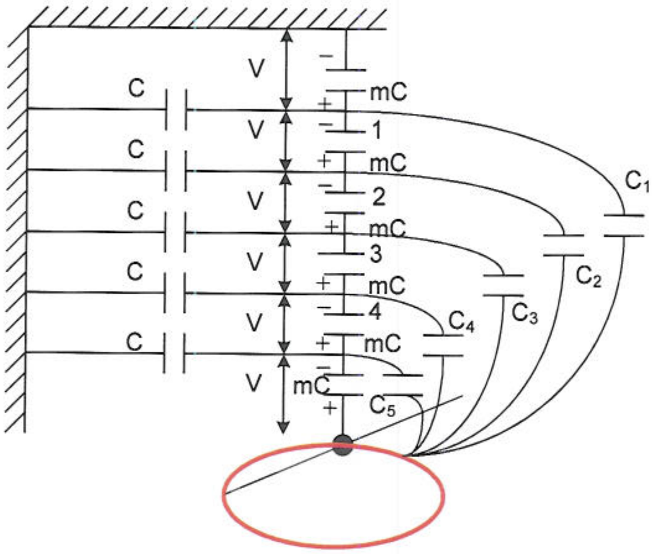
Master - June '08

E4.53

Model Answers 2008

1 a) Explain how string efficiency can be improved using a grading ring.

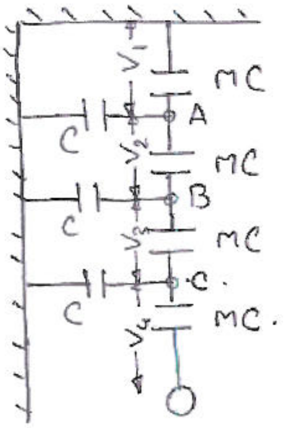
[4]



String efficiency is the measure of non-uniformity of the voltage across different units of a string insulator. This is caused due to shunt capacitance between the pin of each unit to the grounded tower (shown as C in the figure). The effect of this shunt pin-to-earth capacitance can be minimized by providing an alternate bypass path through C1, C2, .. C5 for the charge to reach the ground from the HV conductor. This is provided by a grading ring of suitable design around the HV conductor.

1 b) The individual phase conductors of a three phase overhead line are suspended from the cross arms using suspension insulators each comprising of 4 units. The voltage across the second and third unit is 14.2 kV and 20 kV, respectively. Find the voltage between the phase conductors and the string efficiency.

[10]



At node A

$mCV_2 = mCV_1 + CV_1$

At node B

$mCV_3 = mCV_2 + C(V_1+V_2)$

At node C

$mCV_4 = mCV_3 + C(V_1+V_2+V_3)$

$V_2 = 14.2\ kV$

$V_3 = 20\ kV.$

$$mV_3 = mV_2 + (V_1+V_2) \quad \text{--- (1)}$$

$$mV_2 = mV_1 + V_1 \Rightarrow V_1 = \frac{m}{m+1}V_2 \quad \text{--- (2)}$$

Using (1) and (2)

$$mV_3 = mV_2 + \left(\frac{m}{m+1}+1\right)V_2$$

$$\Rightarrow m^2(V_3-V_2) + m(V_3-V_2-2V_2) - 2V_2 = 0.$$

$$\Rightarrow 5.8m^2 - 22.6m - 28.4 = 0$$

$$\Rightarrow m = 4.8966$$

$$\therefore V_1 = \frac{m}{m+1}V_2 = 11.79\ kV$$

$$V_4 = \frac{mV_3 + (V_1+V_2+V_3)}{m} = 29.39\ kV$$

Total voltage across the string $V = V_1+V_2+V_3+V_4$

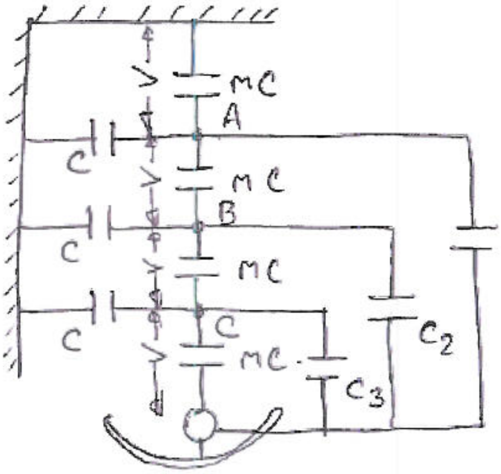
$= 75.38\ kV.$

Voltage between the phase conductors is $\sqrt{3}V = \underline{\underline{130.56\ kV}}$

String Efficiency $= \dfrac{V}{4\times V_4} = \dfrac{75.38}{4\times 29.39}\times 100\% = \underline{\underline{64.12\%}}$

1 c) A suspension insulator string comprising of 4 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.

[6]



Suppose C_1, C_2 and C_3 are the line to pin capacitances required for 100% string efficiency i.e. uniform voltage distribution across each unit i.e. voltage V across each unit.

At node A,

$$mCV + CV = mCV + (nV - V)C_1 \Rightarrow C_1 = \frac{C}{n-1}$$

where n is the total no of units (n = 4 in this case). --- (1)

At node B

$$mCV + 2CV = mCV + (nV - 2V)C_2$$

$$\Rightarrow C_2 = \frac{2C}{n-2} \quad \text{--- (2)}$$

Similarly at node C,

$$C_3 = \frac{3C}{n-3} \quad \text{--- (3)}$$

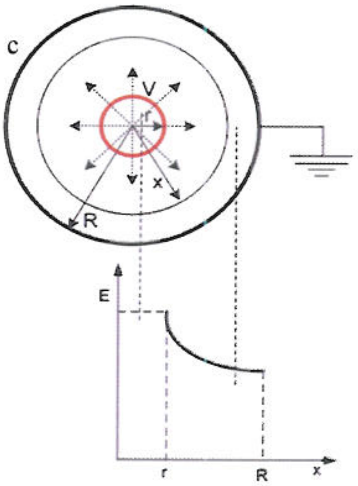
Eqns (1), (2) and (3) shows the required relationship between the line-to-pin and pin-to-earth capacitances for 100% string efficiency.

2 a) 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 b) Derive the expression for the variation of electric stress along the radial direction of a HV cable. Use this expression to find the optimum dimension in order to ensure the best use of the dielectrics of the cables.

[5]



$$V = \int_r^R E_x dx = \int_r^R \frac{q}{2\pi x \varepsilon} dx = \frac{q}{2\pi\varepsilon} \ln \frac{R}{r}$$

$$E_x = \frac{q}{2\pi x \varepsilon} = \frac{V}{x \ln \frac{R}{r}}$$

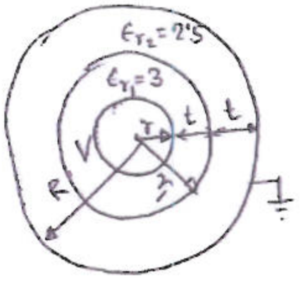
Optimum dimension would support maximum voltage (V) with a minimum electric field (E_m) at the conductor surface and minimum R

$$E_m = \frac{V}{r \ln(R/r)} = \frac{V}{\frac{R}{p}(\ln p)} = \frac{V}{R}(\frac{p}{\ln p}), \quad p = \frac{R}{r}$$

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

2 c) A single core cable has a conductor of 10 mm diameter and two layers of different insulating materials, each 10 mm thick with relative permittivity 3.0 (inner) and 2.5 (outer). Decide whether it is safe to use a material of dielectric strength of 5 kV/mm for the inner layer of insulation given the maximum voltage between the conductor and the sheath is 60 kV.

[11]



$r = \frac{10}{2} = 5$ mm.

$t = 10$ mm.

$r_1 = r + t = 15$ mm.

$R = r + 2t = 25$ mm.

Suppose E_{m_1} and E_{m_2} be the maximum electric field (strength) at the conductor surface and the junction of the two dielectrics, respectively.

$$E_{m_1} = \frac{q}{2\pi\epsilon_0\epsilon_1 r} \quad ; \quad E_{m_2} = \frac{q}{2\pi\epsilon_0\epsilon_2 r_1}$$

$$\therefore \quad \frac{r_1 E_{m_2}}{r \, E_{m_1}} = \frac{\epsilon_1}{\epsilon_2}$$

$$V = V_1 + V_2 = E_{m_1} r \ln\frac{r_1}{r} + E_{m_2} r_1 \ln\frac{R}{r_1}$$

$$= r E_{m_1}\left(\ln\frac{r_1}{r} + \frac{\epsilon_1}{\epsilon_2}\ln\frac{R}{r_1}\right)$$

$$\Rightarrow 60 = 5 E_{m_1}\left(\ln\frac{15}{5} + \frac{3}{2.5}\ln\frac{25}{15}\right)$$

$$= 8.558\, E_{m_1}.$$

$$\therefore E_{m_1} = \frac{60}{8.558} = 7 \text{ kV/mm}.$$

As the maximum stress on the inner dielectric is 7 kV/mm, it would not be safe to use a material with dielectric strength 5 kV/mm.

3 a) What is corona?

[2]

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 and production of ozone (typical smell) and oxide of nitrogen. This is known as corona.

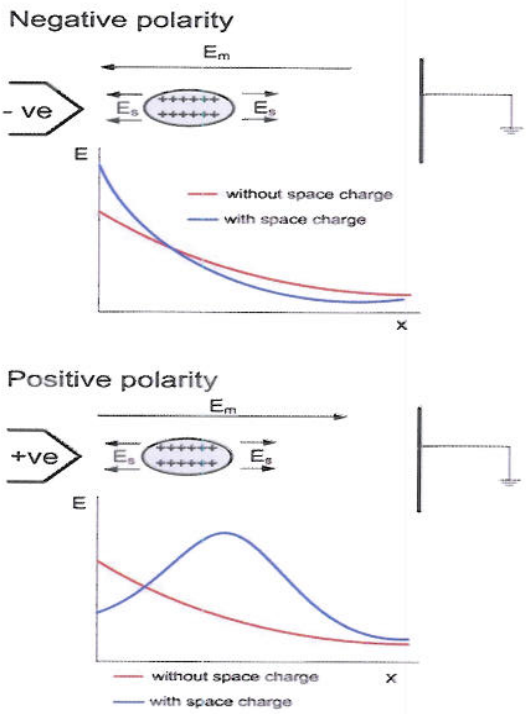
3b) Explain why corona is self-checking?

[2]

During corona, the effective diameter of the conductor increases due to ionization of the surroundings air. Increase in effective radius causes lower voltage stress on the surface which tends to check the progress of corona. Thus corona is a self-checking process.

3 c) Explain how the corona inception voltage depends on the polarity of the overhead HVDC line.

[5]



In non-uniform electric field, corona inception voltage depends on the polarity of the electrode due to effect of space charge. Overhead lines create a non-uniform filed with respect to ground and hence corona inception voltage for DC lines depends on the polarity.

For negative polarity, the space charge field (E_s) adds to the main field (E_m) near the electrode leading to high resultant field in that region.

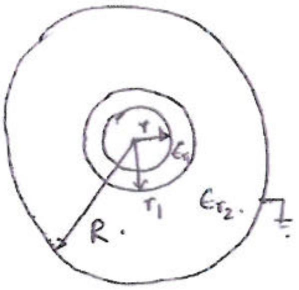
For positive polarity, space charge field (E_s) opposes the main field (E_m) near the electrode leading to low resultant field.

Thus corona inception voltage is lower (higher) for negative (positive) polarity.

3 d) A porcelain bushing having relative permittivity $\varepsilon_r = 4.0$ is used to isolate the HV conductor of 3.0 cm diameter from the tank of a 33 kV (rms) three-phase transformer. The internal and external diameters of the bushings are 3.3 and 10 cm, respectively.

i) Determine whether or not the corona will be present in the air space surrounding the conductor.

[7]



$$r = \frac{3}{2} = 1.5 \text{ cm.}$$

$$r_1 = \frac{3.3}{2} = 1.65 \text{ cm.}$$

$$R = \frac{10}{2} = 5 \text{ cm.}$$

$$E_{m_1} = \frac{q}{2\pi\varepsilon_0\varepsilon_{r_1} r} \quad ; \quad E_{m_2} = \frac{q}{2\pi\varepsilon_0\varepsilon_{r_2} r_1}$$

$$V = V_1 + V_2$$

$$= E_{m_1} r \ln\frac{r_1}{r} + E_{m_2} r_1 \ln R/r_1$$

$$= \frac{q}{2\pi\varepsilon_0}\left[\frac{1}{\varepsilon_{r_1}}\ln\frac{r_1}{r} + \frac{1}{\varepsilon_{r_2}}\ln\frac{R}{r_1}\right].$$

Without oil.

$$\frac{q}{2\pi\varepsilon_0} = \frac{\frac{33}{\sqrt{3}} \times \sqrt{2}}{\ln\frac{1.65}{1.5} + \frac{1}{4}\ln\frac{5.0}{1.65}} = 72.34 \text{ kV.}$$

Hence, electric field at the surface of the conductor would be

$$E_c = \frac{q}{2\pi\varepsilon_0 r} = \frac{72.34}{1.5} \text{ kV/cm} = 48.23 \text{ kV/cm}$$

As $E_c > 30$ kV/cm, there would be corona.

ii) Would the situation be different if an oil filled bushing is used with oil having relative permittivity $\varepsilon_r = 2.5$?

[4]

<u>With oil.</u>

$$\frac{q}{2\pi\epsilon_0} = \frac{\frac{33\sqrt{2}}{\sqrt{3}}}{\frac{1}{2.5}\ln\frac{1.65}{1.5} + \frac{1}{4}\ln\frac{.5}{1.65}} = 85.46 \text{ kV.}$$

$$E_c = \frac{q}{2\pi\epsilon_0\epsilon_r r} = \frac{85.46}{2.5\times1.5} = 22.79 \text{ kV.}$$

As $E_c < 30$ kV/cm, there would be no corona in oil-filled bushing.

4 a) What are the requirements for a surge arrester?

[4]

The basic requirements for a surge arrester are the following:

- should not allow any current under normal voltage
- break down as quickly as possible 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

4 b) Why are arcing horns or rod gaps not the best option for diverting surges?

[2]

Rod gaps are not the best option for diverting surges as they are not good at interrupting the follow-on current. Following a flashover of the rod gap, it takes some time for the fresh air to replace the ionized air and regain the insulating property of the gap. Thus it might not be able to interrupt the follow-on current.

4 c) Explain the function of the ground wires on HV transmission lines.

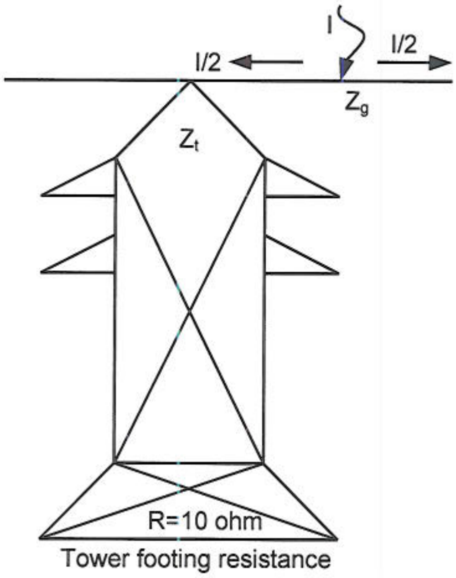
[4]

Ground wire reduces the possibility of direct lightning strikes on the HV lines. They should be kept adequately high above the line conductors and disposed in such a way so as to interrupt the direct stroke. Phase conductors need to be located within the protective zone of the ground wire.

Ground wire also reduces the stress on the insulators. For a lightning strike on the transmission tower, the incident over-voltage is relatively less as the effective surge impedance is reduced in presence of the ground wire.

4 d) Lightning strikes the ground wire nearby a 30 m high transmission tower. The lightning current is 15.0 kA, the surge impedance of the ground wire is 500 ohms, that of the tower is 125 ohms and the tower footing resistance is 10 ohms. Find the voltage that would appear across the line insulators after 0.2 μs from the lightning strike. The speed of propagation of the travelling wave through the tower can be assumed to be 3×10^8 m/s

[10]



Velocity of travelling wave is 300×10^6 m/s

Time to reach the base of the tower is $\frac{30}{300} = 0.1 \mu s$.

By 0.2 μs the reflected voltage from the tower base would appear across the insulators.

$I = 15$ kA

$Z_g = 500\ \Omega$

$Z_t = 125\ \Omega$

Incident overvoltage

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

$Z_{eq} = Z_g \,||\, Z_t = 100\ \Omega$

Voltage transmitted on to the tower

$$V_t = \frac{2 Z_{eq}}{Z_{eq} + Z_g} V_i = 1250 \text{ kV}$$

Reflected voltage from tower footing ($R = 10\ \Omega$)

$$V_r = \frac{R - Z_t}{R + Z_t} V_t = -1064.8 \text{ kV}$$

Voltage across the line insulators after 0.2 μs is

$$V_{ins} = V_t + V_r = \underline{\underline{185.19 \text{ kV}}}.$$

5 a) What factors make the DC transmission a superior alternative over its AC counterpart?

[5]

- DC carries same power with 2 conductors as AC does with 3. Therefore less RoW, lower conductor and insulator costs and simpler towers are required for DC.
- Losses in DC lines is 2/3rd that of AC. Moreover, there is much less skin effect.
- Charging current is much less for DC and is therefore, the only option for cable transmission beyond a certain distance.
- Interconnection through DC does not increase the fault level unlike AC
  DC enable control over power flow and hence improvement of system stability

5 b) What are the major applications areas for which HVDC transmission is considered?

[3]

- Cable transmission beyond 30-40 km e.g. offshore wind farms
- Asynchronous interconnections
- Power transfer over long distance where use of AC is limited due to stability considerations

5 c) A mono-polar DC line is operating at its rated voltage of 200 kV and rated current of 1 kA with an extinction angle of 15 deg at the inverter end. The line to line AC voltage is 176 kV at the rectifier end. The DC line resistance is 20 ohms and the commutating resistance at either end is 10 ohms. Calculate the reactive power at both ends assuming lossless 6-pulse bridge converters.

[12]

$V_{dr} = 200$ kV.

$I_d = 1$ kA.

$\gamma = 15°$

$E_R = 176$ kV.

$R_d = 20\,\Omega$.

$R_c = 10\,\Omega$.

$Q_R = ?$

$Q_I = ?$

$$V_{dor} = \frac{3\sqrt{2}}{\pi} E_R = \frac{3\sqrt{2} \times 176}{\pi} = 237.68 \text{ kV.}$$

$V_{dr} = 200$ kV.

$$\cos\phi_r = \frac{V_{dr}}{V_{dor}} = \frac{200}{237.68} = 0.84.$$

$$P_{dr} = V_{dr} I_d = 200 \times 1 = 200 \text{ MW.}$$

$$Q_R = P_{dr} \tan\phi_r$$

$$= 200 \times 0.6459 = \underline{\underline{129.19}} \text{ MVAr.}$$

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

$$= 200 - 20 \times 1$$

$$= 180 \text{ kV.}$$

$$V_{di} = V_{doi} \cos\gamma - R_c I_d.$$

$$V_{doi} = \frac{V_{di} + R_c I_d.}{\cos\gamma} = \frac{180 + 10 \times 1.}{\cos 15°} = 196.70 \text{ kV.}$$

$$\cos\phi_I = \frac{V_{di}}{V_{doi}} = \frac{180}{196.70} = 0.9151.$$

$$P_I = V_{di} I_d = 180 \text{ MW.}$$

$$Q_I = P_I \tan\phi_I = 180 \times 0.44 = \underline{\underline{79.32}} \text{ MVAr.}$$

6 a) Explain the constraints on the variables used for the control of a HVDC system.

[3]

The firing angle (α) for a rectifier and the extinction angle (γ) for an inverter should be low for high power factor. However, α should be above 5^0 to ensure adequate forward voltage across the valves (i.e. commutation) during firing. Normal range of α is 15^0 to 20^0 to allow adequate margin to increase the rectifier voltage. A minimum γ is required to avoid commutation failure. γ should typically be 15^0 to 18^0 for acceptable margin

6 b) Explain the behaviour of a HVDC system following a fault in the link.

[3]

Following a fault in the DC link the rectifier current increases and inverter current goes down. CC control restores the rectifier current back to normal. Inverter switches from CEA to CC to hold the decreasing current. The rectifier tries to maintain I_{ord} and the 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).

6 c) A 250 kV, 500 MW mono-polar DC link has the following parameters. Line resistance R_d = 10 ohms, commutating resistance, R_c = 6 ohms at either end. The rectifier is initially operating under CC control with α = 18 deg whereas the inverter is set a CEA control with γ = 15 deg. The minimum limit for the rectifier firing angle (α) is 5 deg 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]

250 kV, 500 MW.

$V_d = 250\text{kV}$.

$I_d = \frac{P}{V_d} = 2\text{kA}$.

$R_d = 10\Omega$.

$R_c = 6\Omega$.

$\alpha = 18^\circ$

$\gamma = 15^\circ$

$\alpha_{min} = 5^\circ$.

$I_n = 0.15 \times 2$
$= 0.3\text{ kA}$.

$I_d' = I_d - I_n$
$= 1.7\text{ kA}$.

$$V_{dr} = V_{dor}\cos\alpha - R_c I_d.$$

$$V_{dor} = \frac{V_{dr} + R_c I_d}{\cos\alpha} = \frac{250 + 6\times 2}{\cos 18^\circ} = 275.48\text{ kV}$$

$$V_{dor}' = 0.8 \times V_{dor} = 220.39\text{ kV}$$

Under CC control at the rectifier end, α would reduce to maintain I_d constant.

$$\cos\alpha' = \frac{V_{dr} + R_c I_d}{V_{dor}'} = \frac{262}{220.39} > 1.$$

Rectifier would be shifted to α_{min} operation & inverter would take up constant current control.

$$I_d' = I_d - I_n = 1.7\text{ kA}.$$

$$V_{dr}' = V_{dor}'\cos\alpha_{min} - R_c I_d'$$
$$= 220.39 \times \cos 5^\circ - 6\times 1.7\text{ kV}$$
$$= 209.35\text{ kV}.$$

continued to next page

$$P_r = V_r' I_r' = 209.35 \times 1.7 = \underline{\underline{355.89}} \text{ MW.}$$

$$\cos\phi_r = \frac{V_{dr}'}{V_{dor}'} = \frac{209.35}{220.39} = 0.95.$$

$$Q_r = P_r \tan\phi_r.$$

$$= 355.89 \times 0.33 = \underline{\underline{116.98}} \text{ MVAr.}$$

$$V_{di}' = V_{dr}' - R_d I_d' = 209.35 - 10 \times 1.7$$

$$= 192.35 \text{ kV.}$$

Before drop in rectifier voltage

$$V_{di} = V_{dr} - I_d R_d.$$

$$= 250 - 2 \times 10$$

$$= 230 \text{ kV.}$$

$$V_{doi} = \frac{V_{di} + R_c I_d}{\cos\gamma} = \frac{230 + 6 \times 2}{\cos 15^\circ}$$

$$= 250.54 \text{ kV.}$$

$$\therefore \cos\phi_I = \frac{V_{di}'}{V_{doi}} = \frac{192.35}{250.54} = 0.77.$$

$$P_i = V_{di}' I_d' = 192.35 \times 1.7 = \underline{\underline{327 \text{ MW}}}.$$

$$Q_i = P_i \tan\phi_I$$

$$= 327 \times 0.82$$

$$= \underline{\underline{270.96 \text{ MVAr.}}}$$

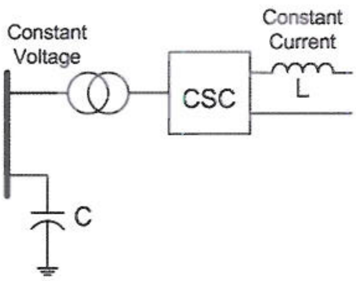
7 a) Explain which harmonics are likely to be present in the DC side for a bipolar HVDC system with two six pulse bridges connected to YY and YΔ transformer.

[4]

For an ideal 6 pulse converter, harmonic order on the DC side is restricted to six and its integral multiples, $h = 6n$, $n = 0,1,2$....In a bipole system with 2 six-pulse bridges (YY and YD), 6^{th} , 18^{th} harmonics are out of phase, while 12^{th} , 24^{th} ... are in phase. The out of phase components cancel and in phase components produce harmonic currents in line i.e. only harmonics of order 12 and their integral multiple are present on the DC side.

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

[5]



AC side

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

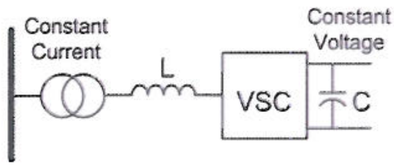
DC side

- 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

7 c) What is the main advantage and application area of VSC technology over CSC?

[4]

With VSC technology, rapid control over both active and reactive power can be exerted independently of each other. Unlike CSC technology, converters do not always demand reactive power and can even provide reactive power support for weak ac systems. Therefore, VSC is especially useful for connections to weak AC systems like an isolated grid (island).

7 d) A six-pulse rectifier has a direct voltage output of 40 kV. The transformer leakage reactance is 10 ohms/phase. Calculate the power delivered by the rectifier for a firing angle of 15 deg with the AC side line to line voltage at 70.7 kV.

[7]

$V_d = 40$ kV.
$X_L = 10\ \Omega/$phase.
$\alpha = 15°$.
$E_{Lac} = 70{\cdot}7$ kV.

$$V_{dor} = \frac{3\sqrt{2}}{\pi} E_{Lac} = 95{\cdot}48 \text{ kV}.$$

Commutation resistance $R_c = \frac{3}{\pi} X_L$
$= \frac{3}{\pi} \times 10 = 9{\cdot}55\ \Omega$

$$V_d = V_{dor}\cos\alpha - R_c I_d.$$

$$\Rightarrow I_d = \frac{V_{dor}\cos\alpha - V_d}{R_c}.$$

$$= \frac{95{\cdot}48\cos(15°) - 40}{9{\cdot}55}\ \text{kA}$$

$= 5{\cdot}65$ kA.

Power delivered by the rectified

$P_d = V_d I_d$
$= 40 \times 5{\cdot}65$
$= \underline{\underline{226 \text{ MW}}}$