IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2011

EEE PART IV: MEng and ACGI

Corrected Copy

HIGH VOLTAGE TECHNOLOGY AND HVDC TRANSMISSION

Tuesday, 3 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) Explain how the shape of the pin insulators for low voltage distribution lines help minimise leakage current and also provide mechanical strength.

[5]

b) Define flashover and puncture in the context of porcelain insulators for overhead lines and explain why insulators are designed to have lower flashover voltage than puncture.

[5]

c) State three ways in which the string efficiency of overhead insulators can be improved highlighting the problems associated with each of these.

[5]

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

[10]

2. a) Explain why formation of voids within cable insulation could be detrimental for the life of the cable.

[5]

b) How does a condenser type construction help improve the stress distribution in a transformer bushing?

[5]

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

[5]

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]

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

[3]

3. a) What are the advantages and disadvantages of using bundled conductors for high voltage power transmission?

[5]

b) With necessary ideal assumptions explain the tripling of supply peak voltage while interrupting capacitive current under light load condition.

[5]

c) Define surge impedance loading (SIL) for high voltage transmission and state its physical significance.

[5]

d) Lightning strikes the ground wire near a 30 m high transmission tower. Based on the following information, find the voltage that would appear across the line insulators after 0.2 μs from the lightning strike.

Lightning current: 15.0 kA, surge impedance of the ground wire: 500 ohms, surge impedance of the tower: 125 ohms, tower footing resistance: 10 ohms. Speed of propagation of the travelling wave through the tower: 3×10^8 m/s

[10]

4. a) Explain why the power loss in a DC line is less than that in an AC line of equivalent power rating.

[5]

b) State four major disadvantages of DC transmission.

[5]

c) Describe the impact on active and reactive power as the firing angle of a current source HVDC converter is varied from 0 to 180 degrees.

[5]

d) The inverter end of a CSC-HVDC link is operating at 200 kV drawing 2 kA. The ignition advance angle (β) is set at 40 degrees with a commutation overlap (μ) of 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 the inverter side ac system voltage that is permissible without causing commutation failure. Neglect any mode shift.

[10]

5. a) Why are the rectifier and inverter sides responsible for current and voltage (or extinction angle) control, respectively under normal operation?

[5]

b) Using the individual converter characteristics explain how power reversal is achieved in a current source converter (CSC) based HVDC link.

[5]

c) What is voltage dependent current order limit (VDCOL) and why is it important for converter control in HVDC links?

[5]

d) The rectifier (assume 6 pulse bridge) station of a CSC-HVDC link is fed from a 33/110 kV transformer. The rectifier is operated with a firing angle (α) of 20 degrees with a commutation overlap (μ) of 18 degrees. If the primary side AC voltage is 36.5 kV and the direct current at the rectifier end is 2 kA, find the dc output voltage and the reactive power on the primary side assuming the converters to be lossless.

[10]

6. a) Why is the voltage source converter (VSC) technology a better choice compared to the traditional current source converter (CSC) based systems from the sub-sea cable point of view?

[5]

b) Explain the difference between pulse-width modulation (PWM) and multi-level approach for controlling voltage source converters (VSCs)

[5]

c) Starting from the AC power flow equations describe the four steps towards power flow analysis for combined AC/HVDC systems. Assume current source converter (CSC) HVDC. No need to write the equations explicitly.

[5]

d) State and explain three typical application areas where the voltage source converter (VSC) is almost essential for DC connection.

[5]

e) Explain one major advantage and a disadvantage of using the voltage source converter (VSC) technology for multi-terminal HVDC systems.

[5]

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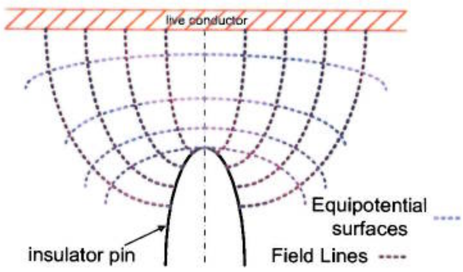
Model Answers 2011

1. a) *Explain how the shape of the pin insulators for low voltage distribution lines help minimise leakage current and also provide mechanical strength.*

[5]



- 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

b) *Define flashover and puncture in the context of porcelain insulators for overhead lines and explain why insulators are designed to have lower flashover voltage than puncture.*

[5]

Flashover is 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.
Puncture is breakdown of the solid (porcelain) dielectric wherein the arc passes through the body of the insulator.

Flashover is a temporary failure and insulator is back in action once it is over while puncture causes permanent damage. Hence insulators are designed such that flashover voltage is considerably lower than puncture voltage

c) *State three ways in which the string efficiency of overhead insulators can be improved highlighting the problems associated with each of these.*

[5]

- 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
  - provides a parallel path to charge the pin-to-earth(tower) capacitances, thereby, improving the voltage distribution

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

[10]

At the node closest to the cross-arm: $mCV_2 = mCV_1 + CV_1$

At the next node below: $mCV_3 = mCV2 + C \times (V_1+V_2)$

At the next node below: $mCV_4 = mCV_3 + C \times (V_1+V_2+V_3)$

$V_2 = 14.2$ kV, $V_3 = 20$ kV

Solving above equations m = 4.8966

$V_1 = [m / (m+1)] \times V_2 = 11.79$ kV

$V_4 = [mV_3 + (V_1+V_2+V_3)]/m = 29.39$ kV

Total voltage across the string i.e. phase-to-ground voltage, $V = V_1+V_2+V_3+V_4 = 75.38$ kV

Voltage between the phase conductors is equal to the line-to-line voltage i.e. $\sqrt{3}V = 130.56$ kV

String efficiency = $[V / (4\times V_4)]\times 100\% = 64.12\%$

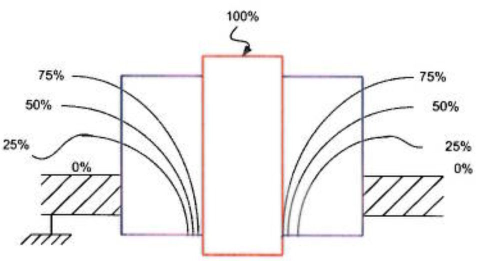
2. a) *Explain why formation of voids within cable insulation could be detrimental for the life of the cable.*

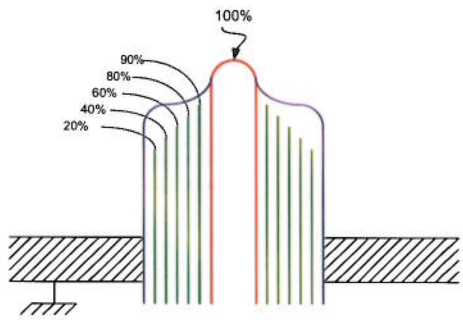
[5]

- Repeated heating and cooling due to load cycles causes void formations
- Voids (ε=1) have much higher stress than surrounding dielectrics (ε>1) whereas the strength of the void is much less, so partial breakdown initiates in the voids
- A discharge takes places at voltage V_1, the voltage across the void collapse and the ionization in the void vanishes. As the supply voltage rises further and the voltage across the void increases producing a series of discharges in every cycles. This causes erosion and carbonization which gradually proceeds both way slowly, a process known as tracking and coring
- Usually when the tree has proceeded for a certain distance, repeated discharges lead to high temperature rise and dielectric decomposition causing final breakdown. This is known as thermal instability

b) *How does a condenser type construction help improve the stress distribution in a transformer bushing?*

[5]

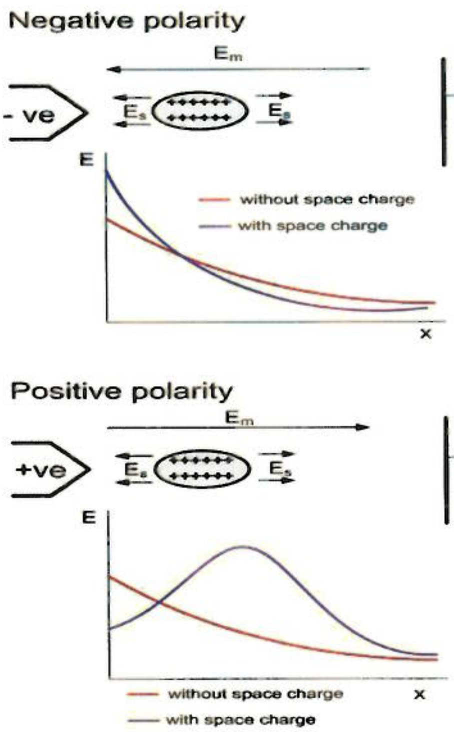




- Axial stress near the earth tank and radial stress over the conductor surface are high requiring large axial length and diameter
- Condenser type construction is employed for voltages above 33kV
- A layer of aluminum or tin foils are introduced inside the dielectric to reduce the axial stress near the earth plate of the bushing.
- Axial length can be reduced by using condenser bushing
- Bushings above 33kV voltage rating employs condenser type construction

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

[5]



Negative polarity
Space charge field (E_s) adds to the main field (E_m) near the electrode leading to high resultant field

Positive polarity
Space charge field (E_s) opposes the main field (E_m) near the electrode leading to low resultant field

Hence for non-uniform electric field corona inception voltage is lower (higher) for negative (positive) polarity

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]

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

[3]

d –i)

$r = 3/2 = 1.5$ cm, $r_1 = 3.3/2 = 1.65$ cm, $R = 10/2 = 5$ cm

Without any oil fill:

$$\frac{q}{2\pi\varepsilon_0} = \frac{V}{\frac{1}{\varepsilon_1}\ln\frac{r_1}{r} + \frac{1}{\varepsilon_2}\ln\frac{r_2}{r_1}} = 33\times\sqrt{(2/3)} / [\ln(1.65/1.5) + (1/4)\times\ln(5/1.65)] = 72.34 \text{ kV}$$

Electric filed at the surface of the conductor $E_c = q / (2\pi\varepsilon_0 r) = 48.23$ kV/cm

As $E_c > 30$ kV/cm, corona would be present on the conductor surface

d-ii)

With oil filled bushing:

$$\frac{q}{2\pi\varepsilon_0} = \frac{V}{\frac{1}{\varepsilon_1}\ln\frac{r_1}{r} + \frac{1}{\varepsilon_2}\ln\frac{r_2}{r_1}} = 33\times\sqrt{(2/3)} / [(1/2.5)\ln(1.65/1.5) + (1/4)\times\ln(5/1.65)] = 85.46 \text{ kV}$$

Electric filed at the surface of the conductor $E_c = q / (2\pi\varepsilon_0\varepsilon_r r) = 85.46 / (2.5 \times 1.5) = 22.79$ kV

As $E_c < 30$ kV/cm in presence of oil fill, there won't be any corona on the conductor surface

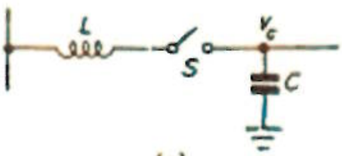
3. a) *What are the advantages and disadvantages of using bundled conductors for high voltage power transmission?*

[5]

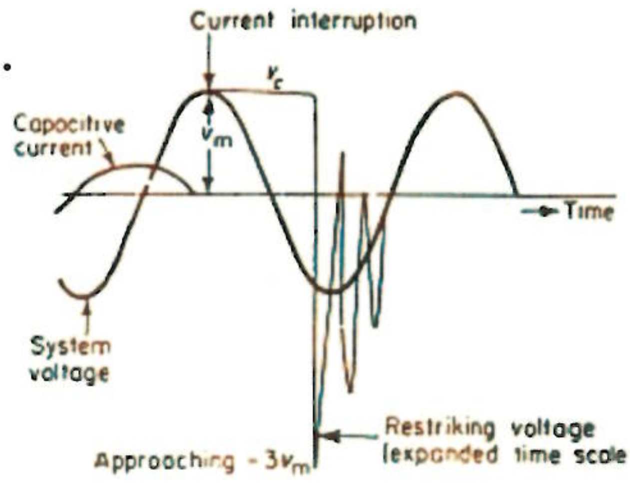
- Advantages
  - less corona loss and radio interference
  - less skin effect
  - reduced reactance
- Disadvantages
  - increased ice and wind loading
  - higher cost
  - higher charging current due to high capacitance

b) *With necessary ideal assumptions explain the tripling of supply peak voltage while interrupting capacitive current under light load condition.*

[5]



(a)



- 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 $3V_m$

c) Define surge impedance loading (SIL) for high voltage transmission and state its physical significance.

[5]

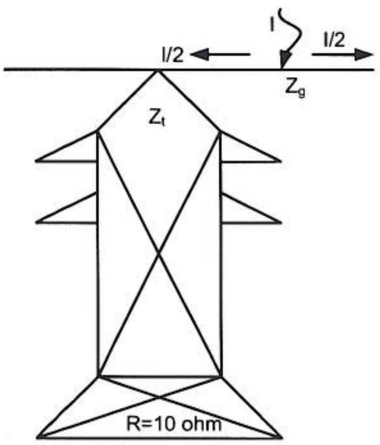
Power delivered by a transmission line at rated voltage terminated at its surge impedance is known as the natural load or surge impedance load (SIL).

- At SIL or natural load, reactive power generated by C is equal to that absorbed by L for each incremental line length
- No reactive power is generated or absorbed at either end of the line
- Voltage and current profiles are flat throughout the entire line length
- Capacity of a line is expressed in terms of its natural load or SIL

d) Lightning strikes the ground wire near a 30 m high transmission tower. Based on the following information, find the voltage that would appear across the line insulators after 0.2 μs from the lightning strike.

Lightning current: 15.0 kA, surge impedance of the ground wire: 500 ohms, surge impedance of the tower: 125 ohms, tower footing resistance: 10 ohms. Speed of propagation of the travelling wave through the tower: 3 x 10^8 m/s

[10]



Tower footing resistance

Time for travelling wave to reach the tower base is 30/300 = 0.1 μs

I = 15 kA, Z_g = 500 ohms, Z_t = 125 ohms

Incident overvoltage, $V_i = Z_g \times I/2 = 3750$ kV

At the junction $Z_{eq} = Z_g \parallel Z_t = 100$ ohms

Voltage transmitted on the tower $V_t = [2Z_{eq} / (Z_{eq} + Z_g)] \times V_i = 1250$ kV

Reflected voltage from tower footing (R = 10 ohms) $V_r = [(R-Z_t)/(R+Z_t)] \times V_t = -1064.8$ kV

Voltage across the insulators after 0.2 μs is $V = V_t + V_r = 185.19$ kV

4. a) *Explain why the power loss in a DC line is less than that in an AC line of equivalent power rating.*

[5]

For bipole HVDC, 2 DC lines can carry the same amount of power as 3 AC lines (in 3-phase AC systems) for equivalent conductor and insulator ratings. So for same transmitted power losses in DC is 2/3rd of that in AC.

Also skin effect is virtually absent for DC. So the effective area of conduction is more for AC as compared to DC which results in lower resistance and hence lower transmission losses for DC lines.

b) *State four major disadvantages of DC transmission.*

[5]

- Breaking DC currents, costly circuit breakers
- Transformers cannot be used to change voltage levels
- High cost of conversion equipment
- Generation of harmonics, costly filters
- Complexity of control

c) *Describe the impact on active and reactive power as the firing angle of a current source HVDC converter is varied from 0 to 180 degrees.*

[5]

As firing angle increases from 0 to 90 deg, active power transfer over the DC link, P decreases, but reactive power consumption, Q increases. From 90 to 180 deg, active power P is negative i.e. power flow reverses but reactive power, Q is still positive and is zero at 180 deg. Whether the converter is acting as rectifier or inverter it draws reactive power from the system.

d) *The inverter end of a CSC-HVDC link is operating at 200 kV drawing 2 kA. The ignition advance angle (β) is set at 40 degrees with a commutation overlap (μ) of 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 the inverter side ac system voltage that is permissible without causing commutation failure. Neglect any mode shift.*

[10]

$V_d = 200$ 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 %

5. a) *Why are the rectifier and inverter sides responsible for current and voltage (or extinction angle) control, respectively under normal operation?*

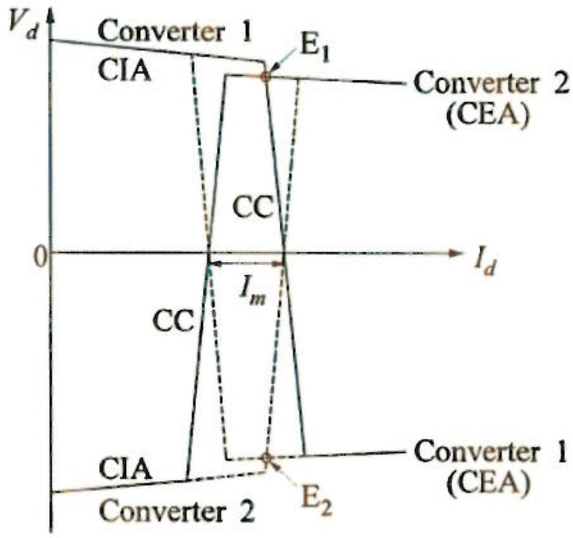
[5]

Normally current regulation is done by the rectifier and voltage (extinction angle) regulation by the inverter as:

- current control (a) at rectifier leads to less reactive power consumption at higher loadings
- current control at inverter worsens the power factor at high loadings as g has to be increased
- better voltage regulation is achieved
- fault currents are automatically limited with rectifier under current control

b) *Using the individual converter characteristics explain how power reversal is achieved in a current source converter (CSC) based HVDC link.*

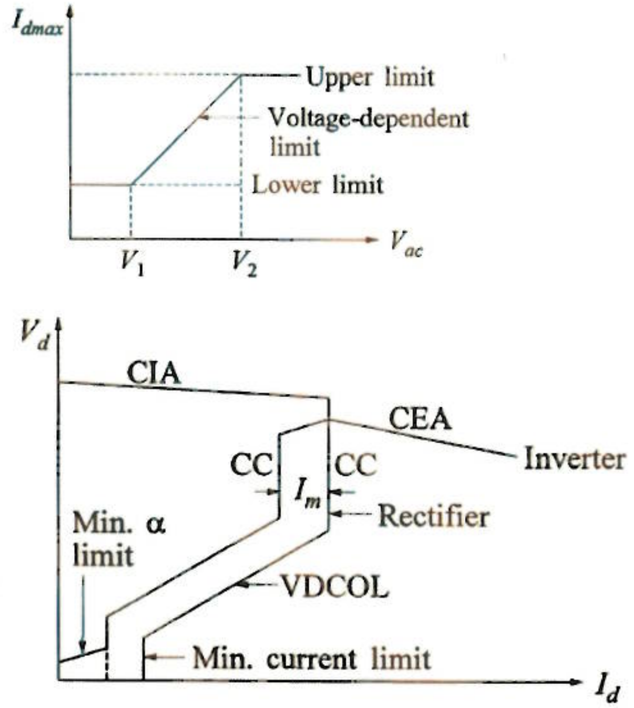
[5]



- Each converter is required to act as either rectifier or inverter and hence provided with a combined characteristics
- Solid lines represent power transfer from converter 1 to 2
- Reverse power flow for dotted line characteristics
- Power flow reversal is achieved by making the current order setting of converter 2 more than that of 1

Power transfer over dc lines is controlled and reversed) by current order and current margin setting *c) What is voltage dependent current order limit (VDCOL) and why is it important for converter control in HVDC links.*

[5]



- VDCOL reduces the current order when voltage (ac or dc) is below a threshold
- Constant current operation is not desirable under low voltage (inverter) condition as:
  - reactive power demand increases due to increase in a
  - reactive power supplied by the terminal filters and capacitors decreases with reduced voltage
  - risk of commutation failure and voltage instability

d) The rectifier (assume 6 pulse bridge) station of a CSC-HVDC link is fed from a 33/110 kV transformer. The rectifier is operated with a firing angle (α) of 20 degrees with a commutation overlap (μ) of 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.

[10]

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

6. a) *Why is the voltage source converter (VSC) technology a better choice compared to the traditional current source converter (CSC) based systems from the sub-sea cable point of view?*

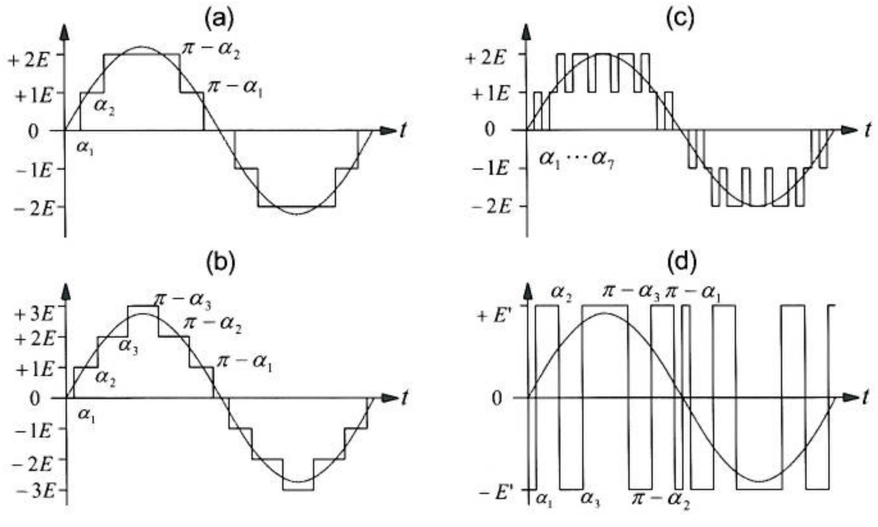
[5]

- VSC cables do not have to be designed for polarity reversal
- Simple cable design permitting polymeric (XLPE) insulation rather than mass impregnated which is the only option for CSC
- Polymeric insulation can withstand high stress, repeated flexing and suits deep water insulation better
- Galvanised steel wire armour can be used while AC/CSC cables need non-magnetic, less strong armour

b) *Explain the difference between pulse-width modulation (PWM) and multi-level approach for controlling voltage source converters (VSCs)*

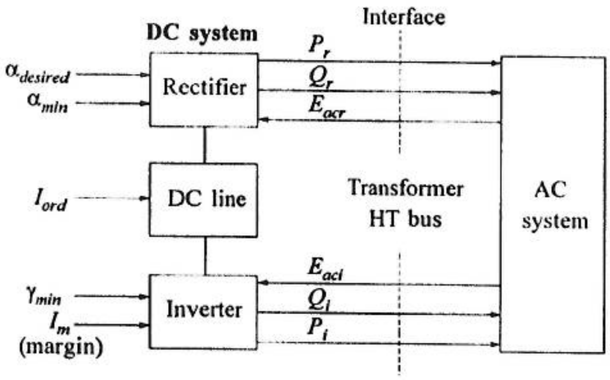
[5]

- Pulse-width modulation uses high frequency switching of a DC voltage to produce a specified fundamental component of controllable average magnitude. Desired fundamental and harmonic voltages are controlled by modulating the width of the voltage pulses.
- Multi-level converters switch between a number of available DC voltage levels to synthesise "staircase" approximations to sine waves.
- Two approaches can be combined as well.



c) Starting from the AC power flow equations describe the four steps towards power flow analysis for combined AC/HVDC systems. Assume current source converter (CSC) HVDC. No need to write the equations explicitly.

[5]



1) Solve AC power flow equations for E_{acr} and E_{aci} starting with initial values for P_r, Q_r, P_i, Q_i
2) Use E_{acr} and E_{aci} to solve DC side equations and update P_r, Q_r, P_i, Q_i
3) Solution of DC side equations depends on the control mode of rectifier and inverter
4) If mismatches in P_r, Q_r, P_i, Q_i are greater than a tolerance, go back to step 1 and solve AC power flow equations

d) State and explain three typical application areas where the voltage source converter (VSC) is almost essential for DC connection.

[5]

- Connecting wind farms to onshore power grids – lower offshore footprint, lighter, stronger sub-sea cables
- Providing shore power supplies to islands and offshore oil & gas platforms - – lower offshore footprint, lighter, stronger sub-sea cables
- Connecting weak grids like city centre in-feed, remote islands – lack of reactive power support

e) Explain one major advantage and a disadvantage of using the voltage source converter (VSC) technology for multi-terminal HVDC systems.

[5]

Advantage:
VSC allows fast and easy power reversal without changing the voltage polarity unlike the CSC where voltage polarity has to be reversed

Disadvantage:
For faults on the DC side of a VSC multi-terminal, the only way to clear the fault is open all the AC side circuit breakers. This leads to a complete shutdown of the multi-terminal system and could results in unacceptable loss-of-infeed for the terminal AC network utilities.