. Tests are done in turn with (i) the outer cell and with only the brass screw and the perspex cover of the inner cell in position, (ii) the inner electrode screwed in and (iii) the liquid introduced into the test cell. The circuit is adjusted for resonance at the same frequency in each case, with the half-power points also determined. These permit the relative permittivity and the loss tangent of the oil to be determined.



[2 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: These tests are done to determine whether the particular design is suitable for the purpose. 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 μs 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.

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. *[1 mark]*

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. *[1 mark]*

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. *[1 mark]*