IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2015

EEE PART IV: MEng and ACGI

HVDC TECHNOLOGY AND CONTROL

Corrected Copy

Thursday, 30 April 10:00 am

Time allowed: 3:00 hours

There are SIX questions on this paper.

Answer 2 questions from Part A and 2 questions from Part B. Use a separate answer book for each section.

All questions carry equal marks.

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

Examiners responsible First Marker(s) : A.S. Chaudhuri, M. Merlin
Second Marker(s) : B.C. Pal

Part A: Answer any 2 questions out of 3 from this part

1. a) Explain two major drawbacks of using the line commutated converter (LCC) technology for connecting offshore wind farms through HVDC links.

[5]

b) State and explain two problems that are only likely to be encountered at the inverter end of a LCC HVDC link but not at the rectifier end.

[5]

c) Considering a non-zero overlap angle (μ) less than 60°, determine the firing angle (α) at which the reactive power drawn by the 6-pulse rectifier of a LCC HVDC link would be maximum.

[5]

d) Discuss the role of commutation resistance in the context of LCC HVDC and explain physically (not using analytical expressions) what decides the value of the commutation resistance. There is no need to derive any expression.

[5]

2. a) What are the three important considerations towards designing the smoothing reactor for a LCC HVDC link?

[5]

b) Explain how a short circuit on a LCC HVDC overhead line is detected, limited and cleared.

[5]

c) Consider a set of balanced 3-phase voltages with a-b-c phase sequence. The expression for phase 'a' voltage (e_a) is given below in equation (2.1). Using this, derive an expression for the no-load ideal direct voltage (V_{d0}) for a 6-pulse LCC in terms of the AC line voltage (E_{LL}). Neglect firing delay (α) and commutation overlap (μ).

$$e_a = E_m \sin \omega t \tag{2.1}$$

[5]

d) Describe the roles of bridge control, pole control, master control and system level control as part of LCC HVDC control hierarchy.

[5]

3. The planned 2.2 GW, ±600 kV (bipole) Western HVDC link in the UK would be connected to the 400 kV AC grid at Hunterston and Connah's Quay terminals. The resistance of the DC cable in each pole is 2.0 Ω. Under normal condition, the HVDC link operates with the rectifier end controlling the direct current (I_d) and the inverter end maintaining a constant extinction advance angle (γ) with the following:

Commutation resistance at each end $R_{cr} = R_{ci} = 3.0\ \Omega$
Firing angle at the rectifier end $\alpha = 12°$
Extinction advance angle at the inverter end $\gamma = 18°$
Minimum firing angle limit $\alpha_{llim} = 5°$
AC line voltage at the rectifier bus $E_r = 405$ kV
Direct current through the link $I_d = 1.8$ kA
Current margin $I_m = 15\%$

A short-circuit within the AC system nearer to the inverter end (Connah's Quay terminal)) causes a 20% reduction in AC voltage on the inverter bus and a 2% reduction in AC voltage at the rectifier bus. Considering the ±600 kV bipole Western HVDC link as an equivalent 1200 kV monopolar link with 12-pulse converters (as shown in Figure 3.1) calculate the following: Neglect activation of VDCOL and change of transformer tap ratio due to the short-circuit.

i) Active and reactive power at both ends under normal condition. [4×3]

ii) Firing angle (in degrees) of the rectifier under short-circuit condition. [4]

iii) Active and reactive power at both ends under short-circuit condition. [4×1]

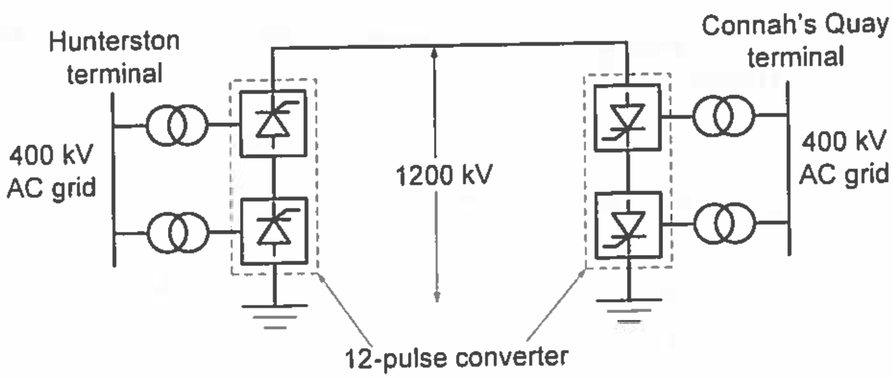

Figure 3.1 - Equivalent monopolar representation of planned Western HVDC link

Part B: Answer any 2 questions out of 3 from this part

4. Classic Voltage Source Converter

a) Present the differences (both pros and cons) between Voltage Source Converters (VSC) and Current Source Converters (CSC) and especially why cable-based transmission HVDC schemes (e.g. offshore windfarms) are based on VSCs?

[4]

b) Explain using a simple drawing of a P-Q diagram the maximum active and reactive power conversion capability of a classic VSC, especially what are the main limiting factors under varying AC voltage magnitudes (e.g. 0.9-1.1 pu).

[4]

c) A 900 MW Voltage Source Converter (VSC) is shown in Figure 4.1. It is connected to a 400 kV (line-to-line) AC grid at 50 Hz and a DC network at ±350 kV.

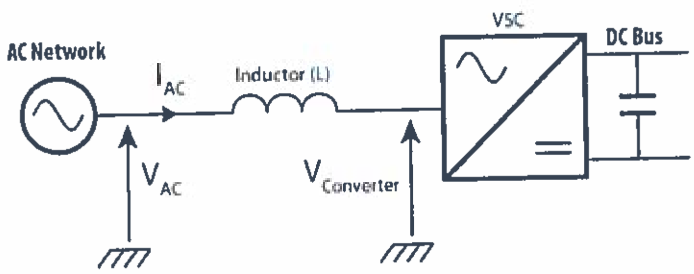

Figure 4.1: Voltage Source Converter

i) When the converter is inverting 600 MW (power going from DC to AC) and generating 300 MVAr of capacitive reactive power, compute the magnitude and phase angle of the AC current.

[3]

ii) Assuming that the phase reactors are 190 mH, compute the magnitude and angle of the converter voltage.

[3]

iii) Determine the modulation index at which the VSC is running?

[2]

d) Draw the electrical diagram of a hybrid DC circuit breaker and explain how it operates, detailing the timing and rating criteria of the different elements of the breaker.

[4]

5. Modular Multilevel Converter

a) Explain the working principles of the Modular Multilevel Converter topology.

[5]

b) A 1.2 GW MMC is connected to the latest DC cable technology rated a ±525 kV. Assuming that each half-bridge submodule is rated at 2 kV.

i) Compute a device count for: the number of IGBT module, submodule capacitors.

[3]

ii) Estimate the minimal capacitance of the cell capacitors assuming that their voltage has to be kept within ±10% of their nominal value and the maximum peak-to-peak energy deviation of a stack is 2.546 MJ for the specified operating envelope of this converter.

[3]

iii) Calculate the total capacitive energy stored per unit power (provide the answer in kJ/MVA).

[3]

c) Explain how the Double Clamped Submodule, shown in Figure 5.1, operates.

[6]

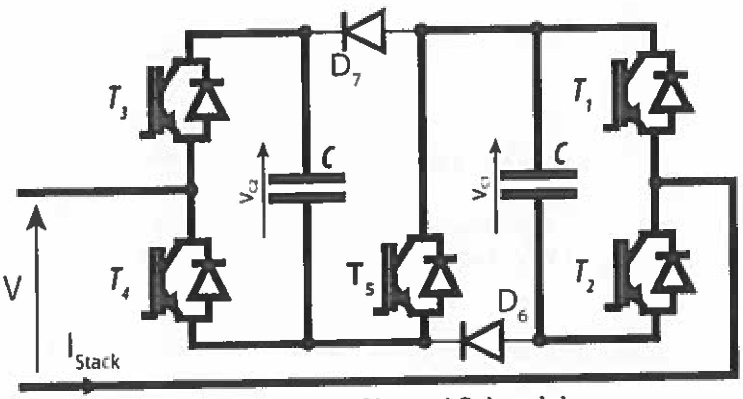

Figure 5.1: Diode Clamped Submodule

6. Alternate Arm Converter

a) Explain how the Alternate Arm Converter (shown in Figure 6.1) operates. [5]

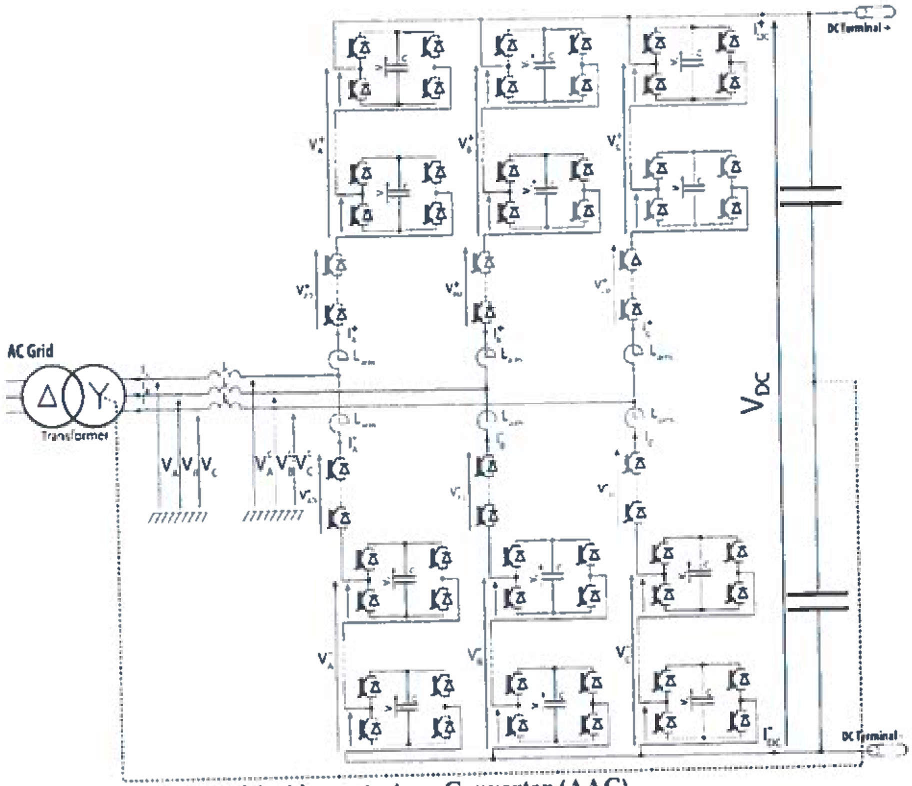

Figure 6.1: Alternate Arm Converter (AAC)

b) A 1.2 GW AAC, operating with 25-degree overlap is connected to the latest DC cable technology rated a ±525 kV. Assuming that each H-bridge submodule is rated at 2 kV.

i) Compute a device count for: the number of IGBT module, submodule capacitors. [3]

ii) Estimate the minimal capacitance of the cell capacitors assuming that their voltage has to be kept within ±10% of their nominal value and the maximum peak-to-peak energy deviation of a stack is 765 kJ for the specified operating envelope of this converter. [3]

iii) Calculate the total capacitive energy stored per unit power (provide the answer in kJ/MVA). [3]

d) During a DC fault event, the AAC can act as a STATCOM and provide reactive power to the grid without the need for a DC bus. Assuming only the bottom stacks are operating and ignoring the inductors' voltage drops, as illustrated in Figure 6.2, calculate the maximum reactive power that a 50 Hz AAC can provide before the 2.5 mF capacitors in its 400 submodules per stack exceed their designed maximum voltage deviation of ±10%.

[6]

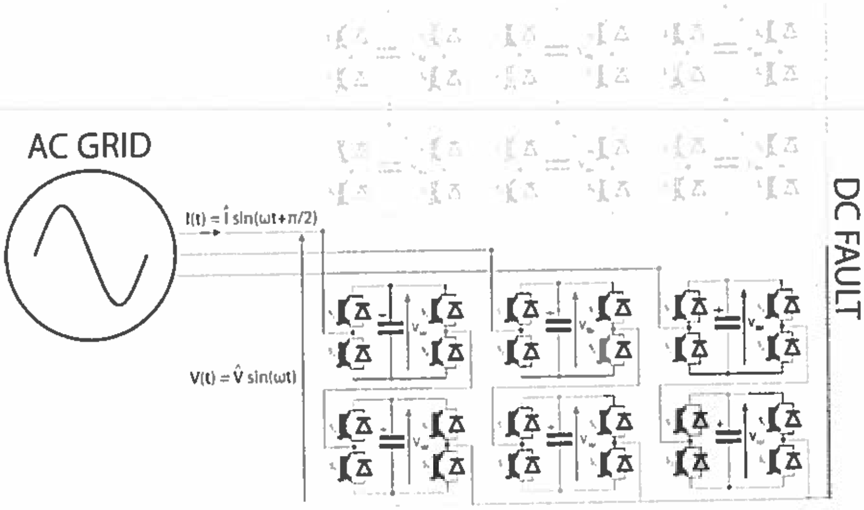

Figure 6.2: AAC as STATCOM

Clue I: For this, it is recommended (i) to find the equation describing the instantaneous power of a stack, (ii) from this obtain the energy equation of a stack, (iii) find the min and max points as a function of the amount of reactive power and (iv) conclude on the maximum power.

Clue II: The relationship between peak-to-peak energy deviation of a single stack and the size of its submodule capacitors for a given maximum relative voltage deviation is: $\Delta E = 2\ N_{SM}\ V_{SM}^2\ \Delta V\ C$ and also use $Q = 3\frac{\hat{V}\hat{I}}{2} = 3\ V_{RMS}\ I_{RMS}$