Tutorial Session:
High Voltage Engineering

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Objectives

- Few real-world examples and numericals

Chapter 1: Introduction

Q1. Calculate the line current in kA for a three-phase, star connected 650 MW synchronous generator that generates power for 21.5 kV at a power factor of 0.9.

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Solution: In a three-phase system, the power is given by

$$P_{3\Phi} = \sqrt{3} V_l I_l \cos\Phi \ \ \text{W}$$

Given $P_{3\Phi} = 650 \times 10^6 \ \text{W}$, $V_l = 21.5 \times 10^3 \ \text{V}$, $\cos\Phi = 0.9$. Therefore,

$$I_l = \frac{650 \times 10^6 \ \text{W}}{\sqrt{3} \times 21.5 \times 10^3 \times 0.9} \text{kA} \quad = 19.39 \ \text{kA}$$

Chapter 2: Electric Fields

Q2. A single core, 500 kV, coaxial, lead-covered power cable insulated with XLPE insulation has the following construction details:

(a) Copper conductor diameter of 30 mm.

(b) Extruded semi-conductive layers on the conductor as well as on XLPE insulation are both of 2 mm thick.

(c) Extruded XLPE insulation thickness is 34 mm, having .

(d) The thickness of the lead sheath over the outer semi-conductive layer is 4 mm.

Answer the following:

(a) Draw a neat sketch of the cross-section of the cable showing the dimensions.

(b) Calculate the maximum and the minimum field intensities in the cable.

(c) Calculate the Schwaiger factor. Classify the type of field existing in the dielectric.

(d) What will be the capacitance per km length of the cable?

(e) Estimate the charging current per km length of the cable at rated voltage.

Make necessary assumptions.

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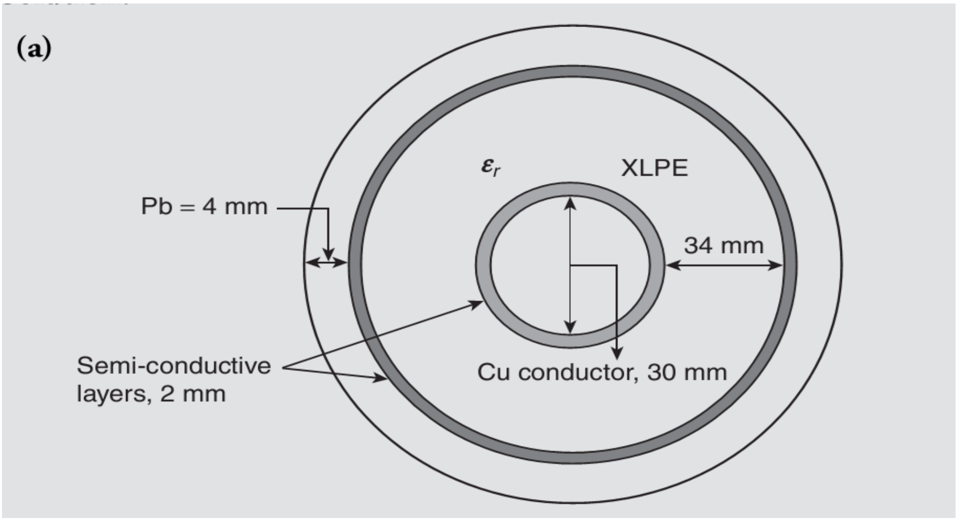
- **Solution_1:**



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- **Solution_2:**

(b) For a coaxial cylindrical system, the field intensities are given by Eq. (2.21).
For single core, 500 kV cable. So

$$U_0 = 500/\sqrt{3} = 288.68\ \text{kV}$$

Diameter of the copper conductor = 30 mm. Therefore, radius of the conductor = 15 mm. Semi-conductive layer is 2 mm thick over the Cu conductor and XLPE insulation. Thickness of XLPE insulation = 34 mm. Therefore

$r_i = 15 + 2 = 17$ mm and $r_0 = 17 + 34 = 51$ mm

Hence,

$$r_0 - r_i = d = 34\ \text{mm}$$

$$E_{\max} = \frac{U_0}{r_i \ln r_0/r_i} = \frac{500}{\sqrt{3}} \times \frac{1}{17} \times \frac{1}{\ln(51/17)} = \frac{500}{\sqrt{3}} \times \frac{1}{17} \times \frac{1}{3} = 15.456\ \text{kV/mm}$$

and

$$E_{\min} = \frac{U_0}{r_i \ln r_0/r_i} = 5.152\ \text{kV/mm}$$

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- **Solution_3:**

(c) Schwaiger factor [using Eq. (2.23)],

$$\eta = \frac{E_{\text{mean}}}{E_{\text{max}}} = \frac{r_i \ln r_0/r_i}{(r_0/r_i)} = 0.549$$

(d) Capacitance of a coaxial cylindrical system is given by Eq. (2.24)

$$\frac{C}{l} = \frac{2\pi\varepsilon}{\ln r_0/r_i} = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln r_0/r_i} = \frac{2 \times \pi \times 8.854 \times 10^{-12} \times 2.3}{\ln 3} \times 10^3 \text{F/km} = 116.5\text{nF/km}$$

(e) Charging current of the capacitor at rated voltage is given as

$$I_c = \omega C U_0 = \omega \times 116.5 \times 10^{-9} \times \frac{500}{\sqrt{3}} \times 10^3$$

$$= 100 \times \pi \times 116.5 \times 288.675 \times 10^{-6}$$

$$= 10.57 \text{ A/km}$$

Chapter 3: Over Voltages

Q3. Lightning strikes on the earth have some preferences.

(a) The new 800kV, 450 km long transmission line from Annapara to Unnao has per phase line inductance of 1.1 mH/km and capacitance of 11.68 nF/km. What is the ideal power transfer capability of this line in MW?

(b) If a lightning strike on this line injects 100 kA of impulse current, calculate the magnitude of overvoltage generated at this site.

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Solution:

The surge impedance Z_c of the line is

$$Z_c = \sqrt{\frac{l}{c}} = \sqrt{\frac{1.1 \times 10^{-3}}{11.7 \times 10^{-9}}}\ \Omega = 307\ \Omega$$

The ideal power transfer capability of the line is given by (Eq. 1.3)

$$P_{3\phi} = \frac{v_1^2}{Z_c} = \frac{800 \times 800}{307}\ \text{MW} = 2085\ \text{MW}$$

The overvoltage generated due to li strike on a transmission line is given by

$$\frac{1}{2} I_{\text{li}} Z_c = \frac{1}{2} \times 100 \times 10^3 \times 307\ \text{V} = 15350\ \text{kV or } 15.35\ \text{MV}$$

Chapter 4: Breakdown in Gases

Q4. What will be the breakdown strength of atmospheric air for small gaps (1 mm and 1 cm) and large gaps (20 cm) under uniform electric field conditions and standard atmospheric conditions.

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Solution:

The breakdown strength of atmospheric air under uniform field condition and standard atmospheric conditions is given by Paschen's Law:

$$\hat{U}_b = 6.72\sqrt{d} + 24.36\,d \text{ or } \hat{E}_b = 24.36 = \frac{6.72}{\sqrt{d}}\text{kV/cm}$$

Substituting for 1 mm gap,

$$\hat{E}_b = 24.36 = \frac{6.72}{\sqrt{0.1}} = 45.61\text{ kV/cm}$$

Substituting for 1 cm gap,

$$\hat{E}_b = 24.36 = \frac{6.72}{\sqrt{1}} = 31.08\text{ kV/cm}$$

Substituting for 20 cm gap,

$$\hat{E}_b = 24.36 = \frac{6.72}{\sqrt{20}} = 25.86\text{ kV/cm}$$

Chapter 4: Breakdown in Gases

Q5. The breakdown voltages of atmospheric air under normal temperature and pressure were measured for ac power frequency voltage between 2.5 cm diameter rod and plane with increasing gap distances. Simultaneous measurement of PD inception voltage revealed that stable PB could be measured only for a gap distance of 5.2 cm and above. At this distance, the peak (Ui) measured was 45.0 kV. If the value of ηlim for the atmospheric air is 0.25, answer the following:

a) Draw a schematic of Ub and Ui with increasing gap distance showing the ηlim and potential gradients at different stages.
b) What could be the breakdown voltage (peak) for the gap distance of 1 cm?
c) Estimate the maximum breakdown field intensity (peak) at the rod if the peak breakdown voltage of 42.5 kV was measured at the gap distance of 5 cm.
d) Which type of stable PB would occur at gap distance above 5.2 cm?
e) Estimate the breakdown voltage of the gap from the schematic in (a) given above for a gap distance of 10 cm.

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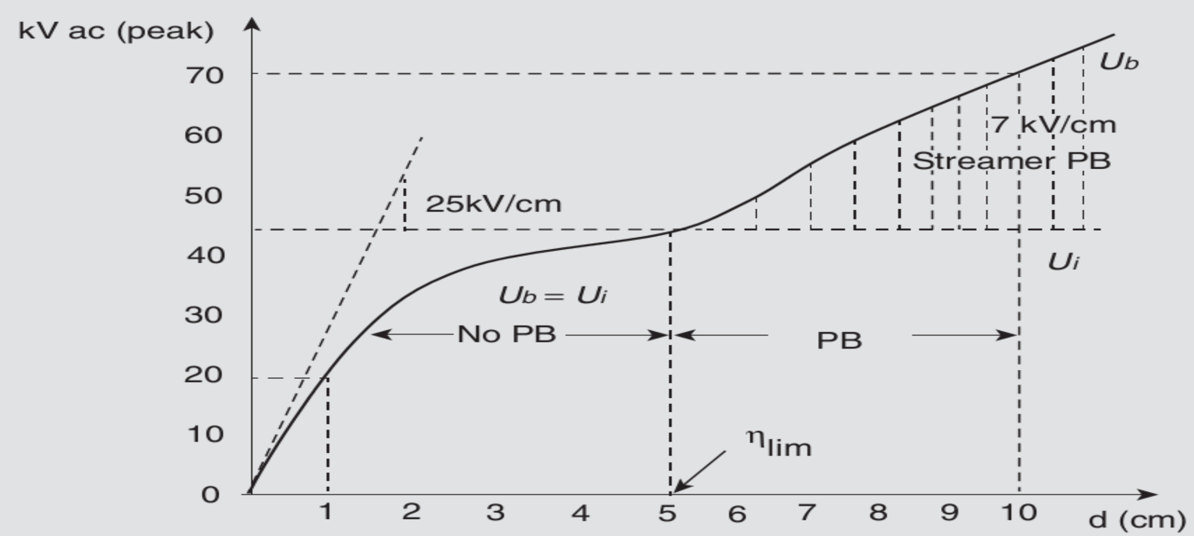
d) Which type of stable PB would occur at gap distance above 5.2 cm?

e) Estimate the breakdown voltage of the gap from the schematic in (a) given above for a gap distance of 10 cm.

Solution:

(a) Refer to Figs. 4.22 and 4.23 to plot the following figure from the given values:



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d) Which type of stable PB would occur at gap distance above 5.2 cm?

e) Estimate the breakdown voltage of the gap from the schematic in (a) given above for a gap distance of 10 cm.

Solution:

For a 2.5 cm diameter rod and plane the field is weakly nonuniform initially till up to the gap distance of 5.2 cm when no PB could be measured (below 5.2 cm gap distance [$U_b = U_i$]. Above this gap distance, the field between the electrodes becomes 'extremely nonuniform' and stable PB takes place before the complete breakdown. Under such conditions, streamer corona would take place because of the above critical amplification of the avalanche.

(b) The breakdown voltage for a gap distance of 1 cm from the graph is estimated to be $\approx$ 18 kV (peak).

(c) Refer to Eq. (4.25) $U_b = E_{b\max} \times d \times \eta_{\lim}$
At $d = 5$ cm, $U_b = 42.5$ kV, assuming $\eta = \eta_{\lim}$ at this d, η given as 0.25.
Therefore, $E_{b\max} = U_b / d \times \eta_{\lim} = 34$ kV/cm

(d) Streamer corona would take place above a gap distance of 5.2 cm as the potential gradient is not so high at the smoothly curved rod electrode; hence, aforementioned critical amplification of avalanche will take place.

(e) As shown in the prepared graph, the breakdown voltage for a gap distance of 10 cm can be estimated to be about 72 kV.

Chapter 4: Breakdown in Gases

Q6. A rod-plane electrode system with hemispherical rod of radius of curvature 5 cm has been chosen to investigate the breakdown characteristics in long gap distance in atmospheric air. Estimate the magnitude of the breakdown voltages with si of shape 60/2500 μs of +ve as well as –ve polarities for:

(a) A gap distance of 1 m

(b) A gap distance of 5 m

The smallest gaps lengths above which stable leader corona with these electrodes take place are 1.2 m for +ve polarity and 1.5 m for –ve polarity.

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Solution_1:

Solution: With increasing gap distance between a 10 cm diameter rod and plane, stable streamer corona may begin above 20 cm. As given, the stable leader corona takes place only at a gap distance of above 1.2 m for +ve polarity and above 1.5 m for -ve polarity si wave shape 60/2500 μs voltage. As discussed in Sections 4.4.1.2 and 4.4.1.3, the following potential gradients across the PB breakdown channels have been estimated in atmospheric air:

+ve streamer corona: 4.5 or 5.0 kV/cm
−ve streamer corona: 10 to 15 kV/cm
+ve leader corona: 1 kV/cm
−ve leader corona: 2 to 3 kV/cm

Considering PB channel to extend up to the opposite electrode just before the complete breakdown, the following estimation can be made:

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(a) A gap distance of 1 m

(b) A gap distance of 5 m

The smallest gaps lengths above which stable leader corona with these electrodes take place are 1.2 m for +ve polarity and 1.5 m for –ve polarity.

Solution_2:

(a) For $d = 1$ m with +ve as well as −ve polarity voltages pure streamer corona extends up to the opposite electrode; hence,

$$\begin{aligned} +\text{ve } U_b &= (4.5 \text{ to } 5.0) \times 100 \text{ kV} \\ &= 450 \text{ to } 500 \text{ kV} \end{aligned}$$

Similarly,

$$\begin{aligned} -\text{ve } U_b &= (10 \text{ to } 15\ ) \times 100 \text{ k V} \\ &= 1000 \text{ to } 1500 \text{ kV} \end{aligned}$$

(b) For $d = 5$ m, assuming the streamer corona to extend for 1.2 and for 1.5 m with +ve and −ve polarity voltages, respectively, and in the rest of the gap the leader corona prevails at the time of breakdown, the breakdown voltages can be estimated as:

$$\begin{aligned} +\text{ve } U_b &= (5 \times 120 + \overbrace{}^{\text{Streamer}} \quad \overbrace{1 \times 380}^{\text{Leader}}) \text{ kV} \\ &= 980 \text{ kV} \\ -\text{ve } U_b &= (12.5 \times 150 + 2.5 \times 350) \text{ kV} \\ &= 2750 \text{ kV} \end{aligned}$$

Chapter 5: Lightening

Q7. A 220 kV, three-phase line has a horizontal configuration of conductors 5 m apart. The ground clearances are 15 m. Design and find the position of the ground wire/wires for lightning protection.

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Solution: Following the practice of stringent angle of protection of 30° for high-voltage line horizontal earth wire, this line can be protected either with (a) two earth wires or (b) single earth wire, as shown in Fig. 5.10.

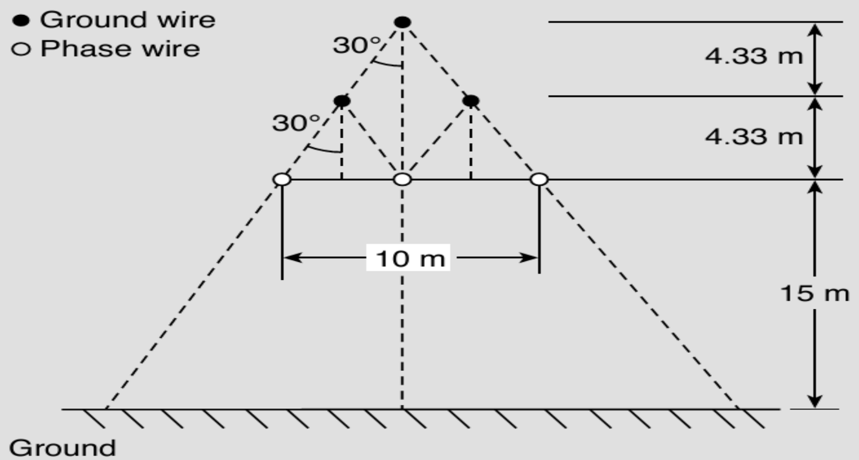

Figure 5.10 ■ Lightning protection by ground wire system for high voltage transmission lines.

(a) Placing of the single ground wire above the centre of the live conductor span works out to be at a height of 8.66 m. Or

(b) Two parallel horizontal ground wires can be placed 5 m apart above the centre of the level of two-phase conductors. Their height works out to be at 4.33 m.
The second configuration of placing the ground wires is followed more as it reduces the overall height of the line towers, a more economical solution.

Chapter 6: Solid and Liquid Dielectrics

Q8. Calculate the ac electric power loss (W/km) and charging current (A/km) of a 110 kV, XLPE insulated, single core coaxial cable having the following dimensions:

(i) Cu wire stranded conductor diameter – 20 mm

(ii) XLPE insulation thickness – 18 mm

(iii) Outer lead sheath thickness – 3.5 mm

The dielectric loss factor of XLPE can be taken to be 2×10^{-4} and its relative permittivity (ε_r) to be 2.3.

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Solution:

Solution: Rated voltage is 110 kV. Therefore, voltage across the line $= \dfrac{100}{\sqrt{3}}$ kV.

Capacitance per unit length of a coaxial cylindrical system cable is given by Eq. (2.24) as

$$C = \frac{2\pi\varepsilon_o\varepsilon_r}{\ln(r_o/r_i)}\,\mathrm{F/m}$$

where $\varepsilon_r = 2.3$, $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m, $r_i = 10$ mm, $r_o = 10 + 18 = 28$ mm. So

$$C = \frac{2 \times \pi \times 8.854 \times 2.3 \times 10^{-12}}{\ln(28/10)} \times 10^3\,\mathrm{F/km} = 124.32\,\mathrm{nF/km}$$

From Eq. (6.11) the charging current is given by

$$I_c = \omega C U = 2\pi \times 50 \times 124.32 \times 10^{-9} \times \frac{100}{\sqrt{3}} \times 10^3 = 2.48\ \mathrm{A/km}$$

ac power loss $= \omega C U^2 \tan\delta$

$$P_{\mathrm{ac}} = I_c U \tan\delta = 2.48 \times \frac{110}{\sqrt{3}} \times 10^3 \times 2 \times 10^{-4} = 31.5\ \mathrm{W/km}$$

Chapter 7: High Test Voltage Generation

Q9. A Cockcroft−Walton type voltage doubler circuit DC generator having two circuits in series has capacitances C_1 and C_2 of 0.01 μF and 0.05 μF, respectively. The supply transformer secondary voltage is 125 kV at a frequency of 50 Hz. If the load current to be supplied is 5 mA, find (a) the percentage ripple, (b) voltage drop, and (c) voltage regulation.

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Solution:

(a) The ripple voltage is given by

$$\delta U = \frac{I_1 T}{C_2} = \frac{5 \times 10^{-3}}{0.05 \times 10^{-6} \times 50} = 2.0 \text{ kV}$$

$$\text{Percentage ripple} = \frac{\delta U \times 100}{2nV_{\max}} = \frac{2\,\text{kV} \times 100}{2 \times 2 \times 125\,\text{kV}} = 4\%$$

(b) Voltage drop is

$$\frac{I_1}{f}\left(\frac{1}{C_1} + \frac{1}{2C_2}\right) = \frac{5 \times 10^{-3}}{50}\left(\frac{10^6}{0.01} + \frac{10^6}{2 \times 0.05}\right) = 11.0\,\text{kV}$$

(c) Voltage regulation is

$$\frac{\text{Voltage drop} \times 100}{2nV_{\max}} = \frac{11\,\text{kV} \times 100}{2 \times 2 \times 125\,\text{kV}} = 2.2\%$$

Chapter 7: High Test Voltage Generation

Q10. A Cockcroft−Walton type voltage multiplier has six stages with capacitance all equal to 0.05 μF. The supply transformer secondary voltage is 100 kV at a frequency of 50 Hz. If the load current to be supplied is 5 mA, find (a) the percentage ripple, (b) voltage drop, and (c) voltage regulation.

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Solution:

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(a) The ripple voltage is

$$\delta U = \frac{I}{2fC} \cdot \frac{(n)(n+1)}{2} = 21.0\,\text{kV}$$

$$\text{Percentage ripple} = \frac{\delta U \times 100}{2nV_{\max}} = \frac{21\,\text{kV} \times 100}{2 \times 6 \times 100\,\text{kV}} = 1.75\%$$

(b) Voltage drop is

$$\frac{I}{Cf}\left(\frac{2}{3}n^3 + \frac{n^2}{2} - \frac{n}{6}\right) = \frac{5 \times 10^{-3}}{0.05 \times 10^{-6} \times 50}(7) = 322.0\ \text{kV}$$

(c) Voltage regulation is

$$\frac{\text{Voltage drop} \times 100}{2nV_{\max}} = \frac{322\,\text{kV} \times 100}{2 \times 6 \times 125\,\text{kV}} = 21.46\%$$

Chapter 8: High Test Voltage Measurement

Q11. We have two spheres of 75 cm diameter in the laboratory. If the lower sphere is grounded and a gap of 100 mm is set between the spheres, find the correct value of positive lightning impulse magnitude applied when a flash takes place. The atmospheric pressure and temperature in the laboratory is 754 mmHg and 25°C, respectively. The flashover voltage for the given sphere and the gap from the table for normal pressure and temperature is 265 kV. The air density correction factor table is given as following:

Reflective air density	Correction factor
0.80	0.82
0.85	0.86
0.90	0.91
0.95	0.95
1.00	1.00
1.05	1.05
1.10	1.09

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Solution:

Solution: From the calibration table for 75 cm spheres for a 100 mm gap spacing between the spheres, and for the positive polarity lightning impulse, the flashover voltage at 20°C and 760 mm Hg is given to be 265 kV.

To work out the correction factor K_d, the relative air density is given as

$$\delta = \frac{p}{p_0} = \frac{273 + t_0}{273 + t}$$

where p_0 is air pressure under normal conditions (760 Hg), t_0 is normal temperature (20°C) and p and t are under measurable conditions. So

$$\delta = \frac{754}{760} \times \frac{273 + 20}{273 + 25} = \frac{754}{760} \times \frac{293}{298} = 0.975$$

Hence, as evident, the correction factor (K_d) from the table should also be 0.975.

The correct value of positive li impulse voltage applied is

$$265 \times 0.975 = 258.5 \text{ kV}$$

Chapter 8: High Test Voltage Measurement

Q12. An electrostatic voltmeter consists of two parallel plates, one movable and one fixed. With 11 kV applied between the plates, it is found that the pull is 10×10^{-3} N on the movable plate. Determine the change in capacitance produced for a movement of movable plate by 1 mm. Diameter of movable plate is 150 mm.

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Solution:

Solution: Area of the plate

$$A = \frac{\pi}{4} \times (150 \times 10^{-3})^2 = 17.6 \times 10^{-3}\ \text{m}^2$$

Force of attraction is given as

$$F = \frac{1}{2}\varepsilon_0 \frac{(U_{\text{rms}})^2}{d^2} A$$

Hence, distance between the plate is given as

$$d = \sqrt{\frac{\varepsilon_0 A}{2F}}\, U_{\text{rms}} = \sqrt{\frac{8.854 \times 10^{-12} \times 17.6 \times 10^{-3}}{2 \times 10 \times 10^{-3}}} \times (11 \times 10^3) = 30.7\ \text{mm}$$

The position of movable plate changes by 1 mm, that is, d changes from 30.7 to $(30.7 - 1) = 29.7$ mm, that is, $d_1 = 30.7$ mm and $d_2 = 29.7$ mm.
Now, for a parallel-plate capacitor: $C = \varepsilon_0 \varepsilon_r A / d$
So, the change in capacitance is

$$\Delta C = \varepsilon_0 \varepsilon_r A \left(\frac{1}{d_2} - \frac{1}{d_1} \right)$$

$$\Rightarrow \Delta C = 8.854 \times 10^{-12} \times 17.6 \times 10^{-3} \left(\frac{1}{29.7 \times 10^{-3}} - \frac{1}{30.7 \times 10^{-3}} \right)$$

$$\Rightarrow \Delta C = 0.17\ \text{pF}$$

Chapter 9: Non-destructive Testing

Q13. A Schering Bridge was used to determine the loss tangent of a 10-mm thick Bakelite sheet at 50 Hz using a parallel-plate electrode configuration. The electrode effective area is 250 sq cm. At balance, the bridge arms are AB: test object C_x; BC: Std. capacitor, C_2 or C_s= 10 pF; CD: variable capacitor in parallel with resistor, C_4 = 100 nF and R_4= 350 Ω; DA: variable resistance, R_3= 70 Ω. Determine the permittivity and loss tangent of the dielectric.

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Solution:

Solution: Capacitance of parallel-plate electrodes $= C_x = \dfrac{\varepsilon_0 \varepsilon_r A}{d}$

$$C_x = \frac{R_4}{R_3} C_s = \frac{350}{70} \times 10 \times 10^{-12} = 50 \text{ pF}$$

$$C_x = \frac{\varepsilon_0 \varepsilon_r A}{d} = \frac{\varepsilon_r \times 8.854 \times 10^{-12} \times 250 \times 10^{-4}}{10 \times 10^{-3}} \text{ F/m} = 50 \text{ pF}$$

$$\varepsilon_r = 2.25$$

$$\tan \delta = \omega C_x R_x = \omega C_4 R_4 = 314 \times 350 \times 100 \times 10^{-9} = 0.110990$$

Chapter 9: Non-destructive Testing

Q14. A high-voltage Schering Bridge has the following arms with their component ranges. Std. capacitor, C_2 : 100 pf ; variable resistor, R_3: 1 to 10 kΩ (decade steps), C_4: 1 nF to 1 μF, and R_4: 100 Ω to 10.100 kΩ. Determine the maximum and minimum value of the capacitance and tan δ that can be measured at 50 Hz.

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Solution:

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$$C_{x(\text{max.})} = \frac{R_{4\,(\text{max.})} \times C_s}{R_{3\,(\text{min.})}} = \frac{10100}{100} \times 100 \times 10^{-12} = 10.1\ \text{nF}$$

$$C_{x(\text{min.})} = \frac{R_{4\,(\text{min.})} \times C_s}{R_{3\,(\text{max.})}} = \frac{100}{10000} \times 100 \times 10^{-12} = 1\ \text{pF}$$

$$\tan\delta_{\,(\text{max})} = \omega R_{4\,(\text{max})} C_{4\,(\text{max})} = 100\,\pi \times 10100 \times 1 \times 10^{-6} = 3.173 \tan\delta_{(\text{min})}$$

$$= \omega R_{4\,(\text{min})} C_{4\,(\text{min})} = 100\,\pi \times 100 \times 1 \times 10^{-9} = 0.0314 \times 10^{-3}$$

Thank You
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