IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2013

EEE PART IV: MEng and ACGI

HIGH VOLTAGE TECHNOLOGY AND HVDC TRANSMISSION

Tuesday, 7 May 10:00 am

Time allowed: 3:00 hours

There are SIX questions on this paper.

Answer FOUR questions.

All questions carry equal marks.

Any special instructions for invigilators and information for candidates are on page 1.

Examiners responsible	First Marker(s) :	B. Chaudhuri
	Second Marker(s) :	B.C. Pal

Answer any 4 questions out of 6

1. a) State two advantages and two disadvantages of using bundled conductors for high voltage power transmission.

[5]

Electric field at the conductor surface is reduced due to increase in effective surface area by having two or more conductors in close proximity per phase

Advantages

- less corona loss and radio interference
- less skin effect
- reduced reactance

Disadvantages

- increased ice and wind loading
- higher cost
- higher charging current due to high capacitance

b) For a single-phase capacitance graded cable the conductor diameter is 10 mm and sheath diameter is 50 mm. The inner layer insulation has a relative permittivity of 4 and peak dielectric strength 6 kV/mm; the outer layer has a relative permittivity of 2.5 and peak dielectric strength 5 kV/mm. Calculate the maximum working voltage (rms) for the cable.

[10]

$$r = \frac{10}{2} = 5 \text{ cm}, \ \mathrm{R} = \frac{50}{2} = 25 \text{ cm}$$
$$E_{m1} = 6 \text{ kV/mm}, E_{m2} = 5 \text{ kV/mm}, \ \epsilon_1 = 4, \ \epsilon_2 = 2.5$$

For a capacitance graded cable:

$$E_{m1}\,\epsilon_1 r = E_{m2}\,\epsilon_2 r_1 = \frac{q}{2\pi\epsilon_0} \rightarrow r_1 = 9.6 \text{ mm}, \frac{q}{2\pi\epsilon_0} = 120 \text{ kV}$$

$$V = \frac{q}{2\pi\epsilon_0}\left[\frac{1}{\epsilon_1}\ln\frac{r_1}{r} + \frac{1}{\epsilon_2}\ln\frac{R}{r_1}\right] = 65.51 \text{ kV (peak)}$$

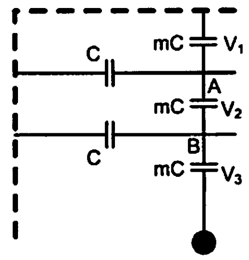
Maximum working voltage is:

$$\frac{65.51}{\sqrt{2}} = 46.32 \text{ kV}$$

c) There are three units (disks) in an overhead line suspension insulator string. For each disk the capacitance between the pin and ground is one-eighth the self-capacitance. If each disk is rated for a peak voltage of 20 kV, calculate the maximum working voltage (rms) of the overhead line. Neglect any capacitance formed between the high voltage conductor and the pins through air.

[10]

$m = 8$



Charge balance at nodes A and B gives:

$mCV_2 = mCV_1 + CV_1 \rightarrow 8V_2 = 9V_1$
$mCV_3 = mCV_2 + C(V_1 + V_2) \rightarrow 8V_3 = 9V_2 + V_1$

Solving the above equations we get:

For $V_3 = 20$ kV, $V_2 = 16.18$ kV, $V_1 = 14.38$ kV

Maximum voltage that the suspension insulator can support is

$V_1 + V_2 + V_3 = 50.56$ kV (peak)

Maximum working voltage is

$\frac{50.56}{\sqrt{2}} = 35.75$ kV

2. a) Derive an expression for the optimum ratio of cable radius to conductor radius in order to support maximum cable voltage with minimum electric strength of the insulating material and smallest cable dimension.

[5]

Maximum electric field on the surface of the conductor is given by:

$$E_{max} = \frac{V}{r \ln \frac{R}{r}} = \frac{V}{R}\left(\frac{p}{\ln p}\right), \quad \text{where } p = \frac{R}{r}$$

To support maximum voltage (V) with minimum electric strength (E_{max}) and smallest cable dimension (R), the following is to be minimized:

$$\frac{R \times E_{max}}{V} = \frac{p}{\ln p}$$

Equating the derivative to zero:

$$\frac{d}{dp}\left(\frac{p}{\ln p}\right) = 0 \Rightarrow p = \frac{R}{r} = e$$

$$R = 2.718\, r$$

b) A three-phase overhead line has 19.53 mm diameter conductors arranged in equilateral formation. The breakdown strength of air is 30 kV/cm under normal atmospheric conditions. Calculate the spacing between the conductors such that the corona takes place only if the line voltage exceeds 210 kV (rms). Assume an air density correction factor of 0.98.

[10]

$$r = \frac{19.53}{2} = 9.77 \text{ mm}$$

$$V_L = 210 \times \sqrt{2} = 296.94 \text{ kV (peak)}$$

$$V_{ph} = \frac{V_L}{\sqrt{3}} = 171.44 \text{ kV (peak)}$$

$$E_{max} = 30 \times \delta \text{ kV/cm} = 29.4 \text{ kV/cm}$$

Maximum electric field on the surface of the conductor is given by:

$$E_{max} = \frac{V_{ph}}{r \ln \frac{D}{r}}, \quad r \ll D$$

$$D = r\, e^{\left(\frac{V_{ph}}{r \times E_{max}}\right)} = 3.82 \text{ m}$$

c) An underground cable with inductance 0.3 mH/km and capacitance 0.4 μF/km is connected to an overhead line having inductance 2.0 mH/km and capacitance 0.014 μF/km. If a 100 kV voltage surge is travelling along the overhead line towards the junction of the overhead line and the cable, calculate the values of the reflected and transmitted voltage surges.

[10]

Surge impedances for the cable and the overhead lines are:

$$Z_{Cable} = \sqrt{\frac{L}{C}} = 27.39\ \Omega$$

$$Z_{OH} = \sqrt{\frac{L}{C}} = 377.97\ \Omega$$

Incident voltage

$V_i = 100$ kV

Reflection coefficient

$$\alpha = \frac{Z_{Cable} - Z_{OH}}{Z_{Cable} + Z_{OH}} = -0.865$$

Reflected voltage

$V_r = \alpha V_i = -86.5$ kV

Transmission coefficient

$$\delta = \frac{2Z_{Cable}}{Z_{Cable} + Z_{OH}} = 0.135$$

Transmitted voltage

$V_t = \delta V_i = 13.5$ kV

3. a) What are the three primary requirements for a surge arrester?

[5]

- should not allow any current under normal voltage
- break down instantly following over voltage
- hold the voltage with little change for the duration of the over voltage
- substantially cease conduction at very nearly the same voltage at which conduction started
- interrupt power frequency follow-on current after flashover

b) The insulation for a 400 kV(rms) circuit breaker is to be designed for a substation where the past records have shown a statistical overvoltage of 600 kV (peak). The statistical safety factor (γ) is related to the risk of failure (R) through the following equation (3.1):

$$R = -0.1995\gamma + 0.2395 \qquad (3.1)$$

If the maximum acceptable risk of failure is 0.001, determine which of the following statistical withstand voltage levels is appropriate for the circuit breaker insulation: 690 kV, 715 kV, 718 kV or 720 kV.

[10]

$$\gamma = \frac{\text{Statistical withstand voltage (SWV)}}{\text{Statistical overvoltage (SOV)}}$$

SOV = 600 kV

Risks of failure (R) for different SWVs are:

SWV (kV)	γ	R	Remark
690	1.150	0.010075	>0.001
715	1.192	0.001762	>0.001
718	**1.197**	**0.00076**	**<0.001**
720	1.200	0.00010	<0.001

Hence 718 kV is the most appropriate SWV where risk of failure less than 0.001

c) Lightning strikes the ground wire at the centre of its span between the two towers. The lightning current is 15 kA. The surge impedance of the ground wire is 500 Ω and that of the two towers are 200 Ω and 50 Ω. Calculate the voltage surge transmitted on to the ground wires in either direction outside the span where the lightning strikes.

[10]

$Z_G = 500\,\Omega, \qquad Z_{T1} = 200\,\Omega, \qquad Z_{T2} = 50\,\Omega$

$I = 15$ kA

Incident voltage due to lightning:

$$V_i = \frac{I}{2} \times Z_G = 3750 \text{ kV}$$

Transmission coefficient at the junction of tower T1 (with $Z_{T1} = 200\ \Omega$):

$$\delta_{T1} = \frac{2(Z_G \parallel Z_{T1})}{Z_G + (Z_G \parallel Z_{T1})} = 0.444$$

Transmission coefficient at the junction of tower T2 (with $Z_{T2} = 50\ \Omega$):

$$\delta_{T2} = \frac{2(Z_G \parallel Z_{T2})}{Z_G + (Z_G \parallel Z_{T2})} = 0.167$$

Voltage surge transmitted on to the ground wire away from tower T1:

$$V_{t1} = \delta_{T1} \times V_i = 1665 \text{ kV}$$

Voltage surge transmitted on to the ground wire away from tower T2:

$$V_{t2} = \delta_{T2} \times V_i = 626.25 \text{ kV}$$

4. a) For a line commutated converter (LCC) based HVDC link, explain why the inverter control characteristics has a minimum firing angle (α) limit and the rectifier control characteristic has a minimum current limit.

[5]

- Inverter control is provided with α_{min} limit (typically 95-110^0) to prevent it from switching to rectified mode in case of communication failure.

- Minimum current limit on the rectifier control characteristics is used to prevent interrupted current and hence high induced voltage and also avoid small overlaps resulting in larger current jumps and stress on the valves

b) In case of a fault on the DC side of an LCC based HVDC link:

i) How is the fault current limited?

[5]

Following a fault on the DC side of an LCC-based HVDC link:

- Rectifier current increase, inverter current decrease
- CC control restores the rectifier current back to normal
- Inverter switches from CEA to CC control to hold the decreasing current
- Rectifier tries to maintain I_{ord} and inverter $I_{ord} - I_m$ in opposite direction both being in CC mode
- Fault current is thus limited to only margin current I_m (10-15% of rated current)

ii) How is the fault detected and cleared?

[5]

- Faults on the DC side are detected by collapse of DC voltage and decrease in inverter current
- Rectifier is driven to inversion (α= 140°) keeping the inverter as it is (β < 80°)
- Current attempts to reverse, cannot because of valves and is rapidly (within 10.0 ms) reduced to zero
- Overhead lines are restarted automatically after a short time (recovery in 200 to 300 ms, more for weaker ac systems)
- Automatic restarts are not attempted for cables

d) An existing three-phase, double circuit AC transmission corridor is to be converted to three bipole DC circuits. Assuming identical conductor and insulator ratings, unity power factor and no skin effect, show that the

i) ratio of the total power transfer for the DC and AC option is 1.41

[6]

Ratio of total power transfer for AC and DC option is:

$$\frac{P_{AC}}{P_{DC}} = \frac{2 \times 3\ V_{LN} I_{AC} \cos\phi}{3 \times 2\ V_{DC} I_{DC}}$$

Identical conductor rating for AC and DC option implies:
$I_{AC} = I_{DC}$

Identical insulator rating for AC and DC option implies:
$\sqrt{2} V_{LN} = V_{DC}$

Hence assuming power factor $\cos\varphi = 1$,

$$\frac{P_{AC}}{P_{DC}} = \frac{2 \times 3\ V_{LN} I_{AC} \cos\phi}{3 \times 2\ V_{DC} I_{DC}} = \frac{2 \times 3 \times 1}{3 \times 2 \times \sqrt{2}} = 1.41$$

ii) ratio of the percentage power loss for the DC and AC option is 0.71.

[4]

Ratio of the percentage power loss for the DC and AC option is:

$$\frac{\%P_{Loss-AC}}{\%P_{Loss-DC}} = \frac{\frac{P_{Loss-AC}}{P_{AC}}}{\frac{P_{Loss-DC}}{P_{DC}}} = \frac{2 \times 3\ I_{AC}^2 R}{3 \times 2\ I_{DC}^2 R} \times \frac{P_{DC}}{P_{AC}} = 0.71$$

5. a) For a line commutated converter (LCC) based HVDC link why is it important to limit the direct current order if the AC side voltage drops below a certain threshold?

[5]

If the AC system voltage at one end drops below a certain threshold, the reactive power consumption by the converter at the other end increases which could have adverse effect on the AC system. A higher firing angle (α) or extinction angle (γ) at the remote converter causes the reactive power consumption to increase.

Reduced AC system voltage decreases the reactive power supplied by the filters and capacitors which often supplies most of the reactive power consumed by the converters.

Hence voltage dependent current order limit (VDCOL) is used to limit the direct current order o if the voltage drops below a certain threshold.

b) The six-pulse inverter terminal of monopole line commutated converter (LCC) based HVDC link is operating with a constant extinction angle $\gamma = 15°$. The rectifier terminal is set to control the DC link current at 2.0 kA. The three-phase AC system at both ends has a line voltage of 275 kV. The commutating resistance at either end is 5.0 Ω and the DC line resistance is 2.0 Ω. The margin current is 10% of the rated current.

i) Calculate the reactive power consumed by the converters at each end under the above condition.

[10]

Inverter end:

$$V_{doi} = \frac{3\sqrt{2}}{\pi} E_{LLi} = 371.38 \text{ kV}$$

$$V_{di} = V_{doi} \cos\gamma - R_c I_d = 348.73 \text{ kV}$$

$$P_{di} = V_{di} \times I_d = 697.45 \text{ MW}$$

$$\cos\phi_i = \frac{V_{di}}{V_{doi}} = 0.94$$

$$Q_i = P_{di} \tan\phi_i = 253.14 \text{ MVAr}$$

Rectifier end:

$$V_{dr} = V_{di} + R_L I_d = 352.73 \text{ kV}$$

$$V_{dor} = \frac{3\sqrt{2}}{\pi} E_{LLr} = 371.38 \text{ kV}$$

$$P_{dr} = V_{dr} \times I_d = 705.46 \text{ MW}$$

$$\cos\phi_r = \frac{V_{dr}}{V_{dor}} = 0.95$$
$$Q_r = P_{dr}\tan\phi_r = 232.42 \text{ MVAr}$$

ii) The inverter side AC system voltage drops by 20% as a result of which the extinction angle (γ) is increased to 20° to prevent commutation failure. Calculate the change in reactive power consumption at the rectifier under this condition. Neglect commutation failure, tap changer action, effect of voltage dependent current order limit (VDCOL) and any upper limit on firing angle (α).

[10]

$$V_{doi}{}' = 0.8 \times \frac{3\sqrt{2}}{\pi} E_{LLi} = 297.10 \text{ kV}$$

Assuming rectifier terminal is able to maintain the DC link current at 2.0 kA

$$V_{di}{}' = V_{doi}{}' \cos\gamma' - R_c I_d = 269.18 \text{ kV}$$

$$V_{dr}{}' = V_{di}{}' + R_L I_d = 273.18 \text{ kV}$$

$$\cos\alpha' = \frac{V_{dr}{}' + R_c I_d}{V_{dor}} = 0.76 \Rightarrow \alpha' = 40.3°$$

$$P_{dr}{}' = V_{dr}{}' \times I_d = 538.36 \text{ MW}$$

$$\cos\phi_r{}' = \frac{V_{dr}{}'}{V_{dor}} = 0.74$$

$$Q_r{}' = P_{dr}{}' \tan\phi_r{}' = 495.81 \text{ MVAr}$$

Reactive power consumption increases by:

$$\frac{Q_r{}' - Q_r}{Q_r} \times 100 = 113\%$$

6. a) State two main advantages and two challenges associated with the use of modular multi-level converters (MMC) for voltage source converter (VSC) based HVDC links.

[5]

Benefits

- Low switching frequency and hence less converter switching losses (<1% per station)
- Near-sinusoidal AC voltage and current: no filters, standard transformers
- Modular, flexible and easily scalable

Challenges

- Complex control of modules
- Charge balance across module capacitors is a problem

b) Explain why inner loop current control in d-q frame of reference is commonly used for voltage source converters.

[5]

Inner loop current control is used to explicitly monitor and limit the current references in order to protect the IGBTs from over current.

Synchronously rotating *d-q* frame of reference is used to translate the sinusoidal set point tracking problem into equivalent DC set point tracking. This could be achieved with a much low bandwidth controller which has a number of advantages.

c) Starting from the expressions for instantaneous active and reactive power, explain how proper choice of *d-q* reference frame (with *q*-axis leading the *d*-axis) could decouple the power (P^*, Q^*) and current (i_d^*, i_q^*) references.

[5]

$$P(t) = \frac{3}{2}\left[v_d(t)i_d(t) + v_q(t)i_q(t)\right]$$

$$Q(t) = \frac{3}{2}\left[-v_d(t)i_q(t) + v_q(t)i_d(t)\right]$$

If the AC system voltage V_s is locked with the *d*-axis,

$$v_d(t) = V_s,\ v_q(t) = 0$$

$$P(t) = \frac{3}{2}V_s i_d(t),\ Q(t) = -\frac{3}{2}V_s i_q(t)$$

The current references are:

$$i_d^* = \frac{2P^*}{3V_s}, \qquad i_q^* = -\frac{2Q^*}{3V_s}$$

Thus, the power and current references are decoupled

d) Mention three main challenges associated with the operation of a voltage source converter (VSC) based multi-terminal DC (MTDC) grid.

[5]

- Limiting fault current and clearing DC side faults
  - Open ALL AC breakers
  - DC breaker and/or fault blocking converter
- Detecting and locating DC side faults
- Large loss of in-feed
- Interaction with AC systems
  - Autonomous Power sharing
  - Frequency support
  - Stability

e) In a multi-terminal DC (MTDC) grid, what is the problem if only one converter station controls the DC side voltage while the other converter stations control the active power? Explain how the above problem can be resolved.

[5]

If only one converter station controls DC link voltage (slack), the rest controls active power:

- Any converter outage puts a large burden on slack
- Outage of the slack converter could bring the whole DC grid down

This could be resolved by allowing all the converters to control the DC link voltage with appropriate P-V_{dc} droop. The advantage is:

- Burden shared equitably following any converter outage
- There is no single point of failure
- However, choice of droop constant is the key