Worked out Tutorial Questions

***NB:** The suggested solutions to the given problems are by no means absolute*

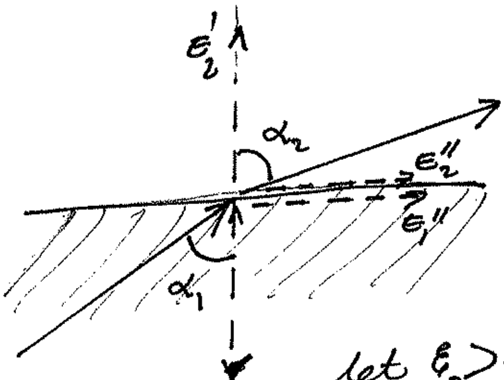
Electric Fields and Gas Breakdown Mechanisms

Question 1

a) There are important characteristics of electric fields that need to be taken into account when plotting the electric field equipotential lines; what are these characteristics?

- An electric field line/flux enter or leave an equipotential plane at right angle
- leave & terminate on electrode surfaces at right angle
- E-field/flux lines tend to repel each other
- diffract at dielectric boundaries
- On leaving an electrode surface e-field lines spread out.

b) Explain the behaviour of electric field lines at the boundary interface regions of different dielectrics. What are the implications on the design of insulation in high voltage apparatus?

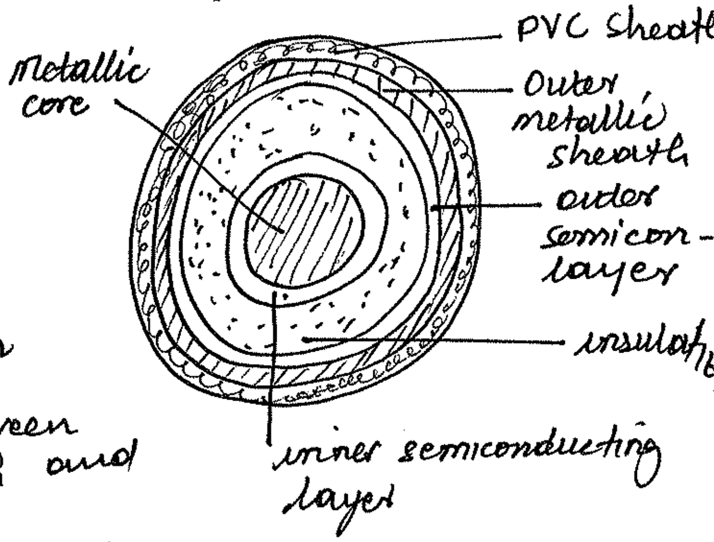


let $\varepsilon_2 > \varepsilon_1$

- The tangential components of the e-field lines on both sides of the boundary are equal i.e. $E_1'' = E_2''$
- Normal components are inversely proportional to the permitivities of the adjacent components i.e. $E_2' = \frac{\varepsilon_1}{\varepsilon_2} E_1'$
- The ratios of the tangent of incident angles is equal to the ratio of the corresponding dielectric constants $\frac{\tan\alpha_1}{\tan\alpha_2} = \frac{\varepsilon_1}{\varepsilon_2}$. or $\tan\alpha_1 = \frac{\varepsilon_1}{\varepsilon_2}\tan\alpha_2$

c) Sketch and label a cross-sectional view of a typical shielded medium voltage XLPE cable showing the six basic cable components. Give brief explanations of the function of each of the components.

Component	Function
Metallic core	current carrying
Inner semi-con	Smooth interface of core & insulation
Insulation	electrical ~~of~~ separation of core
Outer semi-con	smooth interface between outer metallic sheath and insulation
Outer metallic sheath	Earth return & also fault current



d) What are the criteria used in selecting a power cable for use in connecting 2 points in a power network.

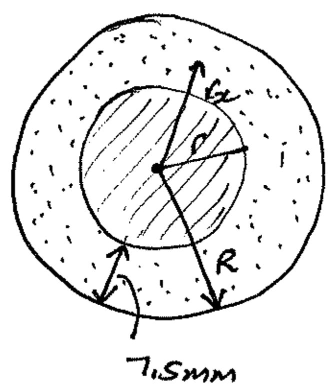
- Voltage drop $V_{drop} = IZ \leq$ maximum allowable
- fault current rating $\Rightarrow$ size to be big enough to carry the worst fault current in the circuit
- Thermal rating $\Rightarrow$ should be able to carry normal load under worst thermal conditions

e) A single core power cable for working AC voltage of 6.5/11 kV rms has a core conductor of 10 mm overall diameter, which is insulated with impregnated paper to a radial thickness of 7.5 mm and then lead covered – PILC cable.

i) Calculate the maximum stress (kV/mm) that the insulation would be subjected to.

E-field strength at a point r_x from the core centre is given by

$$E_x = \frac{V}{r_x \ln\left(\frac{R}{r}\right)}$$



Max E-field occurs where $r_x = r$

i.e. $E_{max} = \dfrac{V}{r \ln\left(\frac{R}{r}\right)}$

$r = \frac{10}{2} = 5\text{mm}$

$V = 6{,}5 \text{ kV}_{rms}$

$$\therefore \quad = \frac{6{,}5}{5 \ln\left(\frac{12{,}5}{5}\right)}$$

$$= \underline{1{,}42 \text{ kV}_{rms}/\text{mm}}$$

ii) In order to determine the optimal overall size of the cable (i.e. the inner (r_i) and outer (R_o) diameters), the optimal ratio of the sheath and core radii has to be considered. Use the electric field equation given below to evaluate whether the core diameter of 10 mm is optimal for the given cable.

Note: The equation for the electric field between two electrodes in a co-axial system is given by:

$$E = \frac{V}{r \ln\left(\frac{R_o}{r_i}\right)}$$

Where the symbols have their usual meanings.

V & R are normaly the given constraints in cable design procedures. Thus holding V & R constant & varying r, the expression of stress has minimum value when the denominator $r \ln\left(\frac{R}{r}\right)$ is max and this occurs when

$\ln\left(\frac{R}{r}\right) = 1$ i.e. $\frac{R}{r} = e = 2,718$

Given that $R = 12,5$ mm

$\Rightarrow \frac{12,5}{r} = 2,419$

$\therefore r = \frac{12,5}{2,418} = 4,6 \simeq 5$ mm. $\Rightarrow$ this is approximatel equal to the given inner radius of the cable $\therefore$ the core is optimally designed.

Question 2

a) Derive the expression for the electric field strength between the following electrode geometries:

i) Two parallel plates separated by a distance d.

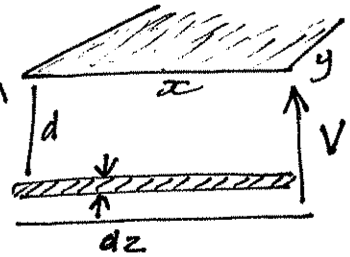
General procedure for deriving E-field expressions for common electrode geometries:

Step 1: Determine E using the Gaussian theorem. ie $AE = \frac{q}{\varepsilon} \Rightarrow E = \frac{q}{A\varepsilon}$ and $q = \varepsilon A E$.

Step 2: Insert E in the eqn $V = \int E dx$

Step 3: Eliminate q in the step 2 using the relationship in Step 1

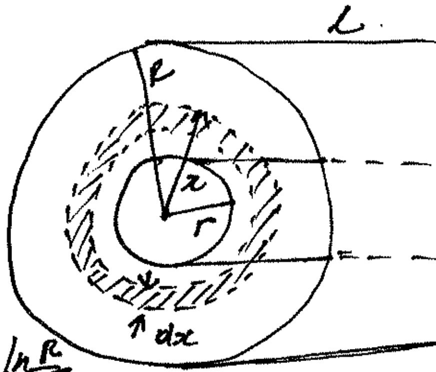
Step 1: $E = \frac{q}{A\varepsilon} = \frac{q}{xy\varepsilon}$ & $q = \varepsilon E xy$



Step 2: $V = \int_{z=0}^{z=d} E\, dz = \int_0^d \frac{q}{xy\varepsilon} dz = \frac{q}{xy\varepsilon} d$

Step 3: Eliminate q in step 2 $\Rightarrow V = \frac{E\cancel{\varepsilon xy}}{\cancel{\varepsilon xy}} \cdot d$ $\therefore E = \frac{V}{d}$.

ii) A coaxial electrode setup of inner conductor radius of r and outer conductor radius of R.



Step 1: $E = \frac{q}{A\varepsilon}$ but $A = 2\pi r l$

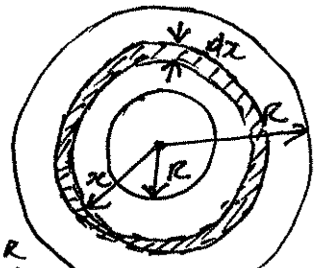
$\therefore E = \frac{q}{2\pi r l \varepsilon}$

Step 2: $V = \int_r^R E_x\, dx = \int_r^R \frac{q}{2\pi x l \varepsilon} dx$

$= \frac{q}{2\pi l \varepsilon} \int_r^R \frac{1}{x} = \frac{q}{2\pi l \varepsilon} \ln \frac{R}{r}$

Step 3: Eliminating q gives $V = \frac{E\, 2\pi r l \varepsilon}{\cancel{2\pi l \varepsilon}} \ln \frac{R}{r}$ $\therefore E = \frac{V}{x \ln \frac{R}{r}}$.

iii) A sphere of radius R; comment on the practical implications on the design of high voltage apparatus.



Step 1: $EA = \frac{q}{\varepsilon}$, $E = \frac{q}{A\varepsilon}$ but $A = 4\pi x^2$

$\therefore E = \frac{q}{4\pi x^2 \varepsilon}$.

Step 2: $V = \int_r^R E\, dx = \int_r^R \frac{q}{4\pi x^2 \varepsilon} dx = \frac{q}{4\pi\varepsilon} \int_r^R \frac{1}{x^2} dx$

Step 3: $V = E \frac{4\pi x^2 \cancel{\varepsilon}}{\cancel{4\pi\varepsilon}} \cdot \left(\frac{1}{r} - \frac{1}{R}\right) = \frac{q}{4\pi\varepsilon}\left(\frac{1}{r} - \frac{1}{R}\right)$

$\therefore E = \frac{V}{x^2\left(\frac{1}{r} - \frac{1}{R}\right)}$ or $\frac{V}{x^2}\left(\frac{Rr}{R-r}\right)$ if $R >> r$ then $E = \frac{Vr}{x^2}$

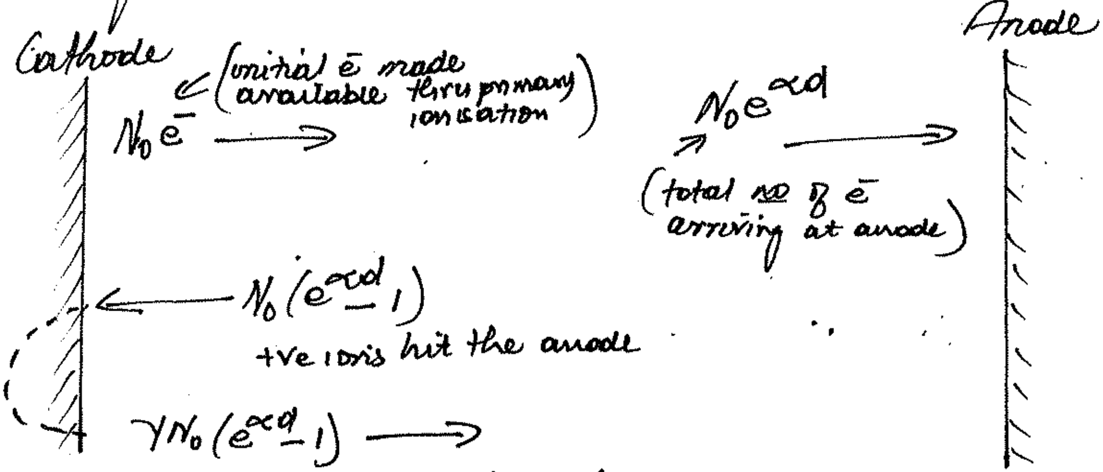
Question 3

a) Compare and contrast Townsend and Streamer gas breakdown mechanisms

Similarities	Differences
Both involve ionisation avalanches	Townsend b/dwn occur in small gaps & @ lower pressure & Streamer is the opposite
Both grow by feedback processes	Townsend is sustained by γ-feedback a fn of the cathode material while Streamer isn't dependent on cathode material
Both result in gap breakdown	
Both emit optical & heat energy	Townsend breakdown is relatively slower than Streamer breakdown
Both require seed electron	Townsend gives out diffuse light while streamer has filamentary bright channels.

b) Townsend's first ionisation coefficient, α, and Townsend's second ionisation coefficient, γ, are important parameters describing breakdown in a gas. By describing the detailed sequence of gas breakdown events in a short, uniform field gap, show the importance of the two Townsend constants.

The diag. below can be used to explain the process.



electrons emitted by the cathode due to feedback processes & these cause further avalanches leading to breakdown

c) Why do we measure different breakdown voltages for the same geometry at sea level and in Gauteng?

The rate of ionisation is a function of the following

1. the mean free path τ of the molecules; this in turn is a function of the gas pressure P.

2. the total number of gas molecules available and this is proportional to the pressure P for a given vol. & temp

3. The electric field strength E that causes the electrons to accelerate & ∴ cause avalanches.

Consequently $\alpha = A.P\,e^{\left(\frac{-BP}{E}\right)}$

Where A & B are constant.

Thus for the same geometry i.e. giving same E, pressure is different at sea level & in Gauteng & ∴ α will be different and giving different breakdown voltages.

d) A steady state current of 235 μA flows through a plane electrode separated by a distance of 6 mm when the voltage applied is 12 kV. The E-field is kept constant and the gap spacing is now reduced to 1.2 mm. A current of 24 μA is measured to flow under this new condition. Hence determine Townsend's first ionisation coefficient, α, for the gas filling the gap between the electrodes.

$$I_1 = I_0 e^{\alpha d_1} \quad \text{---} ① \qquad I_1 = 235\,\mu A;\ d_1 = 6\,mm$$

$$I_2 = I_0 e^{\alpha d_2} \quad \text{---} ② \qquad I_2 = 24\,\mu A;\ d_2 = 1.2\,mm$$

A situation of 2 eqns + 2 unknowns

∴ to solve for α, divide eqn ① by ②

$$\frac{I_1}{I_2} = \frac{\cancel{I_0} e^{\alpha d_1}}{\cancel{I_0} e^{\alpha d_2}}$$

$$= e^{\alpha(d_1 - d_2)}$$

$$\text{or } \ln\left(\frac{I_1}{I_2}\right) = \alpha(d_1 - d_2) \quad \text{or } \alpha = \frac{\ln(I_1/I_2)}{d_1 - d_2}$$

$$= \frac{\ln(235/24)}{(6 - 1.2)} = 0.48 \ \frac{\text{electrons}}{mm}$$

e) Explain the meaning of the term 'electronegative' and hence comment on what makes SF_6 a better insulator than air. Be sure to explain the fundamental processes involved.

<u>Definition</u>: An electronegative gas is one that although the molecules are not ions, they have a tendency to attract & hold on to electrons.

<u>Why SF_6 is better insulator than air</u>

Air is electronegative due to oxygen molecules. SF_6 however is more electronegative ($\eta_{SF_6} > \eta_{air}$) & ∴ avalanches in SF_6 are inhibited as electrons are removed from the avalanche process. It requires bigger e-field strength to satisfy the streamer criterion $\int(\alpha - \eta_{SF_6})\,dx = 18$ in SF_6 than $\int(\alpha - \eta_{air})\,dx = 18$ in air.

d) Two aluminium spheres with radius 150 mm each are suspended in SF_6 with a distance of 40 mm between them and at a pressure of 1 bar.

i) *Estimate* the breakdown voltage for this geometry, and explain the basis for this estimation. Is this likely to be a high or low estimate?

Note: The following equation for the electric field between two identical spheres spaced distance S apart may be used without proof.

$$E = \frac{VR(R+S)}{2S}\left[\frac{1}{(R+x)^2} + \frac{1}{(R+S-x)^2}\right]$$

The streamer criterion may be taken as:

$$\int (\alpha - \eta)dx = 18$$

Ionisation and attachment coefficients for SF_6 are:

$$(\alpha - \eta) = 0{,}028E - 249 \times 10^3 p$$

Where the symbols have their usual meanings.

ii) Show how you would *accurately* predict the breakdown voltage for this geometry. Use of sketches is recommended.

This ~~tests~~ one's knowledge on streamer breakdown phenomenon. It is about estimation of gap breakdown voltage in an electronegative gas, SF_6, in a given electric field environment and in this case a sphere - sphere electrode setup.

① An analytical expression that governs the e-field between given electrodes is normaly given and in this case between two identical spheres is given as $E = \frac{VR(R+S)}{2S}\left[\frac{1}{(R+x)^2} + \frac{1}{(R+S-x)^2}\right]$ ---- ①

② A reminder about the streamer criterion in attaching gas eg. SF_6

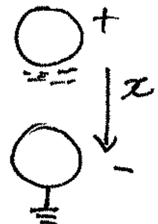
$$\int_0^x (\alpha - \eta)\, dx = 18 \quad ---- ②$$

(3) You are given the ionisation and attachment curves or expression and for SF_6 it is given as

$$\alpha - \eta = 0{,}028E - 249.10^3 P \quad --- (3)$$

The task is to use an iterative method to estimate the breakdown voltage V_{bb}.

(ii) Firstly consider the point with the highest probability for initiating an avanche that turns into streamer.



In this case the electrode being a sphere the electric field is highest nearest the sphere surface i.e. where $x = 0$ // ⇒ important to remember

Substituting $x = 0$ into the expression for E gives E interms of V i.e.

$$E = \frac{VR(R+S)}{2S}\left[\frac{1}{R^2} + \frac{1}{(R+S)^2}\right] \quad --- (1)$$

// For streamer breakdown to initiate in SF_6, // ⇒ important to remember
$\alpha - \eta = 0$ or $\alpha \geq \eta$.

$$\Rightarrow \quad (\alpha - \eta) = 0{,}028E - 249.10^3 P = 0 \quad --- (2)$$

We have 2 unknowns (E & V) and two eqns (1) & (2).

Solve for V by substituting the expression of E as a function of V

⊛ This is the 1st estimate of voltage that causes breakdown. It is a lower estimate because it has been obtained by assuming that $\alpha = \eta$ and yet in reality it will most likely be $\alpha > \eta$ & such conditions gives V higher than that obtained with $\alpha = \eta$.

ii) More accurate breakdown voltage of the gap in SF_6 gas is obtained through an iterative calculation of the following procedure;

We know that $\int_0^x (\alpha - \eta)\, dx = 18$

but $(\alpha - \eta) = 0{,}028E - 249.10^3 p$ for SF_6

$$\therefore \int_0^x (0{,}028E - 249.10^3 P)\, dx = 18 \rightarrow \text{streamer criterion}$$

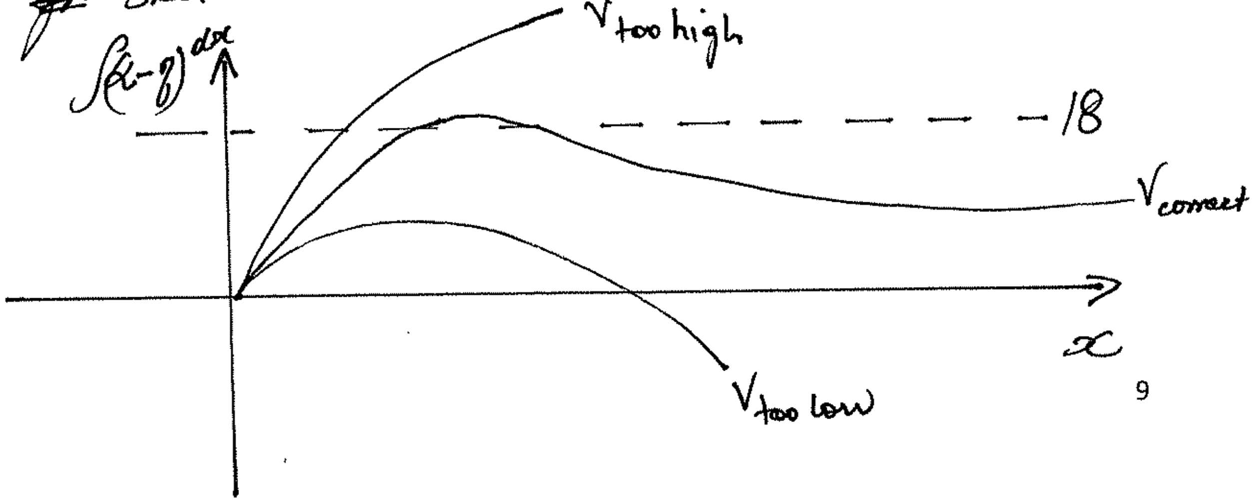
yet $E = \dfrac{VR(R+S)}{2S}\left[\dfrac{1}{(R+x)^2} + \dfrac{1}{(R+S-x)^2}\right]$ as given

Substituting the expression of E into the streame criterion equation gives

$$\int_0^x \left(0{,}028\left[\frac{VR(R+S)}{2S}\left(\frac{1}{(R+x)^2} + \frac{1}{(R+S-x)^2}\right) - 249.10^3 P\, dx = 1\right.\right.$$

We started by assuming $x = 0$ & calculating V_{bb}, using this 1st estimate chose another V & a non-zero x then evaluate the expression and checkout how far it is from 18. Iteratively chose the values of V & x until you get as close as possible to 18.

The ~~gr~~ sketch below illustrates the process



Electric Conduction and Breakdown in Solids

Question 1

a) Figure 1 below shows a section of a single turn motor coil in a stator slot. The insulation around the conductor is 3 mm thick and has been extremely carefully applied and it can be assumed to be void free. However, irregularities in the slot make it possible to have a gap between the outer surface of the insulation and the slot side of 0.2 mm.

Assuming this space to be filled with air at a pressure of 1.0 bar, determine the RMS value of the voltage which, when applied between the conductor and the slot, will cause partial discharge activity to commence. The relative permittivity of the insulating material can be assumed to be 2,8. All equations used must be derived from first principles.

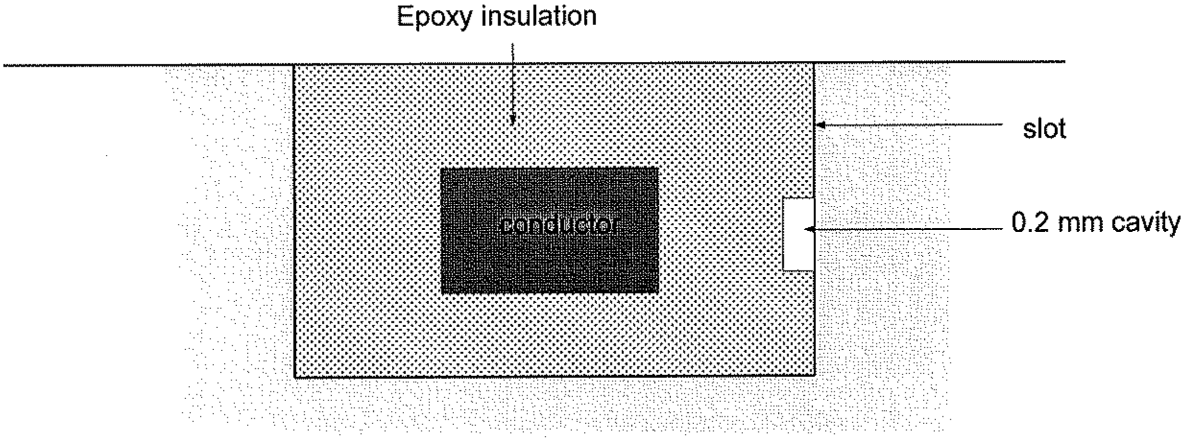
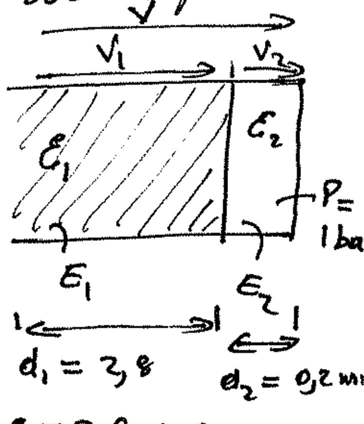


Figure 1: An air filled cavity trapped in insulation in a motor stator slot

This is a situation of an air-filled cavity trapped in a multilayered dielectric. It is of interest to find the value of the e-field strength in the air-filled fissure & whether this causes PD in the cavity. It is also of interest to know the v-age across the electrodes that would produce E_2 in the cavity which causes PD.



$\varepsilon_1 = 2,8$ & $\varepsilon_2 = 1$ (air)

From knowledge of e-field behaviour @ boundaries

$\frac{E_2}{E_1} = \frac{\varepsilon_1}{\varepsilon_2}$ & $V = \int E_x \, dx$ and for parallel plate electrodes

$V = V_1 + V_2$ $\quad V_1 = d_1 E_1$ & $V_2 = d_2 E_2$

$$\Rightarrow V = d_1 E_1 + d_2 E_2$$

$$= \frac{\varepsilon_2}{\varepsilon_1} d_1 E_2 + d_2 E_2$$

from Paschen curve

$$\therefore E_2 = \frac{V?}{\left(\frac{\varepsilon_2}{\varepsilon_1} d_1 + d_2\right)} = \frac{V_2}{d_2}$$

Read out V_2 from the Paschen curve that corresponds to a pd of 1 bar × 0,2 mm ie 0,2 mm bar & this is ≈ 1,5 kV peak

$$\therefore \frac{1{,}5}{0{,}2} = \frac{V}{\left(\frac{1}{2{,}8}\cdot 3{,}8 + 0{,}2\right)} \Rightarrow V = \frac{1{,}2 \cdot 1{,}5}{0{,}2}$$

$$= 9\ kV_{peak}$$

$$= 9\ kV/\sqrt{2}$$

$$= \underline{6{,}4\ kV_{RMS}}$$

b) Explain why this discharge inception voltage is likely to be very much less than the breakdown voltage of the insulation. What steps can be taken to eliminate these discharges.

Because of compactness of molecules in a solid the mean free path (λ) is so small & would thus require very high e-field strength to cause electron avalanches and $\therefore$ breakdown. If an air filled cavity however is encapsulated in the insulation discharges occur in the cavity well before the solid insulation breakdown

Steps to eliminate the discharges include
- making the stator slot walls smooth to avoid cavities
- fill in the gap with insulating grease/liquid if possible

c) If partial discharges initiate in the cavity, explain how this will eventually lead to complete insulation failure.

PD - induced solid insulation breakdown process;

- the PD activity impart energy (heat, optical & photons etc), gas & chemical by-products onto the insulation
- the insulation around the cavity undergoes physiochemical changes
- acid droplets develop on the insulation
- the acid droplets transform into solid crystals
- localised e-field enhancement occurs around the crystals
- Electrical trees initiate around the area of contact between the crystals and insulation
- the electrical trees propagate into the insulation
- the insulation is eventually short circuited & complete failure occurs.

The embedded cavity problems can occur in insulation between coaxial conductors such as in power cables as presented in the problem below:

d) A coaxial cable is shown in cross-section in Figure 2. The insulation consists of polyethylene tape 0,3 mm thick.

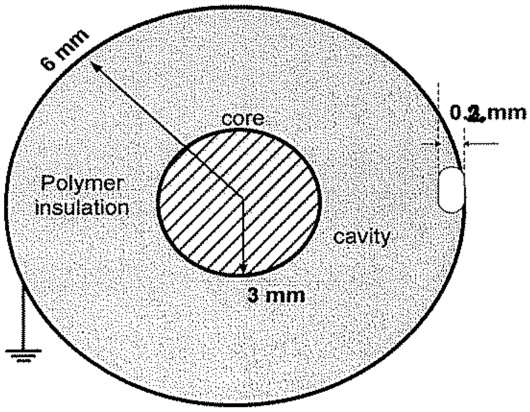


Figure 2: An air filled cavity trapped in insulation between coaxial electrodes

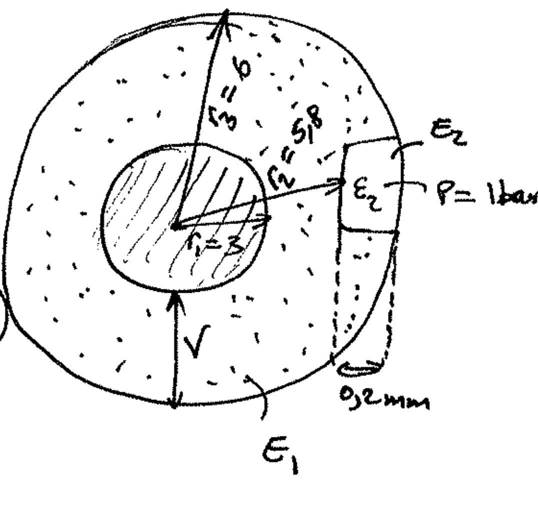
Determine the partial discharge inception voltage for a cavity the thickness of one layer of tape positioned at the surface of inner conductor. The cavity is filled with air at a pressure of 1,0 bar.

Assume that the filled within the cavity is uniform and that the relative permittivity of polyethylene is 2,5.

This is again a multilayed dielectric but between coaxial electrodes

From knowledge of e-field & @ boundaries

$E_2 = \frac{\varepsilon_1}{\varepsilon_2} E_1$, $V = \int E_x \, dx$ & for coaxial electrod setup



$$E_{1r_2} = \frac{V_1}{r_2 \ln\left(\frac{r_2}{r_1}\right)} \quad \& \quad E_{2r_2} = \frac{V_2}{r_2 \ln\left(\frac{r_3}{r_2}\right)}$$

$$V = V_1 + V_2$$

$$= E_{1r_2} r_2 \ln\left(\frac{r_2}{r_1}\right) + E_{2r_2} \cdot r_2 \ln\left(\frac{r_3}{r_2}\right)$$

$$= \frac{\varepsilon_2}{\varepsilon_1} E_2 r_2 \ln\left(\frac{r_2}{r_1}\right) + E_{2r_2} \cdot r_2 \ln\left(\frac{r_3}{r_2}\right)$$

$$\therefore E_{2r_2} = \frac{V\,?}{r_2 \left[\frac{\varepsilon_2}{\varepsilon_1} \ln\left(\frac{r_2}{r_1}\right) + \ln\left(\frac{r_3}{r_2}\right)\right]} = \frac{V_2}{d_2}$$

— read out from the Paschen curve, the value corresponding to a Pd of 0,2 mm × 1 bar = (0,2 mm bar ⟺ 1,5 kV$_{peak}$)

Assuming uniform e-field in the air cavity $E_{2r_2} = \frac{V_2}{d_2}$

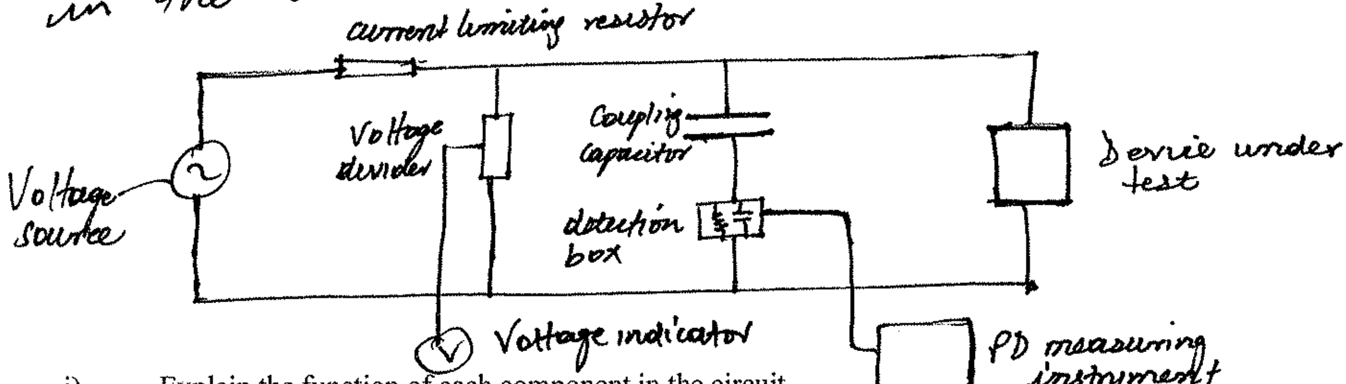
$\therefore$ Substituting gives $$\frac{V}{5{,}8\left[\frac{1}{2{,}5} \ln\left(\frac{5{,}8}{3}\right) + \ln\left(\frac{6}{5{,}8}\right)\right]} = \frac{1{,}5}{0{,}2} \text{ kV}_{peak}$$

or $$\frac{V}{5{,}8\left[0{,}26 + 0{,}034\right]} = 7{,}5$$

$\therefore V = 12{,}8 \text{ kV}_{peak}$ or 9 kV_{rms}

e) Draw the diagram of a circuit which can be used to measure partial discharges in a high voltage device.

You used this PD detection circuit in the Lab & as discussed in the lecture



i) Explain the function of each component in the circuit

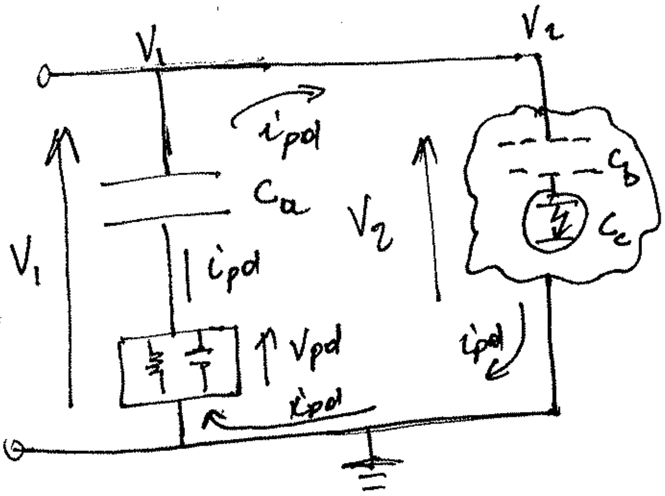
Component	Function
Voltage source	Variable voltage supply for stressing the DUT to create PD
Current limiting resistor	Limit fault current incase of breakdown. Also serves as a filter to block noise from voltage source into the PD detection circuit
Voltage divider	Step down the supply v-age to measurable value
Coupling capacitor	Filters out 50Hz power frequency from the detection box & also acts as a charge current source in the ipd flow circuit

ii) Explain how a partial discharge current pulse is generated and detected

Detection impedence → Creates a PD voltage signal as the PD current flows through

PD measuring instrument → Processes the detected PD voltage signals

DUT → Device Under Test (test object) where the PD signal is generated in the defect



- Prior to PD, $V_1 = V_2$
- at instant of breakdown of C_c, V_2 drops as C_c is short circuited
- i_{pd} flows from C_a
- V_{PD} develops across the detection impedance & is acquired and displayed

iii) Discuss any factors that may influence the sensitivity of the measurement

- the coupling capacitor, C_a, should be >>> capacitance of the test object i.e $(C_b + C_c)$
- the detection impedance frequency bandwidth >>> that of the i_{PD}
- the supply voltage source should be noise free
- the PD measurements should be performed in a noise free environment

Question 2

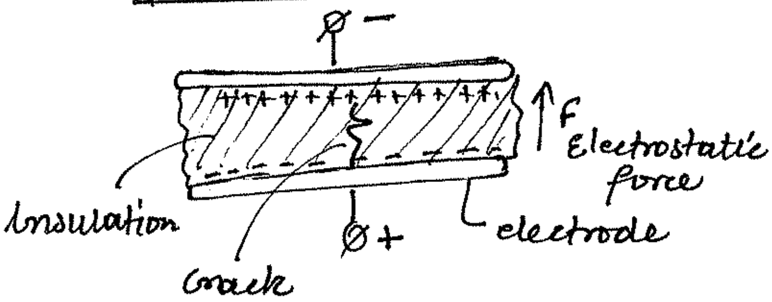
a) Consider the following statement: "The actual breakdown voltage of solid insulation during normal operation in high voltage apparatus is significantly lower than its intrinsic breakdown strength".

i) Define the term "intrinsic breakdown strength" of a solid

Is the voltage that causes electric breakdown of solid dielectric in its pure form.

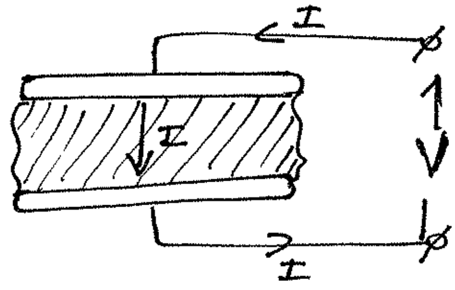
ii) Describe at least two distinct processes (other than intrinsic breakdown) that may lead to breakdown in a solid (Hint: you may wish to use simple sketches to aid your description).

Electromechanical



- opposite charge migrate to opposite surfaces of the insulation
- electrostatic force forms
- the insulation cracks due to the resultant pressure
- electrical breakdown occurs along the crack

Electrothermal



- polarisation & conduction current flows through the insulation
- heat is generated by the current
- If the rate of heat generation is > than rate of heat dissipation thermal runaway occurs leading to breakdown.

iii) Briefly comment on the formation of voids in solid insulation during manufacture

- air-filled cavities (voids) can be accidently trapped at interfaces between the insulation & electrodes (metallic part of the apparatus due to temperature differentials during manufacture.
- Where the solid insulation comprises of laps of insulation tapes, gaps in the laps can accidently occur

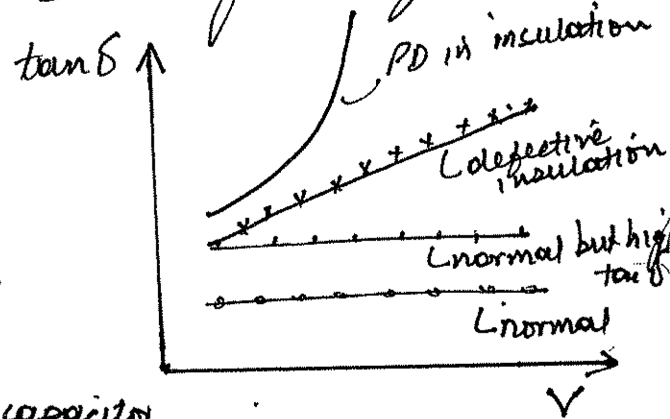
Voids are udesirable in solid insulation as they become source of partial discharges

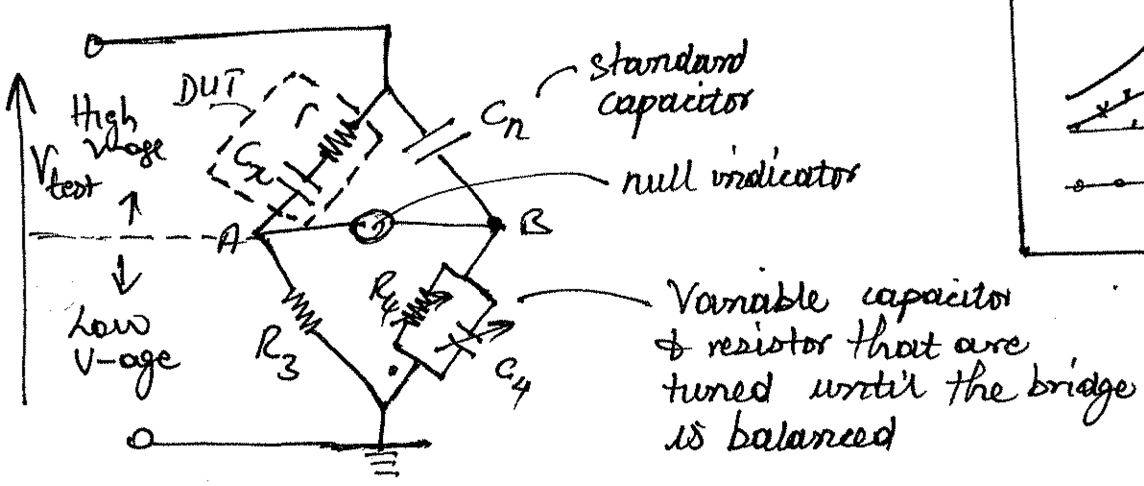
b) Discuss the reasons for performing tan δ tests. Draw and explain the test circuitry used and, by giving trends of some assumed test results, explain how these results may be interpreted.

- The current that flows through insulation due to impurities & polarisation of dipoles generates heat which has two undesirable effects;

1. losses
2. may cause physiochemical degradation of the insulation
3. lead to thermal runaway resulting in electrothermal failure

It is therefore important to measure & quantify the dielectric losses using tan δ tests.
Tan δ tests are normaly conducted using an impedance bridge circuit such as the Schering bridge





a) i) What parameters are used to characterise partial discharge activity? (Be careful! Consider what you would measure!).

Parameters used to characterise partial discharge activity;

- Apparent charge magnitude (pC). ⇒ This is the total charge deduced from the discharge current that flows through the terminals of the test object.

  The measured apparent charge is proportional to the actual charge transfered at the PD source.

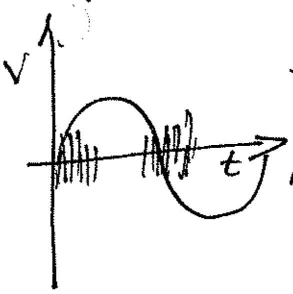
- PD repetition rate ⇒ Number of pulses occuring in a given period such as a cycle of the test voltage wave.

- PD phase resolved pattern (PDRP) or time resolved pattern → how PD pulses are distributed on the power frequency wave

- PD pulse energy or optical intensity.

ii) Explain why corona pulses in air occur on the crests of the power frequency wave while cavity and surface partial discharges occur on the rising and falling edges of the power frequency wave.

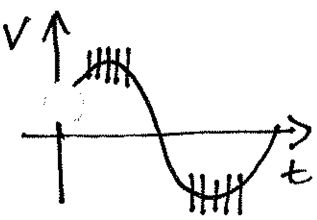
Cavity or Surface PD



Cavity & surface discharges (i.e. discharges occuring in regions bounded by air & insulator surfaces) are largely influenced by residual space charge that is deposited on the insulator surfaces by the PD activity.

The resultant e-filled causing discharge is the vector sum of the background & the residual e-field. The discharges therefore do not necessarilly occur around the peak of the supply voltage wave.

Corona in air



For corona in air, there are no insulation boundary conditions to trap residual charge ∴ the discharge pulses occur when the background field is highest i.e. at supply voltage peak.

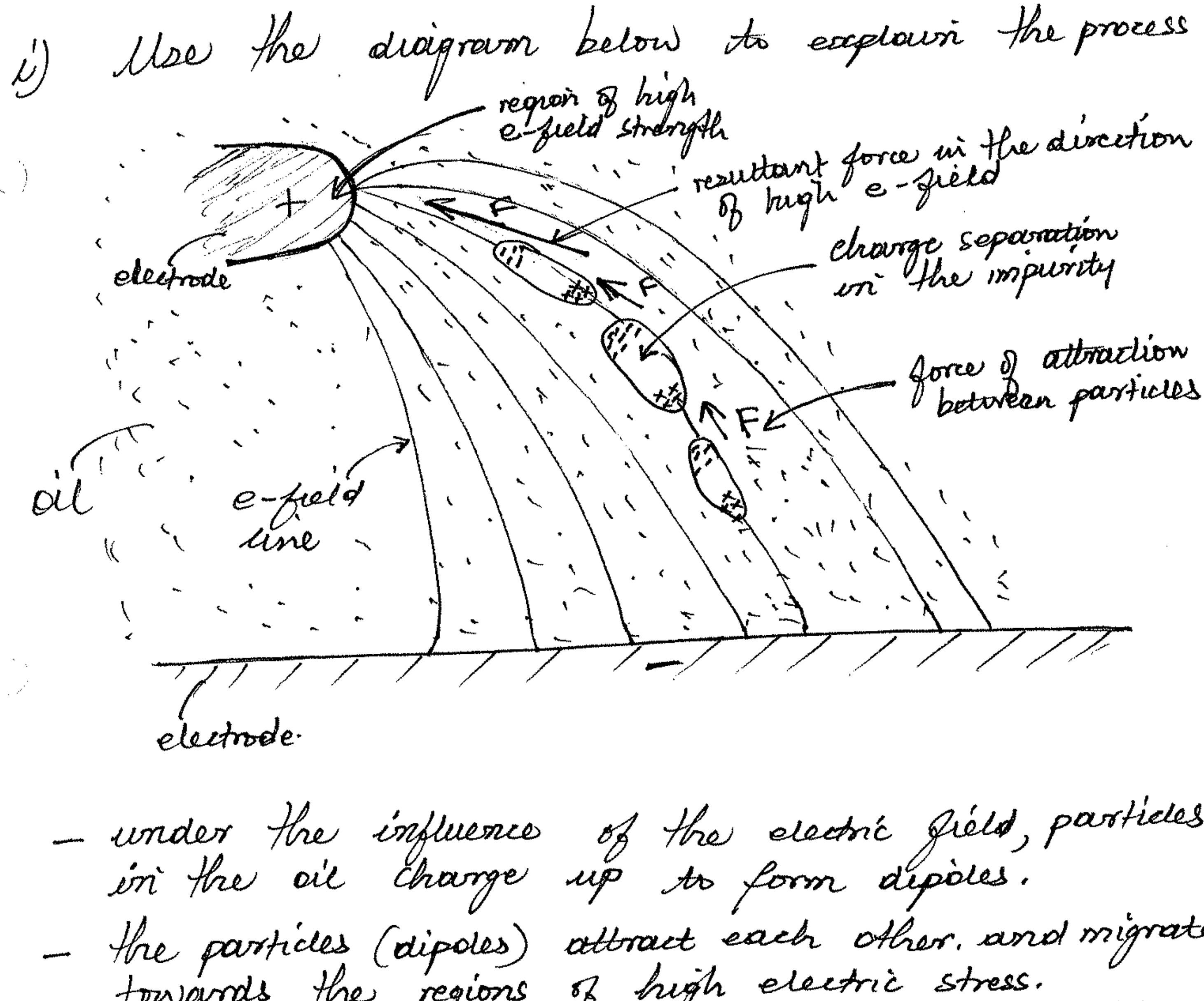
Electric Conduction and Breakdown in liquid dielectrics

Question 1

a) i) Describe in detail the processes which lead to breakdown in transformer oil.
   ii) Explain how the oil insulation properties can be improved.

   iii) Explain why the direction of attraction is independent of voltage polarity on the electrodes and whether it is DC or AC.

i) Use the diagram below to explain the process



- under the influence of the electric field, particles in the oil charge up to form dipoles.
- the particles (dipoles) attract each other, and migrate towards the regions of high electric stress.
- particles eventually form a chain bridging the insulation gap.
- the particle chain becomes the weakest link and causes breakdown.

ii) <u>Mitigation</u>

- keep the oil clean; free from moisture & water
- keep the oil ~~a~~ free from solid particles (impurities)
- introduce solid insulation barriers

iii) <u>Why force of attraction is independent of voltage polarity or whether dc or ac.</u>

The polarity of the charged particles (dipoles) is always in sync with that of the electrodes. The resultant force therefore is always in the direction of the region of higher electric field.

$$F = \varepsilon_{liquid}\, r^3 \left(\frac{\varepsilon - \varepsilon_{liq}}{\varepsilon + 2\varepsilon_{liq}}\right) \cdot E\, dE/dx$$

Where r is equivalent radius of the particle
ε is permittivity of the particle
E is the electric field strength
dE/dx is the e-field gradient

b) Explain how partial discharges can take place within insulating oil in transformers and indicate what the consequences of partial discharges would be.

- PD can occur in air bubbles in the oil & this creates more bubbles as more gas is produced from the discharge. Oil disintegrates into gaseous products
- PD can occur in regions of enhanced stress where the stress > than oil breakdown v-age & this results in oil disintegration into gaseous by products such as CH_3, C_2H_2 etc that compromise the oil insulation quality.

c) Mineral insulating oil is widely used in power transformers. Comment on the reasons for this.

- high electric breakdown strength in its pure form
- relatively low permittivity
- cooling effect
- low viscousity thus enabling it to flow into small pockets & displace air in the transformer

d) Under what circumstances is it desirable to use oil filled transformers. What alternatives are there?

- Where there is space limitation
- where forced cooling is needed

e) Explain the intrinsic breakdown mechanisms in insulating liquids.

- electrons are emitted from asperities on electrode surfaces through mechanisms such as Schottky or field emission mechanisms
- electrons accelarate under the influence of the high electric field.
- On bombarding the oil molecules, energy is imparted that causes the molecules to ionise and release more electrons thus initiating sustained avalanches
- the avalanches eventually bridge the electrodes thus causing complete breakdown.

Breakdown under impulse voltages

Question 1

a) A test engineer is given a prototype generator stator bar to test for lightning impulse voltage breakdown. Using an impulse generator, she applies a single short standard lightning impulse on the stator bar. It breaks down at a point (*B*) on the tail of the impulse voltage as shown in the Figure 6. Give reasons why the breakdown may not have happened on the impulse peak (*A*). If the engineer fires another identical impulse shot and the breakdown does not occur exactly at point B, explain why.

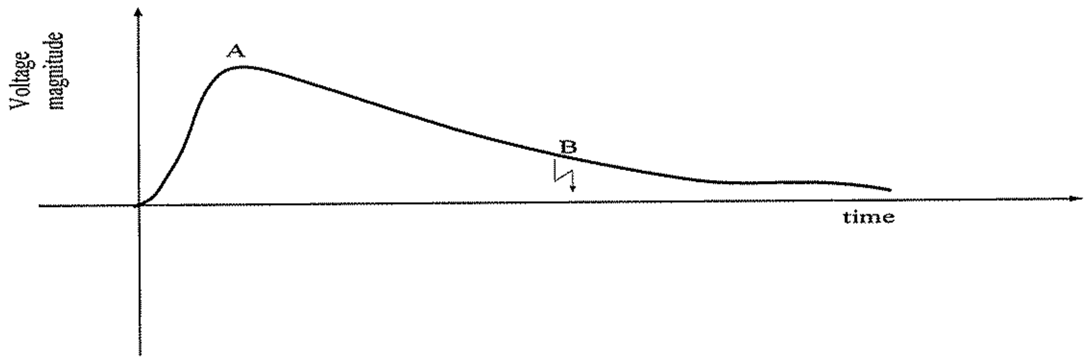
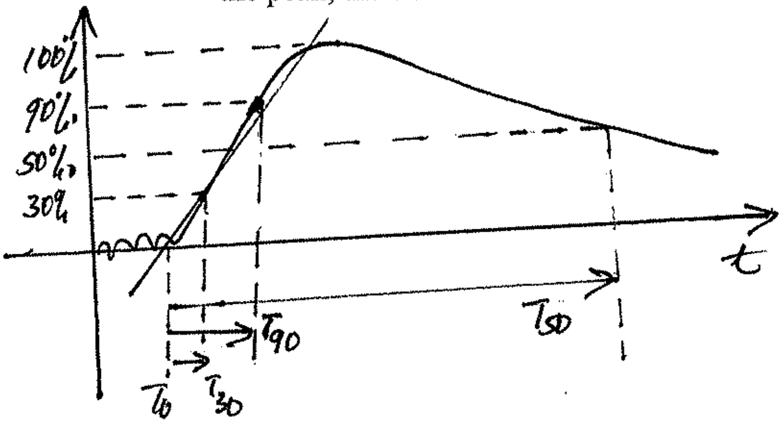


Figure 3: Illustration of the point of breakdown on the tail of an impulse voltage

Breakdown of air under impulse voltage is a function of statistical time delay (t_s) and formation time (t_f). The latter is a function of the e-field intensity & therefore depending on the impulse peak magnitude, breakdown occurs on wave front, at peak or on the tail. For the same impulse shape & peak, breakdown may not repeat at the same point because of statistical variation & t

b) In order to protect the terminal equipment connected to an 11 kV distribution line against conducted lightning surges, it is decided to use arcing horns (which may be considered to be a rod-rod gap which are positioned across the bushing connected to the terminal equipment. To determine the breakdown of this gap, a multistage Marx impulse generator is to be used.

i) Using a simple labelled sketch explain the definition of a lightning voltage impulse as given in the standards and comment on the tolerance accepted for the peak, the rise and the fall times.



$t_r = 1.57\,(T_{90} - T_{30})$

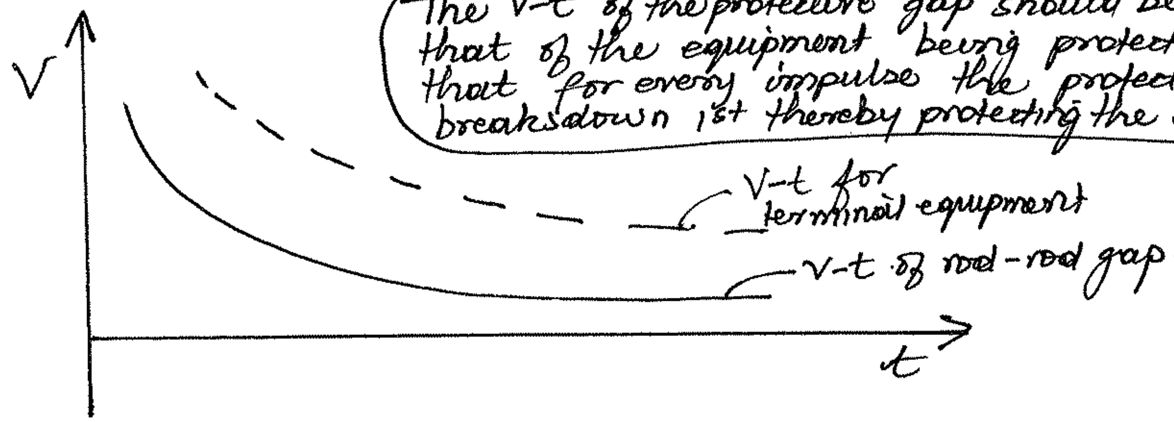
$= 1.2 \pm 30\%\ \mu s$

$t_f = T_{50} = 50 \pm 20\%\ \mu s$

$\hat{V} \pm 3\%$ tolerance

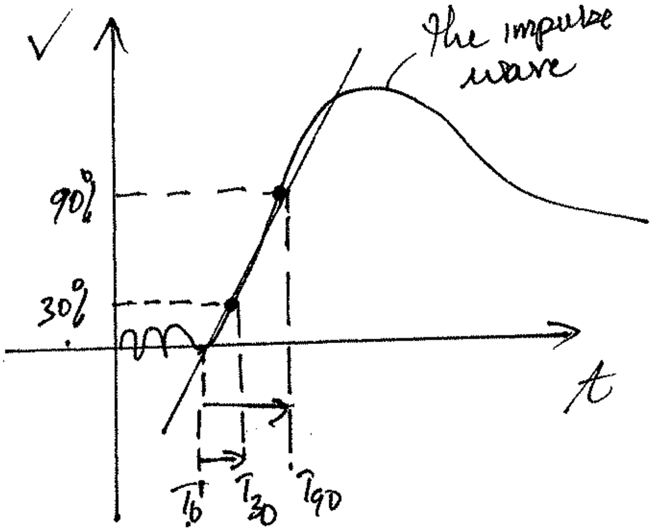
ii) Using a sketch, and assuming a probable V-t curve for the terminal equipment to be protected, show on the same set of axes the relative location of the V-t curve for the protective arcing horns (rod-rod gap). Explain your answer.

The V-t of the protective gap should be below that of the equipment being protected so that for every impulse the protective gap breaksdown 1st thereby protecting the equipment



iii) Explain why and how, unlike for switching impulse voltage, only a portion of the lightning impulse voltage waveform front is taken into account for determining the rise-time of the impulse.

The initial portions of the impulse (upto 30%) and between 90% & 100% of rise time, the impulse wave can be distorted by inductances in the circuit and therefore is discarded in the rise-time measurement.



A line is drawn connecting 30% & 90% of the rise time points on the wave front. The point where the crosses the time axis is the virtual zero point.

Rise time is is given by $t_r = 1,57(T_{90} - T_{30})$

iv) In a rural substation equipment layout as shown in the Figure 7, the post insulator (shown in dotted lines in the diagram) provides necessary mechanical support of the jumper conductor from the power line to the transformer. If the impulse breakdown characteristics of the equipment are as shown in Figure 5, and on the account of budget constraints only protection spark gaps have to be used, what type of protection gaps would you install across the transformer and across the post insulator? Explain your decisions.

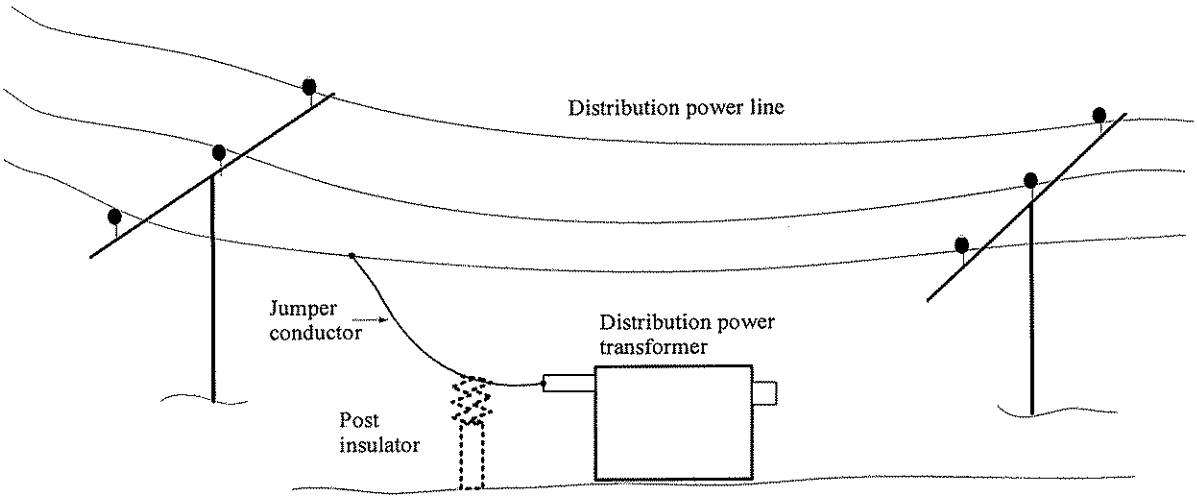


Figure 4 : Equipment layout where surge protection gaps have to be installed

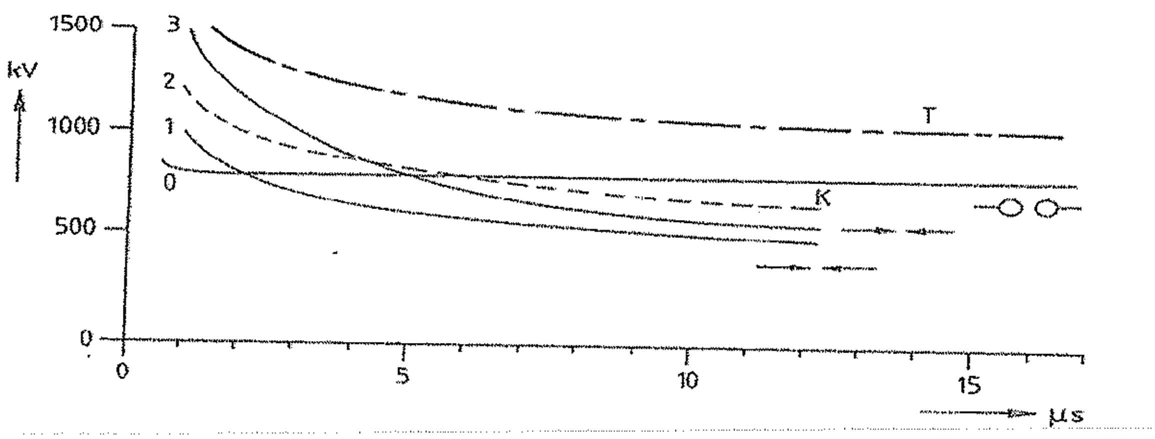


Figure 5: Examples of impulse breakdown voltage characteristics of various electrode gaps where 0: sphere gap1: small rod gap, 2: line insulator k, 3: Rod gap, larger than gap 1 and 4: Transformer

The V-t curves that are completely below that of the transformer are that of the sphere-sphere gap, ~~and~~ rod-gap larger than sphere-gap & the rod-rod gap offer protection as they are all below the transformer V-t curve. For the insulator post however only the small rod-gap gives protection.

v) A lightning flash of magnitude 20 kA strikes a conductor of an overhead transmission line at its mid-span. The line has a surge impedance of approximately 220 Ω. The transmission line conductors are supported by metallic pylons with grounding resistance of approximately 10 Ω and inductance of 20μH as illustrated in the Figure 2.2. Comment critically on the possibility of a flashover across the suspension insulators (from the line to the pylon). If the lightning strikes the pylon directly, comment on how this may result in back-flashover (i.e. from the pylon to line). How can incidences of lightning-induced flashover across the insulators be minimised?

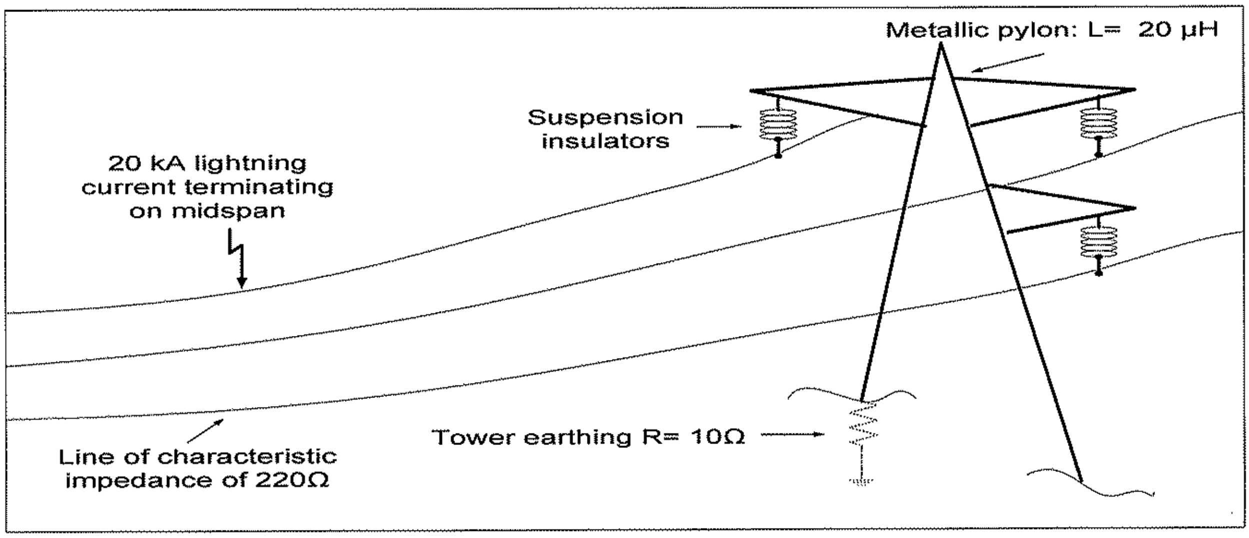


Figure 6: Lightning striking an overhead power line

Termination on the phase conductor

The lightning current divides into two and flows in opposite directions from the point of strike on the line i.e. $I = \frac{20}{2} kA = 40kA$

A travelling voltage wave travels along the line

$$V = IZ$$
$$= 20.10^3 . 220$$
$$= 4400.10^3$$
$$= 4.4 mV!$$

When this voltage surge reaches the point at which the line insulator attaches to the conductor there is flashover from the conductor (phase) to the tower.

Lightning stroke termination on the tower

The whole 40kA flows to ground through the tower grounding impedance.

The voltage build-up on the tower due to the current flowing through the grounding impedance 10 Ω is given by $V_{tower} = I_{lightning} \cdot R_{tower\ earthing}$

$$= 40.10^3 \times 10$$

$$= \underline{400kV}$$

A potential difference of 400kV appears across the insulator relative to the voltage on the phase conductor. It is therefore possible that the potential difference across the line insulator can be > 400kV backflashover from tower to the line conductor can occur if the insulator is not designed to withstand the impulse. In reality the tower inductance can cause the total tower impedance to be higher than just the earthing resistance and this gives more back flashover voltage.

Once a back-flashover occurs, the ionised air around the insulator causes short circuit for the power frequency voltage on the line and this results in line to earth fault.

Question 2

a) What is "U_{50}" for an electrode geometry

U_{50} is the voltage that causes 50% probability of breakdown across the gap of the given electrode geometry.

b) Develop an equation that can be used to determine the U_{50} for any electrode geometry and hence determine the U_{50} for the data given below. Clearly define any symbols used.

Voltage (kV)	Number of withstands	Number of breakdowns
2200	0	8
2100	2	9
2000	6	8
1900	8	6
1800	10	2
1700	11	0

Bookwork! Refer to Kuffel page 482 & the U_{50} HVLab task.

Question 3

a) Compare and contrast cloud-ground negative and positive lightning

Similarities	Differences
- Both involve discharges in air at very high temps	- +ve less prevalent (<10%) while -ve is more prevalent (>90%) of all cloud-ground lightning discharges
- Both are cloud to ground discharges	- +ve lightning transferes +ve charge to ground while the opposite is true for -ve lightning.
- Both produce light, heat & sound	- +ve has bigger currents than -ve lightning
- Both have destructive effects at pt. of termination	- +ve mechanism has a single stroke while -ve lightning comprises of multiple strokes.

b) Explain in detail the cloud to ground negative lightning mechanisms

The key processes in negative cloud-ground lightning discharges can be illustrated using sketches & the summary of the processes is;

1. Initial intracloud discharge where the lower positive charge layer (LP) is discharged by the bigger negative charge lay (N)
2. Formation of downward stepped leader & upward positive streamers
3. Attachment of downward stepped leader & upward +ve streamers
4. Return stroke where -ve charge flows from cloud to ground through the ionised channel.
5. H & K processes (intra-cloud discharges as remaining charg 'gather' in prep for the dart leader)
6. Dart leader discharge → a continuous single discharge from cloud to ground through the ionised channel.
7. 2nd return stroke → the dart leader attaches to the +ve upward leader & 2nd return stroke of -ve charge flow occurs

c) Explain the various possible modes of lightning injuries associated with cloud to ground lightning discharges. Give possible safety measures.

The explanations and sketches (illustrations should be about;

Injury mechanisms

1 direct strike
2 Side flash / induced strike
3 Contact / touch potential
4 Step potential
5 Positive leaders

Safety precautions during lightning activity

- Keep feet together
- Sit in a crouched position
- avoid standing under trees during lightning activity.
- Seek shelter and the best shelter would be one with conductive walls; Farady cage.

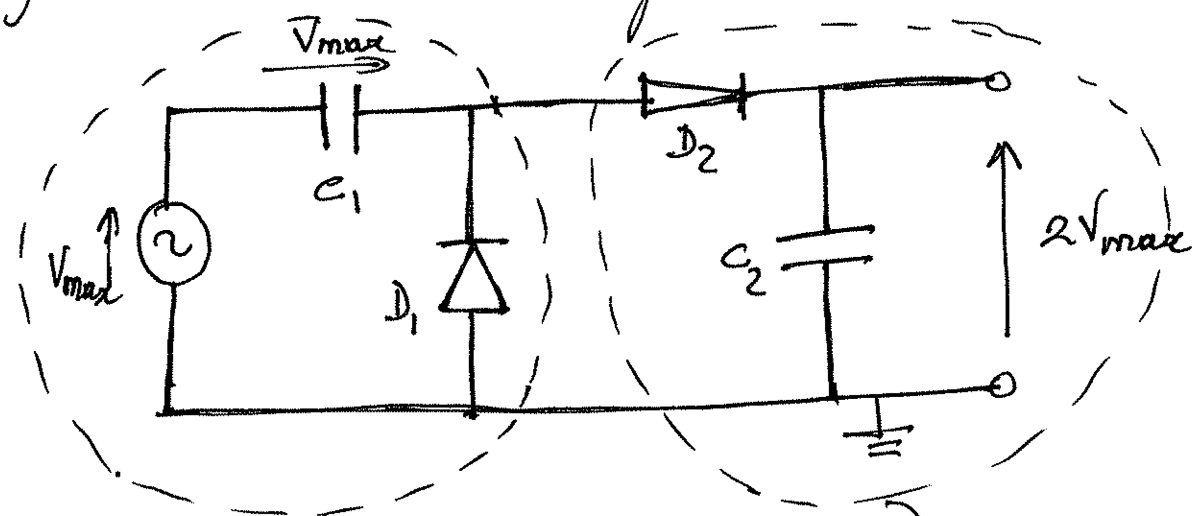
Generation and Measurement of high Voltages

Question 1:

a) In a comprehensive High Voltage laboratory there are the following items of equipment:
   i) a Greinacher voltage doupler
   ii) a 5 stage Cockroft-Walton multiplier
   iii) a 10 stage impulse generator
   iv) a power frequency cascade transformer set
   v) a resonant test set

Explain what sort of tests would be possible with each of these generators. Explain the reasons for the performance of these tests. Draw single line circuit diagrams of these items of equipment, and identify the role each component plays.

i) Greinarcher Voltage Doubler



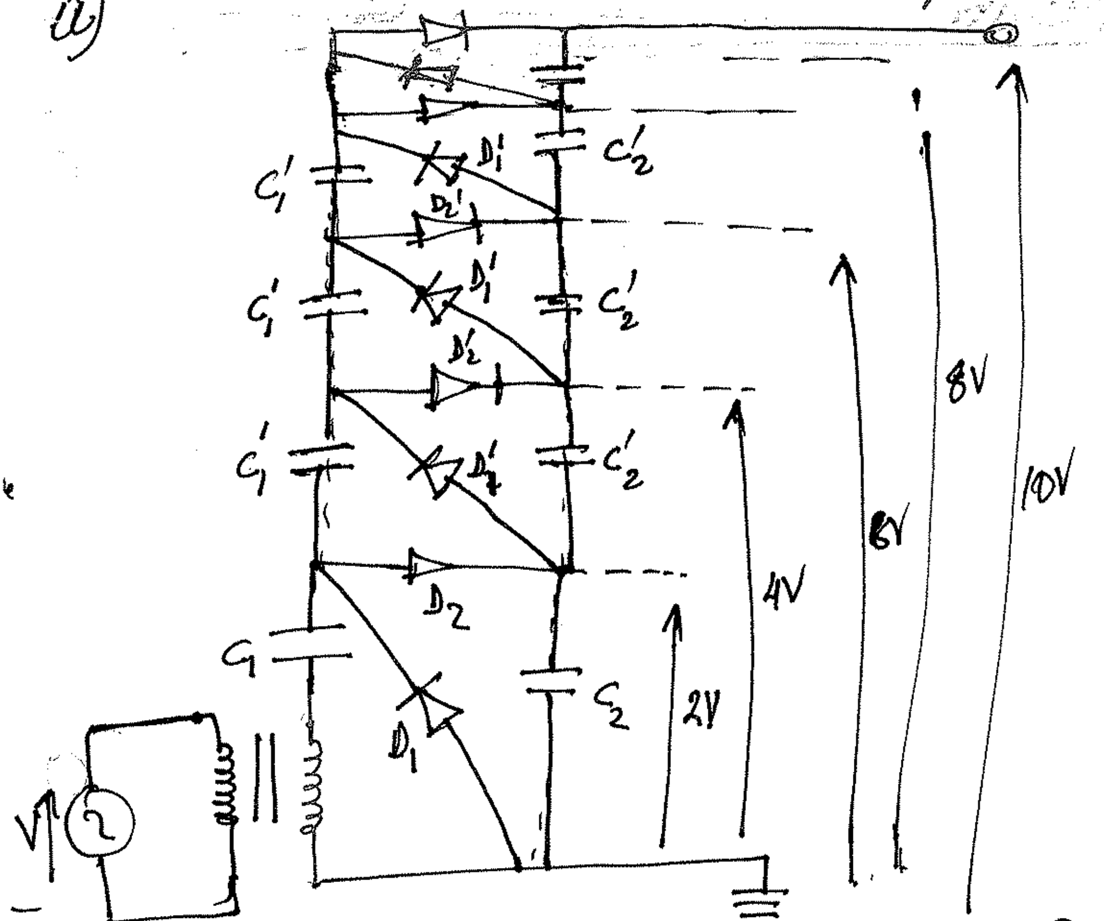
Voltage double part of the circuit

Half wave rectifier with the smoothing capacitor C_2.

Applications

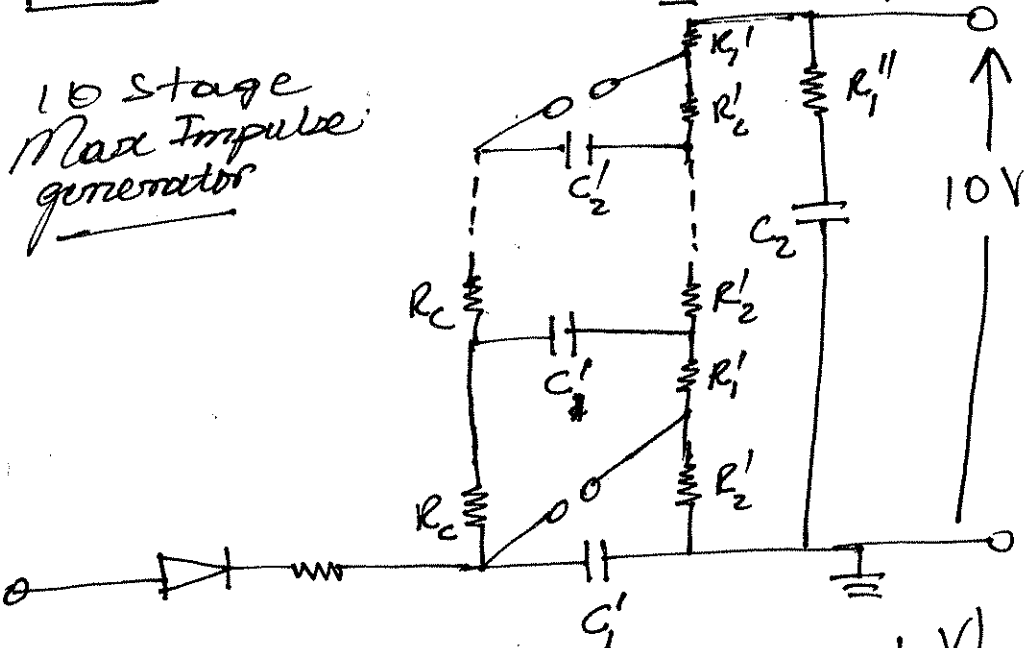
- high voltage withstand tests of DC equipment
- DC voltage source for partial discharge diagnostic tests under DC conditions
- Testing of high capacitance equipment such as HV capacitors and non-extruded insulated power cable circuits.

ii) 5-Stage Cockroft-Walton generator



Applications are similair to the Greinarchar voltage generator but where higher voltages are needed.

iii) 10 Stage Max Impulse generator

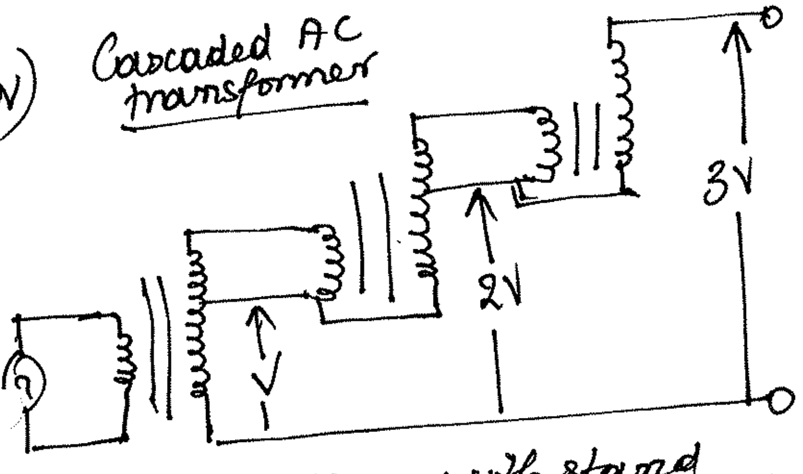


Used to generate transient high voltages for test such as

a) lightning impulse voltage withstand

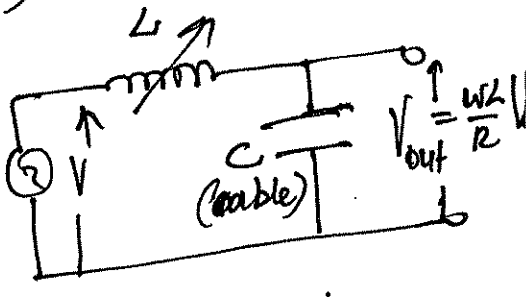
b) Switching impulse voltage withstand tets

iv) Cascaded AC transformer



- for HVAC withstand test of AC equipment.

V) Resonant test set



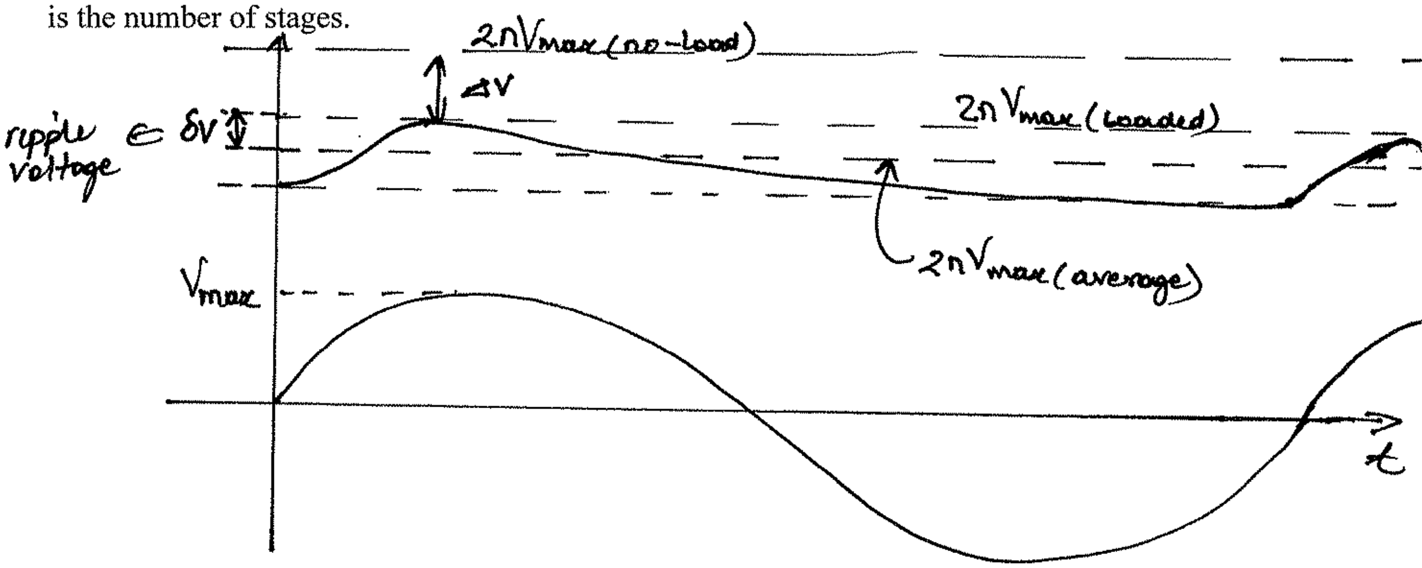
- for testing power cable circuits

b) Consider a 10-stage Greinacher generator with each capacitor being 2 μF. If this multiplier supplies a current of 100 mA to a test object, and the RMS value of the input voltage is 50 kV at 50 Hz, determine the average value of the output voltage, the ripple voltage, percent ripple factor and the voltage drop.

Hint you may use the following formulae without deriving:

Ripple voltage: $\partial V = \frac{I}{2fC}\left[\frac{n(n+1)}{2}\right]$ and voltage drop: $\Delta V = \frac{I}{fC}\left[\frac{2n^3}{3} + \frac{n^2}{2} - \frac{n}{6}\right]$

Where f and C are frequency of supply and capacitance of each capacitor respectively and n is the number of stages.



Source voltage $= 50\,kV_{rms} = \sqrt{2} \cdot 50\ kV_{peak}$
$= 70{,}7\ kV_{peak}$

$2nV_{max(no\text{-}load)} = 2 \cdot 10 \cdot 70.7\ kV = 1414{,}2\ kV$

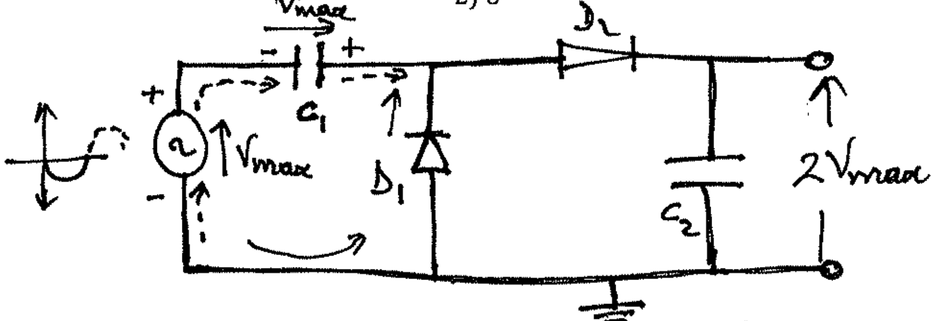
Ripple Voltage $\delta V = \frac{100 \cdot 10^{-3}}{2 \cdot 50 \cdot 2 \cdot 10^{-6}} \cdot \left[\frac{10(10+1)}{2}\right]$
$= 27{,}5\ kV$

Voltage drop $\Delta V = \frac{100 \cdot 10^{-3}}{50 \cdot 2 \cdot 10^{-6}}\left[\frac{2(10)^3}{3} \cdot \frac{(10)^2}{2} - \frac{10}{6}\right]$
$= 715\ kV$

Average output voltage $= 2nV_{max(no\text{-}load)} - \Delta V - \delta V$
$= 1414.2 - 715 - 27.5\ kV$
$= 671.7\ kV$

$\therefore$ % ripple
$= \frac{\delta V}{2nV_{max(average)}} \times 100\ \%$
$= \frac{27.5}{671.7} \times 100\ \%$
$\approx 4\ \%$

c) Explain how the Greinacher voltage multiplier circuit works. Show that the ripple voltage is given by $\partial V = \frac{I}{2fC}$



- During supply source −ve half cycle D_1 conducts & C_1 charges to V_{max}
- In the next +ve half cycle, D_1 blocks & the source voltage adds up with that retained on C_1 to give $2V_{max}$. D_2 conducts & charges C_2 with $2V_{max}$
- Cycle continues as C_1 charges & discharges

$$Q = CV = C.2\delta V$$
$$C2\delta V = IT$$
$$\delta V = \frac{IT}{2C}$$
But $T = \frac{1}{f}$
$$\therefore \delta V = \frac{I}{2fC}$$

d) A circuit of a single stage impulse generator is shown in the Figure 7 below.

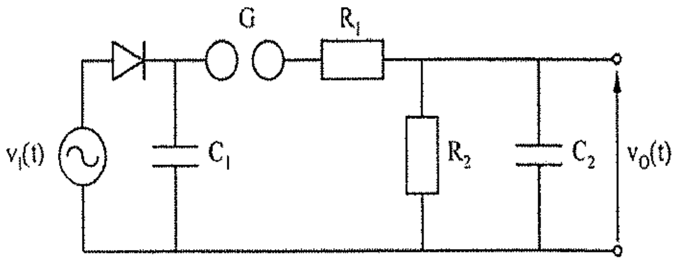


Figure 7: Single stage circuit of impulse generator.

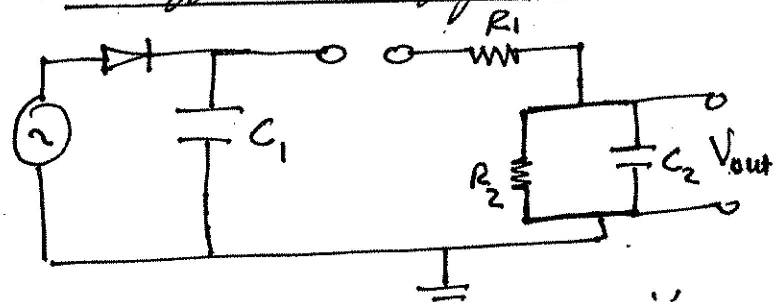
i) Briefly discuss the operation of the circuit. Also include in your discussion the effect that inductance in series with R_1 will have on the response of the circuit.

- C_1 is charged by the DC source and when the voltage is large enough, the air gap across the trigger gap breaks down. Through R_1, C_2 is charged as $R_2 >> R_1$. When C_2 is fully charged & since $C_1 >> C_2$, both C_1 & C_2 the discharge through R_2. The charge & discharge event of C_2 gives an impulse $V_o(t)$

- Inductance in series with R_1 would introduce ringing effect (oscillations) on the front of the impulse wave

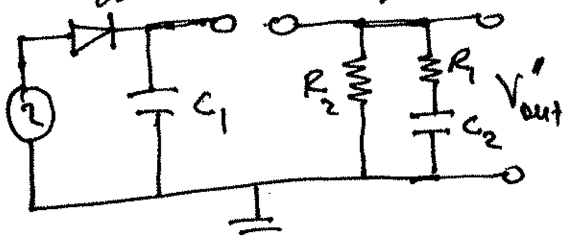
ii) Draw an alternative circuit of the single stage impulse generator that has a higher efficiency. Give reasons for your choice, based on the DC response of the circuit.

Less efficient configuration



- R_1 + R_2 form potential divider thus reducing output voltage

More efficient configuration



- No voltage division as R_2 & R_1 are in parallel ∴ $V'_{out} > V_{out}$. i.e. more efficient

iii) Where higher output impulse voltages are required, the single stage impulse generator falls short of the required performance. Discuss the limitations of the single stage impulse generator in that regard?

- Individual generator components need to be insulated at the generator output voltage and this poses a challenge at higher voltages. The components (and the whole generator) become physically too big.
- The bigger the components & generator size, the more difficult it is to limit inductance giving rise to oscillations in the generated impulse voltage.
- Pronounced corona losses and interferances at higher voltages
- Increased dielectric losses resulting in reduced power efficiency at higher voltages.
- Air-gap switching precision becomes compromised at higher voltages.

iv) From a frequency domain analysis of the single stage impulse generator circuit, it can be shown that:

$$V_0(s) = \frac{V_0}{k}\left(\frac{1}{s^2 + xs + y}\right)$$

Where:

$$x = \left(\frac{1}{R_1C_1} + \frac{1}{R_2C_2} + \frac{1}{R_1C_2}\right)$$

$$y = \left(\frac{1}{R_1R_2C_1C_2}\right)$$

$$k = R_1C_2$$

$V_0(s)$ = the output of the generator.

If we can assume that $R_1 << R_2$ and $C_2 << C_1$, show how the time constants for the front and tail of the impulse voltage can be determined.

Hint: Use of Laplace transforms is recommended and note that you don't have to derive $V_0(s)$

If $R_2 >> R_1$ & $C_1 >> C_2$ then x ~~reduce~~ reduce to

$$x = \left(\cancel{\frac{1}{R_1C_1}}^{0} + \cancel{\frac{1}{R_2C_2}}^{0} + \frac{1}{R_1C_2}\right) \approx \frac{1}{R_1C_2}.$$

(becoz of R_1) (becoz of R_2)

The expression of $V_0(s)$ $\therefore$ becomes;

$$V_0(s) = \frac{V}{K} \cdot \frac{1}{s^2 + \frac{1}{R_1C_2}s + \frac{1}{R_1R_2C_1C_2}}$$

P.T.O

$$V_{0(s)} = \frac{V}{K} \cdot \frac{1}{\underbrace{s^2 + \frac{1}{R_1C_2} s + \frac{1}{R_1R_2C_1C_2}}}$$

this expression can be re-written as;

$$\frac{1}{(R_1C_2 - R_2C_1)} \cdot \left(\frac{1}{(s - R_1C_2)} - \frac{1}{(s - R_2C_1)} \right)$$

Same when R_1C_2 & R_2C_1 are the roots of the denominator when equated to zero

$$\therefore V_{0(s)} = \frac{V}{K} \cdot \frac{1}{(R_1C_2 - R_2C_1)} \cdot \left[\frac{1}{(s - R_1C_2)} - \frac{1}{(s - R_2C_1)} \right]$$

$$V(t) = \mathcal{L}^{-1} V_{0(s)} = \mathcal{L}^{-1} \left[\frac{V}{K} \cdot \frac{1}{(R_1C_2 - R_2C_1)} \cdot \underbrace{\left(\frac{1}{(s - R_1C_2)} - \frac{1}{(s - R_2C_1)} \right)} \right]$$

$$=$$

Looking up in the tables the corresponding time domain expression is

$$\left(e^{-\left(\frac{1}{R_1C_2} t\right)} - e^{-\left(t/R_2C_1\right)} \right)$$

$$\therefore V(t) = \frac{V}{K} \cdot \frac{1}{(R_1C_2 - R_2C_1)} \cdot \left[e^{-\left(t/R_1C_2\right)} - e^{-\left(t/R_2C_1\right)} \right]$$

Where front time constant is $\Rightarrow R_1C_2$

Tail time constant is $\Rightarrow R_2C_1$

v) A 3-stage Marx impulse generator has parameters and configuration as shown in the Figure 8 below with the following components: each of the distributed internal front resistors is 75 Ω, tail resistors each 2 kΩ, external front resistor 100 Ω, the internal storage capacitors each 0.25 μF and external discharge capacitor 2 nF. Calculate its total equivalent storage capacitance C_1, front resistor R_1 and tail resistor R_2. Also calculate the corresponding time constants in the time domain impulse voltage wave expression.

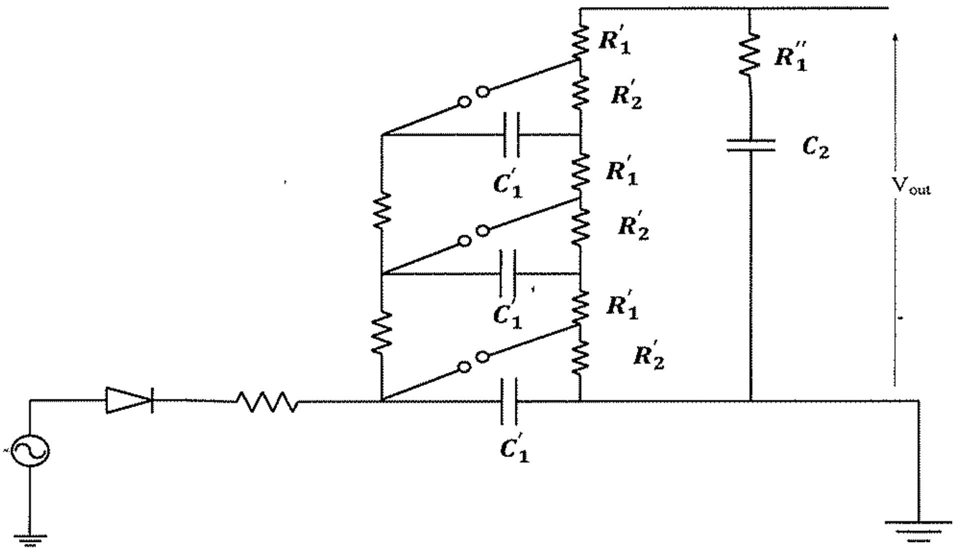


Figure 8: A 3-stage impulse voltage generator

Total front resistance $= 3R_1' + R_1'' = (3\times 75) + 100$
$= 325\,\Omega$

Total tail resistance $= 3R_2' = 3 \times 2\,k\Omega$
$= 6\,k\Omega$

Total storage capacitance (series connection when charging) $\frac{1}{C_{total}} = \frac{1}{C_1'} + \frac{1}{C_1'} + \frac{1}{C_1'}$
$= \frac{3}{C_1'}$

$\therefore C_{total} = \frac{C_1'}{3} = \frac{0.25\,\mu F}{3}$
$= 0{,}083\,\mu F$

Time constants

Rise $= R_1 C_2 = 325 \cdot 2 \cdot 10^{-9}$
$= 650\,nS$ or $0{,}65\,\mu S$

Tail $= R_2 C_1 = 6 \cdot 10^3 \cdot 0{,}083\,\mu F = 498\,\mu S$

e) You are required to specify a test source for testing a 2 km length of buried cable which will operate at 66 kV. The cable has a total capacitance of approximately 5 μF. What are the challenges in testing such a cable and therefore what test source would you recommend? Determine the main parameters of the source and state what advantages it has over competing systems. If necessary it can be assumed that the reactor can be wound with a ratio of inductive reactance at 50 Hz to resistance (ie quality factor of 40).

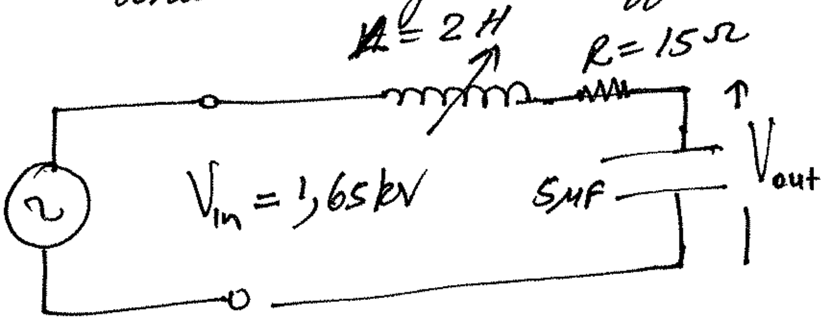
Challenges of carrying high voltage tests on a long power cable circuit

- high charging current requiring high capacity test voltage source

$I_{charging} = V/Z_{cable} = 66.10^3 / (1/2\pi.50.5.10^{-6}) = 103.7A$

$\therefore P = V.I = 66kV \times 103.7A = 6.8$ MVAR!

- In the case of a short circuit during the testing procedure huge fault currents flows which may be difficult to handle



$$V_{out} = \frac{1}{j\omega C} \cdot \frac{V_{in}}{R + j\omega L + \left(-\frac{j}{j\omega C}\right)}$$

@ resonance $j\omega L = \frac{1}{j\omega C}$

$$= \frac{V_{in}}{j\omega CR} \quad \text{but } j\omega L = \frac{1}{j\omega C}$$

$$= \frac{j\omega L}{R} . V_{in} \quad \text{but it is given that } \left|\frac{\omega L}{R}\right| = 40$$

$\therefore |V_{out}| = 40 V_{in}$. If the required $V_{out} = 66kV$.

$\therefore V_{in} = \frac{66.10^3}{40} = 1,65 kV$ and $|\omega L| = \left|\frac{1}{j\omega C}\right|$

$\therefore L = \frac{1}{\omega^2 C} = \left((2\pi 50)^2 . 5.10^{-6}\right)^{-1} = 2H$

$\frac{\omega L}{R} = 40 \therefore R = \frac{2\pi 50 . 2}{40} = 15 \Omega$

f) A length of a cable has a capacitance of 5 nF. The solid dielectric is cross linked polyethylene (XLPE). You are to test it at 150 Hz using a series resonant test set. You have available a single supply transformer with an output inductance of 150 H and a resistance of 250 Ω. The equivalent circuit is shown in the Figure 9 below.

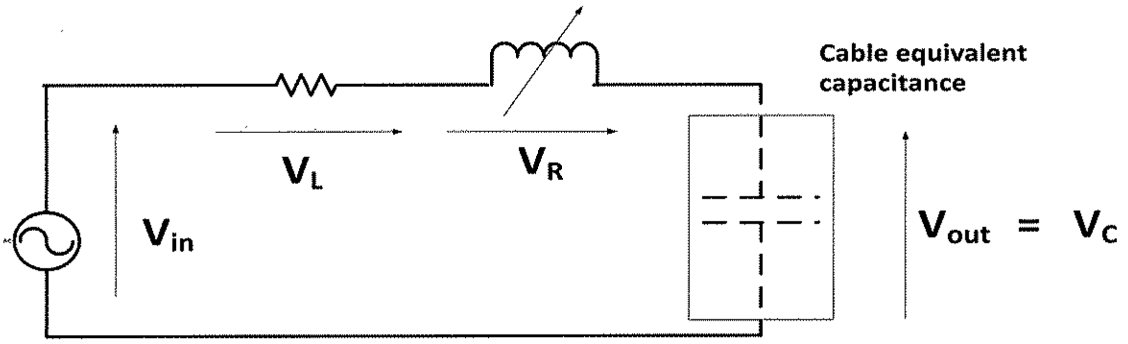
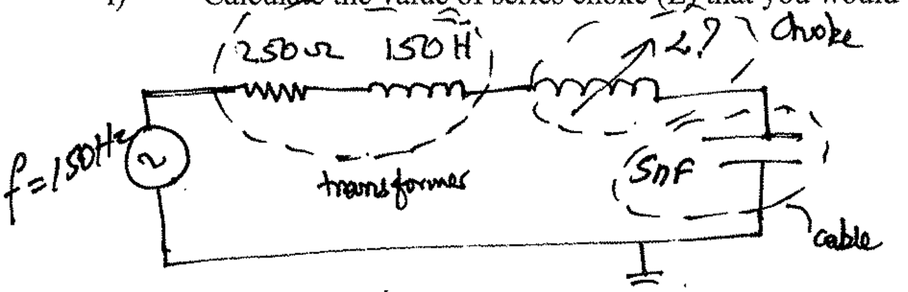


Figure 9: A resonant test circuit

i) Calculate the value of series choke (L) that you would use in this circuit.



$$\omega L' = \frac{1}{\omega C} \quad \& \quad L' = L + l = L + 150$$

$$(L + l) = \frac{1}{\omega^2 C}$$

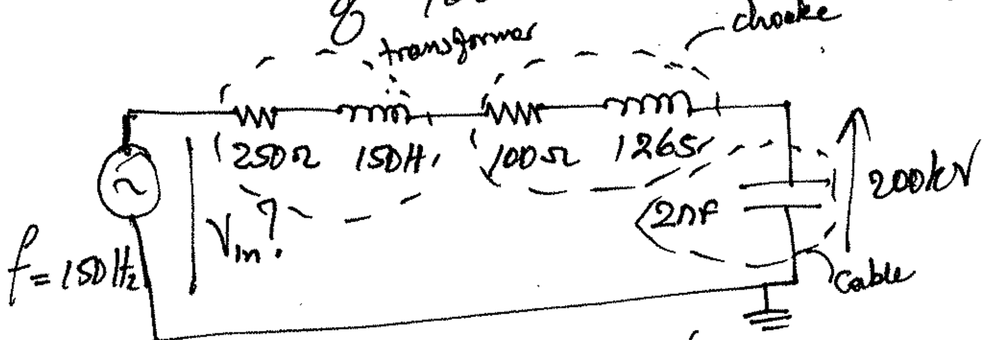
$$L = \frac{1}{\omega^2 C} - l$$

$$= \frac{1}{(2\pi(150))^2 \cdot 5 \cdot 10^{-9}} - 150$$

$$= 1265\,H$$

ii) Calculate the transformer output voltage if you are required to develop 200 kV into the cable. You may assume that the choke has an equivalent resistance of 100 Ω.

If the choke has an equivalent resistance of 100Ω then the equivalent cct becomes



$$H_{total} = 1265 + 150 = 1415$$

$$R_{total} = 250 + 100 = 350\,\Omega$$

$$V_{out} = \frac{\omega L}{R} \cdot V_{in}$$

$$\therefore V_{in} = \frac{R}{\omega L} \cdot V_{out}$$

$$= \frac{350}{2\pi\, 150 \cdot 1415} \cdot 200\,kV$$

$$= 52.5\,V$$

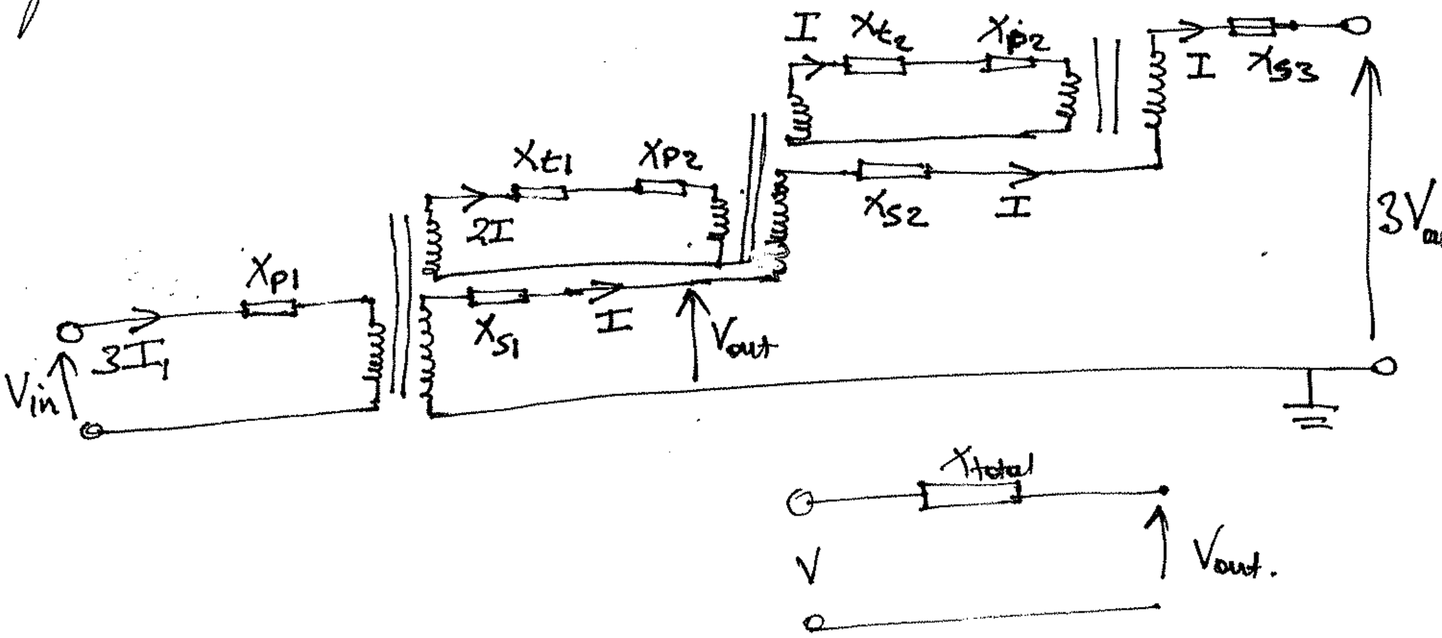
Question 2

a) Discuss the advantages and disadvantages of using cascaded HVAC test set for the provision of high voltage power frequency test supply.

Advantages	Disadvantages
- Individual units are rated at relatively lower voltage & yet the overall transformer output voltage can be orders of magnitude higher	- Unequal distribution of load over the cascade where the the primary of the 1st in the cascade carries the total load & ∴ has to be designed to cater for this
- high internal impedance this limiting fault currents	- the tanks of the subsequent units have to be insulated from ground & the more the units there here the voltage
- Flexible configuration	- total internal impedance of the cascade is complicated to determi[ne]

b) Deduce the effective internal impedance of a 3-stage cascade voltage transformer arrangement, and comment on the magnitude of this impedance compared with that of a single stage transformer for the same application.

Equivalent circuit of a 3-stage ~~impulse~~ cascaded AC generator



Assuming no magnetic losses (stray flux)

$N_pI_p = N_sI_s + N_tI_t$

or $N_pI_p - N_sI_s - N_tI_t = 0$ for each ~~stage~~.

Assuming a 3 lossless transformer cascaded system equivalent resistance is negible and therefore

$Z_p = jX_p$; $Z_s = jX_s$ & $Z_t = jX_t$

Let $N_p = N_t$ for all stages.

$$I^2 X_{total} = (3I)^2 X_{p1} + (2I)^2 X_{p2} + I^2 X_{p3} + I^2 X_{s1} + I^2 X_{s2} + I^2 X_{s3} + (2I)^2 X_{t1} + (I^2) X_{t2}.$$

If the transformers are identical then

$X_{p1} = X_{p2} = X_{p3}$; $X_{t1} = X_{t2} = X_{t3}$ & $X_{s1} = X_{s2} = X_{s3}$

Therefore;

$$I^2 X_{total} = (3I)^2 X_p + (2I)^2 X_p + I^2 X_p + I^2 X_s + I^2 X_s + I^2 X_s + (2I)^2 X_t + I^2 X_t$$

$$= 14 I^2 X_p + 3 I^2 X_s + 5 I^2 X_s$$

$$= I^2 (14 X_p + 3 X_s + 5 X_s)$$

$$\therefore X_{total} = 14 X_p + 3 X_s + 5 X_t$$

and this is much higher than the arithmetic sum of the winding impedances as would be given by $X_{total} = 3(X_p + X_s) + 2X_t$.

Question 2

Describe how, you would design a divider to give wideband performance. Be sure to consider both component values and voltage ratings in your discussion. Note that it is not necessary to calculate any component values (unless you think that this will aid your discussion) but you must propose a suitable circuit.

A high voltage divider that gives a wideband performance is characterised as given in the table below

Performance criteria	Design solution
- sensitive to as low frequency as dc	- use resistors
- sensitive to as high frequencies as possible	- use capacitors
- able to withstand high voltage	- connect components in series & also provide insulation
- no distortions, adequate time response for transient voltage measurement	- no inductance in the cct, use non inductive resistors & capacitor & also ensure compact construction
- Consistent accuracy over the entire measurable voltage range	- use temperature stable components and also minimise or eliminate stray capacitances.
- The divider to draw minimal current	Use losseless components & also mitigate corona by avoiding sharp points & also using corona rings.
	Use high value components in the voltage division ratio