IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2013

EEE PART IV: MEng and ACGI

FACTS AND POWER ELECTRONICS

Wednesday, 15 May 10:00 am

Time allowed: 3:00 hours

There are SIX questions on this paper.

Answer FOUR questions.

All questions carry equal marks.

Please use a separate answer book for Sections A and B.

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

Examiners responsible	First Marker(s) :	T.C. Green, B.C. Pal
	Second Marker(s) :	B.C. Pal, T.C. Green

Special instructions for invigilators

None

Special instructions for students

Use separate answer book for Part A and Part B

Part A

1.

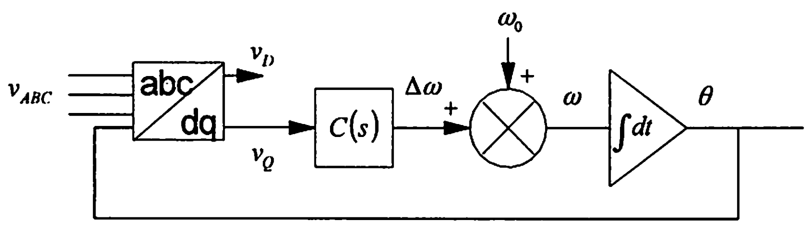
(a) **Explain in outline how the DQ transform is achieved and what advantageous properties it has for the design of controllers for power converters.** [4]

The DQ transform is achieved in two steps. The first transform treats the three-phases as being mutually 120° apart in space and resolves them onto two orthogonal axes, alpha and beta. A third term (or axis) is formed by finding the common-mode/zero-sequence term. The second stage applies a backward rotation to the alpha and beta terms such that if they were a positive sequence set they will become stationary.

The advantage is that for normal conditions, in which a three-phase system is balanced and composed of positive sequence sets of voltages and currents, all variables become stationary (no rotation) under the DQ transform and only the variations in amplitude and phase angle remain. Common tasks such as regulating a three-phase sets now become a task of regulating the transformed variable to be constant which is often easily achieved with a PI controller in contrast to following a sinusoidal reference in ABC form.

(b) **Explain how a DQ transform can be used to form the phase-comparator of a phase-locked loop.** [4]

The DQ block will be arranged as shown



with the angle used for the rotation being supplied by the local oscillator (an integration of the local frequency here). Assuming a balance three-phase input, the DQ transform will produce outputs of

$$v_D = V\cos(\theta_G - \theta_A)$$

$$v_Q = V\sin(\theta_G - \theta_A)$$

If the PLL is close to lock and the angle is small this approximates to:

$$\theta_G - \theta_A \approx 0$$

$$v_D \approx V$$

$$v_Q \approx V \times (\theta_G - \theta_A)$$

In which the Q-axis term becomes proportional to the phase difference and therefore acts as an indication of phase error.

(c) **Figure Q1 shows a DC/AC power converter with a connection to a three-phase grid via interface inductors. The inductors have some series resistance in addition to their inductance and the currents have been marked for a convention in which the normal power flow is AC to DC. This converter will have two layers of control: an inner current controller (for the AC currents) and an outer voltage controller (for the DC link voltage). The power converter is equipped with a pulse-width modulator to convertr voltage references into appropriate signals for driving the switching elements.**

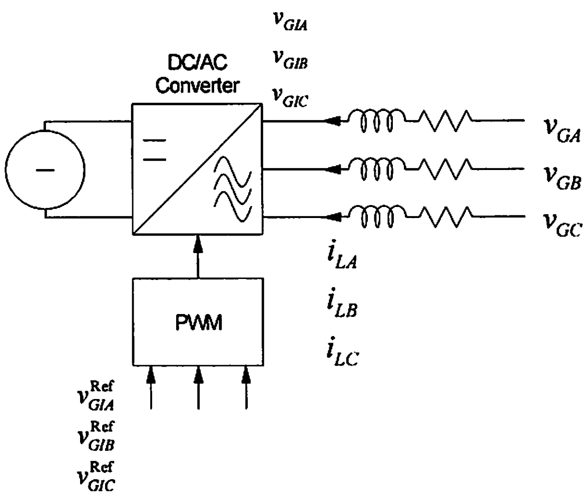


Figure Q1 – DC/AC Power Converter with Coupling Inductor and Pulse-Width Modulator

(i) Write Kirchhoff's Voltage Laws equations for the AC-side in ABC and DQ form. [4]

In phase coordinate form:

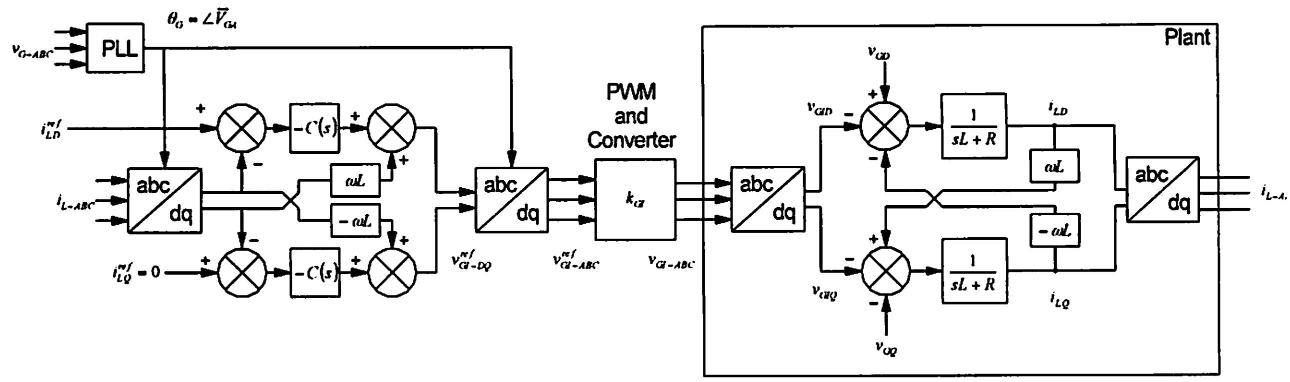
$$\frac{di_{LA}}{dt} = \frac{1}{L}\left(v_{GA} - v_{GIA} - R_L i_{LA}\right)$$

In DQ form:

$$\frac{di_{LD}}{dt} = \frac{1}{L}\left(v_{GD} - v_{GID} - \omega L \times i_{LQ} - R_L i_{LD}\right)$$
$$\frac{di_{LQ}}{dt} = \frac{1}{L}\left(v_{GQ} - v_{GIQ} + \omega L \times i_{LD} - R_L i_{LQ}\right)$$

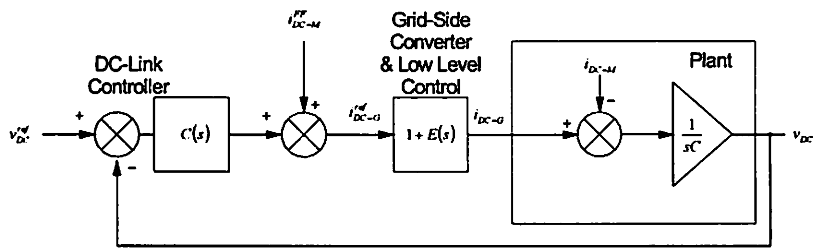
(ii) Sketch and describe the form of the current controller including any transformation blocks needed. [4]

A two channel controller is needed, one for the D-axis and one for the Q-axis. Feedback from the plant of the current is passed through an ABC to DQ transform in which the angle is supplied by a PLL. The current controller is formed using a difference block to identify the current error which is applied to a control gain to yield a voltage to be applied to the inductor by the power converter. Since there are known coupling terms in the plant that create voltage drops in one axis due to current flow in the other, we can apply feed-forward decoupling terms.



(iii) **Sketch and describe the form of the voltage controller.** [4]

The voltage controller applies an error in the DC link voltage to a control gain which then sets the current needed to be drawn in via the power converter from the DC side. This is designed assuming that the converter and its inner control loop form a near-perfect controlled current source. If the DC current drawn from the DC link is known it can be added as a feed-forward term.



2.

(a) Sketch phasor diagrams of the phase voltages and phase current of a Voltage Source Converter, (VSC) for operation in all 4 quadrants of the P-Q plane. Use the current and voltage conventions illustrated in Figure Q2. [3]

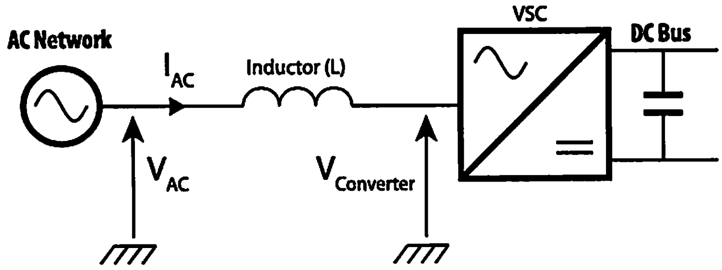
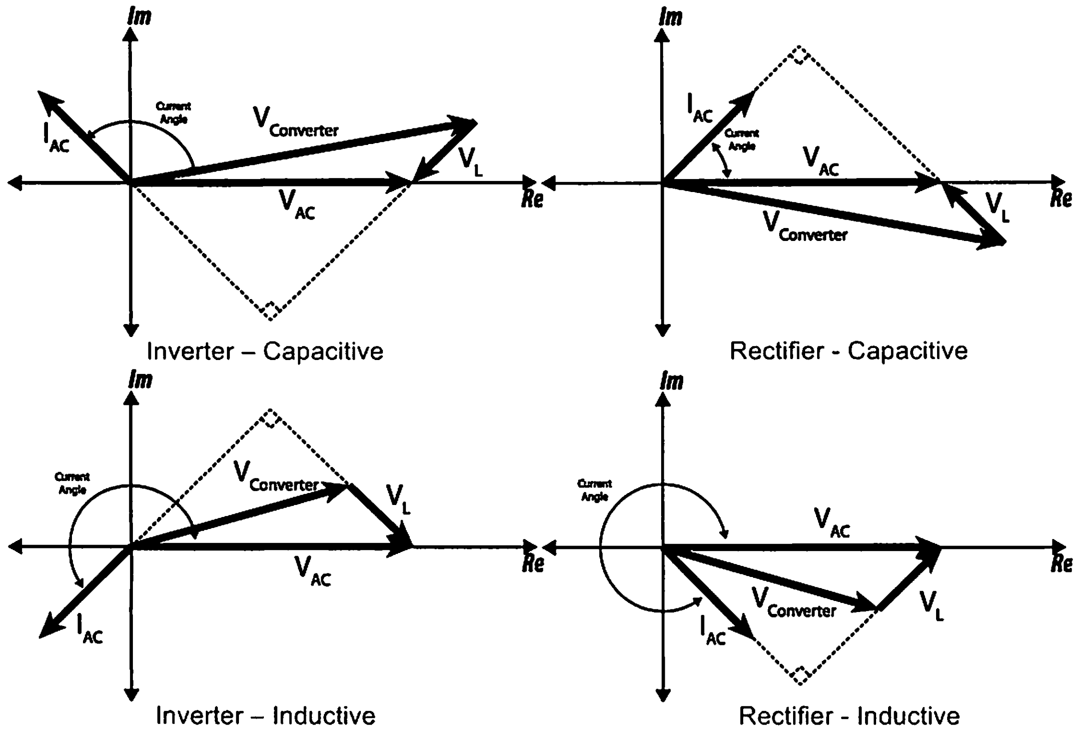


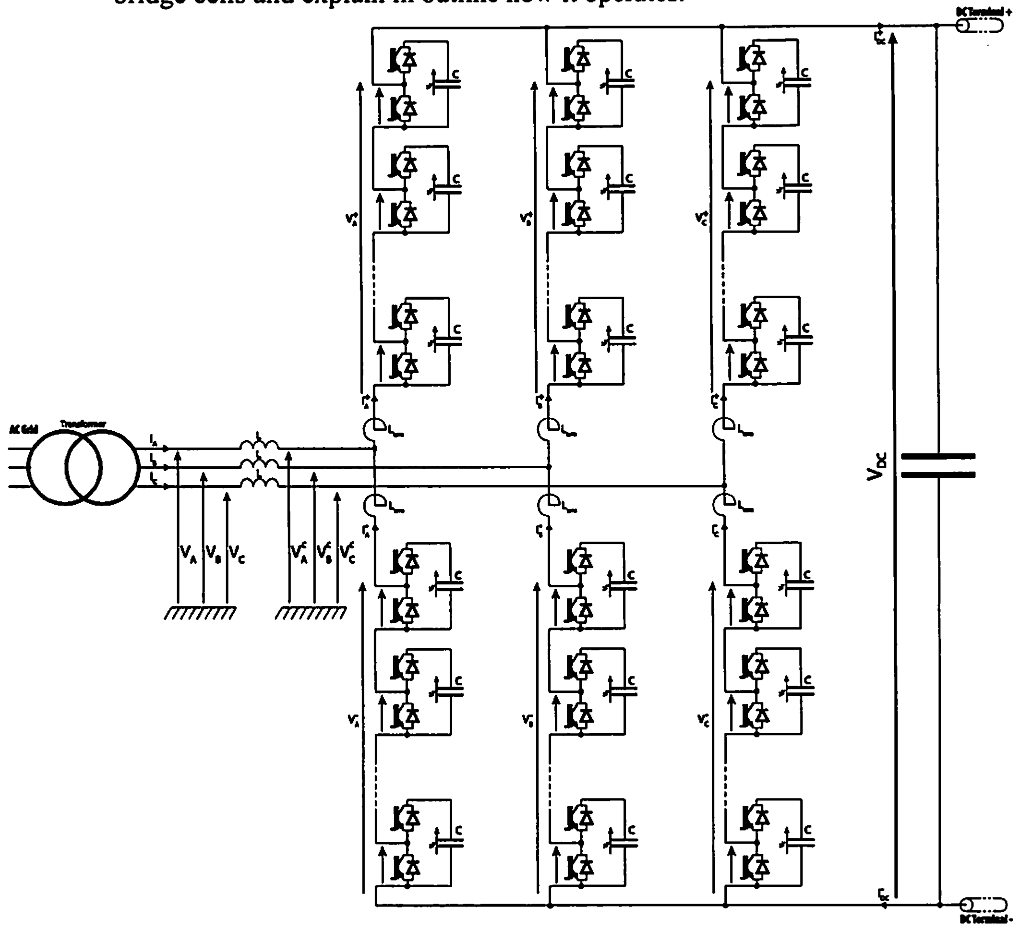
Figure Q2 – Typical Connection of a VSC



(b) Compare a 2-level and a multi-level voltage source converter in terms of the distortion present in the AC current waveforms. [3]

The amount of distortion in the AC current is of concern to the network operator which sets tight limits on the maximum harmonic content. 2-level VSCs can switch at approximately 1 kHz and use PWM to follow a sinusoidal pattern reasonably well but will normally require a passive (LC) filter to attenuate the switching frequency components of current and some of the low order harmonics. The multi-level converter has a large number of closely spaced voltage levels that can be used to construct its voltage waveform. With a sufficient number of levels (over about 40), the requirement for both AC filters and PWM is removed, saving both footprint and cost and without a disadvantage in switching loss. A 2-level converter could only operate without a filter if a high switching frequency were used which, even if possible, would create high losses.

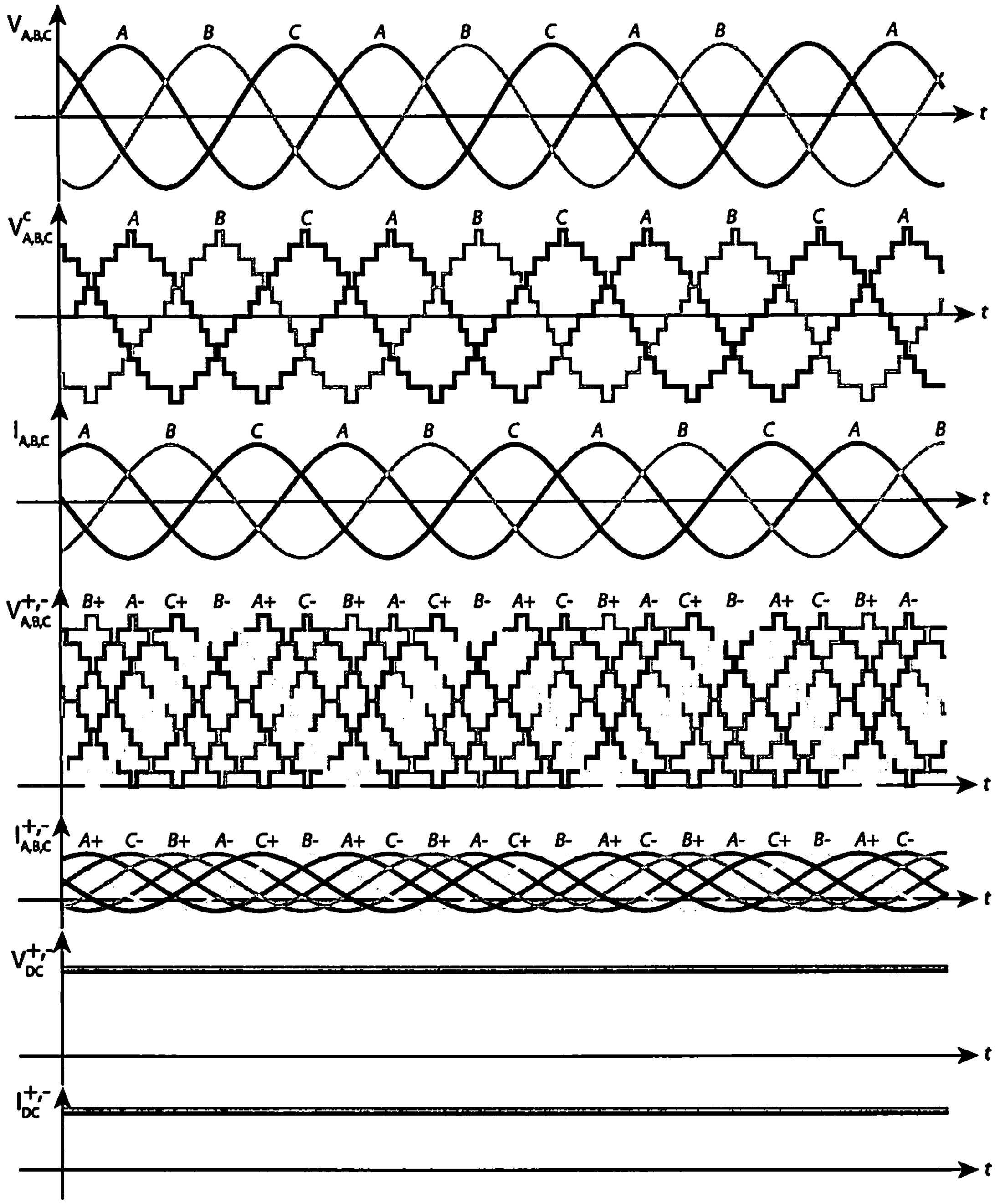
(c) **Sketch the circuit of a Modular Multi-Level Converter (MMC) that uses half-bridge cells and explain in outline how it operates.** **[6]**



The main objective of the MMC is to increase significantly the number of voltage levels available to construct the converter AC voltage waveform. This topology relies on a stack of H-bridge cells in each of its arms, each of these cells capable of providing a relatively small voltage step by switching its pre-charged capacitor into the main circuit path or can exclude it from the path by using the alternative switch in the cell. Achieving a good representation of a sinewave voltage is one objective but the current flows need to be carefully managed to ensure proper operation. The AC current of each phase is controlled to be split equally between the top and bottom arms of each leg of the converter, in the process charging the cell capacitors. Meanwhile, a third of the total DC current is run through each leg (using both arms) to transfer energy from the cells to the DC bus. Since all three AC currents meet at the DC terminals, they sum to zero, thus ensuring that the MMC operates with a ripple-free DC current.

[KEYWORDS]: Stacks of cells, phase inductors, arm inductors, AC current split between arms, 3-phase AC currents cancel at the DC terminal, ripple-free DC current

Answer could make use of sketch of waveforms but is no strictly needed.



(d) An MMC rated at 800 MW ±320 kV is required. It will be formed of cells rated at 2 kV and when operating will experience a peak energy fluctuation in each arm of 780 kJ. Calculate number of IGBTs and capacitors required for the complete converter and the value of the cell capacitor assuming that the cell voltage must be kept within 20% of its nominal value. [4]

Standard calculation,

Preliminary calculation: Number of cells per arm: $\frac{V_{DC}}{V_{cell}} = \frac{2\times 320\ 10^3}{2\ 10^3} = 320$

Answers: Total number of IGBTs: $6\times 2\times N_{cell} = 12\times 320 = 3840\ IGBTs$ [1]

Total number of capacitors: $6\times N_{cell} = 6\times 320 = 1920\ Capacitors$ [1]

Cell Capacitor: $\frac{2\,\Delta E}{N_{cell}\,V_0^2(1.2^2-1)} = 2.77\ mF$ [2]

(e) **Describe the energy management tasks required in an MMC including the types of energy imbalance and the corrective mechanism for each..** **[4]**

The DC capacitors in each cell are subject to large current flows that perturb their voltages. Each is perturbed somewhat differently because of the different duty cycles of each cell. While these voltages will inherently fluctuate over the course of an AC cycle, the energy management has to ensure that the amount of energy stored inside each capacitor remains at their nominal value over time.

The first level of energy management ensures that the amount of energy coming from the AC side equals the amount going to the DC side; otherwise the difference will end up in the stacks. This can be achieved by adjusting either the AC or DC current magnitudes.

The second level monitors the distribution of energy between the different converter legs (phases) and corrects any discrepancies by adjusting the levels of DC currents in each leg.

The third level ensures that the energy is correctly distributed between top and bottom arms in each leg. The solution here consists of running an additional AC current at the fundamental frequency in the affected phase. This current has to be cancelled in order to keep the smooth DC current feature of the MMC. The trick to accomplish this is to run related corresponding currents in the other leg converters but in quadrature (90 degrees) to their phase voltages in order to avoid affecting their own arm-to-arm energy balance.

The final level controls the priority order of utilization of the cells in a stack in order to ensure an even distribution of the charge between them. This is mainly achieved by swapping the duty of the different cells.

[KEYWORDS]: cell capacitors, AC/DC energy balancing, horizontal balancing, vertical balancing, cell rotation

3.

a) The silicon power BJT dropped out of use when reliable power MOSFETs and IGBTs became available. Explain why the MOSFET is preferred when using silicon-based devices, and why SiC BJTs may be significantly better for power electronics applications than Si BJTs.

[4]

[interpretation of knowledge]

In order to achieve high voltage blocking, a BJT needs a long base region. Unfortunately, this means that the current gain is low (sometimes as low as 5 for a power device) so that a significant amount of control terminal (base) current is required. The power MOSFET, by contrast, exhibits near perfect control input characteristics in that almost no DC current is required to hold the device on.

[2]

The SiC BJT may bring BJTs back into use. SiC can support higher electric field strengths than Si and so a narrower base can be used to block a given voltage than in SiC, meaning relatively high gains should be achievable, over what could be achieved with Silicon.

[2]

b) Figures Q3.1 and Q3.2 show steady-state I-V traces of two Mitsubishi silicon IGBTs, of the same family and current rating, but of different voltage ratings.

Mitsubishi IGBT Characteristics (graphs from Mitsubishi datasheets)

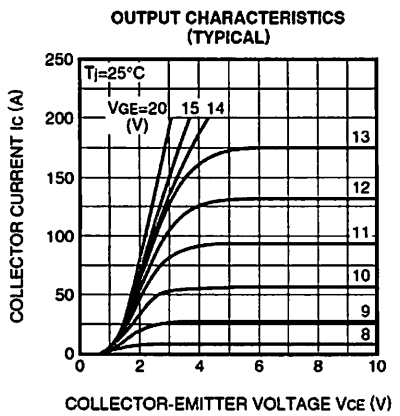


Figure Q3.1: IV curves for 600V, 100A device

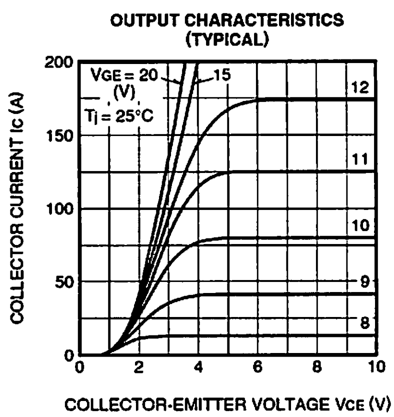


Figure Q3.2: IV curves for 1200V, 100A device

i) Considering the construction of the IGBT, explain why the collector current does not start to rise immediately for rising collector-emitter voltage, even when a significant gate voltage is applied.

[2]

[Bookwork]

The back side of the wafer on an IGBT has a strong p-doped layer to inject holes and conductivity modulate the n-drift region. Consequently the IGBT characteristic shows a typical pn junction voltage drop (which can be seen in the above plots as the expected 0.7V for a silicon device)

[2]

ii) What are the fundamental similarities and differences in construction between these two ratings of IGBTs?

[4]

[Interpretation of knowledge]

We are told that the IGBTs are the same family so the basic construction will be the same, i.e. if one is trench gate, so is the other. The feature size and hence cell size are also likely to be the same given these are devices from the same family.

[1]

The differences are in the doping density and length of the n- region, and in the device area (number of cells). The length will be greater (around a factor of 2) in the 1200 V device over the 600 V device, as is necessary to block the higher voltage. In order to block higher voltage, the doping in the n-region will be lower in the 1200 V device. The temptation is to say that as these devices have the same current rating they have the same area, but in order to control heat flow and reduce losses, the higher voltage device will have a greater area than the lower voltage device.

[3]

c) **You must design a valve for use in an application where the valve must block 1600 V and conduct a current which has a peak of 90 A, an average current of 29 A and an RMS current of 45 A. Three possible designs are considered using the Mitsubishi devices of figures Q3.1 and Q3.2:**

- **Two 1200 V devices in series**
- **Three 600 V devices in series**
- **One 1200 V and one 600 V device in series**

i) **The conduction power loss can be calculated by approximating the voltage drop across the IGBT as a fixed on-state voltage in series with a resistive element. Approximate these values for each IGBT for a gate voltage of 20 V.**

[2]

[Simple calculations from plots]

This is simple, but the students may not have done this data extraction before. Taking a best-fit, the on-state voltages can be approximated at 1.2 V for the 600 V device and 1.8 V for the 1200 V device. The on-state slope resistances are approximately 9mΩ for the 600 V device and 9.6 mΩ for the 1200 V device. Some tolerances are allowed in these answers as they are derived from the plots.

[2]

ii) **Show that the valve containing a mixture of device ratings has the lowest power loss.**

[5]

[Calculation]

The point to note here is that the contributions to the power loss from the on-state voltage drop and the resistive element must be calculated using different quantities from the current. In particular, the contribution to the conduction loss from the voltage drop is from average current, and the contribution from the resistive loss is from RMS current

[2]

Then, the calculations are as follows:

- Two 1200V devices have a conduction loss of 2*(1.8*29 +9.6e-3*45^2) = 143.3 W
- Three 600V devices have a conduction loss of 3*(1.2*29+9e-3*45^2) = 159.1 W
- One 1200V and one 600V device have conduction losses of (1.2*29+9e-3*45)+(1.8*29+9.6*45^2) = 124.7 W

[3]

iii) **What may be the disadvantages of using a valve made using devices of different ratings?**

[3]

In order to allow voltage sharing of devices in a series string at turn off and in the steady off state, a chain of resistors and capacitors are placed in parallel with the devices (for steady state and transient sharing respectively). The ancillary passives are smaller and cause less power loss the more closely matched the devices in the stack are to each other. For different device ratings, the off-state characteristics and recovery charge will be quite different – meaning the balancing resistors must be relatively small and the balancing capacitors quite large. This reduces the overall efficiency of the valve and may increase the size.

A diagram of a valve with these passives could be sketched but is not necessary.

[3]

Part B

4.

a)

i) Describe, briefly, how power transfer capacity of an AC transmission line is affected by the transmission distance.

[4]

As the power transmission distance is increased the power frequency line impedance increases. The shunt admittance also increases. For shorter transmission length such as less than 80 km, the transfer capacity is depended on the allowable temperature rise limit of the conductor. The current carrying capacity is depended on ambient air temperature surrounding the conductors. Accordingly the transfer capacity is seasonal.

For medium length line typically between 80 -320 km, the voltage stability influences the transfer capacity. Too much loading under such situation leads to poor voltage at the receiving end of the line. For longer line beyond 320 km the angular separation between the two ends becomes large thus reducing or even passing the stability limits of the system. The power transfer under such situation is reduced to satisfy or maintain specified stability limit. The transfer capacity in these situations is appreciably lesser than thermal capacity or even natural loading. [4]

ii) Describe how a compensation scheme can increase transfer capacity.

[3]

The shunt admittance of transmission line always produces capacitive VAr while the series inductive part consumes reactive var. The net VAr generation is negative for line power transfer beyond natural loading. The consequence is poor voltage at the receiving end and higher losses in the line. The situation is opposite during light loading (precisely for loading less than the level of natural loading) when inductive var absorbed per unit distance is less than the capacitive VAr generated by the line. The effect is voltage rise at the receiving end. At times this rise is more than the allowed limits- thus require balancing this surplus var generation by absorbing that through inductive var compensation (shunt reactor). Additional reactive power is generated by way of introducing capacitive compensation. This lifts the receiving voltage. When reactive power compensations in both directions are in place the receiving end voltage is brought within the limit of variation.

b) An electric power utility is expanding its network to meet the growing demand through providing additional generation. It has made an investment decision to build three new power lines of 60 km, 200 km and 400 km in length to support the growth in demand and generation. It is anticipated that these lines will be required to carry power beyond their natural loading (surge impedance loading) limits. Explain what type of compensation will be most effective in each of these three cases

[8]

The line which is 60 km is not expected to suffer from voltage drop problem. Hardly any compensation will be required. [1]

The circuit of 200km will require arrangement for shunt (capacitive) compensation as during higher loading the voltage at the receiving end will drop. The compensation arrangement has to be modular/flexible and switchable so that with variation a good voltage profile is maintained. Preferably SVC depending on the importance and criticality of the load will be best option although an expensive one.

[3]

The line with 400 km in length will require series compensation as the small disturbance stability or steady state stability is a likely to be encountered as the loading increases. The best option is series capacitor with discrete modules that can be switched on and off by thyristor control. Several fixed capacitor is also an option depending on the criticality of the line, its proximity to nearby multi-stage steam generator. The values etc., must be worked out after detailed torsional oscillations (sub synchronous resonance study) study. The protection of the capacitor banks as well as the distance protection of the line needs to be redesigned.

[4]

c) A 500 km long, 400 kV double circuit line was built 20 years ago with twin conductors. Because of the need to serve growing demand, the twin-conductor lines are being replaced with quad-conductor lines. For the assumption that the receiving end voltage is kept at its nominal value, determine what increase in loading the line can now accommodate (expressed as a percentage of the previous natural loading limit).

[5]

With doubling of the number of conductor per phase, the inductance of the quad-conductor will be approximately halved. The impact of this natural impedance is evaluated as follows:

$Z_0 = \sqrt{\dfrac{L}{C}}$ is the natural impedance (surge impedance) or the characteristic impedance of the of the line; This will reduce Z0 by about 30% (0.707 of original value). The natural loading limit $SIL = \dfrac{V_0^2}{Z_0}, V_s = V_r = V_0$ is re-evaluated as:

$$\frac{\mathrm{SIL}_2}{\mathrm{SIL}_1} = \frac{Z_{01}}{Z_{02}} = \sqrt{2} = 1.407;$$

The natural loading limit will be about 140% of the existing loading.

5

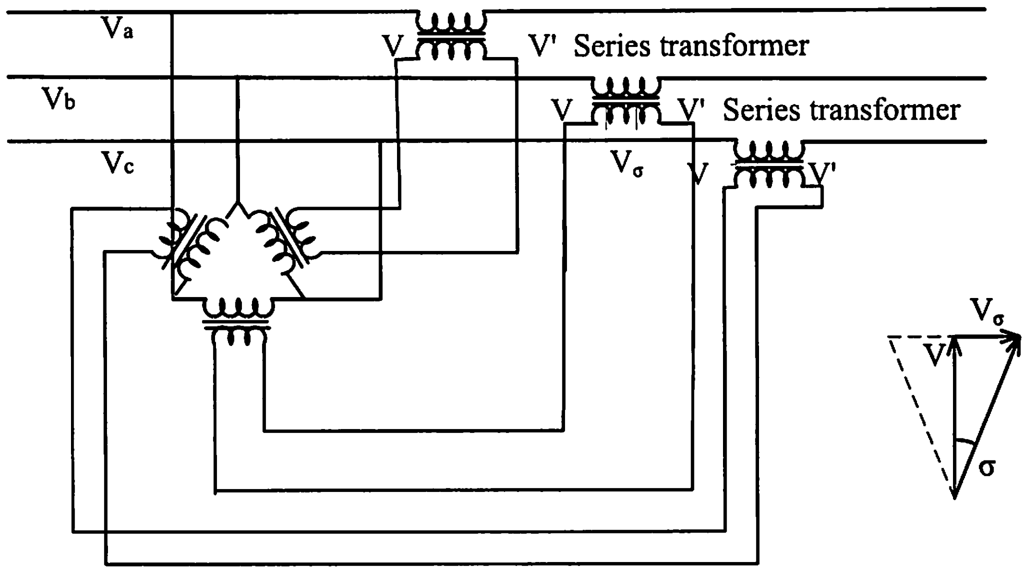
a) Much before the concept of FACTS became popular, many transmission system operators have adopted the quadrature-booster

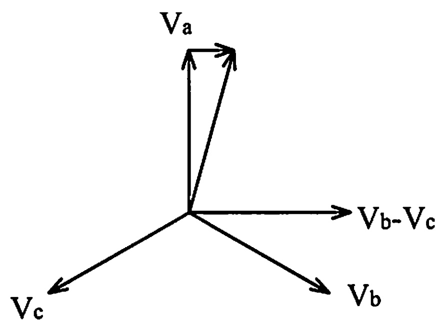
i) Briefly describe how a quadrature booster provides a control function in an AC network.

[5]

The quadrature-booster produces a phase angle shift while influencing the magnitude of the voltage variation minimally. To compensate in phase A, it uses electromagnetic transformer that is fed from the voltage between phases B and C. The voltage is reduced by suitable transformation ratio and usually to less than 5% of the primary line voltage. The reduced voltage produced by the secondary winding is injected in series with phase A with the help of another small transformer. This added voltage is in quadrature with phase A voltage. This results in phase A voltage of the system being phase shifted by an angle tan-1 (quadrature voltage /phase uncompensated voltage). As long as the quadrature voltage is a small fraction of phase 'a' voltage the magnitude is not influenced but the phase is. That is the reason it is known as phase shifter and because of the devices introduces voltage in quadrature to phase voltage it is known as quadrature booster. The other two phases 'b' and 'c' are controlled by connecting the other two primary windings of the 3-ph transformer across line ac, and ab respectively.

The effectiveness of this device is in power flow control by phase angle control. The following diagram is useful to understand the principle of operation more clearly.





ii) Give one important advantage and one important disadvantage of the quadrature booster.

[2]

The most important advantage is, it is very simple, reliable and does not involve any power electronic switching. The disadvantage is it only offers fixed amount of phase compensation irrespective of variable requirement as dictated by the network operating scenarios.

b) Some transmission networks make use of fixed shunt capacitor banks at the receiving end of a transmission line during heavy loading and change these to fixed reactors during light loading.

i) Discuss the advantages and disadvantages of voltage control using fixed capacitors and reactors.

[5]

Fixed capacitors/inductors are very cheap and reliable technology. They are switched in and switched out by a circuit breaker through remote switching command from the control room. They are easy to maintain- losses are minimal. They cause little harmonic impact to the network

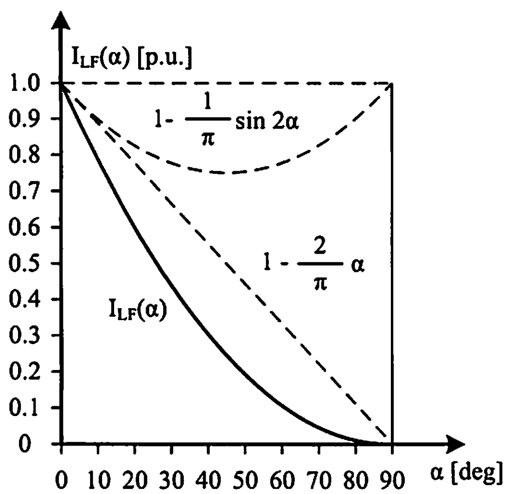
The disadvantages are many: they are not smoothly controllable, only fixed amount of compensations are possible irrespective of the need. They are very slow in action as mechanically controlled circuit breakers are used to open and close them. They cannot respond to very rapidly varying voltage control requirement such as industrial process. The fixed capacitor is not very effective during low network voltage as the reactive power generated by this is function of the square of the voltage. So it is a passive device as far as the reactive power and voltage support is concerned.

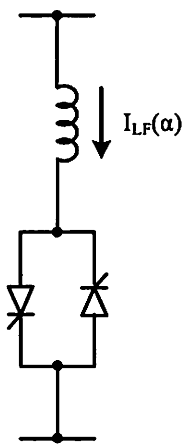
[5]

ii) With reference to the operating characteristics of a Static VAr Compensator (SVC), describe how some of the disadvantages of fixed reactors and capacitors are overcome by SVCs.

[8]

The static var compensator (SVC) on the other hand uses a fixed capacitor and thyristor controlled reactor combination in parallel.
Voltage compensation is achieved by static var sources. They are, passive inductor or capacitor or thyristor controlled reactor (TCR), switched capacitor and any combination. This section will discuss basic characteristics.
Let consider a thyristor controlled reactor. The TCR provides variable admittance to the system through firing angle delay control.
In practice the maximal magnitude of the applied voltage and that of the corresponding current will be limited by the ratings of the power components (reactor or thyristor switch) used. Hence a practical TCR can operate in anywhere in the V-I plane limited by the maximum admittance, voltage and current rating. This V-I characteristic of TCR is shown in Fig A5.2 and Fig A5.3. Any point inside the hatched region is realizable. This arrangement only absorbs inductive var can not generate. That can be done by a capacitor in parallel to this. The capacitor can either be fixed or thyristor switched. Irrespective of whether the capacitor is fixed or thyristor switched, the V-I characteristic will be as shown in Fig A.5.4.





$$I_{LF}(\alpha) = \frac{V}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right)$$

Fig A5.2 Thyristor controlled reactor

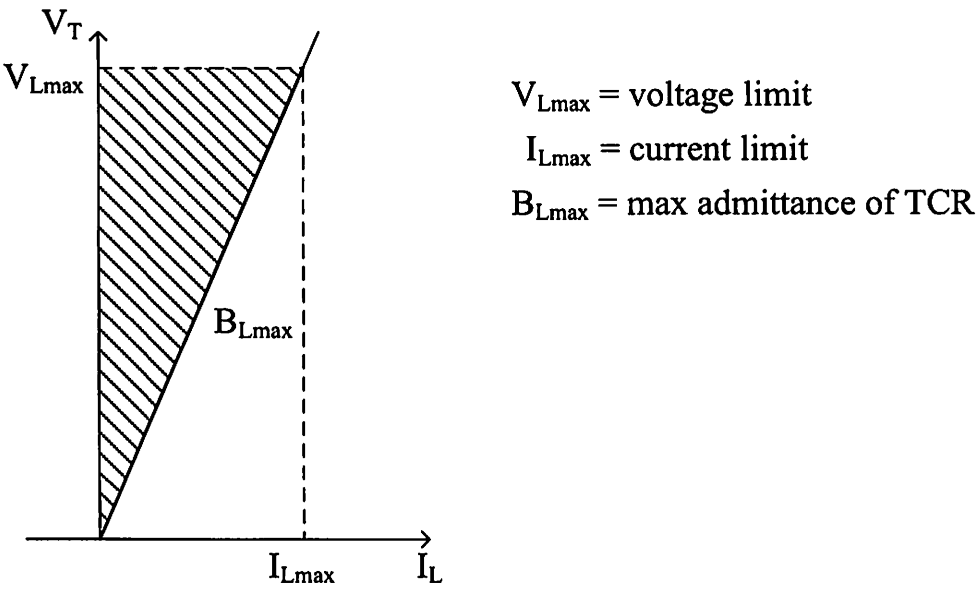


Fig A.5.3: V-I characteristic of TCR

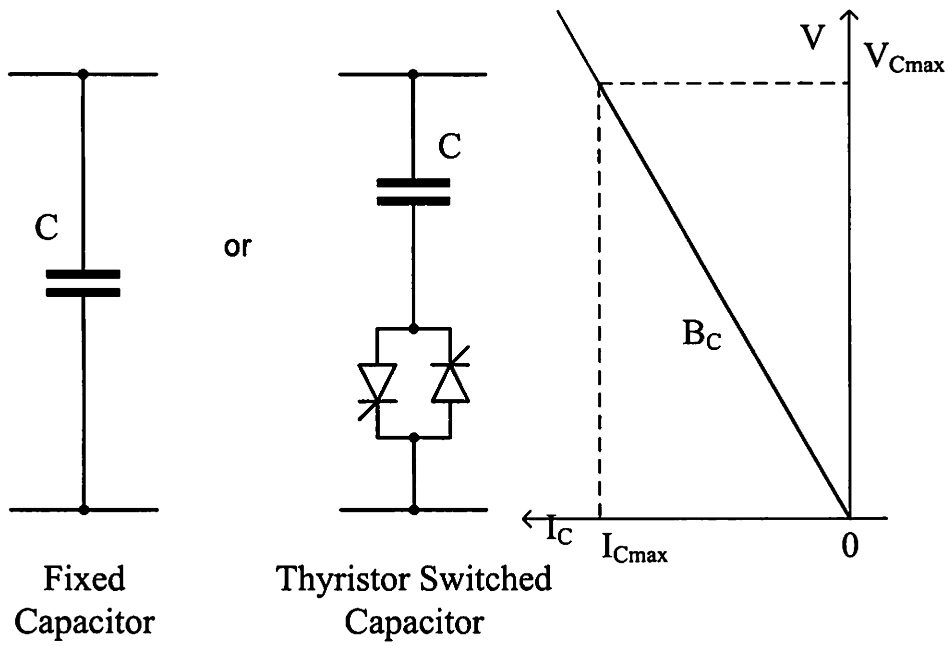


Fig A.5.4: V-I characteristic of FC or TSC

Based on the choice of capacitor, two standard topologies for var source can be realized: One comprises of fixed capacitor and thyristor control reactor (FC+TCR). The other one is thyristor switched capacitor and thyristor control reactor (TSC+TCR) type.

Fig A5.5 shows arrangement for FC+TCR with its associated V-I area. It can be seen that the var generator can be made to work anywhere in the hatched area through proper control within the limits of voltages and currents.

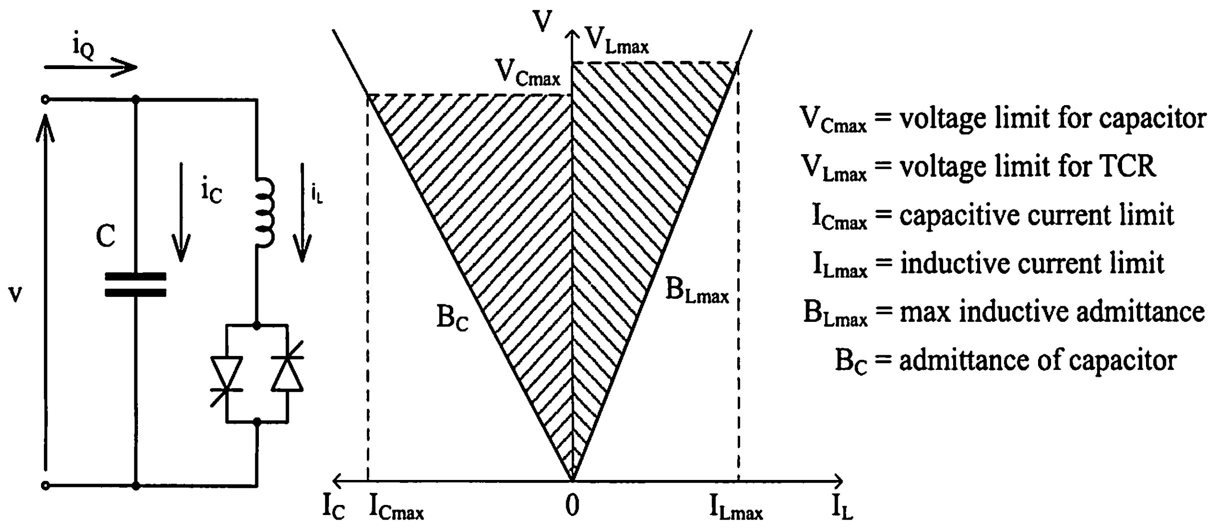
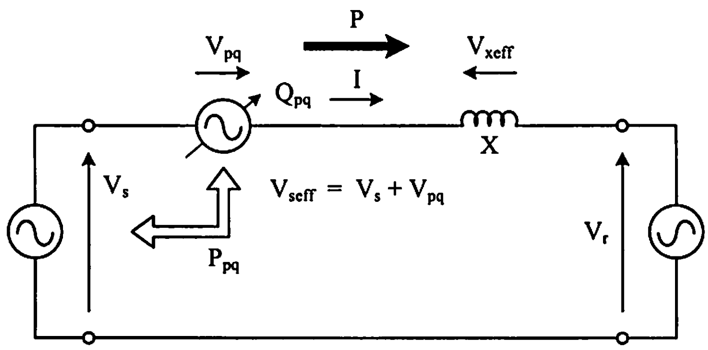


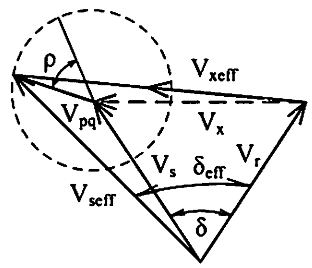
Fig A 5.5: Basic topology and associated V-I characteristic of FC+TCR

6

a) Sketch various functional modules of a unified power flow controller (UPFC) [4]

The UPFC is the most versatile members of the FACTS family as virtually the operating characteristics of all the other FACTS controllers discussed so far can be realised with it. Fig A.6.1 shows various block diagrams and operating characteristic of the device.





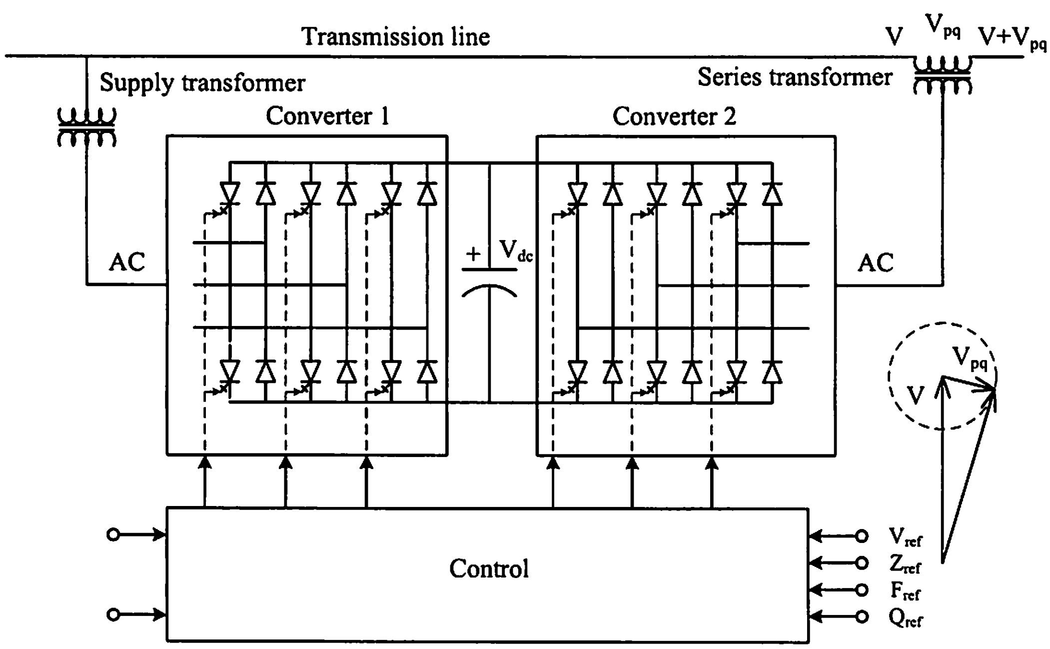
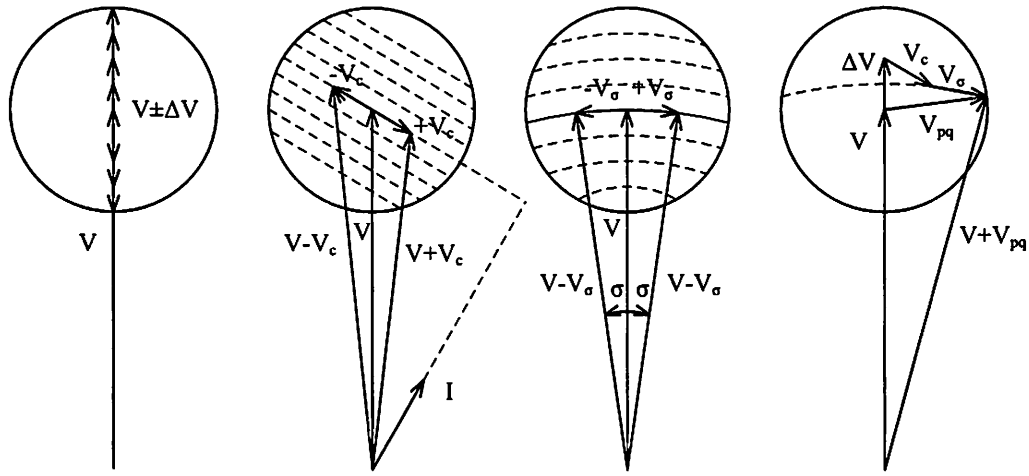


Fig A6.1: Unified Power Controller topology and circuit model

b) Show how the functions of voltage regulation, series compensation and phase compensation are realised by the UPFC.

[8]

With respect to various modules of the VI characteristics can be shown as follows.



(a) Voltage regulation

(b) Line impedance compensation

(c) Phase shifting

(d) Simultaneous control of voltage, impedance and angle

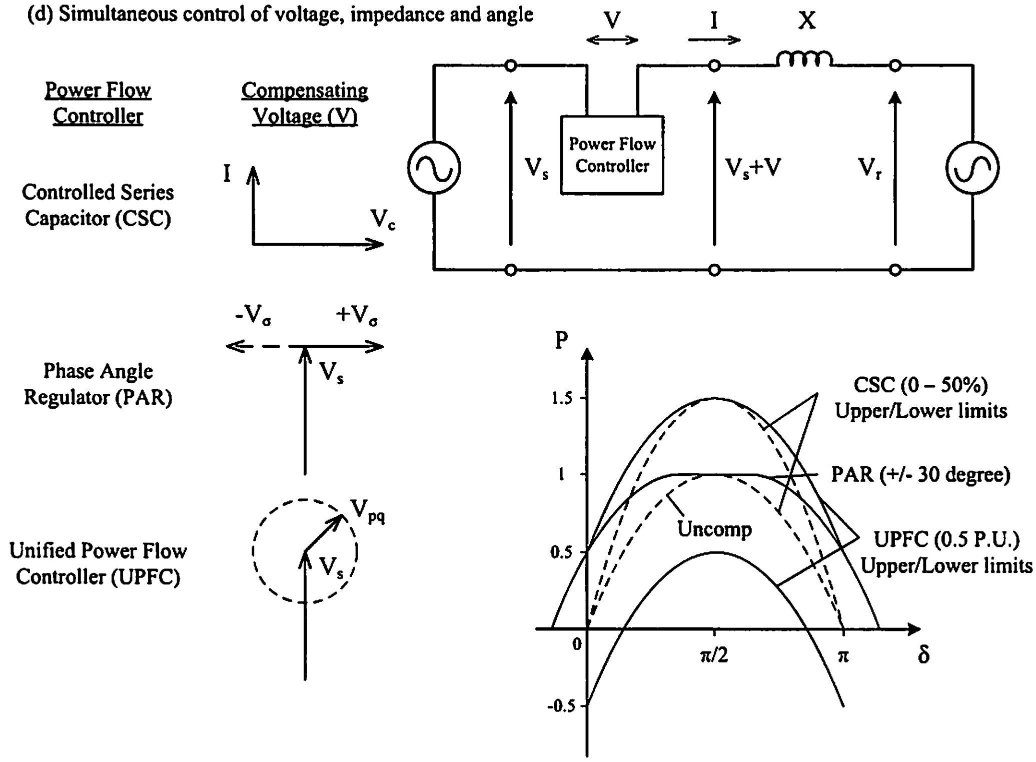


Fig A6.2: V-I and power angle characteristic of UPFC

c) A 750 km long, 765 kV transmission circuit was constructed 20 years ago. The line was designed with a stability margin of 45°. A UPFC is now to be installed to facilitate increased power transfer without compromising the stability margin. Consider that the control mode of the UPFC has been set to line impedance compensation only with a compensation of up to 30%.

When the UPFC control is set for impedance compensation mode- it exhibits the characteristics of controllable series compensation. The power angle relationship of controllable series compensation is applicable. Let us assume the magnitudes of the voltage at both ends are:
V_s, V_r. and the angle between the two ends are δ, the impedance of the line is X
The power angle equation with degree of compensation k
$P = \frac{V_s V_r}{(1-k)X} sin\delta = \frac{P_{mu}}{1-k} sin\delta$
$P_{mu}$is the maximum power transfer for uncompensated case. With a 45 degree margin of stability and at no compensation (k= 0) $P_1 = 0.707P_{mu}$

i) Find the additional stability margin that can be obtained with the UPFC for the same power transfer as previously obtained.

[4]

For k = 0.3, and for the same amount of power transfer the power transfer angle can be obtained from the power angle relationship as follows:

$$P_1 0.707P_{mu} = \frac{P_{mu}}{1-k} sin\delta = \frac{P_{mu}}{1-0.3} sin\delta;$$
$$sin\delta = 0.50;\ \delta = 30^0$$

The additional stability margin is 15 degree.

ii) Find the increase in power transfer (as a percentage) between the compensated and uncompensated cases if the stability margin is maintained at 45°.

[4]

$$P = \frac{P_{mu}}{1-0.3} \sin(45^0) = 1.414 * 0.707P_{mu}(\frac{0.707}{0.7}) \approx 1.414P_1$$

141% of uncompensated power can be transferred while respecting 45 degree stability margin.