Final

E4.49

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2010

FACTS AND POWER ELECTRONICS

Wednesday, 5 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

The Questions

Part A

1.

(a) Explain why the switching frequency that can be used in a high-power power converter is lower than that in a low-power converters. [3]

(b) Triplen harmonics (e.g., 3^{rd}, 9^{th}, 15^{th} harmonics) have particular properties in three-wire, three-phase systems. Explain the relevance of this to the way optimal PWM is applied to high power DC/AC converters and to the harmonic elimination observed in multi-pulse DC/AC converters. [5]

(c)

i) What is a natural loading of an AC line? Draw the voltage profile of the line versus transmission distance. [3]

ii) An AC transmission line have controllable reactive power source at both ends. Draw the voltage profile across the line for loading beyond natural loading to explain that this not acceptable for efficient operation. Suggest the most effective location and type of reactive power compensation to improve the overall voltage profile if a single device is available for the purpose. [5]

(d) Explain with the aid of diagrams why modern IGBTs and MOSFETs use trench gate structures, rather than a planar structure on the surface of the wafer [4]

2.

a)

i) Explain why thyristors are able to conduct significant current between anode and cathode after the application of only a small gate current but cannot be turned off with the application of even a large negative gate current. [3]

ii) Explain the changes made to a standard thyristor which convert it into a GTO and explain why this device can be turned off by an action at the gate terminal. Explain the disadvantage of making these changes. [3]

b) Commercial thyristors are available with ratings up to around 6000 A, 6000 V. However, it is very common in FACTS applications that the circuit ratings are significantly higher than this.

i) Explain why individual devices are not made to larger ratings in order to serve FACTS and HVDC applications. [4]

ii) Explain why new materials, such as SiC, are being used to make some modern power devices [2]

c) You are required to design a valve that can block 10 kV and conduct 1000 A average current. The valve must be capable of being turned off in a controlled way. Two devices are proposed:

Device Specifications	**IGBT**	**GTO**
Max Voltage [V]	3300	2500
Max Rated Average Current [A]	1200	1050
Leakage Current [mA]	50-100	40-50
On-state voltage drop at 1000 A [V]	3-3.2	2-2.2
Reverse recovery charge at 1000 A [μC]	800-1000	700-800
Material	Si	SiC

i) Design two valves, one from IGBTs and one from GTOs, using the minimum sensible number of devices in each case. [5]

iii) Assuming conduction losses dominate, calculate the power losses in each valve with a 50% duty cycle and comment on the relative cooling requirements for each valve. [3]

3.

(a) High-power power converters can be formed either by forming valves by series combination of devices (IGBTs or GTOs) or by forming multi-level converters. Explain why such steps are necessary and whether there advantages of one approach over another. [5]

(b) Several circuit topologies have been proposed for high-power power converters.

(i) The diode-clamped converter and flying capacitor converter have not been used in power networks as FACTS controllers. Discuss some of their disadvantages that may have prevented their use. [5]

(ii) The chain-cell converter has been used for reactive power compensation (*i.e.*, as a STATCOM). Discuss the features of this topology that explain why it suits reactive power use. [5]

(iii) The multi-modular converter has recently been built for both reactive power use and for HVDC links. Discuss the prospects for future use of this converter. [5]

PART B

4

a) Sketch and describe the St Clair curve for AC power transmission. Explain why it has been so useful to planning engineers.

[5]

b) With the help of the St Clair curve suggest with reasons the most effective type of compensation arrangement for uncompensated transmission lines having the following lengths:

i) 60 km

ii) 200 km

iii) 400 km

[6]

c) What is loop flow in a meshed system? How can this be minimised with FACTS controllers?

[3]

d) List various benefits of FACTS technologies.

[6]

5.

a) What is series compensation in power systems? With the help of a basic circuit representation of a simple series compensated power system and power angle sketch, show the effectiveness of series compensation in improving the power transfer capacity of a line.

[7]

b) Figure 5.1 shows a simple model of an interconnected power system. The voltage at the two ends 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. The line transfers power with 25% capacity margin.

i) Find an expression for the real power flow through the line as a function of voltage magnitudes, angle difference of two voltages and the reactance of the line with a capacitor $X_c = kX_L$. Where k is the degree of series compensation?

[5]

ii) What degree of compensation (k) is needed to improve this margin to 50% for the same level of MW transfer?

Useful hints: capacity margin: $\left(\frac{P_{max}-P}{P_{max}}.100\%\right)$; P_{max}: *maximum real power that can be transferred*

[8]

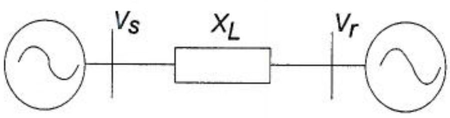

Fig 5.1: A simple interconnected power system model

6.

a)

i) Discuss the operating principle of a static compensator (STATCOM).

[6]

ii) With the appropriate sketch in the V-I plane, argue how a STATCOM offers better dynamic voltage performance over the thyristor based static var compensator (SVC).

[6]

b)

i) Sketch an equivalent circuit model of a static synchronous series compensator (SSSC) and also sketch the power angle relation.

[5]

ii) Explain how the device influences the power transfer characteristics of the line it is connected in.

[3]

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The Answers 2010

1.

(a) Explain why the switching frequency that can be used in a high-power power converter is lower than that in a low-power converters. [3]

High-power converters must use bipolar devices, IGBTs or GTOs, not majority carrier devices such as MOSFETs so slower operation is expected because of the need to inject and remove stored charge to switch the device. Further, the devices are physically large and the large capacitance and charge spreading times also lead to slower switching. Package power limits for large devices scale poorly and switching loss is constrained by proportion of the loss limit occupied by conduction loss.

(b) Triplen harmonics (e.g., 3^{rd}, 9^{th}, 15^{th} harmonics) have particular properties in three-wire, three-phase systems. Explain the relevance of this to the way optimal PWM is applied to high power DC/AC converters and to the harmonic elimination observed in multi-pulse DC/AC converters. [5]

Balanced harmonic distortion results in triplen harmonics that are co-phasal. The time-shift between the three phase signals is the equivalent to 120deg of the fundamental but this is 360deg of the third harmonic. Thus triplen harmonics are common-mode and would flow via the neutral line. If that line is not present, then no triplen current can flow. In three-wire systems, triplen voltage harmonics in a source voltage cause a neutral-to-ground voltage that leaves the load phase-to-neutral free from triplen harmonic. Thus, in three-wire, three-phase systems triplen harmonics do not cause current flow and are not present in load voltages. There is therefore no need to eliminate them from the PWM spectrum which allows the available degrees-of-freedom to be used to optimise/eliminate further non-triplen harmonics. Similarly, the phase-shift transformers of a multi-pulse converter are chosen to eliminate $5^{th}/7^{th}$ or $11^{th}/13^{th}$ harmonics and not 3^{rd} or 9^{th} since these are not passed through 3-wire transformer winding.

(c)

i) What is a *natural loading* of an AC line? Draw the voltage profile of the line versus transmission distance. [3]

The natural loading of an AC line corresponds to zero reactive power balance achieved by the line parameters. It is the loading which is purely resistive in nature. The line current at any point is in phase with the voltage at that point so no net reactive power flow across the line. The amount of reactive power generated by the shunt capacitance of the line per unit distance is exactly absorbed in the series inductance of the line. The voltage along the transmission distance is thus a flat straight line. The student is expected to draw the sketch of voltage versus transmission distance which is a line with zero slope.

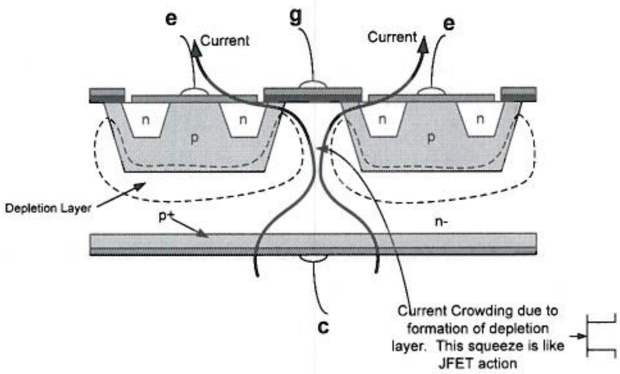
ii) An AC transmission line have controllable reactive power source at both ends. Draw the voltage profile across the line for loading beyond natural loading to explain that this not acceptable for efficient operation. Suggest the most effective location and type of reactive power compensation to improve the overall voltage profile if a single device is available for the purpose. [5]

The voltage profile of a line supported by reactive power source at both ends depends on the line loading. At loading higher than natural loading the amount of reactive power required by the line to support the real power flow is more than the line can generate. This situation requires voltage difference between sending end and any other point for the extra current to flow resulting in gradual decline in voltage along the transmission distance. The voltage profile start improving towards the receiving end as the receiving end has the reactive power source. When both end voltage is identical in p.u. (which is often the case with reactive power control at both ends), it is the midpoint of the line that experiences maximum drop in voltage magnitude. The student can explain this more effectively through voltage versus distance with a centenary shaped curve. Since the voltage is lowest at the midpoint, it is this point which requires the reactive power control device to be placed. The voltage being less than nominal, a shunt capacitive compensation is necessary. The most effective solution is to put a static var compensation (SVC) type device with both capacitive and reactive range of compensation which can address the voltage impact of variation in loading in both range (less than or more than natural loading of the line).

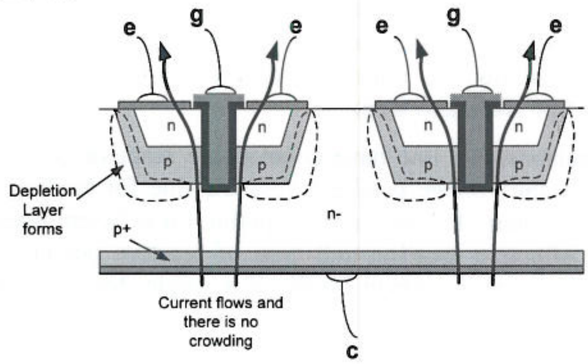
(d) Explain with the aid of diagrams why modern IGBTs and MOSFETs use trench gate structures, rather than a planar structure on the surface of the wafer

[4]

A device (MOSFET or IGBT) with a planar gate structure suffers from JFET effect when pushed into high levels of conduction. As the drain-source/MOSFET (collector-emitter/IGBT) voltage increases, there can be significant current crowding in a planar gate structure device due to the shape of the depletion layer that grows in the n- drift region. This effect is shown below:



If a trench gate is used, very little current crowding occurs as the depletion layer does not grow into the region where the current flows.



2.

(a)

(i) Explain why thyristors are able to conduct significant current between anode and cathode after the application of only a small gate current but cannot be turned off with the application of even a large negative gate current.

[3]

[bookwork]

- *Thyristors exhibit positive feedback. When current flows into the gate, the loop gain of the two BJTs causes the current between anode and cathode to increase until it is many times greater than the gate current (assuming external conditions allow)*
- *In order to turn off the thyristor, it would be necessary to divert the vast majority of the anode current out of the gate in order to cut off one the action of the npn BJT*
- *The cathode area is significantly larger than the gate area of the thyristor making it difficult to pull enough current out of the device to turn it off. In addition, the intrinsic resistance in the bulk of the device prevents all the current being diverted out of the gate terminal.*

(ii) Explain the changes made to a standard thyristor which convert it into a GTO and explain why this device can be turned off by an action at the gate terminal. Explain the disadvantage of making these changes.

[3]

[bookwork]

- *It is necessary to make the gate area much larger – which requires a reduction of the cathode anode. The gate and cathode islands must be interdigitated to allow an easy current path for the anode current flow out of the gate rather than the cathode*
- *Heavily doped n+ sections are added into the p+ layer that is covered by the anode metallisation. This allows fast removal of minority carriers from the base the pnp transistor allowing faster turn off*
- *The disadvantage is that the on-state conduction losses for a given cross sectional area of device will be more than a standard thyristor.*

(b) Commercial thyristors are available with ratings up to around 6000 A, 6000 V. It is very common in FACTS applications that the circuit ratings are significantly higher than this.

(i) Explain why individual devices are not made to larger ratings in order to serve FACTS and HVDC applications.

[4]

[bookwork]

- *Designing devices to work with large currents requires large area and designing for high blocking voltage requires the use of a deep wafer.*
- *Assuming a certain rate of imperfection per unit area in manufacturing, as the cross sectional area of the device increases, the yield will reduce as the device area (current rating) is increased.*
- *Making a very large area device (even with no perfections) may result in significant temperature variation across the device leading to local concentration of current and failure*
- *A deep device required to block large voltages will have poor thermal conductivity between the centre of the device and the heatsink so the device cannot be made arbitrarily deep.*

(iii) Explain why new materials, such as SiC are being used to make some modern power devices

[2]

[bookwork]

- *SiC has higher mobility so that greater current densities can be achieved*
- *SiC can operate at higher temperatures than Silicon devices*

(ii) You are required to design a valve that can block 10 kV and conduct 1000 A average current. The valve must be capable of being turned off in a controlled way. Two devices are proposed:

Device Specifications	**IGBT**	**GTO**
Max Voltage [V]	3300	2500
Max Rated Average Current [A]	1200	1050
Leakage Current [mA]	50-100	40-50
On-state voltage drop at 1000 A [V]	3-3.2	2-2.2
Reverse recovery charge at 1000 A [μC]	800-1000	700-800
Material	Si	SiC

Design two valves, one from IGBTs and one from GTOs, using the minimum sensible number of devices in each case

[5]

[calculation]

For the IGBT:

10000/3300 = 3.03 which rounds to 4 devices in series

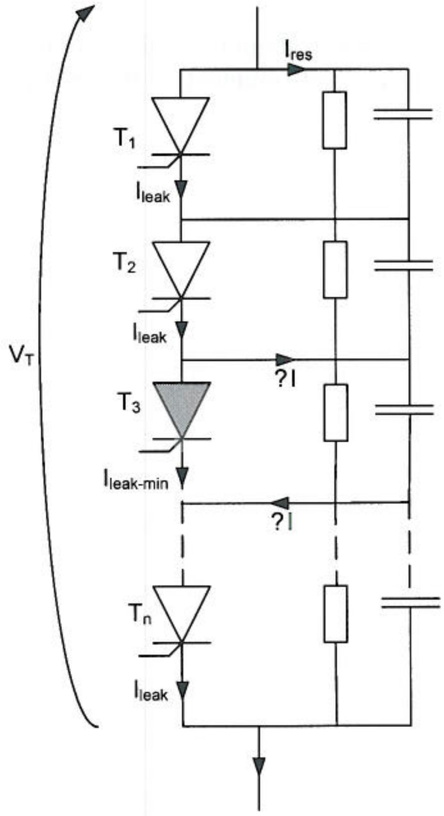
No parallel devices are needed

For the GTO:

10000/2500 = 4 which requires 5 devices in series to account for process variation and operation of the sharing network

No parallel devices are needed

The valve should looks like this (with either 4 IGBTs or 5 GTOs as the semiconductors):



To calculate the values of the sharing resistors, the worst case scenario is when all devices but one have the largest leakage and 1 has the minimum leakage:

$$\therefore R = \frac{nV_{BD} - V_T}{(n-1)\Delta I}$$

*For the IGBT case, this give R= (4*3300-10000)/(3*5e-3) = 213 kΩ*

*For the GTO case, this gives R=(5*2500-10000)/(4*10e-3) = 62.5 kΩ*

To calculate the sharing capacitors, the worst case is when one device has the minimum recovery charge and the rest have the maximum:

$$C = \frac{(n-1)\Delta Q}{nV_{BD} - V_S}$$

*For the IGBT, this gives C = (3*200e-6)/(4*3300-10000)=187.5 nF*

*For the GTO case, this gives C = (4*100e-6)/(5*2500-10000) = 160 nF*

(iii) Assuming conduction losses dominate, calculate the worst case power losses in each valve with a 50% duty cycle and comment on the relative cooling requirements for each valve.

[3]

The conduction losses for the IGBT valve are:

*P in IGBTs is 4*0.5*3.2*1000 = 6.4 kW*
*Power in sharing network is = 0.5*10000^2/(213e3*4)=58 W*

The conduction losses for the GTO valve are:

*Power loss in GTOs is 5*0.5*2.2*1000 = 5.5 kW*
*Power in sharing network = 0.5*10000^2/(62.5e3*5)=160 W*

The overall cooling for the GTO valve will be significantly less than the IGBT valve because whilst they dissipate similar amounts of power as conduction losses, the GTO can run at much higher temperatures due to the use of SiC rather than Silicon

3.

(a) High-power power converters can be formed either by forming valves by series combination of devices (IGBTs or GTOs) or by forming multi-level converters. Explain why such steps are necessary and whether there advantages of one approach over another. [5]

Semiconductor switches, whether IGBTs or GTOs, have forward blocking voltages of no more than about 5kV (and are probably utilised at nominal forward voltages of about 50-70% of this). Direct connection to a transmission system requires voltages in the region of 400 kV, and transformer connection would perhaps require 40 kV. It is clear that single devices are not useful in this context. The simple approach is to series connect devices into valves which act as a composite switch with every actual device switched on and off together. An alternative is to form multi-level circuits in which each device operates from a DC voltage within its ratings and several such voltage levels are combined to form the overall output voltage. Multi-level power converters can synthesise sinewaves through "staircase" approximations which can achieve very low harmonic distortion if enough levels are used. Series valves are normally used in standard 2-level inverters and PWM used to approximate a sinewave.

Series valves switched in a 2-level inverter suffer a difficult trade-off over switching frequency. A higher frequency allows better quality waveforms and less passive filtering (a significant factor) but increases the power loss. Series valves of high numbers of devices pose significant practical issues in ensuring voltage sharing during turn-off.

Multi-level converters can use low frequency switching of each device since they do not all need to switch at each output voltage transition. This means switching power loss is much lower and a higher number of transitions can be used and the output filer can be small or even omitted. In all designs, capacitors are used to define each voltage level and charge balance on these capacitors is an intricate control task. The capacitors are many and large and must be so to ensure low voltage deviation.

The number of devices used to obtain a given overall voltage and current rating of the power converter is the same in both approaches.

(b) Several circuit topologies have been proposed for high-power power converters.

(i) The diode-clamped converter and flying capacitor converter have not been used in power networks as FACTS controllers. Discuss some of their disadvantages that may have prevented their use. [5]

In the diode clamped converter he number of clamp diodes grows as the square of the number of levels. This is cost and becomes unfeasible from a layout point of view at high numbers of levels (200 levels are used in some other designs). Each level is unique in its role and unique in this clamp arrangement and so this converter is not modular in form and does allow redundancy to be provided readily. Capacitor charge balance in real power transfer is problematic unless in match back-to-back mode.

Similarly, the flying capacitor has a number of clamp capacitors that grows as the square of the number of levels which is problematic. There is some redundancy in switching state selection but the converter is not modular and has a difficult capacitor charge balance problem. It does however have a single DC-link connection.

(ii) The chain-cell converter has been used for reactive power compensation (*i.e.*, as a STATCOM). Discuss the features of this topology that explain why it suits reactive power use. [5]

This circuit uses series connection of H-bridge cells via their AC terminals. This structure is truly modular and any cell can perform any switching duty. This allows redundant cells to be built in and maintenance intervals to be extended. Capacitor charge balancing is required but considerable flexibility exists in allocating duties to achieve this. A basic duty oration scheme can achieve reasonable balance and additional duty-swapping can be based on cell voltage measurement. There is a difficulty in transferring real power is power must be supplied (or extracted) from a great many cell capacitors that are at arbitrary and changing potential with respect to ground. However, provided the cells can be pre-charged, this is not a barrier to use for reactive power only exchange with the AC system.

(iii) The multi-modular converter has recently been built for both reactive power use and for HVDC links. Discuss the prospects for future use of this converter. [5]

M2C uses half-bridge cells series connected via the AC terminals to replace the 6 switches of simple DC/AC converter. The topology is truly modular which scales linearly (like a chain cell converter) and yet has a single DC-link (like a flying capacitor converter). Redundancy can be readily incorporated and it is well suited to real power applications.

In comparison with 2-level series valve converter, it can have lower switching loss (and better efficiency) and better quality voltage with little or no filtering. It has an intricate control system that must coordinate very many (perhaps 1200) cells and balance the charge on each but this may not be much more onerous that active voltage sharing in series valves.

Because low losses, low footprint (filter size) and internal redundancy are all features sought by network operators and all can be offered by the M2C, it would appear to be the topology that will be favoured in the next phase of FACTS and HVDC. Siemens presently offers products and ABB and Areva indicate they will shortly.

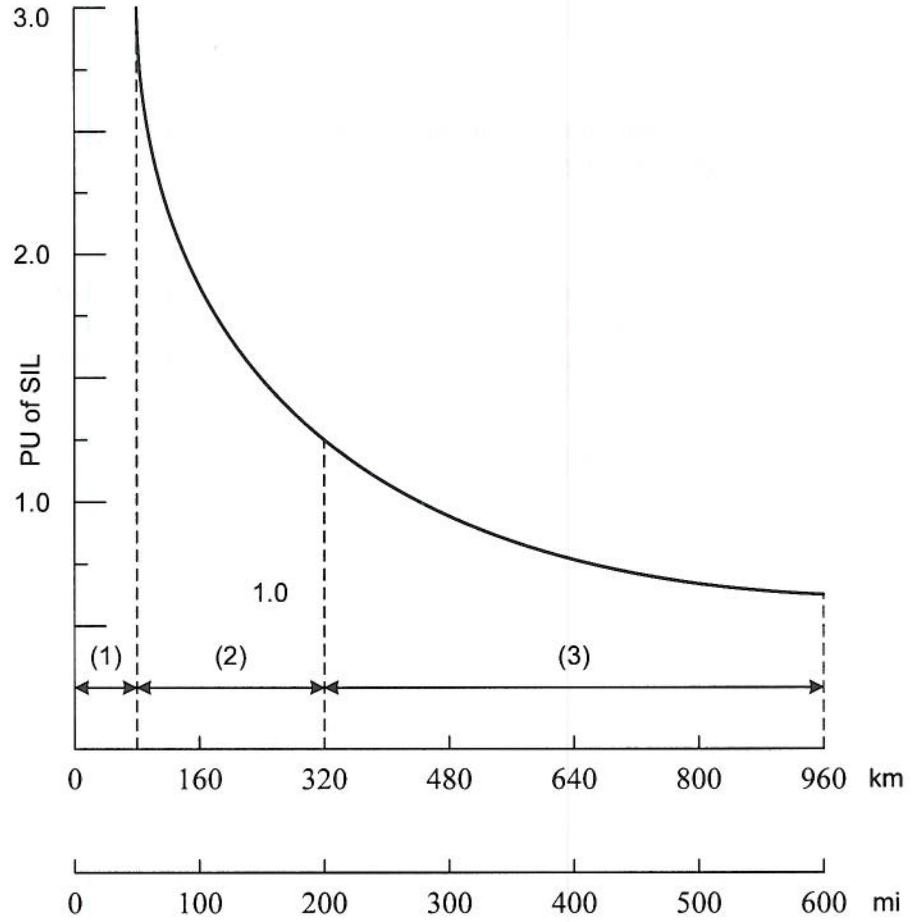
4

a) *Sketch and describe the St Clair curve for AC power transmission. Explain why it has been so useful to planning engineers.*

[5]

Back in 1950s, H.P St Clair, expressed power transfer capability of transmission line as percentage of surge impedance loading versus line length based on design and practical experience. This curve, shown in Fig A.4, is universal and quite useful for transmission planning as well as for operation and is most commonly known as St. Clair Curve Three factors limit the loadability of a line:

- Thermal (up to 50 miles or 80 km)
- Voltage drop (dielectric) (between 50 – 200 miles, (80-320 km))
- Stability (beyond 320 km)



(1) 0 - 80 km: Region of thermal limitation

(2) 80 - 320 km: Region of voltage drop limitation

(3) 320 - 960 km: Region of small-signal (steady-state) stability limitation

Fig A.4: Transmission Line loadability curve

The curve shows how with transmission distance the power capacity of the line drops; requiring various compensation arrangement. This is useful to planning engineer as it helps in arriving at proper conductor configuration, and rating of reactive power devices.

b) *With the help of the St Clair curve suggest with reasons the most effective type of compensation arrangement for uncompensated transmission lines having the following lengths:*

i) 60 km

ii) 200 km

iii) 400 km

[6]

i) For a line of 60 km, the capacity can be close to thermal capacity without any compensation

ii) A line of 200 km is more likely suffer voltage drop due to heavy loading, the shunt capacitive compensation will be required to improve the voltage

iii) A long line of 400 km in length will not suffer from voltage instability rather angle instability. The most effective option is to have series compensation. The effect of the series compensation is to reduce the effective transmission length and angle, thus improving stability margin.

c) *What is loop flow in a meshed system? How can this be minimised with FACTS controllers?*

[3]

The power flow in meshed AC system follows general principle of KCL and KVL. Usually inductive reactance of lines is much larger than the resistance. The resistance for low voltage lines are higher than that of high voltage lines. The power flows through different routes to reach a single point resulting in loop flows and loss of power in the system. The FACTS controller can reduce the loop flows through control and thus minimising losses due to loop flows; this results in increased transmission efficiency.

d) *List various benefits of FACTS technologies.*

[6]

- Control of power flow as ordered and suit to follow a contract.
- Increase the loading capability of lines to their thermal capabilities including short term and seasonal
- Increase the system security through raising large and small signal stability margin and limiting short circuit current
- Provide secure tie line connections to neighbouring utilities and reasons thereby decreasing overall generation reserve requirements on both sides.
- Providing greater flexibility in siting new generation
- Upgrade of lines
- Reduce reactive power flows thus allowing lines to carry more active power
- Reduce loop flows
- Increased utilisation of lowest cost generation

5.

a) *What is series compensation in power systems? With the help of a basic circuit representation of a simple series compensated system and power angle sketch, show the effectiveness of series compensation in improving the power transfer capacity of a line.*

[7]

The series capacitor works by increasing the voltage across the transmission line that is function of line current. This happens as part of the inductive voltage drop in the line is compensated by the capacitive drop. The conventional view is that the series capacitor cancels a portion of the series reactance and thereby reducing the effective transfer reactance. An interesting physical view is in to order increase the current through the line increased voltage has to be impressed across the physical line, this can be accomplished by adding series connected circuit element (passive or active) that would provide a voltage in phase opposition to the voltage prevalent across the series line reactance. A simple capacitor can be used to do this but a synchronous voltage source can also do the job in much controlled way.
The technology has matured from fixed capacitor (FC) to controllable one. In FC, fixed value of capacitance is connected in series with the line. The module is achieved through large number of units. The amount of series compensation is expressed as percentage of total line reactance. Typically it varies from 10-70 %. The percentage of compensation is defined as k*100%, where k is degree of compensation. The effective transmission reactance is given by

$$X_{eff} = X_L - X_c \; ; \; k = \frac{X_C}{X_L}$$

'k' is known as the degree of series compensation.

It is seen that the power transfer capacity is enhanced because of reduction 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. The series capacitor is being used for over last 50 years.
The value of 'k' is fixed during the operation. This is very effective in long distance power transfer. It is easy to incorporate in Y-bus matrix used for power flow and stability study. There are some potential system interaction issues such as sub synchronous resonance (SSR) involving multistage steam turbine shaft with series network. The protection of the series compensated line also requires special technique. The technologies to overcome these problems are available though. It is widely used in the network having long lines.
The degree of compensation required by the system is varied with operating condition. With FC, it becomes difficult to suit with this requirement. This necessitates the effectiveness of variable series compensation or controllable series compensation (CSC). In controllable series compensation, part of the capacitance is usually fixed and part of it variable. This variability is achieved either through thyristor switched capacitor (TSC) or thyristor control reactor.
It offers smooth variation of degree of compensation. This is achieved automatic and online through proper control.

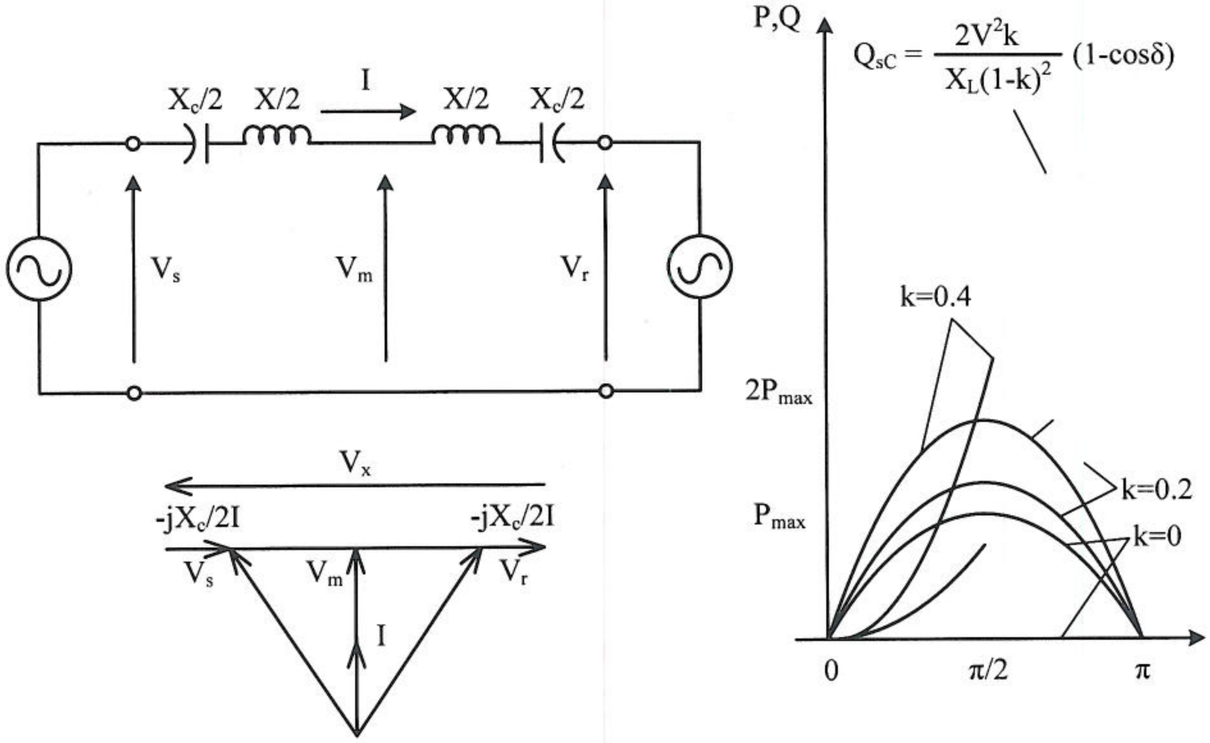


Fig B.1 Power flow control through fixed capacitor

b) *Figure 5.1 shows a simple model of an interconnected power system. The voltage at the two ends 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. The line transfers power with about 25% capacity margin.*

i) *Find an expression for the real power flow through the line as a function of voltage magnitudes, angle difference of two voltages and the reactance of the line.*

[5]

ii) *If the line is to be compensated with a capacitor* $X_c = kX_L$*, what degree of compensation k is needed to improve this margin to 50% for the same level of MW transfer?*

Useful hints: capacity margin: $\left(\frac{P_{max}-P}{P_{max}}.100\%\right)$; P_{max}: *maximum real power that can be transferred*

[8]

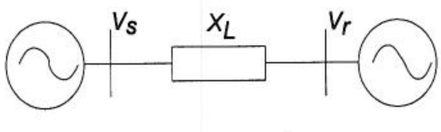


Fig 5.1: A simple interconnected power system model

The student is expected to start from the basic power angle derivation (VI*) and comes with the following expression.

$$P = \frac{V^2}{(1-k)X}\sin\delta, Q_c = \frac{2V^2}{X}\frac{k}{(1-k)^2}(1-\cos\delta)$$

ii)

The insertion of capacitor lifts the maximum power transfer capacity and hence the margin for the same amount of transfer.

The power angel relationship $P = \frac{V_s V_r}{X_L}\sin\delta$,

With capacitor X_c , it is $P = \frac{V_s V_r}{X_L - X_c}\sin\delta'$

$$= \frac{V_s V_r}{(1-K)X_L}\sin\delta', \quad \text{Where, } K = \frac{X_c}{X_L}$$

The impact of capacitor is to increase the maximum value in power -angle relation and thus reduces angle ($\delta' < \delta$) for same amount of transfer,

Let. $P = P_{max}\sin\delta$

$P = P'_{max}\sin\delta'$, with degree of compensation, -Capacity margin (CM)

$$CM = \frac{P_{max} - P}{P_{max}} = 1 - \frac{P}{P_{max}}$$

$$CM' = \frac{P'_{max} - P}{P'_{max}} = 1 - \frac{P}{P'_{max}}$$

Where, $P_{max} = \frac{V_s V_r}{X_L}$, $P'_{max} = \frac{V_s V_r}{(1-K)X_L}$

$$\frac{P}{P_{max}} = 1 - CM \quad , \qquad \frac{P}{P'_{max}} = 1 - CM'$$

Taking the ratio: $\frac{P'_{max}}{P_{max}} = \frac{1-CM}{1-CM'}$

$$= \frac{1-0.25}{1-0.50} = \frac{0.75}{0.50} = 1.5$$

$$\frac{P_{max}}{P'_{max}} = 1 - K$$

$$(1-K) \times 1.5 = 1$$

$$(1-K) = \frac{1}{1.5}$$

$$K = 1 - \frac{1}{1.5} = 0.33$$

% degree of compensation of $\approx 34\%$ is required to improve the capacity margin to stability level of 50%.

6.

a)

i) *Discuss the operating principle of a static compensator (STATCOM).*

[6]

Operating principle of STATic COMpensator (STATCOM):

A STATCOM is an independent voltage source that can be connected to the system as controllable shunt voltage source. In theory, its magnitude of voltage can be varied independently as long the current injected and absorbed by it remains with in the limit. It can not produce real power unless supported by real power sources.

A static var generator converter comprises a large number of gate-controlled semiconductor switches (GTO thyristors). The gating commands for these devices are generated by the internal converter control in response to the demand for reactive and/or real power reference signal(s). The reference signals are provided by the external or system control, from operator instructions and system variables, which determine the functional operation of the STATCOM. The internal control is an integral part of the converter. Its main function is to operate the converter power switches so as to generate a fundamental output voltage with demanded magnitude and phase angle in synchronism with the ac system. In this way the power converter with internal control can be viewed as a sinusoidal, synchronous voltage source behind a tie reactor (provided by the leakage inductance of the coupling transformer). The magnitude of voltage and its angle determines the real and reactive current draws from and thereby the real and reactive power the converter exchanges with the ac system. When the converter is strictly operated to control the exchange of reactive power, it is operated as static var generator and the reference input to control it is reactive current command. With energy source on the converter, real power exchange is possible. This will require two reference currents, one real component and the other for the reactive component.

Schematic of a STATCOM and V-I characteritic

From system analysis view point, the converter based static var generator can be viewed as synchronous voltage source that will draw either lagging or leading current set to an external reference up to the maximum value independent of ac system voltage. The major difference with respect to thyristor based var generator is that it is independent of system voltage. The power angle characteristic is also shown in Fig C.3. It clearly shows how power transfer capability can be improved with increasing rating of STATCOM at the mid point of the network.

ii) With the appropriate sketch in the V-I plane, argue how a STATCOM offers better dynamic voltage performance over the thyristor based static var compensator (SVC).

[6]

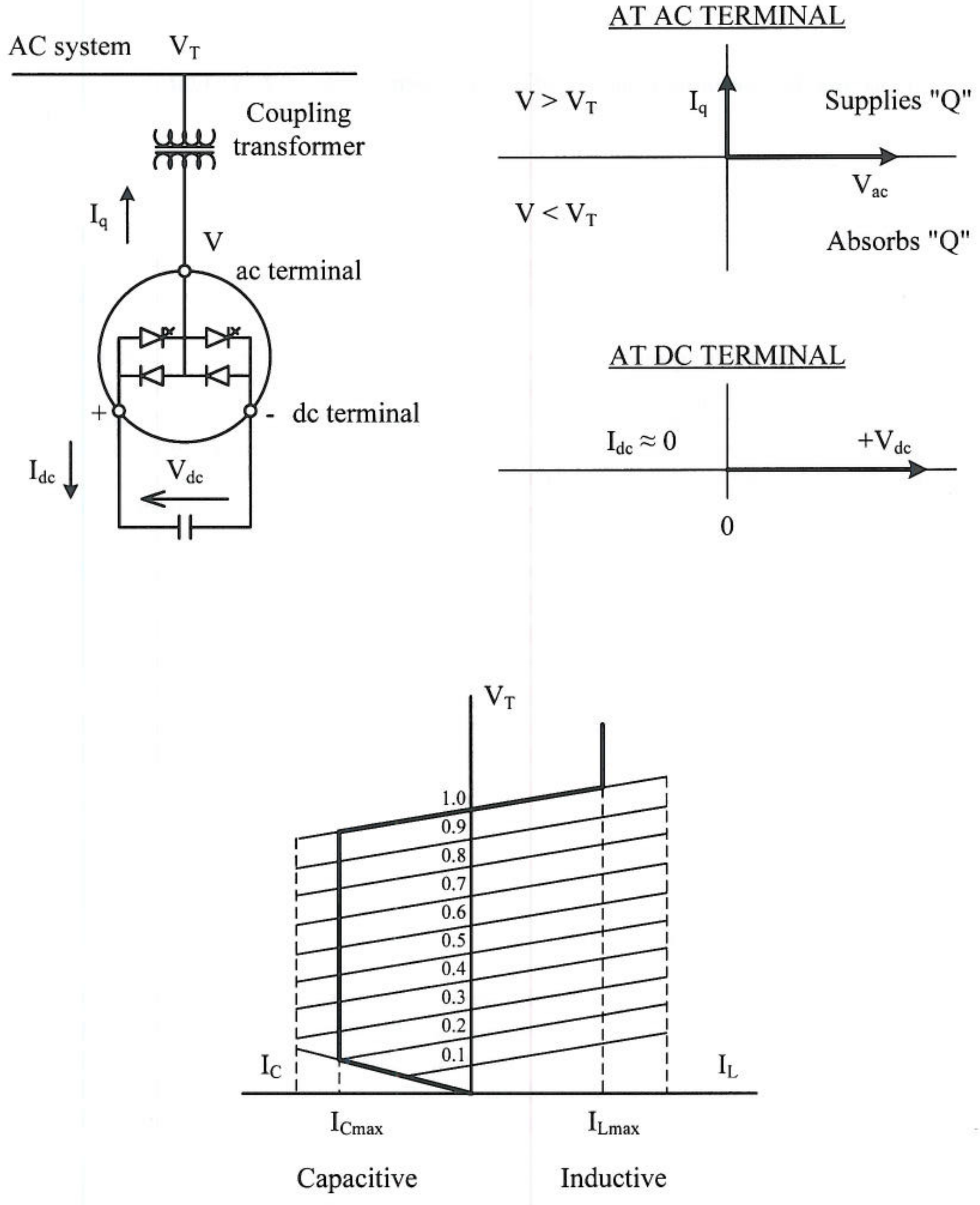


Fig A6.1STATCOM circuit model and V-I characteristics

Following is the topology and V-I characteristics of thyristor controlled static var compensator (SVC). It is clearly seen that the reactive power output and voltage supported by SVCis dependant on the SVC current which is not the case with STATCOM. Because of the capability of STATCOM to support reactive power and current at low network voltage, the overall transient stability performance of the system is better as it slows down the acceleration of the power generator during fault.

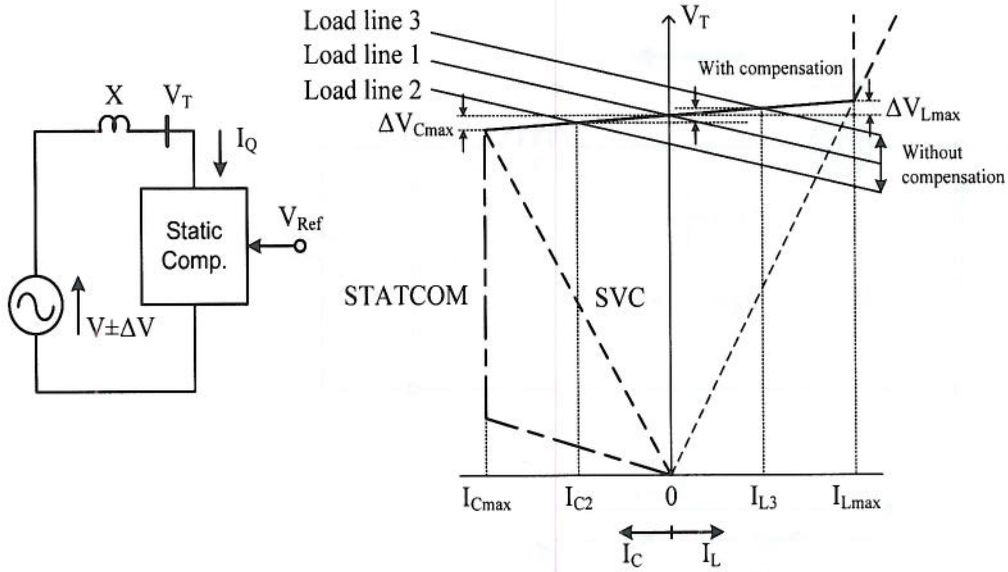
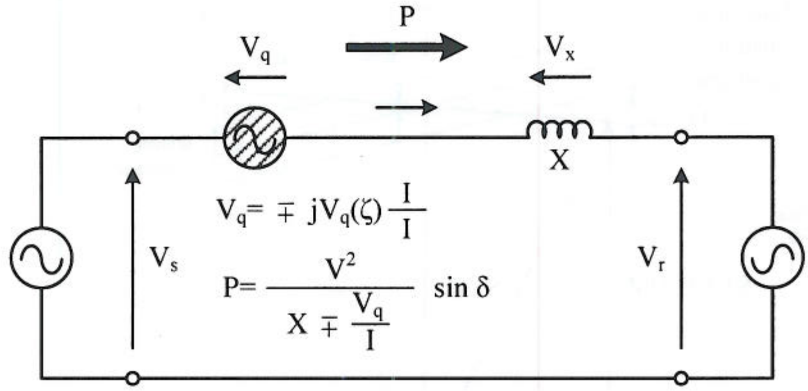


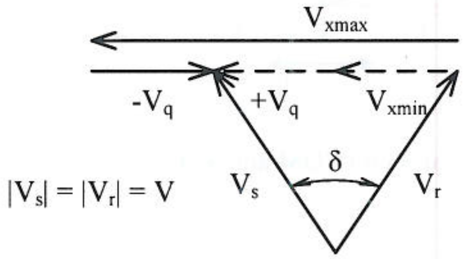
Fig. A6.2: V-I characteristics of STATCOM and SVC

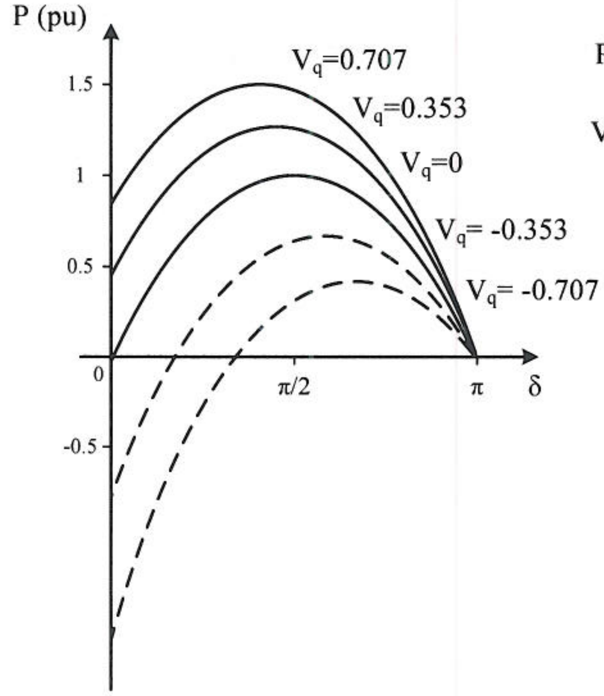
b) i) *Sketch an equivalent circuit model of static synchronous series compensator (SSSC) and also sketch the power angle relation.*

[5]

Fig A6.3 shows the basic circuit schematic and operating characteristic of an SSSC.







$$P = \frac{V^2}{X}\sin\delta + \frac{V}{X} V_q \cos\delta/2$$

$$V_q = \mp jV_q(\zeta)\frac{I}{I}$$

ii) *Explain how the device influences the power transfer characteristics of the line it is connected in.*

[3]

The power angle relationship is given by

$$P = \frac{V^2}{X} sin(\delta) + \frac{V}{X} V_q \cos(\delta / 2):$$

V_q is the magnitude of the voltage injected by the SSSC in series with the line. Note the second term on the right hand side of the equation. As long as voltage V_q is maintained the power characteristic is modified. It should be noted with importance that V_q is produced independently by voltage source coverter and it is not function of line current. This distinguishes it from its thyristor counter part, i.e. TCSC. It is once again clear from the power angle characteristic that SSSC enhances power transfer capability more than a series capacitor of same VA rating.