IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2011

FACTS AND POWER ELECTRONICS

Monday, 16 May 10:00 am

Time allowed: 3:00 hours

Corrected Copy

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

Section A

1.

a) Optimal PWM is used in some 3-wire 3-phase inverters. Explain its benefits and why it applies to 3-wire and not 4-wire systems. [4]

b) Explain why there is a compromise to be struck between the efficiency of a high-power power converter and the physical size of the filter used to attenuate switching frequency distortion at its output. [6]

c) Figure 1.1 shows four types of multi-level converter. Discuss the relative merits of the four designs. [10]

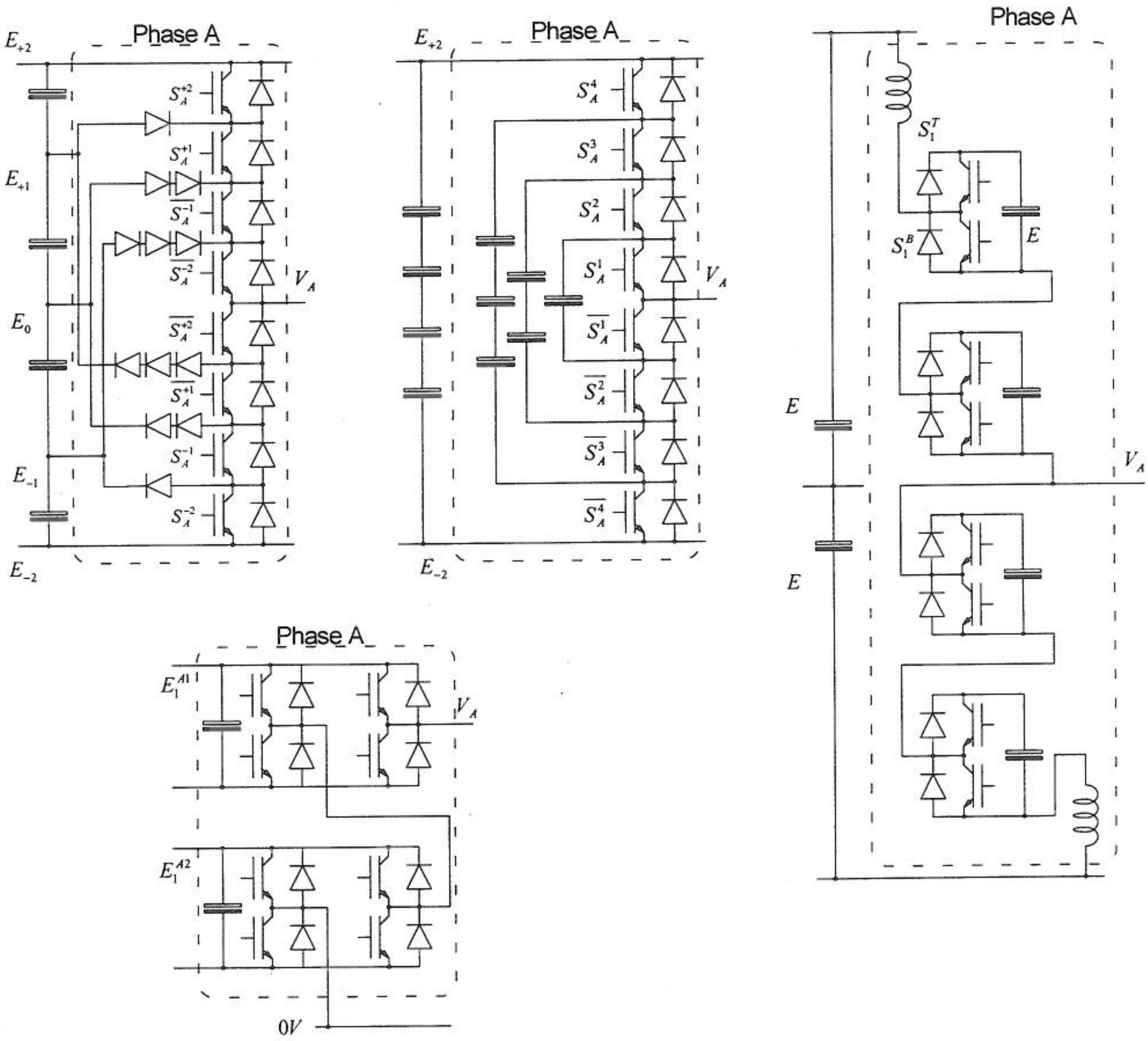

Figure 1.1 Four types of multi-level converter

[4.49]

2.

a) Figure 2.1 shows a DC/AC converter being used to export power from a DC-link which is in turn supplied with power by a PV Array and DC/DC converter.

i) Justify the use of an error term of the DC-link voltage to set the reference for the inner current control system. [2]

ii) Sketch the form of the inner control system based on a DQ control model. [3]

iii) Explain the benefits of using DQ control models. [3]

iv) Describe why feed-forward decoupling terms are often used on DQ control systems. [2]

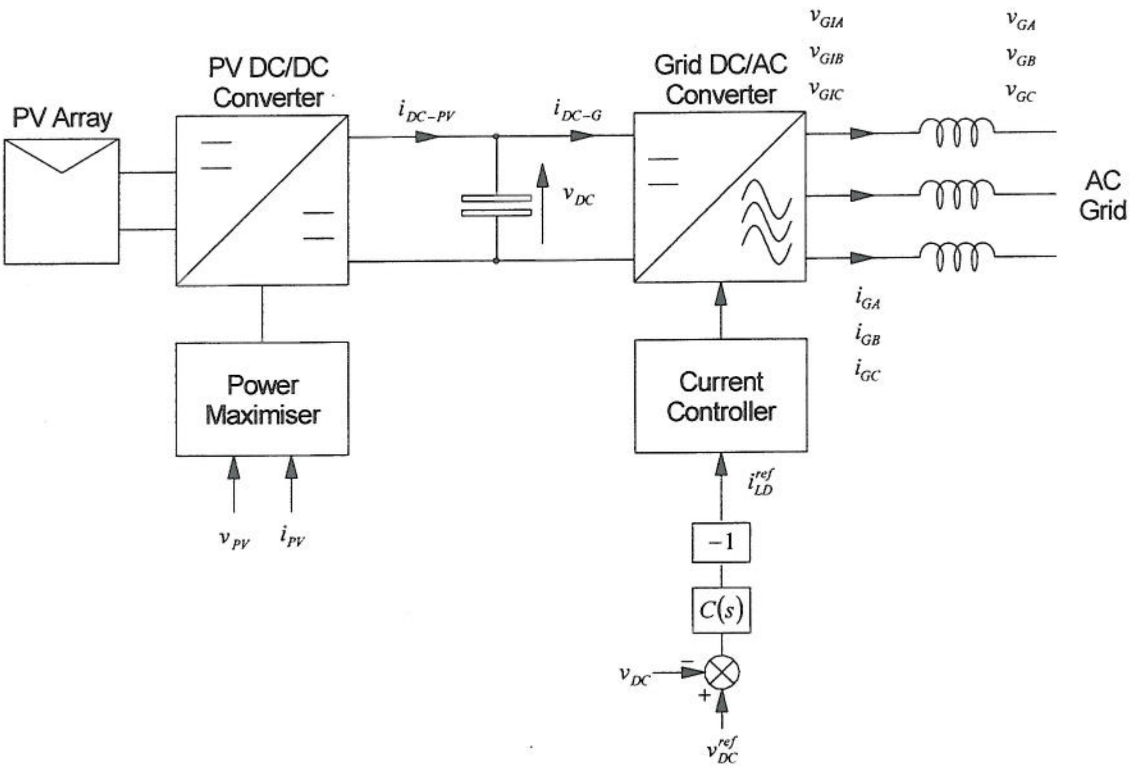

Figure 2.1

b) The circuit in figure 2.2 is an equivalent circuit of an auto-transformer.

i) Consider that the input voltages v_{Iabc} and output currents i_{Oabc} are imposed on the circuit and write the circuit equations in matrix form. [3]

ii) Transform the equations to $dq\gamma$ form. [4]

iii) Sketch the circuit of the transformed system. [3]

[4.49]

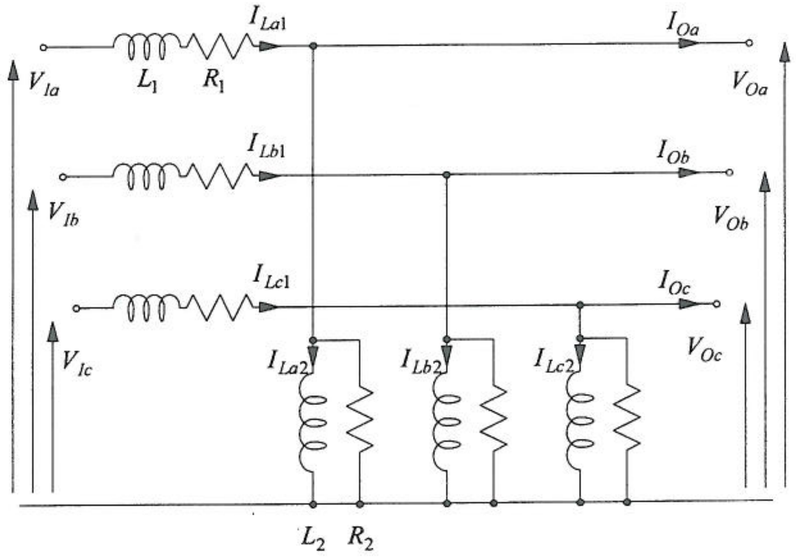

Figure 2.2

[4.49]

3.

a)

i) As semiconductor devices are made larger to handle higher off-state voltage and larger on-state currents, they tend to become slower in terms of switching speed. Explain why this is. [3]

ii) Several companies are investing heavily in moving beyond Silicon as a material for power devices, with SiC product appearing in the market. One company is investing in JFET devices whilst others are pushing MOSFETs. Draw a cross section of a power JFET device and discuss potential advantages and disadvantages over power MOSFETs. [5]

b)

i) Sketch a schematic diagram of a unified power flow controller (UPFC) and label major building blocks. [5]

ii) Show how the functions of series, shunt and phase compensation are realised by this device. [7]

[4.49]

Section B

4.

a)

i) AC power transmission is the norm but there are some difficulties that stem for using AC. List what these difficulties are. [4]

ii) Explain how some of these limitations can be overcome by FACTS technology [4]

b)

i) What is the natural loading of a power transmission line? [4]

ii) Suggest and justify types of FACTS technology to load a 800 km long, 765 kV line beyond its natural loading. [3]

c) What are the structural and functional differences between a Thyristor Control Series Capacitor (TCSC) and a Static Series Synchronous Compensator (SSSC)? [5]

[4.49]

5

a) How is phase angle regulated in a power system? With the help of basic circuit representation of a simple system and a power angle plot, show the effectiveness of phase angle regulation in improving power transfer capacity of a line. [7]

b) Discuss a modular operating strategy for a Thyristor Switched Capacitor and Thyristor Control Reactor (TSC+TCR) and its effectiveness in reducing the overall required capacity of the reactive power sources. [7]

c) Sketch the power loss versus loading characteristic for Fixed Capacitor and Thyristor Control Reactor (FC+TCR) type Static VAR Compensator (SVC). How does the power loss characteristic of the SVC influence the network functions supported by it? [6]

[4.49]

6

a) Using Static Compensator (STATCOM) as an example, describe the operational benefits of voltage source based FACTS controllers [5]

b) Figure 6.1 shows a simple model of an interconnected power system. The voltages at the two ends of the interconnection are $V_s\angle\delta$ and $V_r\angle 0$ p.u. The line is modelled by a series inductance and expressed as X_L p.u.

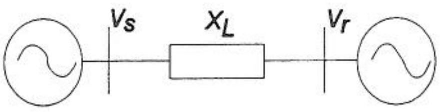

Fig 6.1: A simple interconnected power system model

i) The line is now equipped with a series capacitor of variable capacitive reactance $X_c = kX_L$ where k is controllable. Sketch the variation of power with δ for k ranging between 0.0 to 0.4. With the help of the sketch, justify the influence of the series capacitor in power flow control. [10]

ii) Name at least two potential problems that network operation is likely to face and briefly discuss how they can be addressed. [5]

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[4.49]

1.

(a) Optimal PWM is used in some 3-wire 3-phase inverters. Explain its benefits and why it applies to 3-wire and not 4-wire systems. [4]

Optimal PWM is not strictly a modulation scheme but an optimisation of all of the switching angles across a cycle with an objective in terms of the harmonic amplitudes in the resulting waveform. The odd and even symmetry is imposed which together mean that the quarter cycles are symmetric and that even harmonics are zero amplitude. If there are N switching angle choices to be made in a quarter cycle then N output harmonics can be set. The fundamental is set to a desired value leaving N-1 higher odd harmonics that can be set to zero. This alone would not produce a spectrum much better than standard PWM with the same number of switching events. However, the optimisation can exploit the fact that in a 3-wire system the triplen (3k) harmonics are of no consequence and can be allowed in the spectrum at any amplitude. This means that other higher odd order harmonics can be optimised instead and this extends the region of (near) zero distortion further up the frequency range for the same switching frequency. This eases the filtering burden on the post-inverter filter or the load itself.

(b) Explain why there is a compromise to be struck between the efficiency of a high-power power converter and the physical size of the filter used to attenuate switching frequency distortion at its output. [6]

Answer to include the follow points:

- Power losses in a high-power converter are dominated by the conduction loss and switching loss of the power semiconductors.
- Switching loss is linearly dependent on switching frequency and so efficiency decreases with increasing switching frequency.
- If the attenuation of the switching frequency voltage component is to be kept at a specified value, the cut-off frequency of the filter will need to vary as the switching frequency is varied
- The cut-off frequency of a filter decreases with increasing the value of the inductive and/or capacitive elements.
- The physical size of reactive components depends on their stored energy (the stored energy per unit volume being a constant depending on the dielectric or core material). Since the V and I terms in ½LI2 and ½CV2 are essentially equal to the line voltages and currents and are constant, the size depend on value.
- So, if one attempts to increase the efficiency by decreasing the switching frequency then the filter cut-off will need to be lowered leading to a physically larger filter.

(c) Figure Q1 shows four types of multi-level converter. Discuss the relative merits of the four designs. [10]

[4.49]

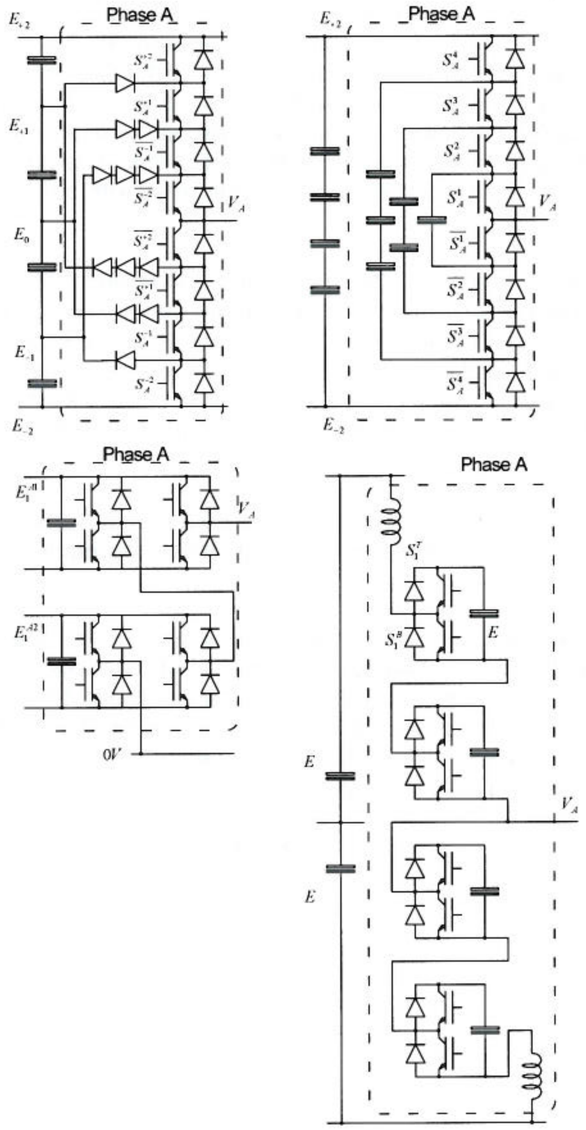


Figure Q1 Four types of multi-level converter

The answer should cover the following points.

The first three structures can achieve the same overall power rating and the same number of voltage levels by using the same number of the same semiconductor switches and so no relative advantages exist in these regards. The fourth achieve half the rating and half the number of levels for the same number of devices, which is a serious disadvantage but there are advantages to the topology too.

The number of additional components in the first three topologies does show a difference. The numbers of diodes and capacitors are important. In the diode-clamped converter, the number of diodes scales quadratically with number of levels and in the flying capacitor converter, the number of capacitors scales quadratically. The cascade converter has no components that scale this way.

[4.49]

A clear advantage of the cascade converter is the modularity of the design and the ability to provide fault tolerance by including more cells than strictly needed. A clear disadvantage of the cascade converter is that there is not one single DC-link but many DC-links that are not ground referenced. To support real power flow through the converter, an isolated path for power must be provided to the DC-links of each of the cells. The need for an isolation transformer for each cell adds complication and expense. An important exception to the disadvantage of isolated DC-links occurs if the cascade converter is used for reactive power compensation. Because only reactive power is drawn from the DC-link of each cell there is no need to provide a power source on the DC-link and each cell can be left floating with only a capacitor present on the DC-side.

There are difficulties in balancing the capacitor voltages of diode-clamped converters (for real power transfers). The devices near the centre of the converter will be switched on and conducting for longest. In the diode-clamped converter there is no way to rotate the duties. This means that more real power is drawn through the inner levels than the outer levels and the inner capacitors discharge at the expense of the outer capacitors. This means it is not sufficient to supply a single charging current to the capacitor chain. A means of moving charge between the capacitors is required or the converter must be operated back-to-back with a matching multi-level converter.

The 3-level diode-clamped converter (often known as a neutral point clamped converter) only has two capacitors and, provided the power transfers in positive- and negative-half cycles are equal, there is no major unbalance problem.

The fourth topology, the Multi-Modular Converter (M2C), has the modular structure of the Chain-Cell that allows incorporation of redundancy and expansion to very high level numbers but, crucially, has a single DC link through which real power is exchanged. It is therefore useful in real power applications where the chain cell is not. These features make it attractive despite the number of devices being double that of the other designs for the same power. (It is worth noting that despite the number of devices being double there is not a significant conduction power loss penalty because of the way the current splits between the upper and lower limbs so the effective number of devices in conduction is the same as the other topologies. The capitalised value of conduction loss is as important as straight capital cost).

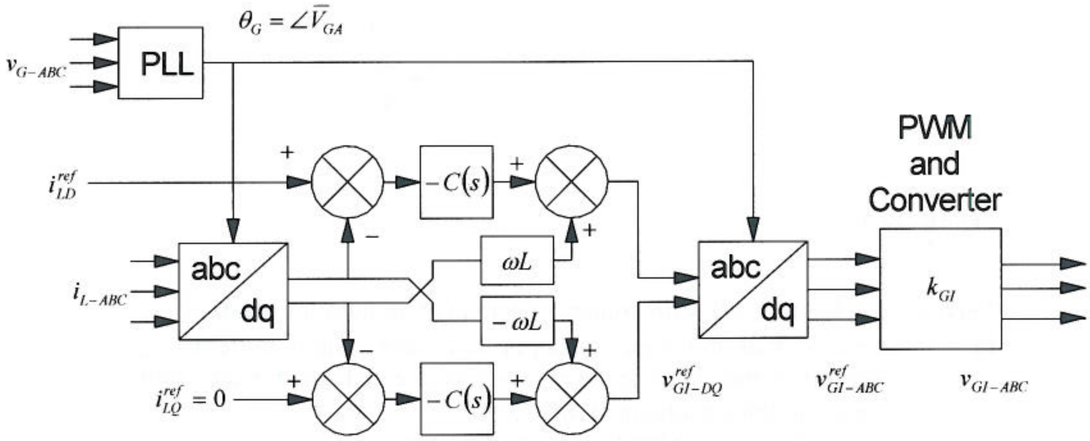
2.

(a) Figure Q2.1 shows a DC/AC converter being used to export power from a DC-link which is in turn supplied with power by a PV Array and DC/DC converter.

(i) Justify the use of an error term of the DC-link voltage to set the reference for the inner current control system. [2]

The basic objective is to export through the inverter all of the power processed by the DC/DC converter. If there is a mismatch between these powers the excess (deficit) will charge (discharge) the DC link capacitor. Thus an error in the DC link voltage indicates whether to increase or decrease the exported power. Advantages of this approach are the avoidance of the measurement of DC-link power or current and the fact that the DC-link error indicates the power error after allowance for the power losses in the converters.

(ii) Sketch the form of the inner control system based on a DQ control model. [3]



(iii) Explain the benefits of using DQ control models. [3]

DQ transforms balance three-phase sets to dc terms on two axes. The objective is then to regulate dc terms rather than follow sinusoidal terms and this makes simple PI controllers easier to apply. The DQ format of the model also makes explicit the coupling that exists between the axes (such a d-axis current in an inductor giving q-axis voltage term). Thus decoupling can be used.

(iv) Describe why feed-forward decoupling terms are often used on DQ control systems. [2]

The coupling terms between the axes in the model give rise to disturbances during transients. Effecting a step change in the d-axis current will perturb the q-axis current because an step change in voltage drop will occur in the q-axis because of the coupling term. The PI regulators have to be designed to reject such coupling disturbances. However, the magnitude of the voltage change can be accurately determined (from the control model parameters) and fed forward as a de-coupling term. The PI regulator then only has to reject the error between the feed-forward term and the actual coupling.

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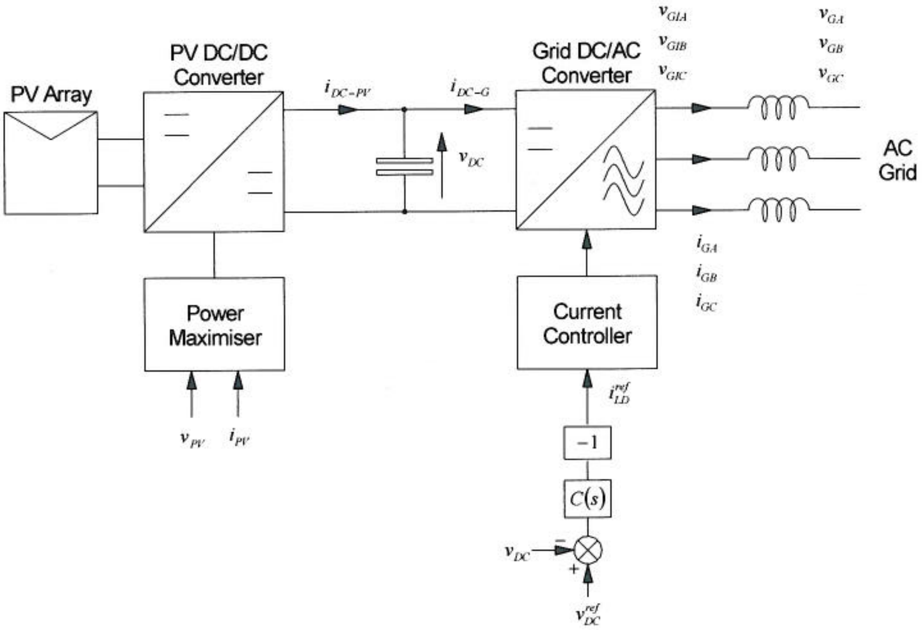


Figure Q2.1

(b) The circuit in figure Q2.2 is an equivalent circuit of an auto-transformer.

(i) Consider that the input voltages v_{Iabc} and output currents i_{Oabc} are imposed on the circuit and write the circuit equations in matrix form. [3]

(ii) Transform the equations to $dq\gamma$ form. [4]

(iii) Sketch the circuit of the transformed system. [3]

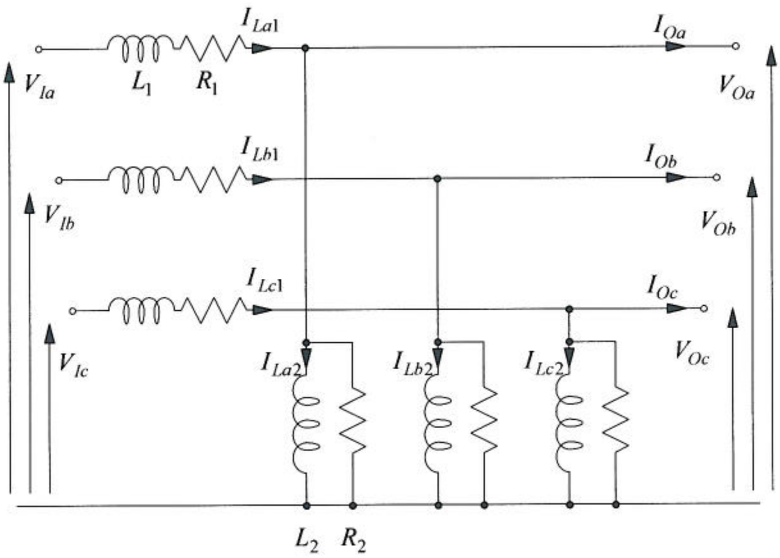


Figure Q2.2

[4.49]

(i) Circuit Equations from KVL and KCL on each phase and then assembled into matrix form to represent 3-phases.

$$v_{Oabc} = R_2\left(i_{L1abc} - i_{L2abc} - i_{Oabc}\right)$$

$$v_{I\,abc} = L_1 \frac{di_{L1abc}}{dt} + R_1 i_{L1abc} + R_2\left(i_{L1abc} - i_{L2abc} - i_{Oabc}\right)$$

$$R_2\left(i_{L1abc} - i_{L2abc} - i_{Oabc}\right) = L_2 \frac{di_{L2abc}}{dt}$$

(ii) Transform into DQ leaves algebraic terms unaltered but derivative terms map to two terms including a rotational voltage or current term.

$$v_{Odq\gamma} = R_2\left(i_{L1dq\gamma} - i_{L2dq\gamma} - i_{Odq\gamma}\right)$$

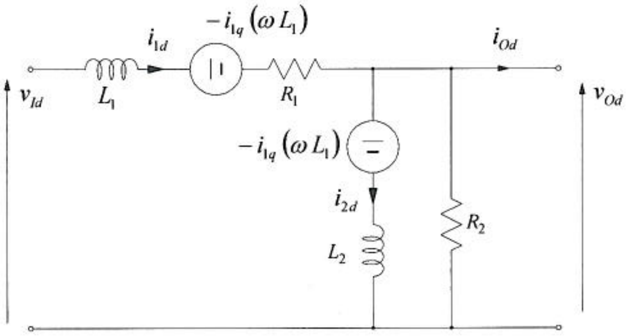
$$v_{I\,dq\gamma} = L_1 \frac{di_{L1dq\gamma}}{dt} + X_1\, i_{L1dq\gamma} + R_1 i_{L1dq\gamma} R_2\left(i_{L1dq\gamma} - i_{L2dq\gamma} - i_{Odq\gamma}\right)$$

$$\text{where } X_1 = \begin{bmatrix} 0 & -\omega L_1 & 0 \\ \omega L_1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

$$R_2\left(i_{L1dq\gamma} - i_{L2dq\gamma} - i_{Odq\gamma}\right) = L_2 \frac{di_{L2dq\gamma}}{dt} + X_2\, i_{L2dq\gamma}$$

$$\text{where } X_2 = \begin{bmatrix} 0 & -\omega L_2 & 0 \\ \omega L_2 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

(iii) Equivalent Circuit Formed from transformed equations includes controlled sources for rotational voltages/current and these only apply to D- and Q-axes.



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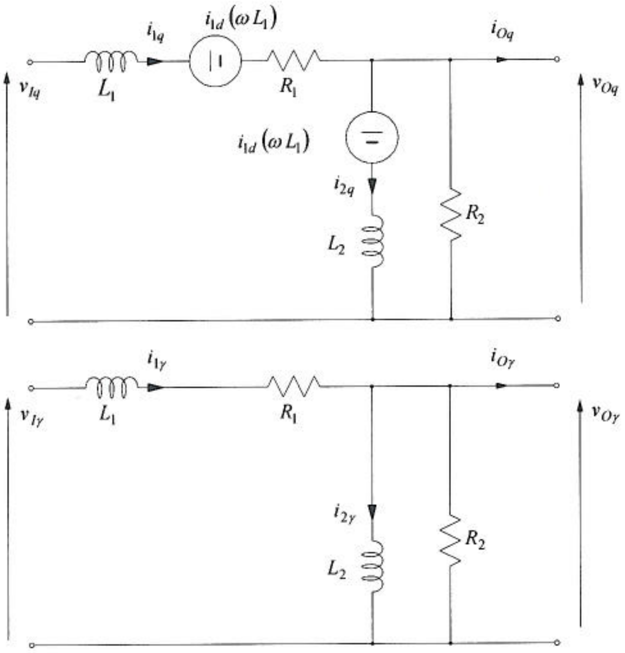


i_{1q}
$i_{1d}(\omega L_1)$
i_{Oq}
v_{Iq}
L_1
R_1
v_{Oq}
$i_{1d}(\omega L_1)$
i_{2q}
R_2
L_2
$i_{1\gamma}$
$i_{O\gamma}$
$v_{I\gamma}$
L_1
R_1
$v_{O\gamma}$
$i_{2\gamma}$
R_2
L_2

[4.49]

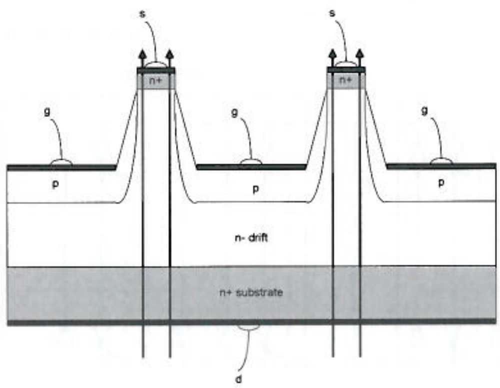
3.

a)

i) As semiconductor devices are made larger to handle higher off-state voltage and larger on-state currents, they tend to become slower in terms of switching speed. Explain why this is. [3]

As voltage blocking capability is increased, the distance between the device power terminals increases due to finite max field strength of that can be achieved in silicon. This increases on-state losses as impedance increases. The solution to bringing down the on-state resistance is to use both holes and electrons to conductivity modulate the material in the on-state. However, minority carrier devices operate slowly when switching large voltages because minority carriers must be removed for junctions to go into blocking mode. This process is analogous to discharging RC circuits and is slow.

ii) Several companies are investing heavily in moving beyond Silicon as a material for power devices, with SiC product appearing in the market. One company is investing in JFET devices whilst others are pushing MOSFETs. Draw a cross section of a power JFET device and discuss potential advantages and disadvantages over power MOSFETs. [5]



- MOSFET can be more difficult to fabricate in SiC due to problems manufacturing the gate structure due to gate oxide leakage and failure
- JFET requires DC gate current, MOSFET does not
- MOSFET has parasitic drain-body diode which is not optimised for conduction and additional diode is normally used instead. JFET does not have this parasitic component.

Or any other sensible observations

b)

i) Sketch a schematic diagram of a unified power flow controller (UPFC) and label major building blocks.

[5]

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Fig A3.1 shows basic circuit of the device.

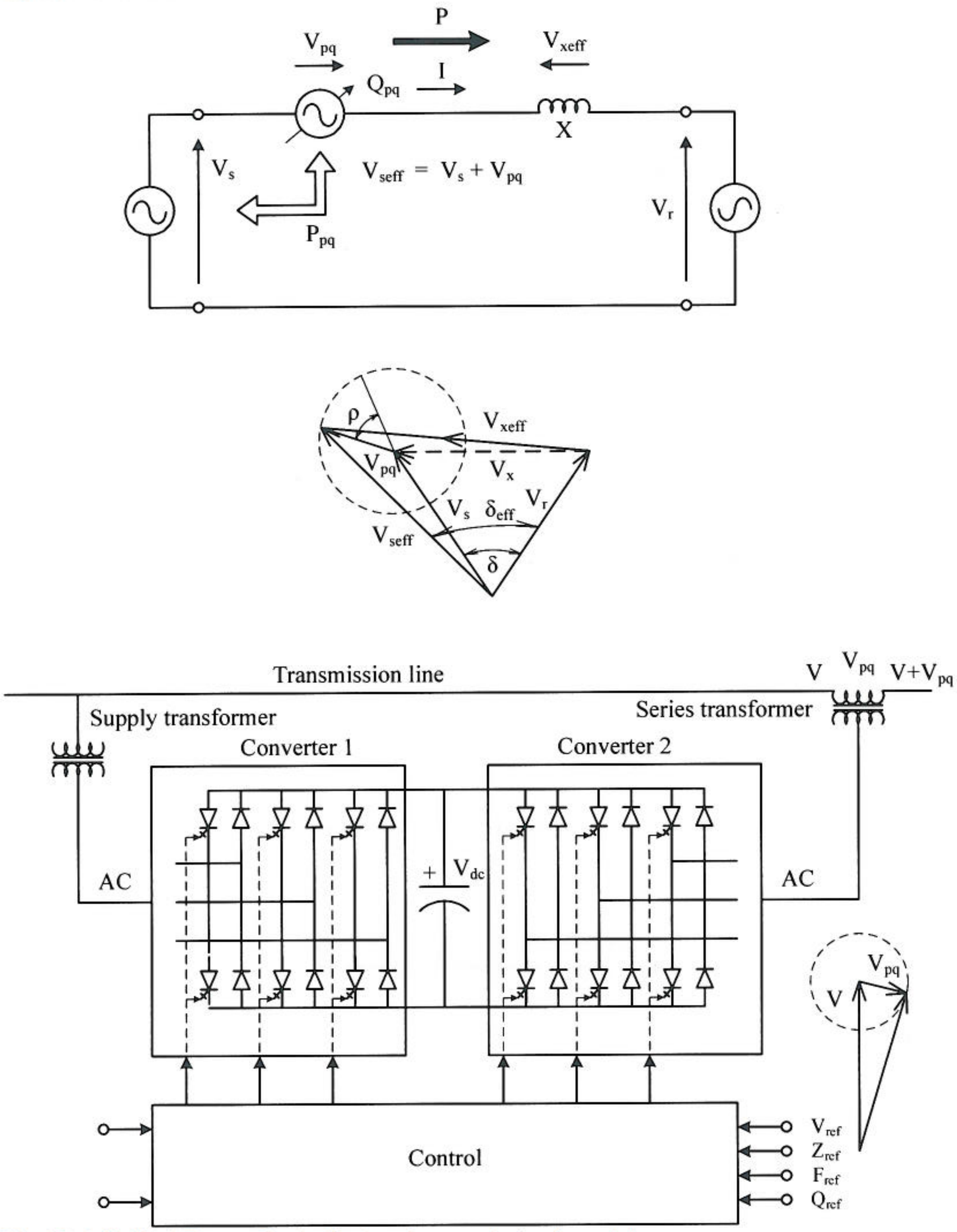

Fig A3.1: Unified Power Controller topology and circuit model

ii) Show how the functions of series, shunt and phase compensation are realised by this device. [7]

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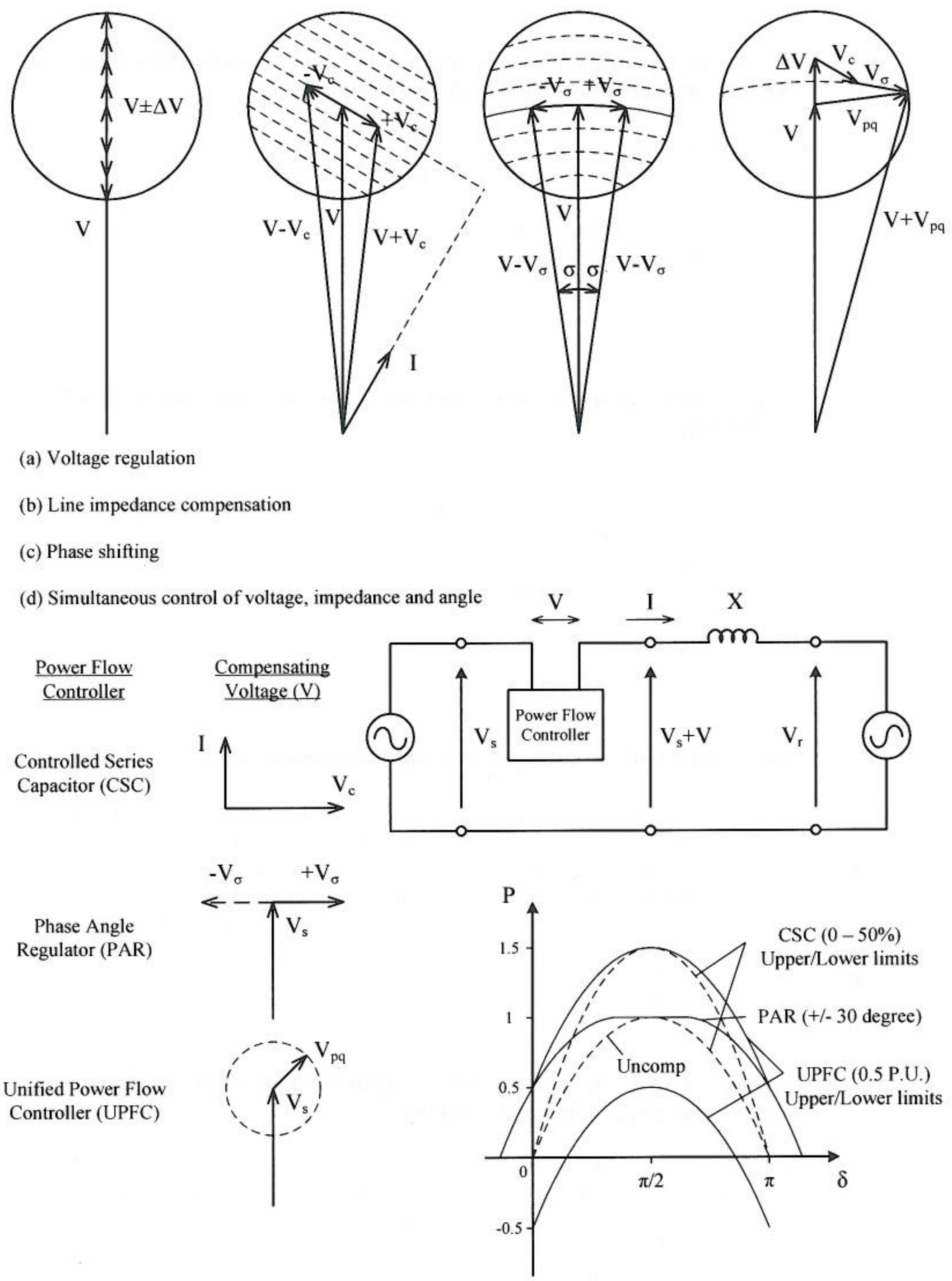


Fig A3.2 V-I and power angle characteristic of UPFC

[4.49]

4.

a)

i) AC power transmission is the norm but there are some difficulties that stem for using AC. List what these difficulties are. [4]

The following points should be included:

- *increased losses in the network because undesirable reactive power flows requiring higher magnitude of current..*
- *lower power transfer capacity because of voltage and angle stability limits*
- *loop flows in meshed network leads higher losses*
- *not easy to control,*
- *under and over voltage problems*

ii) Explain how some of these limitations can be overcome by FACTS technology [4]

The following points should be included:

- *FACTS technology can reduce effective transmission distance (thus reduce reactive power transport requirement between two ends. This comes with reduced current in the line for the same amount of MW transfer.*
- *It can improve voltage across the transmission paths thus reducing reactive power flow over distance cutting the loss down*
- *It offers fast voltage control action*
- *It also improves system stability margin*

b)

i) What is the natural loading of a power transmission line? [4]

The natural loading, also known as the surge impedance loading is when the reactive power generated by the shunt capacitance of the line is just enough to supply the reactive power consumed by the series inductance. It is assumed that the line is lossless (no series resistance). The voltage and current at any point on the line are in phase. The attraction is that the entire transmission line exhibits a flat voltage profile with sending end voltage equal to the receiving end voltage. The difficulty is that the load has to be purely resistive, which is rare. Loading more than the natural loading will lead to under voltage at the receiving end and loading less than this will lead to over voltage at the receiving end. Operation of transmission line at this loading is very rare, but the concept is very useful for reactive power compensation of the line.

ii) Suggest and justify types of FACTS technology to load a 800 km long, 765 kV line beyond its natural loading. [3]

Reactive power compensation either in series or in shunt will be required. The function of the reactive power compensation is to balance the reactive power generation and absorption in the line, which is dependent on loading level. For 765kV, over voltage is more of a problem as it is not always possible to have enough generation at the sending end. A long line will have angle stability problem. The best option will be to use a controllable series capacitor and a shunt reactor.

c) What are the structural and functional differences between a Thyristor Control Series Capacitor (TCSC) and a Static Series Synchronous Compensator (SSSC)? [5]

Structurally, both of them are series devices but the TCSC acts as a dependent current source or variable series reactance where as SSSC voltage is independent of line loading. The current through the line is controlled by the voltage impressed across it. The turn on time thyristor can be controlled not turn off

[4.49]

time. This makes TCSC a slow-acting device. The amount of voltage to compensate drop in the line reactance is dependent on current. The reactive power generated is proportional to the square of the current.

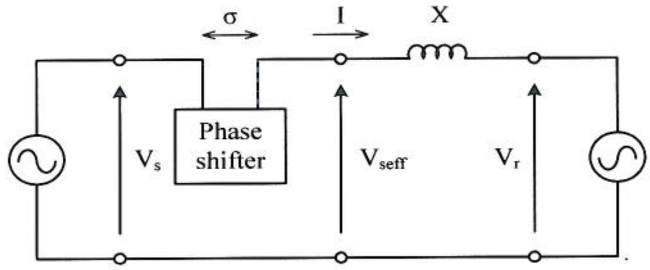
The SSSC on the other hand, employs a voltage source converter where switching on and off the power semiconductors are controlled. The response is faster than TCSC. The device behaves as an independent voltage source with a phase angle difference of 90 degree with line current. The magnitude of voltage produced is not dependant on loading. So, from the line drop compensation and reactive power generation point of view, it is more desirable over TCSC.

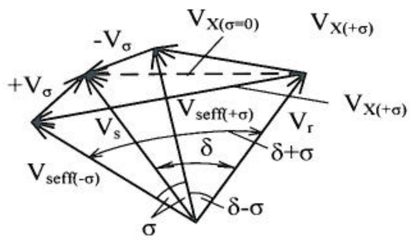
5

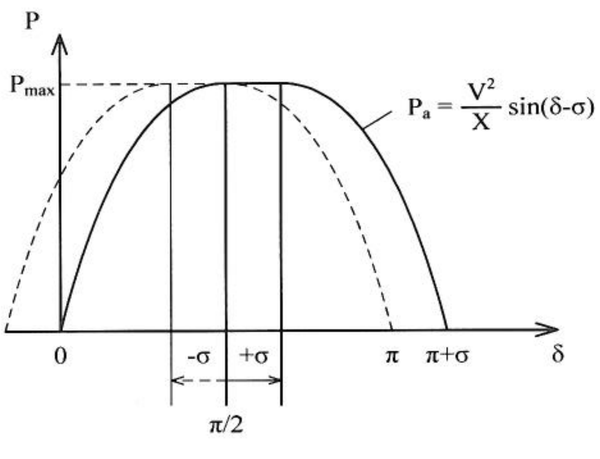
a) How is phase angle regulated in a power system? With the help of basic circuit representation of a simple system and a power angle plot, show the effectiveness of phase angle regulation in improving power transfer capacity of a line [7]

In some practical power systems, it occasionally happens that the transmission angle required for optimum use of transmission line is incompatible for proper operation of the overall transmission system. Such cases occur when two parallel lines of different electrical distance are involved or an inter-tie has insufficient angle between the systems to establish desired power flow. In such situations, phase angle regulator or phase shifter is frequently used.

The basic concept is explained again with the help of the two-machine system in which a phase shifter is inserted in series with the line as illustrated in Fig B.5.







It can be seen from the figure that a small voltage V_σ with an angle σ is added with receiving end voltage in such a way that the overall voltage is not increased rather an additional angle is created between two end voltages thus improving power transfer capacity. The effect can be clearly seen from the power angle diagram where the maximum power point is flattened. A complete schematic of a TCPS is shown in Fig B.6 The expression for power is:

$$P = \frac{V^2}{X} \sin(\delta - \sigma)$$

The maximum value of power is not changed but certainly the effect of the phase shifter is to hold this maximum value in the range $\pi/2 - \sigma \le \delta \le \pi/2 + \sigma$. This means the power angle curve is shifted right (left) by σ if it is positive (negative). These are often used in systems to prevent undesirable loop flows.

b) Discuss a modular operating strategy for a Thyristor Switched Capacitor and Thyristor Control Reactor (TSC+TCR) and its effectiveness in reducing the overall required capacity of the reactive power sources. [7]

A basic single-phase TSC-TCR arrangement is shown in Fig. A5.1 For a given capacitive output range, it typically consists of n TSC branches and one TCR. The number of branches, n, is determined by practical considerations that include the operating voltage level, maximum VAR output, current rating of the thyristor valves etc. The inductive range can also be extended to any maximum rating by including more TCR branches. The operation of the basic TSC-TCR VAR generator can be described as follows:

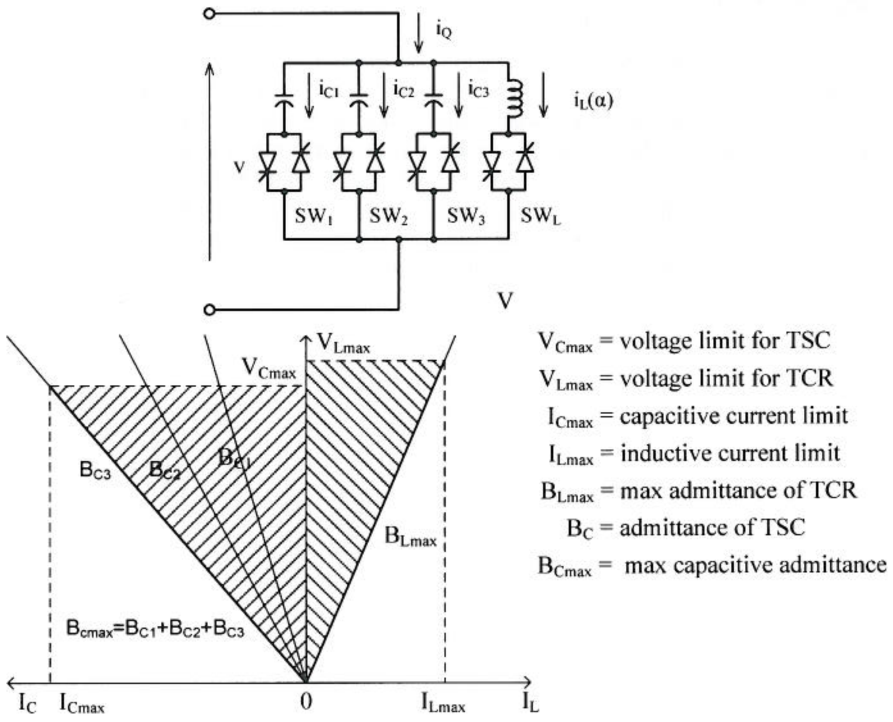


Fig A5.1: TSC+TCR topology and associated V-I characteristic

The total capacitive output range is divided into n intervals. In the first interval, the output of the var generator is controllable in the zero to Qcmax/n range, where Qcmax is the total rating provided by all TSC branches. In this interval, one capacitor bank is switched in by firing associated thyristor, and, simultaneously the current in the TCR is set by appropriate firing angle delay angle so that the sum of the

[4.49]

var output of the TSC (negative) and that of the TCR (positive) equals the capacitive output required. In the subsequent intervals the output is controllable in the range Q_{cmax}/n to $2Q_{cmax}/n$, $2Q_{cmax}/n$ to $3Q_{cmax}/n$ and so on and using the TCR to absorb the surplus capacitive vars.

By being able to switch the capacitor banks in and out within one cycle of the applied ac voltage, the maximum surplus capacitive var in the total output range can be restricted to that produced by one capacitor bank, and, thus, theoretically, the TCR should have the same var rating as the TSC. However, to ensure that the switching conditions at the endpoints of the intervals are not indeterminate, the var rating of the TCR has to be somewhat larger than one TSC unit in order to have enough overlap between 'switching in' and 'switching out'.

From the black box view point both FC+TCR and TSC+TCR can be considered as controllable reactive admittance. The time response between the var demand to var output is mainly decided by the firing delay angle. The response time naturally varies with two topologies with TSC+TCR response taking bit longer. For power system studies, it is fairly reasonable to take a value of T/3 to T/6 where T is the time period of fundamental power frequency.

c) Sketch the power loss versus loading characteristic for Fixed Capacitor and Thyristor Control Reactor (FC+TCR) type Static VAR Compensator (SVC). How does the power loss characteristic of the SVC influence the network functions supported by it? [6]

In addition to dynamic response, the loss versus var output characteristic is also very important consideration in designing and operating static var generators. In FC+TCR topology there are three distinct components of losses: capacitor and associated filter banks which reasonably constant because of fairly constant system voltage, in the inductor, it varies proportional to the square of the current through it, and in thyristor switches where the losses are proportional to the current (linear). Overall when the device absorbs plenty of var through TCR, the loss is high and when it operates as a capacitor, the loss is fairly small. For industrial application where power factor correction is primary objective, FC+TCR can be advantageous because of its low losses. Fig A 5.2 shows its loss characteristics.

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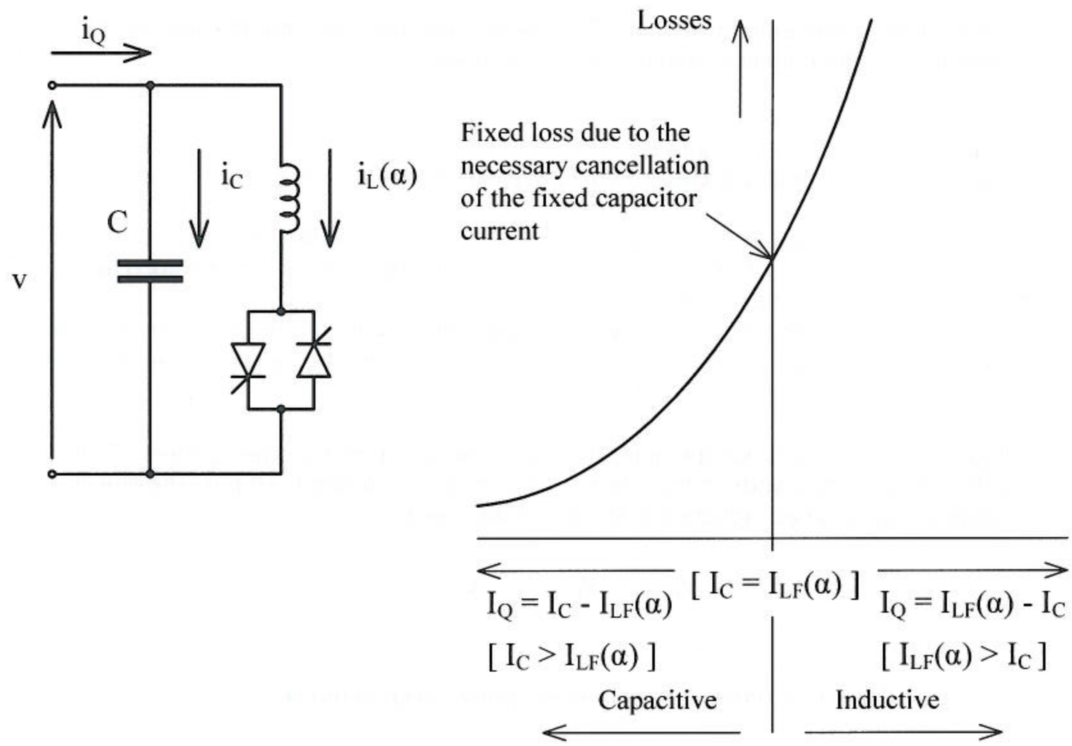

Fig. A5.2: Loss characteristics of FC+TCR type of var generator

[4.49]

6

a) Using Static Compensator (STATCOM) as an example, describe the operational benefits of voltage source based FACTS controllers [5]

The following points should point be made:

- Fast response (no natural commutation)
  Independent of network bus voltage control capability of VAR for the system within the capacity limit.
- STATCOM is a shunt device which is superior to SVC in V-I characteristic. It can stay connected to the system at low voltage which is an advantage over thyristor-based circuits such as the SVC. (Sketch illustrating this may be used)
- The reactive power capability of STATCOM is to some extent independent of the system voltage
- The STATCOM has better transient stability and voltage stability performance over thyristor counterpart simply because it offers controlled turn-off feature.

b) Figure 6.1 shows a simple model of an interconnected power system. The voltages at the two ends of the interconnection are $V_s\angle\delta$ and $V_r\angle 0$ p.u. The line is modelled by a series inductance and expressed as X_L p.u.

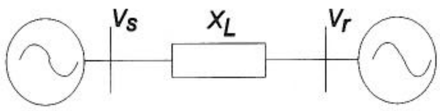

Fig 6.1: A simple interconnected power system model

i) The line is now equipped with a series capacitor of variable capacitive reactance $X_c = kX_L$ where k is controllable between. Sketch the variation of power with δ for k ranging between 0.0 to 0.4. With the help of the sketch, justify the influence of the series capacitor in power flow control. [10]

The first step is to find the power flow in the line with reactance only.
The sending and receiving end voltage are defined as:

$$V_s = Ve^{j\delta}, V_r = Ve^{-j0}$$

The current through the line is given by $I = \frac{V_s - V_r}{jX_L}$

The power is: $V_r I^* = P_r + jQ_r$

The expression for power

$$P_r = \frac{V_s V_r}{X_L} sin\delta$$

$$Q_r = \frac{V_r^2}{X_L} - \frac{V_s V_r}{X_L} cos\delta$$

The percentage of compensation is defined as k*100%, where k is the degree of compensation. The effective transmission reactance is given by

$X_{eff} = X_L - X_c$; $X_{eff} = (1-k)X_L$;$k = \frac{X_c}{X_L}$

The expressions for power with compensation can be easily obtained by replacing Xre given as:

$$P = \frac{V_s V_r}{(1-k)X_L}\sin\delta, Q_c = -\frac{V_r^2}{X_L}\frac{k}{(1-k)^2} + \frac{V_s V_r}{X_L}\frac{k}{(1-k)^2}\cos\delta$$

[4.49]

Consider a two machine power system as shown in Fig A6.1 with magnitude of voltage at both end equal. The power angle equation is as follows:

$P = \frac{V^2}{X_L(1-k)} Sin\delta;\ Q = \frac{2V^2}{X_L(1-k)^2}(1 - cos\delta)$

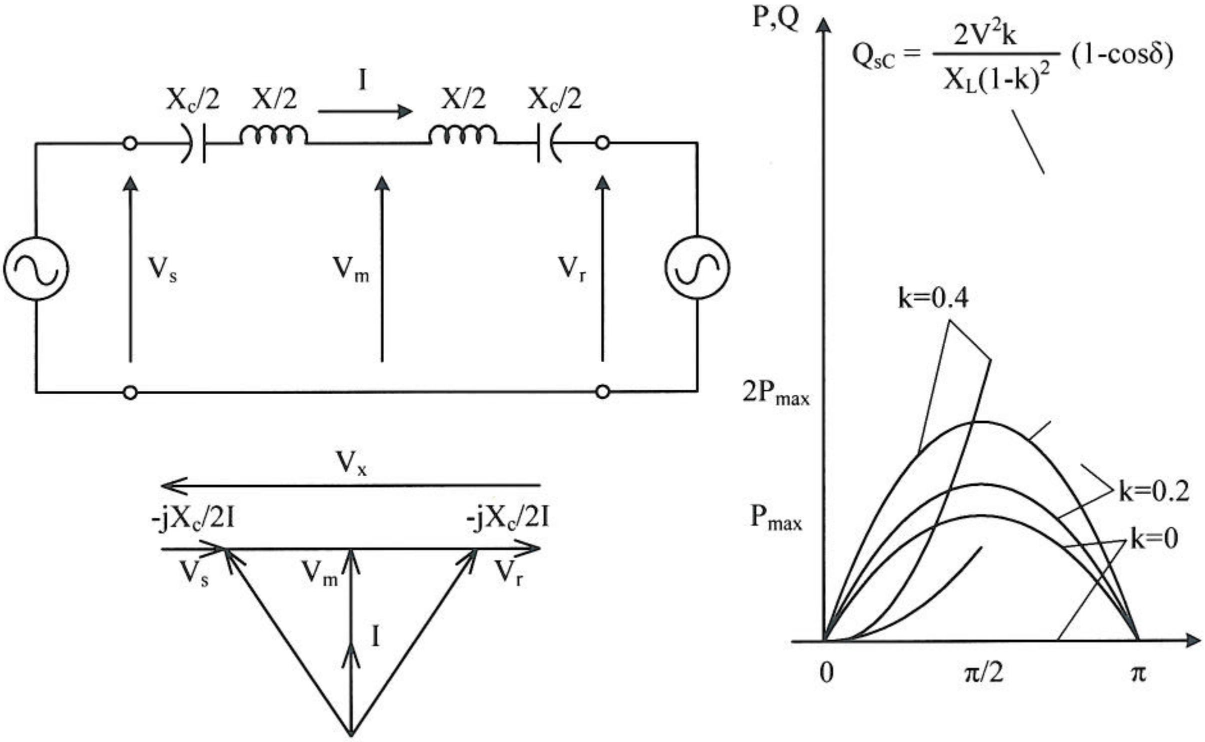

Fig A6.1 Power flow control through fixed capacitor

It is seen that the power transfer capacity is enhanced because of a reduction in the effective line impedance. The power transfer capability increases with degree of compensation. The reactive power supplied by the capacitor to the system also rapidly increases with degree of compensation.

ii) Name at least two potential problems that network operation is likely to face and briefly discuss how they can be addressed. [5]

One potential problem is excitation of torsional oscillations of generator shaft driven by multistage steam turbine. This is particularly true when fixed capacitance is in the line originating from the power plant. There are many solutions: making part of the series compensation controllable; having torsional oscillations filters, power system stabiliser, Hingorani damper.

The other important issue with capacitor compensated line is the dependability and sensitivity of distance protection. This can be addressed through duplication of the protection of the line by other principle such differential over current over pilot communication channel. Coordinated the setting of the capacitor adaptively with computer based distance protection is also a solution.