IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2009

EEE PART IV: MEng and ACGI

Corrected Copy

HIGH VOLTAGE TECHNOLOGY AND HVDC TRANSMISSION

Wednesday, 29 April 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) Justify the shape of a pin insulator profile from leakage current and mechanical strength considerations.

[6]

b) A suspension insulator string comprising of 3 units has to be equipped with a grading ring such that the string efficiency is 100%. Find the line to pin capacitances required to achieve this in terms of the pin to earth capacitance C.

[8]

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

i) voltage distribution across each unit

[8]

ii) string efficiency

[3]

2. a) State the advantages and disadvantages of using bundle conductors for high voltage transmission lines.

[6]

b) Explain the advantage of condenser bushings over normal porcelain bushings.

[4]

c) Explain why the formation of voids within the dielectric can be detrimental for HV cables.

[4]

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 = 4 m. Calculate the maximum electric field at the conductor surface and comment on the possibility of corona under normal atmospheric condition.

[11]

3. a) Comment on the distance between the lightning arrester and the substation transformer from the point of view of surge protection.

[6]

b) Explain the voltage build up phenomenon during switching off a lightly loaded transmission line.

[6]

c) A 500 kV long-tailed surge strikes an overhead line with a surge impedance $Z_o = 400\ \Omega$. The overhead line terminates at a 1 km long cable (see Fig. Q3) having total inductance 265 μH and capacitance 0.165 μF. A transformer with a surge impedance $Z_T = 1000\ \Omega$ is connected at the other end of the cable (see Fig. Q3). Find the surge voltage distribution along the cable 12 μs after the surge arrives at the line cable junction.

[13]

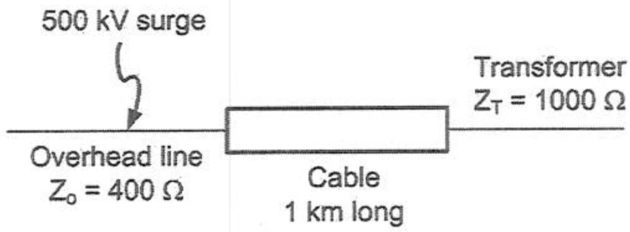


Figure Q3

4. a) Explain the problem of mode stabilisation in HVDC control and describe the way to overcome this.

[7]

b) Explain why a minimum current limit and a minimum firing angle limit is incorporated into the control characteristics of the rectifier and inverter, respectively?

[7]

c) The rectifier (6 pulse) station of a HVDC link is fed from a 33 kV/110 kV transformer. The firing angle (α) is 20 degrees and the commutation overlap (μ) is 18 degrees. If the ac side (primary) voltage is 36.5 kV and the direct current delivered by the rectifier is 2 kA, find the dc output voltage and the reactive power on the primary side assuming the converter to be lossless.

[11]

5. a) Describe the sequence of events at both the rectifier and inverter ends following a fault on the rectifier side AC system.

[6]

b) How is a fault on the DC link detected and cleared?

[5]

c) A 250 kV, 500 MW mono-polar DC link has the following parameters. Line resistance $R_d = 10\ \Omega$, commutating resistance, $R_c = 6\ \Omega$ at either end. The rectifier is initially operating under constant current (CC) control with $\alpha = 18$ degrees whereas the inverter is set at a constant extinction angle (CEA) control with $\gamma = 15$ degrees. The minimum limit for the rectifier firing angle (α) is 5 degrees and the current margin is set at 15%. Calculate the real and reactive power at either ends for a 20% drop in the AC system voltage at the rectifier end.

[14]

6. a) Explain which harmonics are likely to be present in the AC side for a bipolar HVDC system with two six pulse bridges connected to YY and YΔ transformers.

[5]

b) Explain the differences between the voltage source converter (VSC) and current source converter (CSC) technologies used in HVDC transmission.

[8]

c) The inverter end of a HVDC link is operating at 200 kV and 2 kA. The ignition advance angle (β) is 40 degrees and the commutation overlap (μ) is 25 degrees. The equivalent commutation resistance (R_c) is 11.4 Ω. If the minimum permissible value of extinction advance angle (γ_{min}) is 3 degrees, calculate the maximum percentage drop in inverter side ac system voltage that is permissible without causing commutation failure. Neglect any mode shift.

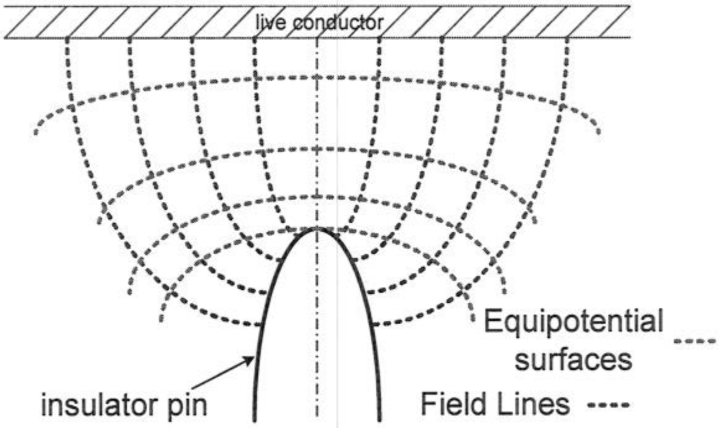
[12]

Final - April 09

Model Answers 2009

1. a) Justify the shape of a pin insulator profile from leakage current and mechanical strength considerations.

[6]

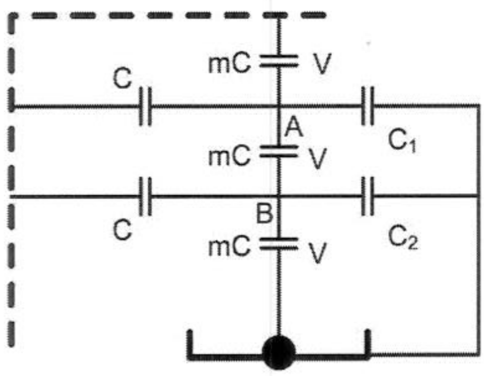


- rain-sheds are along the equipotential surfaces to minimize leakage currents
- main body or stem of the insulator is made along the field lines for mechanical strength

1. b) A suspension insulator string comprising of 3 units has to be equipped with a grading ring such that the string efficiency is 100%. Find the line to pin capacitances required to achieve this in terms of the pin to earth capacitance C.

[8]

100% string efficiency implies equal voltage distribution (say V) across each unit



C = pin to earth capacitance
C_s = self capacitance = mC

Applying charge balance at the junction A,
$mCV + CV = mCV + (3V\text{-}V)C_1 \Rightarrow C_1 = C/2$

Similarly at the junction B
$mCV+2CV = mCV + (2V\text{-}V)C2 \Rightarrow C_2= 2C$

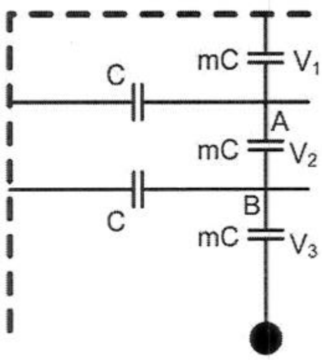
1. c) A string of suspension insulator consisting of three units (disks) is used to support 33 kV peak voltage between the line and the earth. The self-capacitance of each unit is 10 times the capacitance of their pin to earth. Neglecting the effect of grading ring find the following:

i) voltage distribution across each unit

[8]

ii) string efficiency

[3]



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:

$V_1 = 9.68$ kV, $V_2 = 10.65$ kV, $V_3 = 12.68$ kV

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

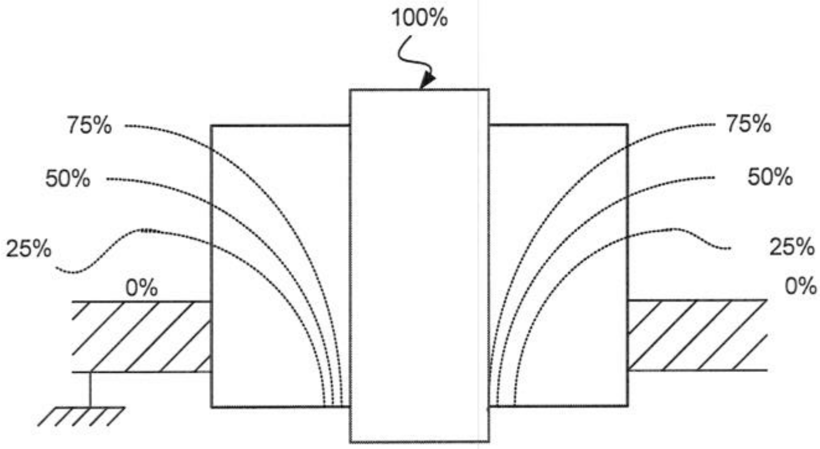
2. a) State the advantages and disadvantages associated of using bundle conductors for high voltage transmission lines.

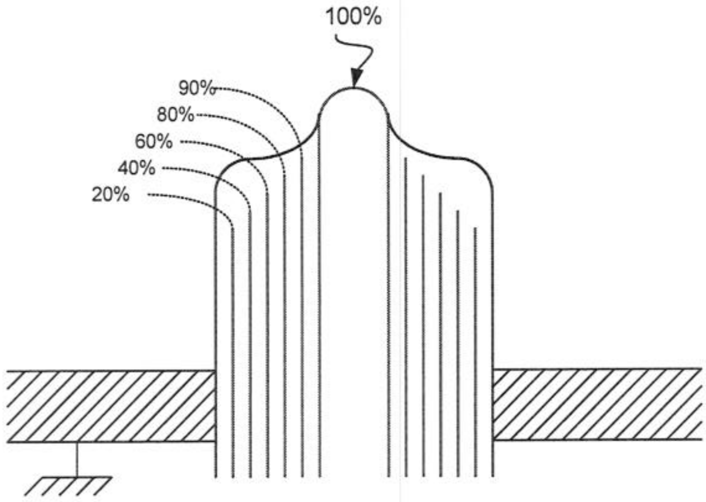
[6]

- 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

2. b) Explain the advantage of condenser bushings over normal porcelain bushings.

[4]





For normal bushings axial stress near the earth tank and radial stress over the conductor surface are high requiring large axial length and diameter. In condenser bushings a layer of aluminum or tin foils are introduced inside the dielectric to reduce the axial stress near the earth plate of the bushing. Hence, axial length can be reduced by using condenser bushing

2. c) Explain why the formation of voids within the dielectric can be detrimental for HV cables.

[4]

Repeated heating and cooling due to load cycles causes void formations in cables. Voids (ε_r=1) have much higher stress than the surrounding dielectrics (ε_r>1) whereas its strength is much less, so the partial breakdown initiates in the voids. As a discharge takes places at a certain voltage V_1, the voltage across the void collapse and the ionization in the void vanishes. As the supply voltage raises further the voltage across the void increases producing a series of discharges in every cycle. This causes erosion and carbonization which gradually extends both ways slowly leading to permanent damage of the cable.

2. 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. Calculate the maximum electric field at the conductor surface and comment on the possibility of corona under normal atmospheric condition.

[11]

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

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

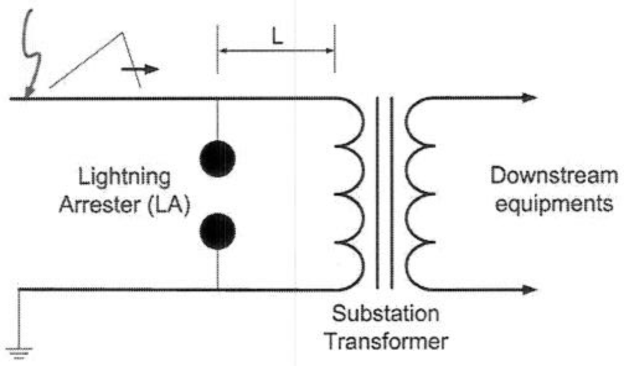
Phase to neutral voltage = $132/\sqrt{3} = 76.2$ kV (rms)
Maximum phase to neutral voltage = $76.2 \times \sqrt{2} = 107.76$ kV

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

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

3. a) Comment on the distance between the lightning arrester and the substation transformer from the point of view of surge protection.

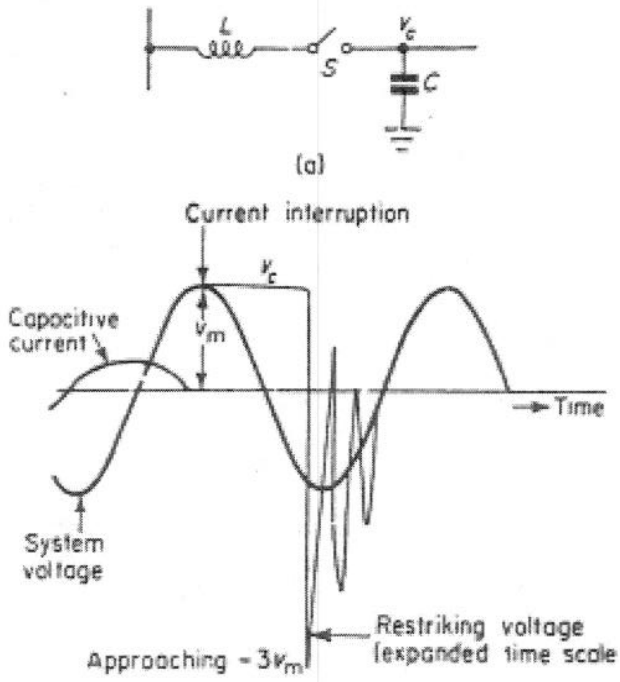
[6]



- 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

3. b) Explain the voltage build up phenomenon during switching off a lightly loaded transmission line.

[6]



- At the instant of current zero C is left charged at v_m
- Half a cycle later system voltage is $-v_m$, imposing $2v_m$ across the gap
- Gap breaks and at the instant of next transient current zero, when voltage across C is maximum at $3V_m$ and leaves it charged at $3V_m$ leading to successive voltage build up

3. c) A 500 kV long-tailed surge strikes an overhead line with a surge impedance $Z_o = 400\ \Omega$. The overhead line terminates at a 1 km long cable (see Fig. Q3) having total inductance 265 μH and capacitance 0.165 μF. A transformer with a surge impedance $Z_T = 1000\ \Omega$ is connected at the other end of the cable (see Fig. Q3). Find the surge voltage distribution along the cable 12 μs after the surge arrives at the line cable junction.

[13]

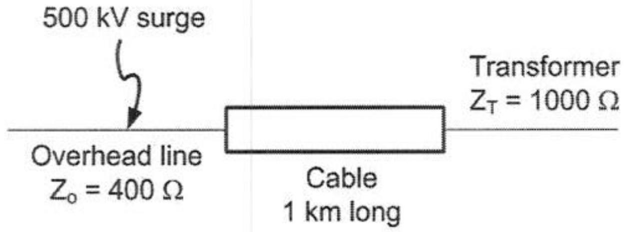


Figure Q3

Surge impedance of the cable $Z_C = \sqrt{(L/C)} = 40\ \Omega$

Velocity of surge in the cable is $1/\sqrt{(LC)} = 0.151$ km/μs

Distance travelled by the surge in 12 μs is $12 \times 0.151 = 1.812$ km

The wave reaches the cable transformer junction and the reflected wave travels 0.812 km towards the cable overhead line junction

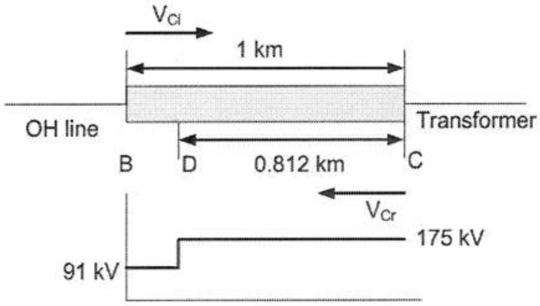
The incident voltage on the cable is same as the transmitted voltage through the line-cable junction

$V_{Ci} = [2Z_C/(Z_o+Z_C)] \times V_i = 91$ kV

The reflected voltage from the transformer end of the cable is $V_{Cr} = [(Z_T - Z_C) / (Z_T - Z_C)] \times V_{Ci} = 84$ kV

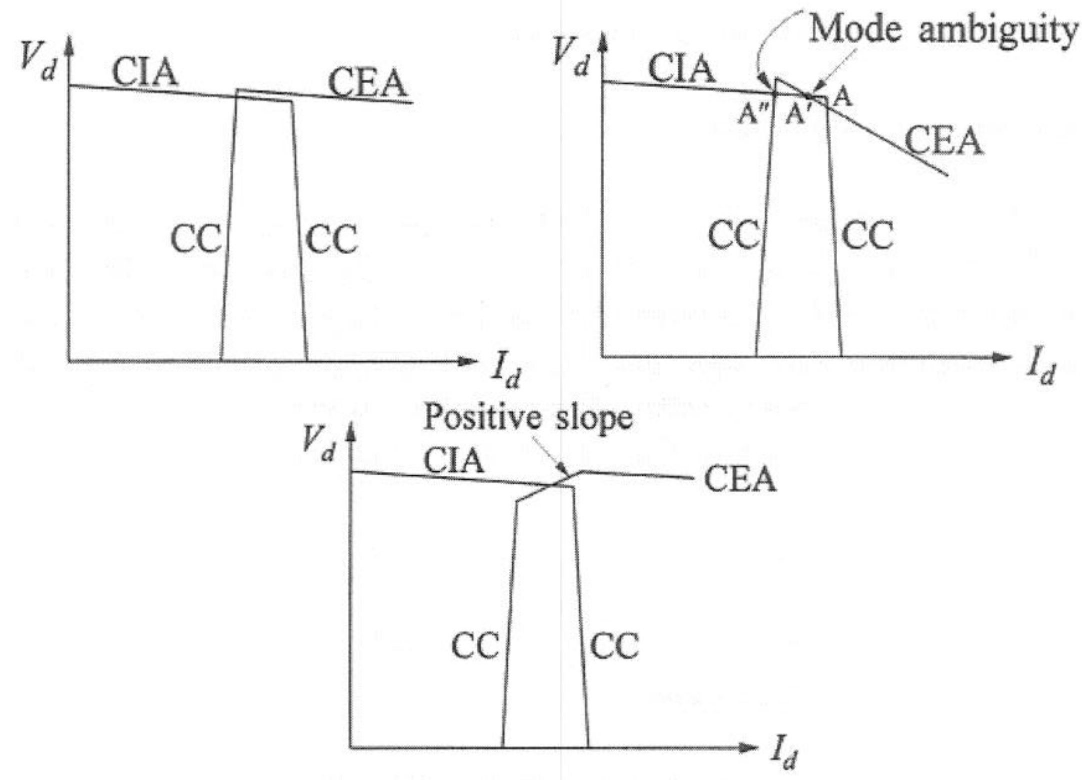
After 12 μs, voltage in the region CD of the cable = $V_{Ci} + V_{Cr} = 175$ kV

Voltage in the region DB is 91 kV



4. a) Explain the problem of mode stabilisation in HVDC control and describe the way to overcome this.

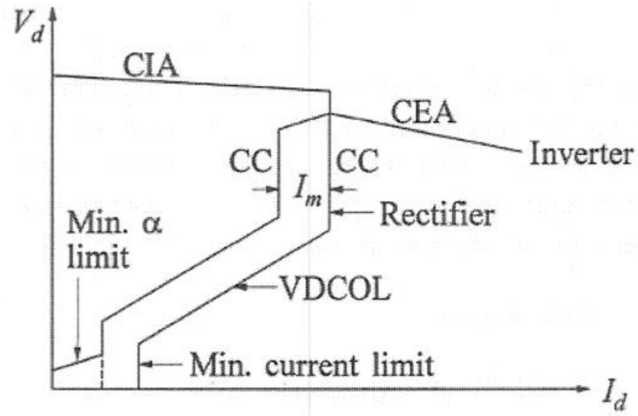
[7]



- Intersections of rectifier CIA and inverter CEA might not be well-defined for certain voltages
- Near the regions of intersection of CEA and CIA, there is a tendency of oscillation between operating points A, A' and A''
- This is avoided by introducing a positive slope (constant b) at the junction of CC and CEA of inverters

4. b) Explain why a minimum current limit and a minimum firing angle limit is incorporated into the control characteristics of the rectifier and inverter, respectively?

[7]



- Inverter control is provided with minimum firing angle limit (typically 95-110^0) to prevent it from switching to rectified mode in case of communication failure
- Minimum current limit is used in rectifier to avoid interrupted current leading to higher induced voltage spikes and also to avoid small overlaps leading to larger stress on the valves

4. c) The rectifier (6 pulse) station of a HVDC link is fed from a 33 kV/110 kV transformer. The firing angle (α) is 20 degrees and the commutation overlap (μ) is 18 degrees. If the ac side (primary) voltage is 36.5 kV and the direct current delivered by the rectifier is 2 kA, find the dc output voltage and the reactive power on the primary side assuming the converter to be lossless.

[11]

No load DC voltage $V_{do} = (3\sqrt{2}/\pi)\times T\times E_{LL} = (3\sqrt{2}/\pi)\times(33/110)\times 36.5$ kV = 164.3 kV

Extinction angle $\delta = \alpha + \mu = 38$ degrees

DC voltage $V_d = V_{do}\,(\cos\alpha + \cos\delta)/2 = 141.9$ kV

Neglecting losses $P_{ac} = P_{dc} = V_d\, I_d = 141.9 \times 2 = 283.8$ kV

Power factor at the high voltage side $\cos\phi \approx V_d / V_{do} = 0.86$

Reactive power on the primary side $Q_{ac} = P_{ac} \tan\phi = 168.4$ MVAr

5. a) Describe the sequence of events at both the rectifier and inverter ends following a fault on the rectifier side AC system.

[6]

- 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 rectifier end voltages is more detrimental to AC system than briefly shutting the DC system down

5. b) How is a fault on the DC link detected and cleared?

[5]

- Faults detected by collapse of DC voltage and decrease in inverter current
- Rectifier is driven to inversion ($\alpha = 140^0$) keeping the inverter as it is ($\beta < 80^0$)
- Current attempts to reverse, cannot because of valves and is rapidly (10 ms) reduced to zero

5. c) A 110 kV, 220 MW mono-polar DC link has the following parameters. Line resistance R_d = 10 Ω, commutating resistance, R_c = 5 Ω at either end. The rectifier is initially operating under constant current (CC) control with α = 18 degrees whereas the inverter is set a constant extinction angle (CEA) control with γ = 15 degrees. The minimum limit for the rectifier firing angle (α) is 5 degrees and the current margin is set at 10%. Calculate the power factor at the inverter end for a 15% drop in the AC system voltage at the rectifier end.

[14]

$V_d = 110$ kV, $I_d = P/ V_d = 2$ kA

$I_m = 0.1 \times 2 = 0.2$ kA, $I_d' = I_d - I_m = 1.8$ kA

$V_{dor} = (V_{dr} + R_c I_d) / \cos\alpha = 126.18$ kV

$V_{dor}' = 0.85\times V_{dor} = 107.25$ kV

With CC control α would reduce to maintain I_d constant

$\cos\alpha' = (V_{dr} + R_c I_d) / V_{dor}' = 1.12 > 1$

Hence rectifier would switch to α_{min} operation and inverter to constant current (I_d') control

$V_{dr}' = V_{dor}' \cos\alpha_{min} - R_c I_d' = 97.84$ kV

Voltage at the inverter before drop in rectifier side ac system voltage

$V_{di} = V_{dr} - I_d R_d = 90$ kV

$V_{doi} = (V_{di} + R_c I_d) / \cos\gamma = 103.53$ kV

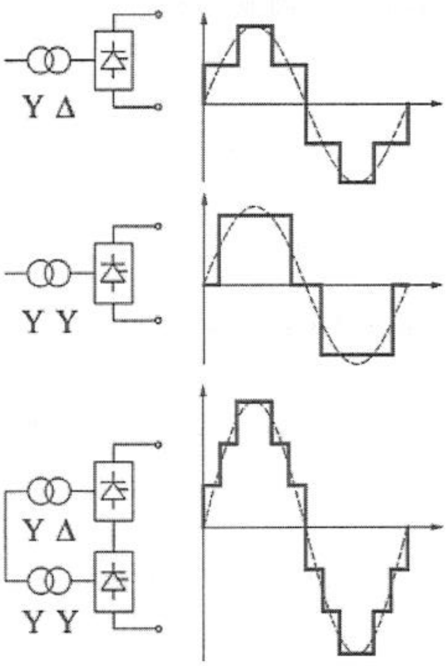
Voltage at the inverter after drop in rectifier side ac system voltage

$V_{di}' = V_{dr}' - R_d I_d' = 79.84$ kV

Power factor at the inverter side $\cos\phi_I = V_{di}' / V_{doi} = 0.77$

6. a) Explain which harmonics are likely to be present in the AC side for a bipolar HVDC system with two six pulse bridges connected to YY and YΔ transformers.

[5]



$$i = \frac{2\sqrt{3}}{\pi} I_d \left(\sin\omega t - \frac{1}{5}\sin 5\omega t - \frac{1}{7}\sin 7\omega t + \frac{1}{11}\sin 11\omega t + \frac{1}{13}\sin 13\omega t - \cdots\right)$$

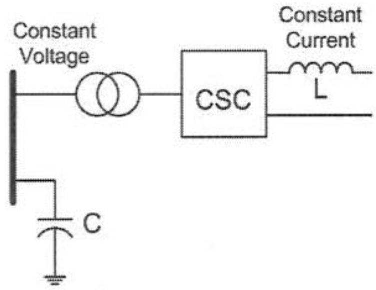
$$i = \frac{2\sqrt{3}}{\pi} I_d \left(\sin\omega t + \frac{1}{5}\sin 5\omega t + \frac{1}{7}\sin 7\omega t + \frac{1}{11}\sin 11\omega t + \frac{1}{13}\sin 13\omega t + \cdots\right)$$

$$i = \frac{2\sqrt{3}}{\pi} 2I_d \left(\sin\omega t + \frac{1}{11}\sin 11\omega t + \frac{1}{13}\sin 13\omega t + \frac{1}{23}\sin 23\omega t + \frac{1}{25}\sin 25\omega t + \cdots\right)$$

The ac side harmonics are of order $h = 12n \pm 1$; $n = 0,1,..,$

6. b) Explain the differences between the voltage source converter (VSC) and current source converter (CSC) technologies used in HVDC transmission.

[8]



AC side

- constant voltage
- capacitor holds the voltage
- reactive power supply required

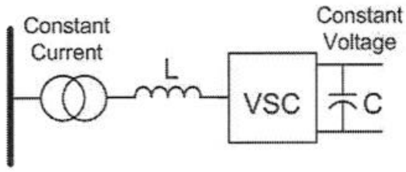
DC side

- constant current
- inductor for constant current
- direct current is unidirectional
- inherent fault current limiting

Switches

- line commutated (thyristor)

power reversal through reversal of dc voltage



AC side

- constant current
- inductor to maintain constant current
- reactive power supply not required

DC side

- acts as constant voltage source
- capacitors holds the voltage
- direct current can reverse
- dc capacitor feeds the fault

Switches

- self-commutated (IGBT, GTO)

power reversal though reversal of dc current

6. c) The inverter end of a HVDC link is operating at 200 kV and 2 kA. The ignition advance angle (β) is 40 degrees and the commutation overlap (μ) is 25 degrees. The equivalent commutation resistance (R_c) is 11.4 ohms. If the minimum permissible value of exctinction advance angle (γ_{min}) is 3 degrees, calculate the maximum percentage drop in inverter side ac system voltage that is permissible without causing commutation failure. Neglect any mode shift.

[12]

$V_d = 200$ kV, $I_d = 2$ kA, $\beta=40^0$, $\mu=25^0$, $R_c = 11.4\ \Omega$, $\gamma_{min} = 3^0$

$\gamma = \beta - \mu = 15$ degrees

$V_{doi} = (V_d + R_c I_d)/\cos\gamma = 230.66$ kV

Without any mode shift V_d and I_d would remain the same

Minimum AC side voltage without risking commutation failure is given by:

$V_{doi}' = (V_d + R_c I_d)/\cos\gamma_{min} = 223.10$ kV

Acceptable percentage drop in inverter side AC system voltage is $[(V_{doi} - V_{doi}') / V_{doi}] \times 100\ \% = 3.28\ \%$