IMPERIAL COLLEGE LONDON

EE4-53
EE9-FPN1-02

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2018

EEE PART IV: MEng and ACGI

Corrected copy

HVDC TECHNOLOGY AND CONTROL

Tuesday, 8 May 10:00 am

Time allowed: 2:00 hours

There are THREE questions on this paper.

Answer ALL questions

Question 1 & 2 carries 25 marks each, Question 3 carries 30 marks

Any special instructions for invigilators and information for candidates are on page 1.

Examiners responsible First Marker(s) : B. Chaudhuri

Second Marker(s) : A. Junyent-Ferre

Answer ALL Questions

Question 1 and 2 carries 25 marks each, Question 3 carries 30 marks

1. a) For an AC system with an embedded LCC HVDC link, state the main steps for solving the combined AC-DC power flow problem using a sequential approach. There is no need to write any analytical expression relating the AC and DC side quantities.

[4]

b) During normal operation of an LCC HVDC link, the rectifier and the inverter operate in current and extinction angle control mode, respectively.

(i) Under such normal condition, how are the firing angles and transformer tap settings determined at the two ends? There is no need to write any analytical expression.

[4]

(ii) If the rectifier end is stuck at the minimum permissible firing angle, the inverter end takes up the current control. Under such condition, how are the firing angles and transformer tap settings determined at the two ends? There is no need to write any analytical expression.

[4]

c) For weak AC systems, a short circuit far from the LCC HVDC terminal could cause the HVDC link to shut down due to a potential runaway problem if the direct current order is held constant.

(i) Explain this runaway problem and its dependence on the AC system strength.

[5]

(ii) How is the converter control strategy modified to mitigate the above problem?

[3]

d) Explain the design trade-offs for the smoothing reactors used on the DC side of a LCC HVDC link.

[5]

2. a) For LCC HVDC links, power flow direction is reversed by changing the polarity of the direct voltage as the direction of direct current is fixed. Explain the implication of this on the following:

(i) Type of sub-sea cables used

[2]

(ii) Implementation of a meshed DC grid

[2]

b) Neglecting commutation overlap and converter losses, show that the power factor of a typical six-pulse converter used in LCC HVDC links is the ratio of the average direct voltage and the no-load ideal direct voltage. The RMS value of the fundamental component of the AC side current can be considered as $\sqrt{6}I_d/\pi$ where I_d is the constant ripple-free direct current.

[4]

c) Two separate AC systems with rated 3-phase line voltages of 400 kV and 380 kV are interconnected through a 1000 MW, ±450 kV bipole LCC HVDC link. At both converter stations, a standard 12-pulse converter arrangement is used for each pole with a commutation resistance of 8 Ω for each 6-pulse bridge. The converter station at the 400 kV end acts as the rectifier and controls the direct current at its rated value with the firing angle set at 15°. The inverter end maintains the rated direct voltage with an extinction angle of 16°. The current margin is set at 20%. The minimum limit in firing angle at the rectifier end is 6°. The DC cable resistance is 5 Ω for each pole. Neglect the converter losses.

(i) For the above base case, calculate the reactive power drawn by the converter stations at both ends.

[5]

(ii) If the AC voltage at the rectifier end drops by 10% while that at the inverter end remains at the initial value, compute the change in reactive power drawn by the converter stations at both ends compared to the base case and the new extinction angle (in degrees) at the inverter end.

[6]

(iii) If the AC voltage at the inverter end drops by 15% while that at the rectifier end remains at the initial value, compute firing angle at the rectifier end and the commutation overlap angle (in degrees) at both ends.

[6]

For part (ii) and (iii), neglect transformer tap-changer action and do not consider activation of voltage dependent current order limit (VDCOL).

3. a) Answer the following questions related to the converter shown in Figure 3.1:

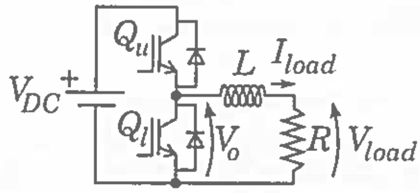

Figure 3.1 – Diagram of a DC-DC converter feeding a resistive load.

(i) What is the Laplace transfer function between $V_o(s)$ and $I_{load}(s)$?

[3]

(ii) A closed-loop controller is used to control I_{load}. The closed-loop transfer function between the current reference, I_{load}*, and the load current, I_{load}, is:

$$\frac{I_{load}(s)}{I^{*}_{load}(s)} = \frac{1}{\tau_c s + 1}$$

with τ_c =2 ms.

- What will the steady-state error be for constant I_{load}* reference values?

[2]

- What will the approximate settling time be for step changes of the I_{load}^* reference?

[2]

- What will the amplitude of I_{load} be if we requested a sinusoidal current of amplitude 1 A and 50 Hz of frequency (specifically: $I^{*}_{load}(t) = \sin(2\pi 50\ t)$)?

[4]

b) Answer the following questions related to the steady-state AC analysis of the three-phase inverter shown in Figure 3.2.

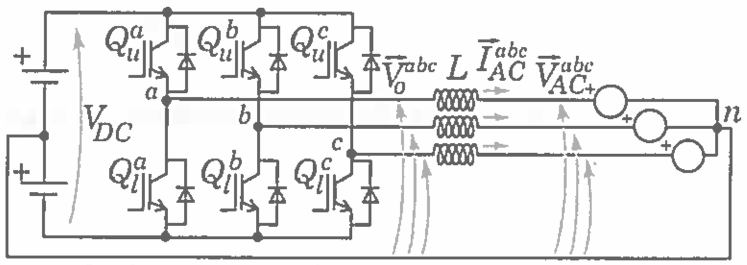

Figure 3.2 – Diagram of an inverter connected to an AC network represented as an AC voltage source.

(i) Calculate the output current I_{AC} for the inverter to deliver P=3kW and Q=300 VAr to the AC network (the converter generates reactive power) if V_{AC}=230V (rms phase-to-neutral voltage).

[4]

(ii) What voltage V_o does the converter need to apply in order to operate under the aforementioned conditions if the filter reactance is $X_L = 10\ \Omega$?

[2]

(iii) What is the minimum V_{DC} required in order for the converter to be able to generate the aforementioned output voltage V_o? Would this answer to this question change if we removed the connection between the DC bus and the neutral point?

[3]

c) A single-arm converter is used to exchange energy between an AC network and a DC network (see Figure 3.3). Answer the following questions related to this converter:

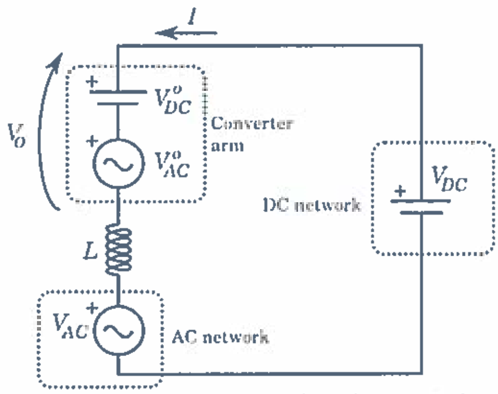

Figure 3.3 – Diagram of a single-arm AC-DC converter exchanging power between an AC network and a DC network.

(i) Write the AC and DC steady-state equations that relate voltages and currents in the circuit.

[3]

(ii) Explain briefly what condition has to be met for the converter arm to have zero net power balance.

[2]

d) An HVDC link with a rated voltage of V_{DC}^{RATED} =320kV and a rated power of 500 MW is protected using a power-electronic HVDC circuit breaker (CB) with a chain of IGBTs in parallel with a chain of varistors. The varistors of the CB are chosen for a clamping voltage of 1.5 times V_{DC}^{RATED} and the IGBTs of the CB have an effective blocking voltage capability of 2 kV. Answer the following questions:

i) How many IGBTs will the CB need?

[2]

ii) Calculate the conduction power losses of the converter when operating at rated power considering that the voltage drop of a single IGBT is approximately:

$$V_{IGBT}(I_{IGBT}) = 2V + 0.8 \times 10^{-3} V/A \times I_{IGBT}$$

[3]