Final

E4.53

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2010

EEE PART IV: MEng and ACGI

HIGH VOLTAGE TECHNOLOGY AND HVDC TRANSMISSION

Tuesday, 11 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.

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Second Marker(s) : B.C. Pal

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Answer any 4 questions out of 6

1. a) Show that the conductor cost for transmission lines is inversely proportional to the square of the operating voltage level and the proportionality constant increases with square of the transmission distance. Make assumptions as necessary.

[6]

b) Define string efficiency and explain three possible ways of improving it.

[8]

c) A string of suspension insulator is used to support 100 kV peak voltage between the line conductor and the tower. The string consists of four units and the capacitance between each link pin and tower is one-tenth of the self capacitance of each unit. Neglecting the effect of grading ring find the following:

i) Maximum voltage appearing across a single unit

[8]

ii) String efficiency

[3]

2. a) Explain the major drawback of three-core belted cables and how it is overcome in H-type cables.

[6]

b) Derive an expression for the variation of electric stress as a function of distance along the radial direction of a cross-section of a HV cable. Using this expression determine the optimum ratio of the inner to outer radius of a cable to ensure best use of the dielectric material.

[8]

c) A single-core, lead covered capacitance graded cable is to be designed for 60 kV peak voltage to ground. The conductor radius is 15 mm and there are two concentric layers of insulation materials with relative permittivity 5 and 3, respectively and maximum permissible electric stress 3.8 and 2.6 kV/mm (peak), respectively. Calculate the minimum inner radius of the lead sheath required for this cable.

[11]

3. a) Define surge impedance and explain why it is typically higher for overhead lines than cables of similar voltage ratings.

[6]

b) Explain the influence of cables in reducing the propagation of surge

[6]

c) An overhead line of surge impedance 400 ohms is connected in series with a 5 km long cable of surge impedance 40 ohms with its far end kept open. The velocities of surge propagation in the overhead line and the cable are 3×10^5 km/s and 1.4×10^5 km/s, respectively. A voltage surge with 100 kV peak travels along the overhead line towards the junction of the line and the cable. Plot the voltage distribution along the length of the overhead line and the cable (show up to 500 meters on either side of the junction) at the instant of 1 microsecond after the surge reaches the junction.

[13]

4. a) Explain why a HVDC system is economically justifiable only beyond a certain threshold transmission distance. How and why is this threshold distance different for overhead lines and cables?

[6]

b) Justify and compare the current source converter (CSC) and voltage source converter (VSC) technologies in terms of i) overall losses, ii) footprint iii) power reversal and iv) dependence on AC system strength.

[8]

c) Two separate AC systems operating at 400 kV (line-to-line) are interconnected with a 500 kV (rectifier side), 1000 MW monopolar HVDC link. The DC line resistance (R_L) is 20 ohms and the commutating resistance (R_C) at either end is 10 ohms. If the inverter is operated with an extinction advance angle (γ) of 15 degrees calculate the reactive power demand from the AC side at both ends. Assume rated conditions on the rectifier side AC system and the dc link and also lossless 6-pulse converters.

[11]

5. a) What is commutation failure and why is it more of a problem on the inverter side of the HVDC link?

[6]

b) Explain the basis for upper and lower limits on the values of the firing angle (α) on the rectifier side and extinction advance angle (γ) on the inverter side.

[6]

c) A monopolar HVDC link with 6-pulse converters at either end is operated with a current of 2 kA and 200 kV on the inverter side. The firing advance angle (β) and the overlap angle (u) for the inverter is maintained at β=40 and μ=25 degrees, respectively. If the leakage reactance of the inverter side transformer is X_{cr} = 11.94 ohms/phase, calculate the maximum permissible drop in inverter side AC system voltage without violating the minimum extinction advance angle (γ_{min}) of 5 degrees from commutation failure point of view.

[13]

6. a) What roles does the smoothing rector on the DC side play for a current source converter (CSC) system? Mention the factors that dictate the upper and lower limit of its inductance.

[5]

b) Explain the sequence of events following a fault on the inverter-side AC system. Include the possibilities of strong and weak system as well as nearby (near inverter terminal) and distant faults.

[7]

c) Why faults on the DC link are a matter of concern for voltage source converter (VSC) systems unlike the current source converter (CSC) systems.

[7]

d) Describe the technical and economic considerations surrounding the use of multi-terminal HVDC systems for transmitting bulk power from remote offshore wind farms.

[6]

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SOLUTIONS - 2010

Answer any 4 questions out of 6

1. a) Show that the conductor cost for transmission lines is inversely proportional to the square of the operating voltage level and the proportionality constant increases with square of the transmission distance. Make assumptions as necessary.

[6]

$$P_T = \sqrt{3} V_L I_L cos\phi$$

$$P_L = 3I^2 R = 3I^2 \frac{\rho L}{A}$$

$$x = \frac{P_L}{P_T}$$

$$Cost_{Cu} = 3LAC_p = \frac{3\rho P_T L^2 C_p}{x V_L{}^2 cos^2\phi} = \frac{K_1}{V_L{}^2}$$

$$K_1 = \frac{3\rho P_T L^2 C_p}{x cos^2\phi}$$

$$Cost_{Cu} = 3LAC_p = \frac{3\rho P_T L^2 C_p}{x V_L{}^2 cos^2\phi} = \frac{K_1}{V_L{}^2}$$

$$K_1 = \frac{3\rho P_T L^2 C_p}{x cos^2\phi}$$

b) Define string efficiency and explain three possible ways of improving it.

[8]

String efficiency is the ratio of the voltage across the whole string over the total no of discs times the maximum voltage across a single disc. In other words it is the ratio of the flashover voltage of the whole string over the total no of discs times the flashover voltage of a single disc. It is the measure of non-uniformity of voltage distribution across a suspension insulator. Higher the string efficiency the more uniform is the voltage distribution and better is the utilization of each discs and less is the number of discs required to support a particular voltage.

String efficiency can be improved by one or more of the following:

- Using longer cross-arms
  - smaller shunt capacitance i.e. higher 'm'
  - higher tower costs

- Using graded discs
  - wider/thinner discs (higher C) with higher e are used towards the HV end
  - manufacturing varying size of discs is not common

- Static shielding by grading ring

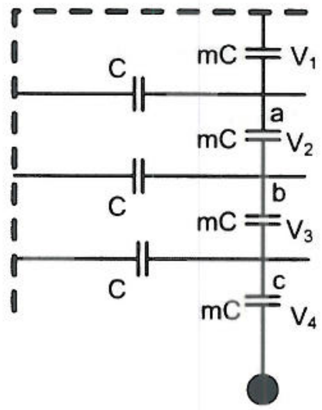
c) A string of suspension insulator is used to support 100 kV peak voltage between the line conductor and the tower. The string consists of four units and the capacitance between each link pin and tower is one-tenth of the self capacitance of each unit. Neglecting the effect of grading ring find the following:

i) Maximum voltage appearing across a single 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

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

Similarly at the junction c

$mCV_3+C(V_1+V_2+V_3) = mCV_4 \Rightarrow 11V_3+V_1 + V_2= 10V_4$

$V_1+V_2+V_3 +V_4= 100$

Solving the four equations:

$V_4 = 32.62$ kV

Maximum voltage across a single unit is 32.62 kV

ii) string efficiency = [100/(32.62 × 4)] x 100 % = 76.64%

2. a) Explain the major drawback of three-core belted cables and how it is overcome in H-type cables.

[6]

Major drawback of a three-core belted cable is:

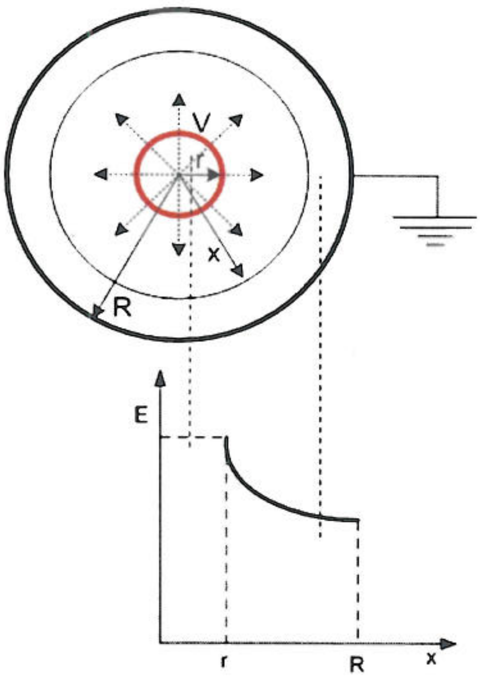
- electric field is not radial
- tangential component of the field leads to discharges as paper has poor tangential strength
- voids in filler material can be a problem
- belted cables cannot be used above 10-15 kV

In H-type cable:

- electric field is made radial by metallic screens around each core maintained at ground potential
- no tangential stress, purely radial stress on paper insulation

b) Derive an expression for the variation of electric stress as a function of distance along the radial direction of a cross-section of a HV cable. Using this expression determine the optimum ratio of the inner to outer radius of a cable to ensure best use of the dielectric material.

[8]



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

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

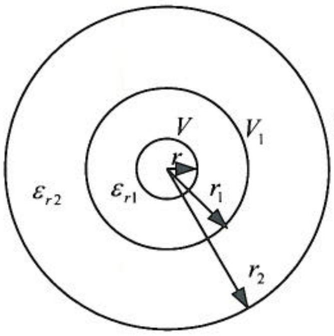
Optimum dimension would support maximum voltage (V) with a minimum electric field (E_m) at the conductor surface and minimum R

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

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

c) A single-core, lead covered capacitance graded cable is to be designed for 60 kV peak voltage to ground. The conductor radius is 15 mm and there are two concentric layers of insulation materials with relative permittivity 5 and 3, respectively and maximum permissible electric stress 3.8 and 2.6 kV/mm (peak), respectively. Calculate the minimum inner radius of the lead sheath required for this cable.

[11]



For a capacitance graded cable:

$$E_{m1} = \frac{q}{2\pi\varepsilon_1 r}, E_{m2} = \frac{q}{2\pi\varepsilon_2 r_1}, E_{m3} = \frac{q}{2\pi\varepsilon_3 r_2}$$
$$E_{m1}\varepsilon_1 r = E_{m2}\varepsilon_2 r_1 = E_{m3}\varepsilon_3 r_2 = \frac{q}{2\pi}$$

$3.8 \times 5 \times 15 = 2.6 \times 3 \times r_1$

$\Rightarrow r_1 = 36.54$ mm

$V - V_1 = E_{m1} \times r \times \ln (r_1/r)$

$\Rightarrow V_1 = 9.25$ kV

$V_1 - 0 = E_{m2} \times r_1 \times \ln (r_2/r_1)$

$\Rightarrow r_2 = 40.27$ mm

Inner radius of the lead sheath needs to be 40.27 mm

3. a) Define surge impedance and explain why it is typically higher for overhead lines than cables of similar voltage ratings.

[6]

Surge or characteristics impedance is the square root of the ratio of inductance to capacitance per unit length.

$$Z_C = \sqrt{\frac{L}{C}}$$

Distance of separation between phase conductors is higher for overhead lines than cables. Also the relative permittivity of air is less that that of dielectric material in the cables. So inductance is larger and capacitance is smaller for overhead lines when compared to cables. Hence the surge impedance is also higher for overhead lines.

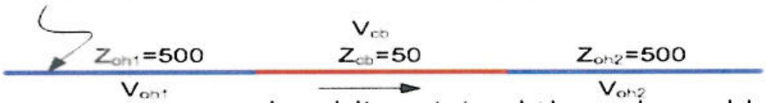
$$L_{OH\ Lines} = 2 \times 10^{-7} \ln \frac{D}{r} \quad H/m,$$
$$D = (d_{ab} d_{bc} d_{ca})^{\frac{1}{3}}$$
$$C_{OH\ Lines} = \frac{2\pi\epsilon_0}{\ln \frac{D}{r}} \quad F/m$$

$$L_{Cables} = 2 \times 10^{-7} \ln \frac{R}{r} \quad H/m,$$
$$R = sheath\ radius$$
$$C_{Cables} = \frac{2\pi\epsilon}{\ln \frac{R}{r}} \quad F/m$$

$$\boxed{\begin{array}{l} D > R \quad \Rightarrow \quad L_{OH\ Lines} > L_{Cables} \\ \epsilon_0 < \epsilon \quad \Rightarrow \quad C_{OH\ Lines} < C_{Cables} \\ \quad \Rightarrow Z_{c-OH\ Lines} > Z_{c-Cables} \end{array}}$$

b) Explain the influence of cables in reducing the propagation of surge

[6]



two overhead lines joined through a cable

$$V_{oh2} = \frac{2Z_{oh}}{Z_{oh} + Z_{cb}} \times \frac{2Z_{cb}}{Z_{cb} + Z_{oh}} V_{oh1} = 0.33V_{oh1}$$

- voltage in the 2nd overhead line is reduced to approximately 1/3rd
- cable is useful in reducing surge transmitted to substations

c) An overhead line of surge impedance 400 ohms is connected in series with a 5 km long cable of surge impedance 40 ohms with its far end kept open. The velocities of surge propagation in the overhead line and the cable are 3×10^5 km/s and 1.4×10^5 km/s, respectively. A voltage surge with 100 kV peak travels along the overhead line towards the junction of the line and the cable. Plot the voltage distribution along the length of the overhead line and the cable (show up to 500 meters on either side of the junction) at the instant of 1 microsecond after the surge reaches the junction.

[13]

$Z_1 = 400$ ohms, $Z_2 = 40$ ohms;

Line to cable reflection coefficient = $(Z_2-Z_1)/(Z_2+Z_1) = -0.818$

Reflected voltage in overhead line = $-0.818 \times 100 = -81.8$ kV

Line to cable transmission coefficient = $2Z_2/(Z_2+Z_1) = 0.182$

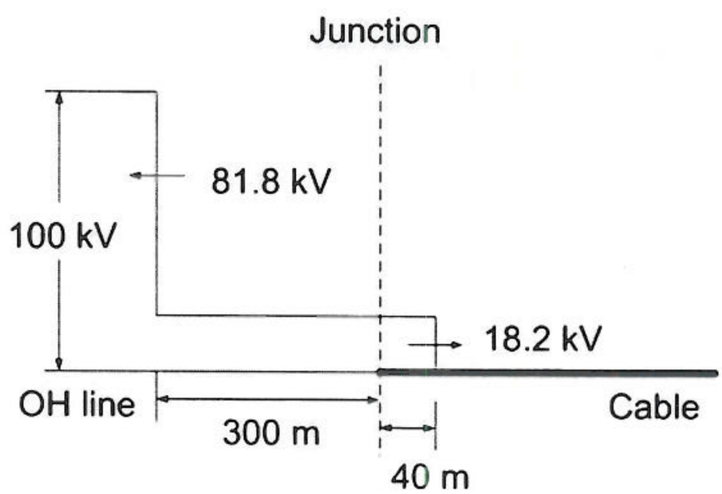
Transmitted voltage in cable = $0.182\times100 = 18.2$ kV

Voltage at the junction just after the lightning strike is 18.2 kV

Distance travelled by the transmitted wave into the cable in 1 μs is: $1.4\times10^8\times10^{-6} = 140$ m

Distance travelled by the reflected wave into the overhead line in 1 μs is:
$3\times10^8\times10^{-6} = 300$ m

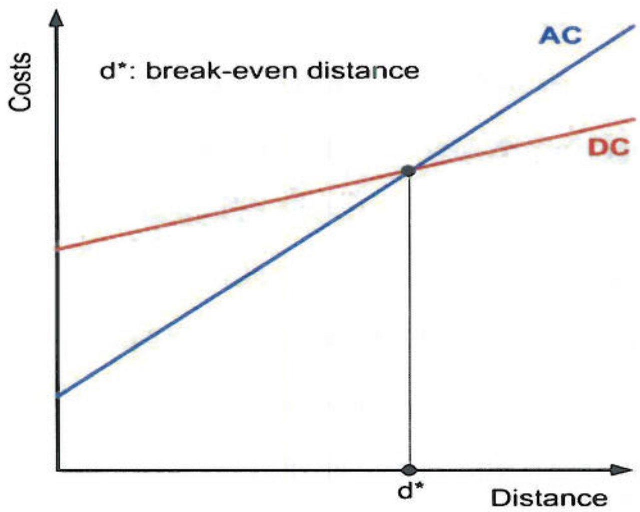
Thus the voltage distribution after 1 μs is given by:



4. a) Explain why a HVDC system is economically justifiable only beyond a certain threshold transmission distance. How and why is this threshold distance different for overhead lines and cables?

[6]

- 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 2/3[rd] 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) Justify and compare the current source converter (CSC) and voltage source converter (VSC) technologies in terms of i) overall losses, ii) footprint iii) power reversal and iv) dependence on AC system strength.

[8]

i) Overall losses

Losses in the converter are less for CSC than VSC because of the high frequency switching involved in the latter. However, overall system losses might be comparable as VSC maintains better voltage profile in the system than what CSC can do. With advancements in VSC technology even the converter losses are going down at a rapid pace.

ii) Footprint

Footprint for VSC technology is much less that CSC because of much less filtering and zero reactive power compensation requirements even though from cooling accessories point of view VSC might be more demanding.

iii) Power reversal

In CSC systems, current can flow in only one direction and power reversal is achieved through reversal of terminal voltages at both ends. For VSC systems, DC link voltage is of fixed polarity and hence power reversal is achieved through reversing the current direction which is possible due to the presence of the diodes in anti-parallel with the IGBTs.

iv) Dependence on AC system strength

CSC technology relies on the AC system voltage for commutation of the valves and therefore, requires strong (SCR > 2) AC systems for satisfactory operation. VSC systems does not reply on AC system voltage and can work with weak AC systems even blackstart.

c) Two separate AC systems operating at 400 kV (line-to-line) are interconnected with a 500 kV (rectifier side), 1000 MW monopolar HVDC link. The DC line resistance (R_L) is 20 ohms and the commutating resistance (R_C) at either end is 10 ohms. If the inverter is operated with an extinction advance angle (γ) of 15 degrees calculate the reactive power demand from the AC side at both ends. Assume rated conditions on the rectifier side AC system and the dc link and also lossless 6-pulse converters.

[11]

$I_d = 1000/500 = 2$ kA

Rectifier side

$V_{dor} = 1.35\ E_{ac} = 540$ kV

$V_{dr} = 500$ kV

$\cos \phi_r = V_{dr}/V_{dor} = 0.9259$

$P_r = V_{dr} \times I_d = 1000$ MW

$Qr = P_r \times \tan \phi_r = 407.92$ MVAr

Inverter side

$V_{di} = V_{dr} - R_d I_d = 500 - 20\times 2 = 460$ kV

$V_{doi} = (V_{di} + R_c I_d)/\cos \gamma = 496.93$ KV

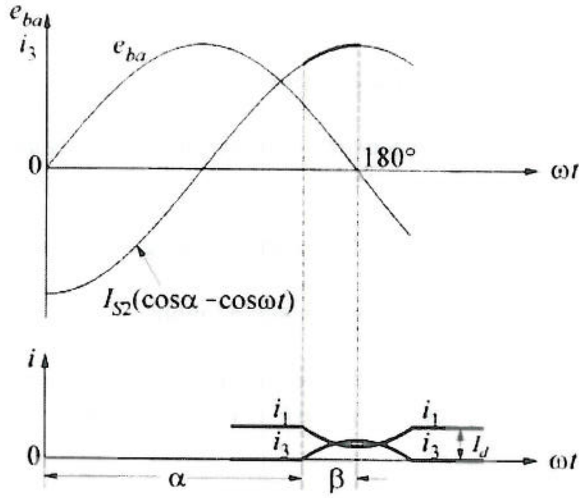
$\cos\phi_I = V_{di}/V_{doi} = 0.9257$

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

$Q_i = P_i \times \tan \phi_I = 375.98$ MVAr

5. a) What is commutation failure and why is it more of a problem on the inverter side of the HVDC link?

[6]



- Failure to complete commutation (say valve 1 to 3) before reversal of commutating voltage (e_{ba})
- Common problem with inverters (not rectifiers) at high direct currents and low voltages
- In case valve 1 fails to turn off before e_{ba} reverses, current in valve 3 would go down to zero
- 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.

b) Explain the basis for upper and lower limits on the values of the firing angle (α) on the rectifier side and extinction advance angle (γ) on the inverter side.

[6]

- α and γ should be low for high power factor
- 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
- Sufficient margin is allowed after completion of commutation to ensure complete deionization of junctions before voltage reverses γ should typically be 15^0 to 18^0 for acceptable margin

c) A monopolar HVDC link with 6-pulse converters at either end is operated with a current of 2 kA and 200 kV on the inverter side. The firing advance angle (β) and the overlap angle (u) for the inverter is maintained at β=40 and μ=25 degrees, respectively. If the leakage reactance of the inverter side transformer is X_{cr} = 11.94 ohms/phase, calculate the maximum permissible drop in inverter side AC system voltage without violating the minimum extinction advance angle (γ_{min}) of 5 degrees from commutation failure point of view.

[13]

Extinction advance angle $\gamma = \beta - \mu = 15$ deg.

Commutation resistance $R_c = 3X_{cr}/\pi = 11.4$ ohms

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

$\cos \gamma_{min} = \cos 5 = 0.9962$

Inverter side AC voltage $V_{doI}' = (V_{dI} + R_c I_d) / \cos \gamma_{min} = 223.65$ kV

Acceptable drop in inverter side AC system voltage:

$(230.66 - 223.65) \times 100/230.66$

$= 3.04$ %

6. a) What roles does the smoothing rector on the DC side play for a current source converter (CSC) system? Mention the factors that dictate the upper and lower limit of its inductance.

[5]

- Smoothes out direct current ripple and prevent discontinuous conduction
- Filters dc line harmonics
- Prevent consequent commutation failure
- Limit fault current near rectifier
- From above considerations the smoothing reactor should be as large as possible. But too large a reactor, in addition to being expensive and space consuming, can cause resonance at low (non-characteristic) frequencies

b) Explain the sequence of events following a fault on the inverter-side AC system. Include the possibilities of strong and weak system as well as nearby (near inverter terminal) and distant faults.

[7]

- Direct current increases
- Inverter stays in CEA mode, rectifier tries to reduce the current in CC mode
- For significant dip in voltage, temporary commutation failure occur before any corrective action is taken
- Resulting increase in reactive power may necessitate reduction of direct current order through VDCOL
- Post-fault recovery depends on AC system strength

c) Why faults on the DC link are a matter of concern for voltage source converter (VSC) systems unlike the current source converter (CSC) systems.

[7]

For CSC systems, following a fault on the DC link:

- 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)

However, for VSC systems:

- Fault in DC links draw uncontrolled currents through the diodes connected in anti-parallel with the IGBTs.
- DC circuit breakers are required to isolate faults which might be tricky and expensive.
- The fault could be "cleared" with AC circuit breakers but this would be needed on all terminals and require a shutdown of the whole system

d) Describe the technical and economic considerations surrounding the use of multi-terminal HVDC systems for transmitting bulk power from remote offshore wind farms.

[6]

Technical issues:

- Power flow control through appropriate droop settings e.g. 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