EE4-53 HVDC Technology and Control

Answer any 4 questions out of 5

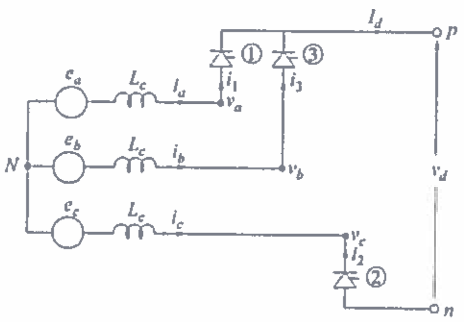
1. a) Explain why AC cables cannot be used for electric power transmission at high voltage levels and over long distances.

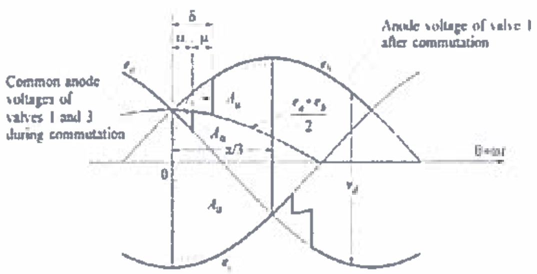
[5]

Cable capacitance is much higher than an equivalent overhead line. This is because separation of HV conductor from ground is more for overhead lines lines (to tower body) than cables (to sheath). Also an overhead line is insulated from the ground mostly by air whose permittivity is less than cable insulation (paper/polymer). Capacitance increases with increasing length of the cable. Hence, charging currents for AC cables could be prohibitively large for long distances and high voltages as charging VAr increase with square of voltage $Q = V^2/X_C$. This leaves very little capacity to transmit real/active power from one end of the cable to the other. Hence, AC cables cannot be used beyond a certain distance and above a certain voltage level.

b) For a six-pulse line commutated converter (LCC), derive an expression for reduction in the average DC voltage due to commutation overlap. The expression should be in terms of no-load ideal voltage, firing angle (α) and extinction angle (δ). Assume commutation overlap angle $\mu < 60°$.

[5]





Let's consider switches 1 and 3 are conducting simultaneously:

$$v_a = v_b = e_b - L_c\frac{di_3}{dt} = \frac{e_a + e_b}{2}$$

$$A_\mu = \int_\alpha^\delta e_b - \left(\frac{e_a + e_b}{2}\right) d\theta = \frac{E_m\sqrt{3}}{2}(\cos\alpha - \cos\delta)$$

Average reduction in voltage

$$\Delta V_d = \frac{A_\mu}{\pi/3} = \frac{E_m 3\sqrt{3}}{2\pi}(\cos\alpha - \cos\delta) = \frac{V_{d0}}{2}(\cos\alpha - \cos\delta)$$

c) A family of *P-Q* capability curves (only the part for positive P is shown) for a typical VSC HVDC converter is shown in Fig. 1.1 for three different values (U = 1.1 pu, 1.0 pu and 0.9 pu) of AC system voltage U. Explain the following:

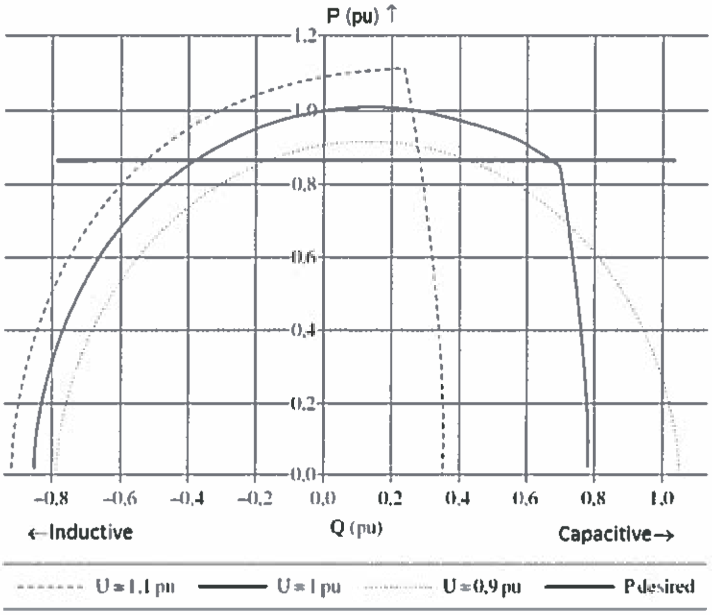


Figure 1.1: P-Q capability curves of a VSC

i) Why does reactive power generation capacity increase with decreasing AC system voltage?

[3]

The reactive power generation capacity is mainly dependent on the difference between the magnitudes of the AC voltage produced at the converter terminal and the AC system voltage. If the AC system voltage is high, the difference between the maximum converter terminal voltage and the AC voltage would be low resulting in moderate reactive power generation capability. For low AC system voltage the above difference and hence the reactive power generation capability increases.

ii) Why does MVA capacity reduce with AC system voltage?

[2]

Maximum MVA circle in the P-Q plane is decided by the product of the current rating of the IGBTs and the AC system voltage. As the AC system voltage goes down the above product i.e. the MVA capacity reduces.

d) Explain the implications of selecting a low or high droop constant (β_j) in the power-voltage droop control (shown in Fig. 1.2) used in converters to achieve autonomous power sharing within a DC grid.

[5]

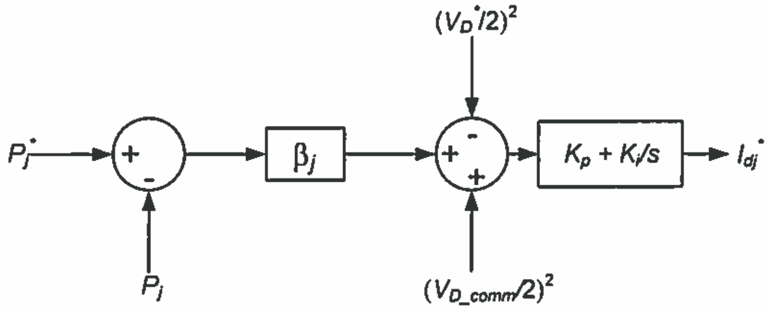


Figure 1.2: Power-voltage droop control for DC grid converters

If power-voltage droop constant is low, the contribution from a fixed power reference control loop is less. Hence the converter can participate more in power sharing i.e. it can take up more burden following an event (loss of another converter).

If the power-voltage droop constant is high, the converter tries to maintain a fixed power exchange. Thus it can contribute very little in autonomous power sharing.

Value of the power-voltage droop constants influences the stability of the overall AC-MTDC grid system and hence proper selection is critical for reliable system operation.

2. a) What are the consequences of interrupting the firing pulses to the thyristors without bypassing the converter bridge while attempting to block a LCC HVDC converter.

[4]

Interrupting firing pulse to all the switches could result in:

- overvoltage due to sudden drop in current
- continuous conduction through previously conducting phases at the inverter end placing the AC voltage on the DC line and direct current on the converter transformer

b) Describe the typical steps involved in ramping up the power level of an LCC HVDC link up to the rated condition starting from a completely de-energised state.

[5]

Typical starting sequence for an LCC HVDC link:

- Open bypass switch at one terminal
- Deblock that terminal with 60-70° firing angle and load to minimum current in rectifier mode
- Open bypass switch at the other terminal and close the bypass pair
- Deblock the second terminal in rectifier mode
- Put the inverter terminal into inversion mode
- Ramp up voltage first by inverter control and then current by rectifier control

c) Justify the range of acceptable values of firing angle (α) at the rectifier and extinction advance angle (γ) at the inverter end of an LCC HVDC link under normal operation.

[4]

- α and γ should be low for high power factor
- α should be above 4-5^0 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

d) The rectifier station of a bipole LCC HVDC link is connected to a 400 kV (line-to-line) 3-phase AC system through 400/200 kV transformers. Two 6-pulse converters are connected in series on the DC side. Under normal operation, each converter operates with a firing angle α=16° and overlap angle μ=22° which causes 1.8 kA current to flow through the DC line.

i) Calculate the commutating resistance (R_c).

[4]

$$V_{d0} = \frac{3\sqrt{2}}{\pi} BTE_{LL} = \frac{3\sqrt{2} \times 2 \times 0.5 \times 400}{\pi} = 540.19 \text{ kV}$$

$$V_d = \frac{V_{d0}}{2}(\cos\alpha + \cos(\alpha + \mu)) = 472.45 \text{ kV}$$

$$\Delta V_d = \frac{V_{d0}}{2}(\cos\alpha - \cos(\alpha + \mu)) = 46.79 \text{ kV}$$

$$R_c = \frac{\Delta V_d}{BI_d} = \frac{46.79}{2 \times 1.8} = 13\,\Omega$$

ii) Determine the reactive power consumed by each converter.

[3]

$$\cos\phi = \frac{V_d}{V_{d0}} = \frac{472.45}{540.19} = 0.875$$

$$Q_{\text{total}} = V_d I_d \tan\phi = 470.52 \text{ MVAr}$$

Q for each converter is 235.26 MVAr

3. a) A point-to-point LCC HVDC link is embedded within an interconnected AC system. Describe using a block diagram how power flow analysis is carried out for such an AC/DC system. There is no need to use any equation.

[5]

b) State the main advantage and disadvantage of equidistant pulse control (EPC) approach over individual phase control (IPC) in the context of firing angle control of LCC HVDC systems.

[4]

- IPC relies on zero crossing of commutation voltage and is thus susceptible to distortions leading to harmonic instability - hardly used nowadays
- For EPC the thyristors are fired independent of the zero crossing of commutation voltage – so this scheme is more immune to harmonic problems
- With EPC less DC voltage is produced under unbalance condition

c) For a point-to-point LCC HVDC link, explain why the rectifier side is usually set up to control the current while the inverter side controls the voltage under normal operation.

[4]

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

- current control 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 at the receiving (load) end
- fault currents are automatically limited with rectifier under current control

d) A monopolar LCC HVDC link is operating with a rectifier terminal voltage V_{dr} = 500 kV and rated current I_d = 2.0 kA flowing through the DC line. The following information is available:

Minimum limit for firing angle α_{min} = 4°,
Minimum limit for extinction advance angle γ_{min} = 10°,
Resistance of DC line R_{line} = 2.0 Ω,
Firing angle α = 18°,
Extinction advance angle γ = 18°,
Margin current I_m = 180 A

The commutating resistances for both rectifier and inverter is R_c = 3.0 Ω. Due to a remote short circuit in the rectifier side AC system, the AC voltage at the rectifier end drops by 20%. Calculate the percentage increase in reactive power drawn by the inverter from pre-fault condition. Assume no change in inverter side AC voltage as a result of the above fault.

[7]

Pre-fault

$$V_{d0r} = \frac{V_{dr} + R_c I_d}{\cos\alpha} = \frac{500 + 3 \times 2}{\cos 18} = 532.04 \text{ kV}$$

$$V_{di} = V_{dr} - R_{\text{line}} I_d = 496 \text{ kV}$$

$$V_{d0i} = \frac{V_{di} + R_c I_d}{\cos\gamma} = \frac{496 + 3 \times 2}{\cos 18} = 527.83 \text{ kV}$$

$$\cos\phi_i = \frac{V_{di}}{V_{d0i}} = \frac{496}{527.83} = 0.94$$

$$Q_i = V_{di} I_d \tan\phi = 360.05 \text{ MVAr}$$

During fault

$$V'_{dor} = 0.8 \times V_{dor} = 425.62 \text{ kV}$$

$$\cos\alpha' = \frac{V_{dr} + R_c I_d}{V'_{dor}} = \frac{500 + 3 \times 2}{425.62} > 1$$

Rectifier is stuck at minimum firing angle and inverter takes up current control

$$I'_d = I_d - I_m = 1.82 \text{ kA}$$

$$V'_{dr} = V'_{d0r} - R_c I'_d = 420.16 \text{ kV}$$

$$V'_{di} = V'_{dr} - R_{\text{line}} I'_d = 416.52 \text{ kV}$$

$$\cos\phi'_i = \frac{V'_{di}}{V_{d0i}} = \frac{416.52}{527.83} = 0.79$$

$$Q'_i = V'_{di} I'_d \tan\phi'_i = 588.32 \text{ MVAr}$$

% change in Q

$$\frac{Q'_i - Q_i}{Q_i} \times 100 = 63.4\%$$

4. a) Explain how a proactive hybrid DC circuit breaker is able to interrupt DC fault currents
very fast while ensuring minimal power losses under normal operation.

[4]

- During normal operation the load current flows through auxiliary breaker while the current through the main breaker is zero
- Once the pre-set overcurrent threshold is exceeded, the current is immediately commutated from the auxiliary breaker to the main breaker which operates like a solid-state DC breaker
- Mechanical disconnector is then opened and as soon as it is in a position to block the recovery voltage, the main breaker could be switched off without arcing which makes the operation very fast
- Power losses incurred in a proactive hybrid breaker is much less than a solid-state breaker as there are significantly less number of IGBTs in the main current flow path

b) What are the main considerations towards designing the compensator *H(s)* used within a phase-locked loop (PLL), shown in Fig. 4.1, which is used for tracking the reference angle $\theta_s(t)$.

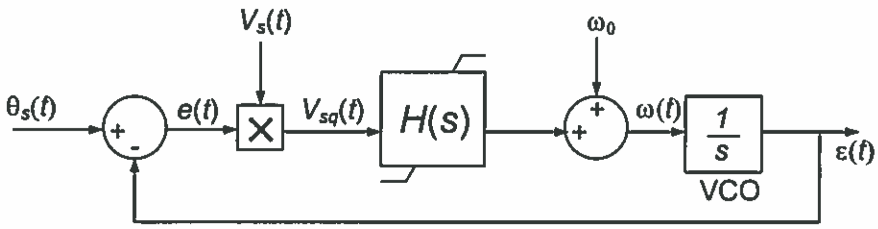


Figure 4.1: Block diagram of a phase-locked loop (PLL)

[4]

- Objective is to design $H(s)$ to track $\theta_s(t)$ accurately and fast
- Input $\theta_s(t)$ is ramp function of time - so the compensator $H(s)$ must have at least one pole at the origin (s=0) to ensure type 2 system required to obtain zero steady-state error
- In its simplest form $H(s)$ could be a PI controller which offers a pole at the origin
- More sophisticated compensator is required to filter out the double frequency pulsations due to unbalance in system voltage

c) Justify the use of inner-loop current control instead of voltage control for VSC HVDC systems.

[4]

For voltage mode control

- P and Q controlled directly by the phase angle and magnitude of VSC terminal voltage w.r.t system voltage which is easy to implement but could result in unacceptably large currents through the switches during AC side faults

- Poor transient performance as power control through control of voltage magnitude and phase angle is based on steady-state relationship

- Control becomes challenging due to low reactance in multi-level VSCs

For current mode control

- P and Q controlled by controlling the AC side current w.r.t. system voltage

- VSC is protected against over current due to AC side faults as reference currents could be constrained by imposing limits

d) Why VSC HVDC is the preferred option for connecting remote offshore wind farms to the onshore grid?

[4]

- No reactive power requirement and less (or no) filtering requirement for VSC. As a result the converter footprint is much less compared to an equivalent LCC. This is attractive for offshore application as there is very little space on offshore platforms

- Stronger and lighter XLPE cables suited for sub-sea applications can be used only for VSC as no voltage polarity reversal is involved.

- VSC can provide voltage support/reactive power compensation for wind farm (if required) unlike LCC where additional compensation devices (e.g. STATCOM) might be required offshore

e) A remote offshore wind farm is connected to the onshore grid through a point-to-point VSC HVDC link. Which variables are likely to be controlled by the outer loop control of the offshore and onshore converters and why?

[4]

- Offshore converter should set the voltage and frequency of the wind farm collection grid so that whatever active power is produced by the wind farm is transmitted on to the DC link. It is difficult to operate the offshore converter with active power control as the active power reference would have to be set according to the fluctuating power output of the wind farm.

- Onshore converter should maintain the DC link voltage and could either regulate the voltage at the onshore connection point or the amount of reactive power exchange.

5. a) Explain the difference between a half-bridge and full-bridge modular multi-level converter (MMC) in terms of the following:

i) DC fault current interruption capability and

[3]

For a half-bridge MMC

- Following a DC cable fault the IGBTs are blocked but the anti-parallel diode provide an uncontrolled path for the fault current
- AC side continue to feed the fault current until AC circuit breakers operate to isolate the entire DC grid

For a full-bridge MMC

- Each module can produce positive, negative or zero voltage
- Following a DC side fault (drop in DC side voltage) the modules can produce a voltage of proper polarity to oppose the AC side voltage and thus control the fault current

ii) Power losses

[3]

- Power losses are more for a full-bridge MMC as two semiconductors are always present in the current path as opposed to just one for a half-bridge MMC

b) Mention three main challenges towards protecting a VSC HVDC system.

[3]

Protecting a VSC HVDC system is more difficult than protecting AC systems:

- In DC cable systems, rate of rise and steady-state value of short circuit currents is very high
- VSCs are very sensitive to overloads and need to be protected against any over-current
- Identifying the faulted cable is not trivial and traditional AC protection methods (e.g. impedance relays) cannot be used
- Time available for the protection system to act is very little (only about 1-2 ms)

c) Explain why VSC is preferred over LCC for sub-sea HVDC cables.

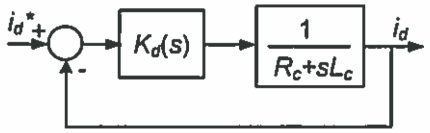
[4]

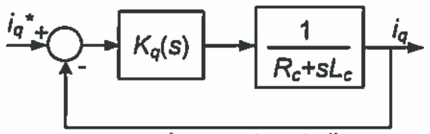
- No reversal of voltage polarity in VSC cables unlike a LCC HVDC link
- Hence stronger and lighter XLPE cables can be used for VSC unlike LCC where a mass-impregnated (MI) cable is the only option
- XLPE can withstand high stress, repeated flexing and suits deep water insulation better which is not the case with MI

d) The current control loop of an active and reactive power controller is to be designed for one end of a 2-level VSC HVDC converter. The DC side is interfaced to the AC system through a phase reactor having resistance R_c = 0.75 mΩ and inductance L_c = 100 μH. The VSC uses PWM with 3.4 kHz switching frequency. Assume ideal phase-locked loop (PLL) and use of appropriate feed-forward resulting in two decoupled control loops. The objective is to make the VSC follow a given active and reactive power reference command. Calculate the proportional and integral gains (K_p, K_i) required for the PI compensators in the current control loop to achieve fastest possible reference tracking performance. Ensure that the closed-loop bandwidth is limited to one-tenth of the switching frequency. Neglect the on-state resistance of IGBTs and diodes.

[7]

With appropriate feed forward cancellation the d and q axis control loops can be decoupled as follows:





q-axis current controller

The compensators would be identical for both loops as the plants are identical.

$$K_d(s) = K_q(s) = K_p + \frac{K_i}{s}$$

Loop gain

$$L(s) = \frac{sK_p + K_i}{s} \times \frac{1}{R_c + sL_c} = \left(\frac{K_p}{sL_c}\right)\frac{s + {K_i}/{K_p}}{s + {R_c}/{L_c}}$$

The plant pole is cancelled by the compensator zero $s = -{}^{K_i}/_{K_p}$

The objective is to achieve a closed-loop response with desired time constant τ i.e.

$$T(s) = \frac{L(s)}{1 + L(s)} = \frac{1}{1 + \tau s}$$

$$L(s) = \frac{K_p}{L_c} = \frac{1}{\tau} \rightarrow K_p = \frac{L_c}{\tau}; \quad K_i = \frac{K_p R_c}{L_c} = \frac{R_c}{\tau}$$

$$\tau \geq \frac{1}{10 \times 3.4 \times 10^3} = 2.9 \text{ ms}$$

$$K_p = \frac{L_c}{\tau} = \frac{100 \times 10^{-3}}{2.9} = 0.034; \quad K_i = \frac{R_c}{\tau} = \frac{0.034}{2.9 \times 10^{-3}} = 11.72$$