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EE4-53

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2012

EEE PART IV: MEng and ACGI

Corrected Copy

(see page 3 for correction/addition)

HIGH VOLTAGE TECHNOLOGY AND HVDC TRANSMISSION

Friday, 18 May 2:30 pm

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) Describe two mechanisms of failure of porcelain insulators and explain why one is desirable than the other.

[5]

b) Explain qualitatively (no equations to be derived) why voltage distribution across the discs of a suspension insulator string is usually non-uniform and how grading rings help improve the voltage distribution.

[5]

c) Describe the advantages and disadvantages associated with ceramic and non-ceramic overhead line insulators.

[5]

d) A string of overhead line insulator consisting of three units (disks) is used to support 33 kV peak voltage between the line and the ground. The self-capacitance of each unit is 10 times the capacitance of the pin to ground. Neglecting the effect of grading ring find the following:

i) voltage across the disk closest to the overhead line

[6]

ii) string efficiency.

[4]

2. a) State how corona is formed around high voltage overhead conductors and explain why corona is self-checking.

[5]

b) Derive an expression for corona inception voltage in terms of the radius of overhead line conductors, distance of separation between them and the correction factor for temperature and pressure.

[5]

c) In a non-uniform electric field explain why breakdown voltage is lower for positive polarity electrode when compared to negative polarity.

[5]

d) A 3-phase, 132 kV, 50 Hz, 150 km long overhead transmission line consists of three stranded aluminium conductors, each of diameter 19.53 mm with asymmetric spacing among them. The conductors are transposed at regular intervals. In one particular transposition cycle the separation between the A-B-C phase conductors are AB = 4 m, BC = 3.6 m and CA = 4m. Would there be any corona under normal atmospheric condition?

[10]

3. a) Explain the choice of classical and statistical approach to insulation coordination for non-self restoring and self restoring insulators.

[5]

b) Explain why the distance between the lightning arrester and the substation transformer in a substation is important from surge protection point of view.

[5]

c) Why is it important to have the tower footing resistance as low as possible?

[5]

d) Lightning strikes at the top of a transmission tower. The lightning current is 10 kA. The surge impedance of the ground wire and tower are 500 ohms and 125 ohms, respectively while the tower footing resistance is 10 ohms. Speed of propagation of the travelling wave through the tower is 3×10^8 m/s.

i) Calculate the incident overvoltage on the tower with and without the ground wire

[6]

ii) Calculate the resultant voltage across the insulator strings after 0.2 μs from the lightning strike.

[4]

Correction/Addition [(Time 15:25)]

Q3d) Tower height = 45 m

4. a) Explain why HVDC transmission is justifiable only beyond a certain transmission distance which depends on whether it is overhead or underground/subsea transmission.

[5]

b) Draw the equivalent circuit of a point to point CSC-HVDC link and explain the significance of each element in the equivalent circuit.

[5]

c) Discuss two major problems, which are typical only at the inverter end of a CSC-HVDC link.

[5]

d) Compare and contrast the current source converter (CSC) and voltage source converter (VSC) technologies from the point of view of i) sub-sea cabling, ii) offshore footprint iii) power reversal and iv) dependence on AC system strength.

[10]

5. a) Explain how fault current is limited following a fault on the DC side of a CSC-HVDC link.

[5]

b) Discuss different hierarchical levels of control that are commonly employed for a CSC-HVDC link.

[5]

c) Explain the sequence of events following an AC system fault on the rectifier-side of a CSC-HVDC link.

[5]

d) A 500 kV, 1000 MW monopole CSC-HVDC line interconnects two isolated 400 kV (line-to-line) AC networks. The DC line resistance (R_L) is 20 ohms and the commutating resistance (R_C) at both ends is 10 ohms. Assuming rated voltage on the rectifier side AC system and the dc link and also lossless 6-pulse converters, what is the maximum allowable extinction advance angle to ensure that the reactive power consumption at the inverter end is limited to 40% of the real power at that end?

[10]

6. a) Why is voltage source converter technology the only realistic option for future multi-terminal DC (MTDC) grids?

[5]

b) Explain the technical and economic considerations behind the use of multi-terminal HVDC systems for bulk power import from remote offshore wind farms.

[5]

c) Discuss why faults on DC cables in a multi-terminal DC grid could be detrimental for system operation.

[5]

d) State four major limitations of the current source converter (CSC) HVDC technology.

[5]

e) Compare the current source converter (CSC) and voltage source converter (VSC) based HVDC schemes from overall (converter and system) power loss considerations.

[5]

Master EE4-53

Solutions - 2012

Answer any 4 questions out of 6

1. a) Describe two mechanisms of failure of porcelain insulators and explain why one is desirable than the other.

[5]

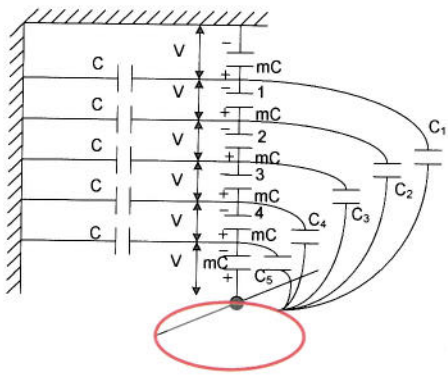
Flashover
- breakdown of adjacent air bridging the high voltage conductor and ground
- either due to line surges or formation of conducting layer over the insulator surface
- is a temporary failure and insulator is back in action once it is over

Puncture
- arc passes through the body of the insulator
- causes permanent damage

To avoid permanent damage and frequent replacements porcelain insulators are designed such that flashover voltage is considerably lower than puncture voltage

b) Explain qualitatively (no equations to be derived) why voltage distribution across the discs of a suspension insulator string is usually non-uniform and how grading rings help improve the voltage distribution.

[5]



Voltage distribution is non-uniform, as charge stored in the pin-to-ground capacitance has to be supplied through the self-capacitance of each disk. Grading ring provides an alternate path for the charge passing through ground capacitances. Thus theoretically, it is possible to design a grading ring to yield uniform voltage distribution.

c) Describe the advantages and disadvantages associated with ceramic and non-ceramic overhead line insulators.

[5]

Ceramic:

- Advantages
  Strength, proven and reliable
- Disadvantages
  Weight
  Vulnerable to shock loads, vandalism

Non-ceramic:

- Advantages:
  weight reduction
  shock resistant
  surface properties
- Disadvantages
  tracking and erosion (much improved now

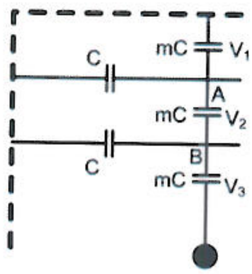
d) A string of overhead line insulator consisting of three units (disks) is used to support 33 kV peak voltage between the line and the ground. The self-capacitance of each unit is 10 times the capacitance of the pin to ground. Neglecting the effect of grading ring find the following:

i) voltage across the disk closest to the overhead line

[6]

ii) string efficiency.

[4]



i) $m = 10$

Applying charge balance at the junction A
$mCV_1 + CV_1 = mCV_2 \Rightarrow 11V_1 = 10V_2$

Similarly at the junction B

$mCV_2+C(V_1+V_2) = mCV_3 \Rightarrow 11V_2+V_1 = 10V_3$

$V_1+V_2+V_3 = 33$

Solving the three equations:

$V_3 = 12.68$ kV

ii) string efficiency = $[33/(12.68 \times 3)] \times 100\ \% = 86.75\%$

2. a) State how corona is formed around high voltage overhead conductors and explain why corona is self-checking.

[5]

- If the electric field at the conductor surface exceeds the nominal breakdown strength of air i.e. 30 kV/cm, the air in the immediate vicinity of conductors ionizes and become conducting. This results in:
  - a faint violet glow around the conductor visible in dark
  - a persistent hissing sound
  - production of ozone (typical smell) and oxide of nitrogen
- Corona is self checking process as the effective diameter of the conductor increases due to the corona causing lower voltage stress on the surface which tends to check the progress of corona

b) Derive an expression for corona inception voltage in terms of the radius of overhead line conductors, distance of separation between them and the correction factor for temperature and pressure.

[5]

Corona inception voltage (V_d) is the conductor voltage at which partial breakdown of air starts just on the conductor surface.

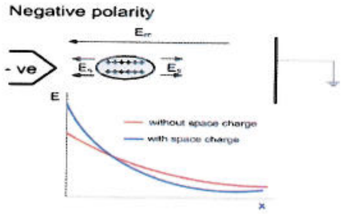
$$E_{\max} = \frac{V}{r \ln \frac{d}{r}} \; kV/cm, \quad r \ll d$$

$$\frac{V_d}{r \ln \frac{d}{r}} = \frac{30}{\sqrt{2}} \times \delta = 21.1 \times \delta$$

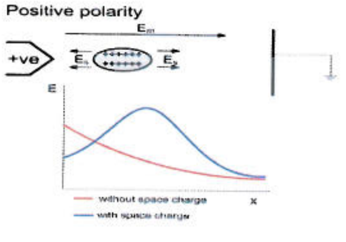
$$V_d = 21.1 \times \delta \times r \ln \frac{d}{r} \; kV$$

c) In a non-uniform electric field explain why breakdown voltage is lower for positive polarity electrode when compared to negative polarity?

[5]



Negative polarity
- Corona is facilitated
- Self checking feature ensures further spread of ionization
-



Positive polarity
- With spread of space charge the resultant peak moves further into the gap extending the region of ionization and eventual breakdown

d) A 3-phase, 132 kV, 50 Hz, 150 km long overhead transmission line consists of three stranded aluminium conductors, each of diameter 19.53 mm with asymmetric spacing among them. The conductors are transposed at regular intervals. In one particular transposition cycle the separation between the A-B-C phase conductors are AB = 4 m, BC = 3.6 m and CA = 4m. Would there be any corona under normal atmospheric condition?

[10]

$E_{max} = V_{LN} / (r \times \ln(D_m/r)$, $D_m = (d_{AB} \times d_{BC} \times d_{CA})^{0.33}$

GMD is $D_m = (4 \times 3.6 \text{ x}4)^{0.33} = 3.86$ m = 386 cm

r = d/2 = 9.77 mm = 0.977 cm

Phase to neutral voltage = $132/\sqrt{3} = 76.2$ kV (rms)
Maximum phase to neutral voltage = $76.2 \times \sqrt{2} = 107.76$ kV

$E_{max} = 107.76/(0.977 \times \ln(386/0.977)) = 18.5$ kV/cm

As $E_{max} = 18.5$ kV/cm < 30 kV/cm, there would not be any corona

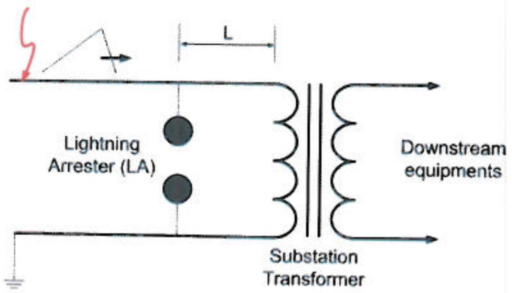
3. a) Explain the choice of classical and statistical approach to insulation coordination for non-self restoring and self restoring insulators.

[5]

- Self-restoring (SR): regains dielectric property following breakdown e.g. air
- Non-self-restoring (NSR): loses insulating property after a disruptive discharge and needs replacement e.g. porcelain
- For NSR, a classical approach is adopted to virtually eliminate the possibility of system failure
- For SR, a calculated risk of insulation failure is taken through a statistical approach, if economically justified

b) Explain why the distance between the lightning arrester and the substation transformer in a substation is important from surge protection point of view.

[5]



- transformer offers very high surge impedance
- voltage at the transformer end doubles the residual voltage of LA
- reflected voltage from LA results in less voltage rise
- distance between LA and transformer is critical in substations

c) Why is it important to have the tower footing resistance as low as possible?

[5]

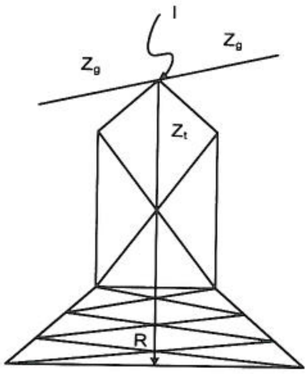
Following lightning strike on the ground wire or the transmission tower itself, reflected voltage wave from the tower footing reduces the incident overvoltage appearing across the insulator string. The sign of the reflected voltage is negative and its magnitude depends on the difference between the tower footing resistance and the surge impedance of the tower. Lower the tower footing resistance, more negative is the reflected component, which is better in terms of reducing the resultant voltage appearing across the insulators.

d) Lightning strikes at the top of a transmission tower. The lightning current is 10 kA. The surge impedance of the ground wire and tower are 500 ohms and 125 ohms, respectively while the tower footing resistance is 10 ohms. Speed of propagation of the travelling wave through the tower is 3×10^8 m/s.

i) Calculate the incident overvoltage on the tower with and without the ground wire [6]

ii) Calculate the resultant voltage across the insulator strings after 0.2 μs from the lightning strike. [4]

i)



$$I = 10\ kA, \quad Z_g = 500\ \Omega, \quad Z_t = 125\ \Omega,$$
$$Z_{eq} = Z_g \parallel Z_t \parallel Z_g = 83.33\ \Omega$$
$$V_i = IZ_{eq} = 833.33\ kV$$

Without ground wire the incident voltage would have been 1200 kV instead of 833.33 kV

ii)

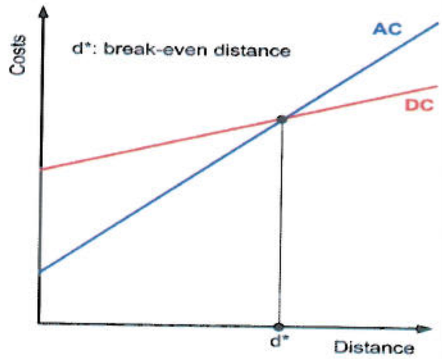
Reflected voltage from tower base (tower footing resistance R = 10 Ω reduces the resultant voltage applied across the insulators as follows:

$$R = 10\ \Omega$$
$$V_r = \frac{R - Z_t}{R + Z_t} V_i = -710\ kV$$
$$V_{ins} = V_i + V_r = 123.33\ kV$$

4. a) Explain why HVDC transmission is justifiable only beyond a certain transmission distance which depends on whether it is overhead or underground/subsea transmission.

[5]

- DC carries same power with 2 conductors as AC does with 3. Thus less RoW, lower conductor and insulator costs and simpler towers are required for DC.
- Losses in DC lines 2/3rd that of AC; no skin effect
- Cost of the converter and converter losses high for HVDC

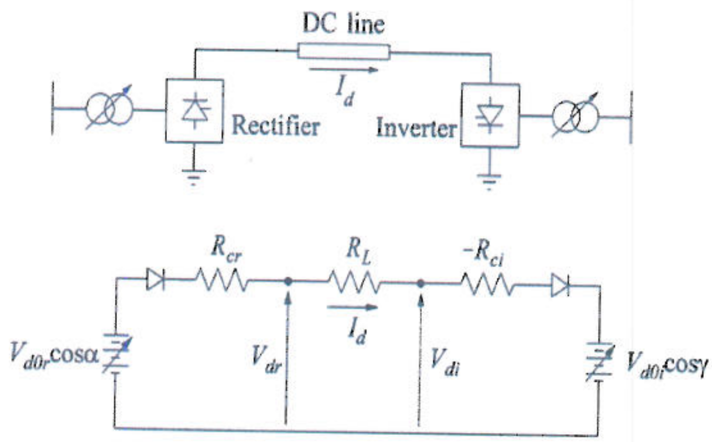


Thus there is breakeven distance beyond which the cost of converter (and losses) is offset by the savings in conductor (and losses) and associated costs.

Cables draw much higher charging current than overhead lines. For HVDC problem of charging current being negligible DC cables make economic sense for relatively shorter (30-50 kms) distances compared to overhead lines.

b) Draw the equivalent circuit of a point to point CSC-HVDC link and explain the significance of each element in the equivalent circuit.

[5]



Controllable voltage sources at either end depend on the AC system voltage and the firing angles. The diodes signify possible flow of current in only one direction due to presence of the thyristor valves. The commutation resistances represent the drop (reduction) in terminal voltage due to commutation overlap.

c) Discuss two major problems, which are typical only at the inverter end of a CSC-HVDC link.

[5]

1. Spurious turn on: Voltage across the thyristor valves is mostly positive (i.e. forward biased) at the inverter end. Hence, those are vulnerable to spurious turn on if there is faulty firing command. The situation is different with rectifiers where the voltage across the valves are mostly negative (i.e. reverse biased)

2. Commutation failure: More of a problem at the inverter side as firing much after the positive zero crossing of the commutation voltage, in fact, very close to the negative zero crossing. So much less time is available for the outgoing valve to cease conduction and pass on the conduction to the incoming one.

d) Compare and contrast the current source converter (CSC) and voltage source converter (VSC) technologies from the point of view of i) sub-sea cabling, ii) offshore footprint iii) power reversal and iv) dependence on AC system strength.

[10]

i) Sub-sea cabling

Unlike CSC, the VSC cables need not withstand voltage polarity reversals. Hence, lighter and stronger cables can be used for VSC technology.

ii) Offshore Footprint

Footprint for VSC technology is much less that CSC due to less terminal components including filters and capacitor banks

iii) Power reversal

In CSC systems, power reversal is achieved through reversal of terminal voltages while for VSC systems its done through reversing the current direction.

iv) Dependence on AC system strength

Operation of CSC technology relies on the AC system strength (SCR > 2) while VSC systems can work with weak AC systems.

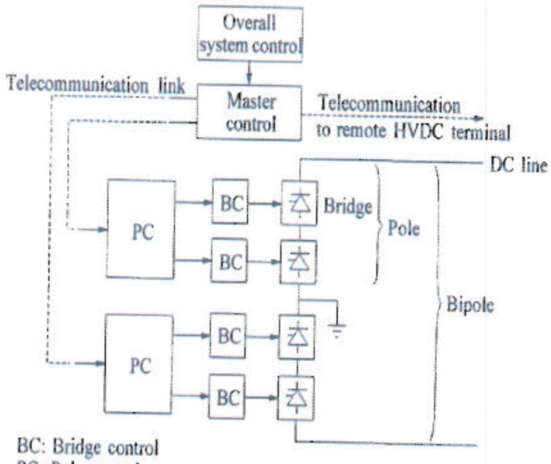
5. a) Explain how fault current is limited following a fault on the DC side of a CSC-HVDC link.

[5]

- Rectifier current increase, inverter current decrease
- CC control restores the rectifier current back to normal
- Inverter switches from CEA to CC 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)

b) Discuss different hierarchical levels of control that are commonly employed for a CSC-HVDC link.

[5]



BC: Bridge control
PC: Pole control

- Bridge control determines the firing instants of the valves within limits for a bridge and takes care of protection (e.g. commutation failure protection)
- Pole control coordinates control of bridges in a pole and provides firing angle orders to individual converters
- Master control determines the current order and suitable current margins to the poles
- Overall system control decides the dc link power flow based on scheduled transactions or ac system stabilization

c) Explain the sequence of events following an AC system fault on the rectifier-side of a CSC-HVDC link.

[5]

- DC voltage at rectifier end and hence current reduces
- Current regulator decreases a to restore current until it hits the limit before switching to CIA mode
- Inverter switches to CC mode

- For large reduction in voltage VDCOL come into play and might even have to shut the DC system down
- Increased consumption of reactive power (high b) at low inverter end voltages is more detrimental to AC system than briefly shutting the DC system down

d) A 500 kV, 1000 MW monopole CSC-HVDC line interconnects two isolated 400 kV (line-to-line) AC networks. The DC line resistance (R_L) is 20 ohms and the commutating resistance (R_C) at both ends is 10 ohms. Assuming rated voltage on the rectifier side AC system and the dc link and also lossless 6-pulse converters, what is the maximum allowable extinction advance angle to ensure that the reactive power consumption at the inverter end is limited to 40% of the real power at that end?

[10]

$I_d = 1000/500 = 2$ kA

Rectifier side

$V_{dr} = 500$ kV

Inverter side

$V_{di} = V_{dr} - R_d I_d = 500 - 20\times2 = 460$ kV

$P_i = V_{di} \times I_d = 920$ MW

$Q_i / P_i = \tan \phi_I = 0.4 \Rightarrow \cos\phi_I = V_{di}/V_{doi} = 0.9285$

$V_{doi} = 495.45$ kV

$\cos \gamma = (V_{di}+R_c I_d)/ V_{doi} = 0.9688 \Rightarrow \gamma = 14.34$ degrees

6. a) Why is voltage source converter technology the only realistic option for future multi-terminal DC (MTDC) grids?

[5]

In MTDC systems reversal of power flow in one branch should not affect the direction of power flow in the rest. VSC allows fast and easy power reversal without changing the voltage polarity unlike the CSC where voltage polarity has to be reversed which would affect the rest of the MTDC system as well.

b) Explain the technical and economic considerations behind the use of multi-terminal HVDC systems for bulk power import from remote offshore wind farms.

[5]

Technical issues:

- Power flow control following outage of one or more converters

- Fault-management in absence of DC circuit breakers

Economic issues:

- Provides some redundancy; but there is question mark over whether the cost-benefit analysis support investment

- It is not certain that interconnecting windfarms through DC links will be economic as:

  - Cables and cable laying are very expensive so shortest routes to shore are favoured
  - The redundancy offered by multi-terminal systems may not bring significant savings in "spilled" energy in the event of an outage

c) Discuss why faults on DC cables in a multi-terminal DC grid could be detrimental for system operation.

[5]

In absence of DC circuit breakers, any fault on DC cables has to be cleared by opening all the circuit breakers at the points of connection with the AC side. Thus the entire MTDC grid would have to be out of operation until the fault is cleared which could be highly disruptive in terms of huge loss-of-infeed.

d) State four major limitations of the current source converter (CSC) HVDC technology.

[5]

- Large reactive power consumption (both rectifier and inverter)
- Large filtering requirements due to low order harmonics
- Dependence on strong AC systems
- Commutation failure

e) Compare the current source converter (CSC) and voltage source converter (VSC) based HVDC schemes from overall (converter and system) power loss considerations.

[5]

The converter switching losses are usually lower for CSC than VSC due to lower switching frequencies used for the former. However, with state-of-the-art technology the gap is narrowing. At the systems level, VSC can ensure better voltage profile than CSC (suffers due to large reactive power consumption at both ends) and hence the transmission losses in the AC network are less with VSC HVDC links as compared to CSC.