UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI

Electrical, Electronic and Computer Engineering
ENEL4HB - High Voltage 2

Main Exam

Internal Examiner: Mohamed Khan
External Examiner: Hugh Hunt

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Instructions

- Answer all questions, show all working and include all necessary comments (it is your reasoning that is being assessed, not the numerical answer)
- Marks will be deducted where no or incorrect units are used, and where figures and plots are labelled incorrectly.
- Time allowed = 2 hours
- Full marks = 100

Question 1 - Outdoor Insulators

1. A glass cap and pin insulator string consists of 4 glass insulator discs. The nominal voltage for the insulator is 44 kV. Determine the voltage across each insulator and the efficiency of the string where the self capacitance is 15 pF and the capacitance to earth is 1 pF. [5 Marks]
2. Describe the pollution flashover mechanism for glass insulators. [5 Marks]
3. Describe the advantages of a silicon rubber insulator over a ceramic insulator. [5 Marks]
4. You have tested the flashover voltage of the insulators below. Using the table for standard system voltages and the table for unified specific creepage distances. You are to determine the voltage rating and the pollution category of each of the insulators [Note: The best fit with justification]. [10 Marks]

Insulator ID	Power Frequency Flashover Voltage (kV)	Measured LIWL (kV)	Creepage Length (mm)
1	80	120	340
2	55	126	300
3	95	165	700

[Total Marks: 25]

Question 2 - Electric Field

A bipolar 800 kV DC high voltage transmission line at sea level has a horizontal pole conductor geometry with a pole conductor height of 20 m and separation between poles of 20 m. The negative pole has a 6 conductor bundle and the positive pole has a 4 conductor bundle each with a sub-conductor radius of 1.75 cm and a geometrical radius $R = 30$cm.

Determine:

1. The equivalent radius of the conductor bundles. [2 Marks]
2. The potential coefficients, the total charge on each of the pole conductor bundles.[10 Marks]
3. The average and average maximum bundle gradient on the pole conductors. [5 Marks]
4. If corona occurs on each of the conductor bundles through the use of Peek's empirical expressions when the temperature is 30^oC, the pressure is 650 torr and the conductor surface roughness is $m = 0.7$. [8 Marks]

[Total Marks: 25]

Question 3 - Partial Discharge

1. Describe the importance of why and where one would measure for partial discharge in a substation. [5 marks]
2. Sketch the standard partial discharge measurement system (including the device under test (cable) and measurement instrument) and discuss each component in the circuit. Include in your answer typical measurement quantities. [10 Marks]
3. The coupling device is an important component of the partial discharge measurement system. Using a sketch, describe the bandwidth of the measurement device in relation to that of the partial discharge. You must also include in your answer details of the frequency limits. [10 Marks]

[Total Marks: 25]

Question 4 - Insulation Co-ordination

Consider an incoming 88 kV sub-transmission line where the line terminates on an 88kV/33kV transformer.

1. Insulation co-ordination can be described in terms of probability curves. Sketch and comment on an overvoltage distribution function and the transformer breakdown voltage distribution function illustrating the risk of failure. Show on this sketch and comment on the effect of installing a protective device before the equipment. [10 Marks]
2. Using a sketch of voltage against applied voltage, describe the operation and use of a metal oxide surge arrester for voltage protection. [*Note: You must describe when the metal oxide arrester needs to operate and when it does not*] [5 Marks]
3. An overvoltage travels on an 88 kV overhead line with a propagation velocity of $v = 0.7c$ and steepness of $S = 1300$ kV/μs. A metal oxide surge arrester is to be installed in front of a transformer with a $U_{LIWL} = 440$ kV. The distance between the arrester and transformer is 20 m. Determine the voltage to earth at the transformer if the surge arrester has a residual voltage of 200 kV. [2 Marks]
4. Comment on why the voltage across the bushing of the transformer is higher than the residual voltage of the surge arrester and whether the transformer is protected or not. [4 Marks]

Table 1: Performance factor for incoming overhead line

Line Type	Factor A (kV)
Transmission lines (1ϕ to earth flashover)	
Single conductor	4500
Double conductor bundle	7000
Four conductor bundle	11000
Six and eight conductor bundle	17000

5. Given that there is one incoming line with a four conductor bundle and a span of 300 m, determine the protection distance that should be used and whether the transformer is currently protected or not. [4 Marks]

[Total Marks: 25]

Useful Formulae

Constants

Standard temperature: $t_0 = 20^o$C
Standard pressure: $P_0 = 760$ torr
Permittivity of free space: $\varepsilon_0 = 8.85 \times 10^{-12}$F/m

Formulae

Electric field in layer k in a uniform dielectric with multiple layers and permittivities:

$$E_k = \frac{V}{\frac{\varepsilon_k}{\varepsilon_1} d_1 + \frac{\varepsilon_k}{\varepsilon_2} d_2 + \dots}$$

Electric field in layer k in a coaxial system:

$$\vec{E} = \frac{V}{r \ln \frac{R_{out}}{r_c}} \tag{1}$$

Electric field in layer k in a coaxial system with multiple layers and permittivities:

$$E_k = \frac{V}{r_k \left[\frac{\varepsilon_k}{\varepsilon_1} \ln \frac{r_2}{r_1} + \frac{\varepsilon_k}{\varepsilon_2} \ln \frac{r_3}{r_2} + \dots \right]}$$

Electric field in relation to a line charge q:

$$\vec{E} = \frac{q}{2\pi\varepsilon_0 r} \angle\theta$$

The equivalent bundle radius:

$$r_{eq} = \left(n r R^{n-1} \right)^{\frac{1}{n}}$$

Relationship between Q and V:

$$[P][Q] = [V]$$
$$[Q] = [P]^{-1}[V]$$

Resultant electric field:

$$\vec{E}_R = \frac{1}{2\pi\varepsilon_0} [P]^{-1}[V] [\tfrac{1}{r} \angle\theta + \tfrac{1}{r'} \angle\theta']$$

Self potential coefficient:

$$P_{ii} = \frac{1}{2\pi\varepsilon_0} \ln \frac{2h_i}{r_i}$$

Mutual potential coefficient:

$$P_{ij} = \frac{1}{2\pi\varepsilon_0} \ln \frac{D_{ij}}{d_{ij}}$$

$$D_{ij} = \sqrt{((x_i - x_j)^2 + (y_i + y_j)^2}$$

$$d_{ij} = \sqrt{((x_i - x_j)^2 + (y_i - y_j)^2}$$

Average bundle gradient:

$$E_a = \frac{q}{n} \frac{1}{2\pi\epsilon_0 r}$$

Average maximum bundle gradient:

$$E_{am} = E_a \left[1 + (n-1) \frac{r}{R} \right]$$

Peek's empirical expressions:

$$|\vec{E_{positive}}| = 33.7 m\delta (1 + \frac{0.24}{\sqrt{\delta r_c}}) \quad [kV/cm]$$

$$|\vec{E_{negative}}| = 31 m\delta (1 + \frac{0.308}{\sqrt{\delta r_c}}) \quad [kV/cm]$$

$$|\vec{E_{acpeak}}| = 29.8 m\delta (1 + \frac{0.301}{\sqrt{\delta r_c}}) \quad [kV/cm]$$

Relative air density:

$$\delta = \frac{P}{P_0} \frac{273 + t_0}{273 + t}$$

Voltage across cap and pin insulator string:

$$V_n = V \frac{\sinh ((\sqrt{\frac{C_p}{C_s}})n)}{\sinh ((\sqrt{\frac{C_p}{C_s}})N)}$$

Efficiency of cap and pin insulator:

$$\eta = \frac{V}{N V_N}$$

Voltage across transformer layers:

$$V_n = V \frac{\sinh ((\sqrt{\frac{C_p}{C_s}})n)}{\sinh ((\sqrt{\frac{C_p}{C_s}})N)}$$

Method of determinants:

$$\Delta = det \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} = a_{11}a_{22} - a_{21}a_{12}$$

$$\begin{aligned} \Delta &= det \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} = \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix} \\ &= a_{11}a_{22}a_{33} + a_{12}a_{23}a_{31} + a_{13}a_{21}a_{32} \\ &- a_{31}a_{22}a_{13} - a_{32}a_{23}a_{11} - a_{33}a_{21}a_{12} \end{aligned}$$

Probability of negative lightning stroke:

$$P = \frac{1}{1 + (\frac{I_p}{31})^{2.6}}$$

Average number of strikes to line:

$$N_s = N_g \left(\frac{28h^{0.6} + b}{10} \right)$$

Attractive radius:

$$R_a = 0.67 h_t^{0.67} I^{0.74}$$

Flashover current:

$$I_{crit} = \frac{2U_{50}}{Z_0}$$

Shielding separation:

$$X_{sp} = R_s - \sqrt{R_p^2 - (Y_s - Y_p)^2}$$

Reflection co-efficient:

$$\rho_r = \frac{Z_2 - Z_1}{Z_1 + Z_2}$$

Insulator flashover volt-time curve:

$$U(t) = \left(400 + \frac{710}{t^{0.75}} \right) W$$

Switching impulse stength of airgaps:

$$U_{50} = k \frac{3400}{1 + \frac{8}{d}}$$

Voltage at protected equipment:

$$U_{equip} = U_a + \frac{2 \times (d + a) \times S}{v}$$

Protective zone:

$$L_p = \frac{N}{A} \left(\frac{U_{BIL}}{1.15} - U_a \right) \times L_{sp}$$

Paschen's eqn:

$$V_b = 6.72\sqrt{pd} + 24.36(pd)$$

PD inception voltage:

$$V_{ai} = E_{cb} t \left[1 + \frac{1}{\varepsilon_r} \left(\frac{d}{t} - 1 \right) \right]$$

Table 2: Standard SANS/IEC System Voltages

Nominal Voltage (kV)	Maximum Voltage (kV)	Power Frequency Withstand Voltage (kV)	Lightning Impulse Withstand Voltage (kV peak)	Switching Impulse Withstand Voltage (kV peak)
11	12	28	75/95	-
22	24	50	125/150	-
33	36	70	170/200	-
44	52	95	250	-
66	72.5	140	350	-
88	100	150/185	380/450	-
132	145	230/275	550/650	-
275	300	460	1050	850
400	420	630	1425	1050
765	-	-	2100	1550

Table 3: Unified Specific Creepage Distance

Pollution Level	Unified Specific Creepage Distance (mm/kV)
a. Very light	22
b. Light	27.8
c. Medium	34.7
d. Heavy	43.3
e. Very Heavy	53.7