SOLUTIONS 2008

EE 4.49 FACTS and Power Electronics

1.

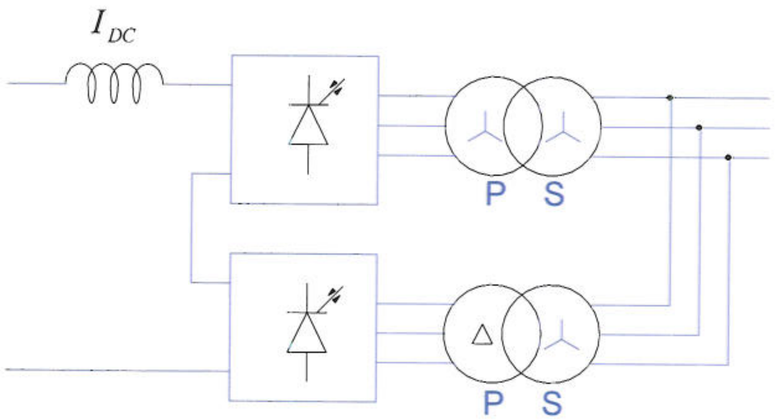
(a) Explain why it is expected that the switching frequency of a high power inverter is less than that of a lower power converter. [5]

The large devices such as GTO Thyristors tend to have long turn-on and turn-off times which give rise to high energy loss per switching cycle and a need to restrict switching frequency to limit the power loss to an acceptable value. The long switching times arise because the high-power devices are all bipolar devices in which minority carriers must be swept away from a junction in order for that junction to recover its voltage blocking capability. This is exacerbated by two factors. First, the devices are four-layer (pnpn) devices and the blocking junction (normally the middle junction) is not directly accessible at both sides to effect rapid removal of stored charge. Second, the devices are large in area (or contain many parallel cells across the area) and it is difficult to ensure all parts turn on and off together because of the time taken to spread charge from the gate contact. To avoid the development of hot-spots caused by uneven turn-on or turn-off, switching times are deliberately slowed at the expense of higher energy loss.

Thermal management of large devices is often difficult. The maximum heat power that can be conducted away through the device package can be very restrictive and after the conduction power loss has been accounted for, the allowable switching power loss can be very small. When combined with the high energy loss per switch-cycle, the switching frequency is, typically,

- *Large IGBT: 1-3 kHz*
- *GTO Thyristor: <1 kHz*
- *Thyristor: 50/60 Hz*

(b) Explain how two 6-pulse converters can be combined to give a 12-pulse converter with some harmonic terms removed from the spectrum. [7]



The figure shows two 6-pulse converters arranged to operate with the same DC-side current and to have their AC-side currents summed through parallel connection of the transformer windings.

The analysis of the 12-pulse current-source converter proceeds as follows.

- *The same network phase-voltage is imposed across both transformer secondaries.*
- *The primary with the delta winding has a fundamental voltage 30° phase delayed compared to that of the star winding.*
- *The turns-ratio of the delta-star transformer is differs from that of the star-star transformer by a factor of $\sqrt{3}$ so that the voltage magnitudes are the same.*
- *The switching of the delta-connected converters is time delayed by $t=30^o/\omega$ to align the current with the voltage.*
- *The converters produce no zero-sequence currents and hence the triplen harmonics are absent.*

[4.49]

- The harmonics currents produced by the delta-connected converter are phase-delay in proportion to the harmonic order: 5^{th} harmonic by 150°; 7^{th} by 210°; 11^{th} by 330 °; 13^{th} by 390° ...
- The currents are phase-shifted in passing through the delta-star transformer such that the negative sequence components phase delayed by 30° and the sequence components phase advanced by 30°.
- The fundamental current is thus brought into phase alignment with that of the converter on the star-star transformer.
- The 5^{th} harmonic is phase delayed by 150°+30°=180° and the 7^{th} harmonic by 210°-30°=180°. These harmonics cancel those produced by the star-star connected converter.
- The 11^{th} harmonic is phase delayed by 330°+30°=360° and the 13^{th} harmonic by 390°-30°=360°. These harmonics add to those produced by the star-star connected converter.

(c) Figure 1 shows three types of multi-level converter. Discuss the relative merits of the three designs. [8]

The answer should cover the following points.

All 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 number of additional components do 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.

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.

[4.49]

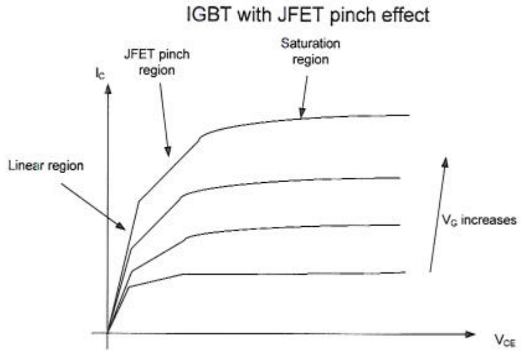
2.

(a) Draw the characteristic I/V curves of an IGBT using a regular surface gate structure and compare them with the characteristic curves of an IGBT that uses a trench gate structure. Highlight and label the different regions of operation. Use these plots to explain the reasons why a trench gate structure is preferred over a surface gate in high voltage IGBT devices.

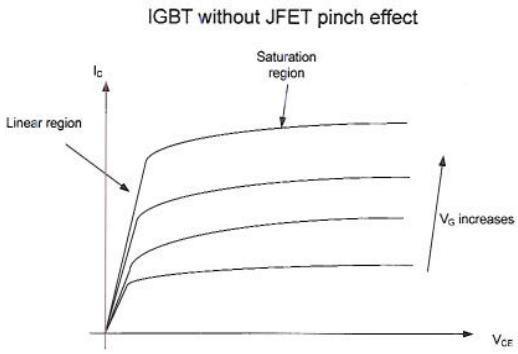
[8]

[essentially bookwork, but will require understanding to give a thorough answer]

The characteristic curves of an IGBT with JFET pinch looks like this:



And without, it looks like this:



A typical IGBT with a lateral gate structure exhibits significant resistance between its collector and emitter terminals due to a growing of a depletion layer at moderate V_{CE} values. This depletion layer grows into the n- drift region of the device from both sides, acting in the same way as a JFET turning off and adds a significant series resistance between the emitter and collector terminals. This effect, known as JFET effect, or JFET pinch, can be avoided by the use of a trench gate structure.

It is very important to avoid this effect, because in power electronics, we want to use power semiconductors towards the edge of their linear region in order to make best use of the silicon without paying the penalty of high conduction losses associated with entering the saturation region. As can be seen from the curves, JFET pinch substantially reduces the available linear region and so should be avoided.

[4.49]

(b) You are required to design a suitable semiconductor valve for use in a FACTS device that will be placed in the medium voltage (33 kV) distribution system. The valve must be able to block the entire 33 kV and be able to conduct 1000 A when turned on. You should use the following semiconductor device:

ABB 5500 V, 1200 A thyristor

The ABB datasheet specifies that the leakage current at breakdown can vary between 100 nA and 400 nA due to manufacturing tolerances.

(i) What is the minimum number of thyristors needed to make the valve? State whether they should be connected in parallel or series.

[3]

(ii) Design the required passive network (values and topology) to ensure reliable operation of the valve in steady state.

[5]

(i) [simple calculation]

The devices should be connected in series so that the entire valve can meet the voltage blocking requirement. There is no need for any parallel connection as individual devices can safely conduct the required current. If 6 devices are used in series, they would appear to just meet the voltage requirements but due to potential uneven voltage sharing in valves at least 7 devices are needed in this case.

(ii) [calculation]

A resistor should be placed in parallel with each thyristor to allow an even sharing of voltage in the off-state. The worst case situation for voltage sharing between devices occurs when 6 of the devices have the maximum leakage current and 1 has the minimum.

The required value of sharing resistor is given by:

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

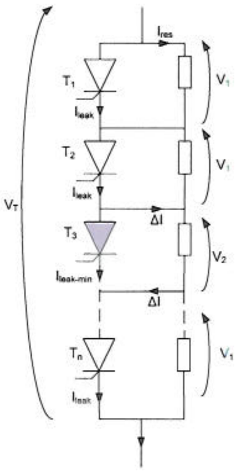
(Which is given in the notes, or can easily be derived by the students in the exam)

Therefore:

*R=(7*5500-33000)/(6*300e-9)=3.06e9Ω.*

The network therefore looks as follows:

[4.49]



Where there are 7 devices in series and the resistors have a value of 3.06e9Ω

(c) A FACTS device is designed to operate at 11 kV and 500 A. The total conduction losses in the semiconductors in the converter are 200 kW. Explain the likely total conduction losses in the converter if the same topology of converter is suitably scaled for use on the 33 kV system but rated at only 200 A.

[4]

[application of knowledge of semiconductor scaling laws]

The approximate scaling laws for conduction losses in semiconductor devices are that:

$$P_{loss} \propto I\sqrt{V_{block}}$$

Thus, increasing from 11 kV to 33 kV would increases losses by a factor of $\sqrt{33/11} = 1.73$

Reducing the current rating from 500 A to 200 A would reduce losses to 200/500=0.4 of their previous value.

Therefore the total losses of the converter would be expected to be around 0.69 of the original design, or around 138 kW.

[4.49]

3.

(a) For each of the signals u_1, u_2 and u_3, state whether they contain positive, negative or zero sequence components. Describe the expected form of transformed signals when the matrices T and T_R are applied. [6]

$$u_1 = \begin{bmatrix} U_1 \cos\left(\omega t + \frac{\pi}{4}\right) \\ U_1 \cos\left(\omega t - \frac{2\pi}{3} + \frac{\pi}{4}\right) \\ U_1 \cos\left(\omega t + \frac{2\pi}{3} + \frac{\pi}{4}\right) \end{bmatrix}$$

$$u_2 = \begin{bmatrix} U_0 + U_2 \cos(\omega t) \\ U_0 + U_2 \cos\left(\omega t - \frac{2\pi}{3}\right) \\ U_0 + U_2 \cos\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix}$$

$$u_3 = \begin{bmatrix} U_1 \cos(\omega t) \\ U_1 \cos\left(\omega t + \frac{2\pi}{3}\right) \\ U_1 \cos\left(\omega t - \frac{2\pi}{3}\right) \end{bmatrix}$$

$$T = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \qquad T_R = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) & 0 \\ -\sin(\omega t) & \cos(\omega t) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

u1 *is a positive sequence set at an angle of $\pi/4$.*
When transformed by T, two orthogonal components will result with the third term equal to zero.
When further transformed by T_R, the time variation is removed leaving

$$u_{1D} = \sqrt{\tfrac{3}{2}}\, u_1 \cos\left(\tfrac{\pi}{4}\right) \quad u_{1Q} = \sqrt{\tfrac{3}{2}}\, u_1 \sin\left(\tfrac{\pi}{4}\right) \quad u_{1\gamma} = 0$$

u2 *is a sum of a DC zero sequence set and positive sequence set at an angle of 0.*
When transformed by T, two orthogonal components will result with the third term equal to the zero sequence component.
When further transformed by T_R, the time variation is removed and because the positive sequence set is at an angle of zero the quadrature term is equal to zero.

$$u_{2D} = \sqrt{\tfrac{3}{2}}\, u_2 \quad u_{2Q} = 0 \quad u_{1\gamma} = \sqrt{3}\, u_0$$

u3 *is a negative sequence set at an angle of 0.*
When transformed by T, two orthogonal components with negative sequence will result and the third term will be equal to zero.
*When further transformed by T_R, the time variation is **not** removed. In fact the rotation of the set is doubled because the transform matrix rotates in the same direction as a negative sequence set.*

(b) The circuit in figure 3.1 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. [4]

(ii) Transform the equations to $dq\gamma$ form. [5]

(iii) Sketch the circuit of the transformed system. [5]

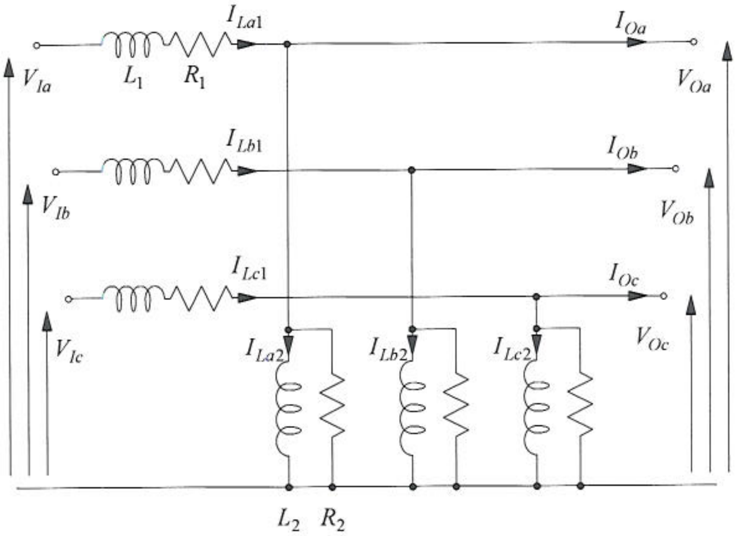


Figure Q3.1

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

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

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

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

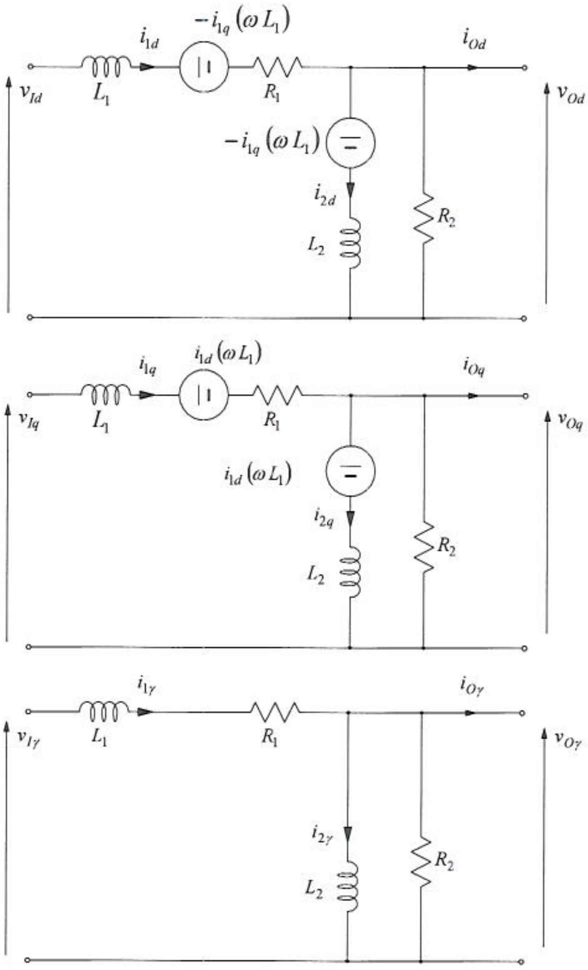
$$v_{I\,dq\gamma} = L_1 \frac{di_{L1dq\gamma}}{dt} + X_1\, i_{L1dq\gamma} + R_1 i_{L1dq\gamma} R_2\left(i_{L1dq\gamma} - i_{L2dq\gamma} - i_{Odq\gamma}\right)$$

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

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

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

[4.49]


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

[4.49]

4

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

[7]

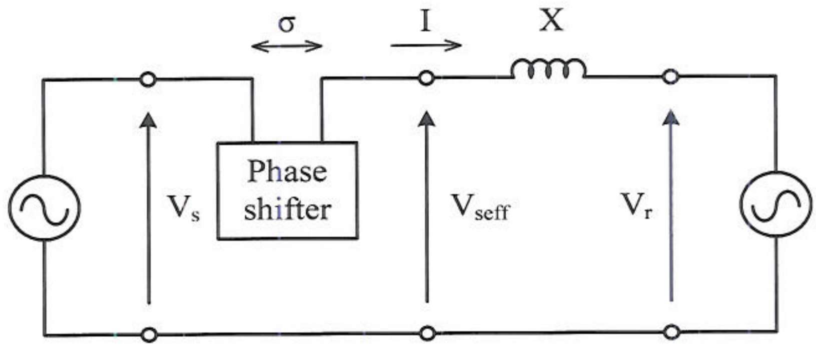
In some practical power system, it occasionally happens that the transmission angle required for optimum use of transmission line is incompatible for proper operation of the overall transmission system. Such cases occur, especially when two parallel lines of different electrical distance are involved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

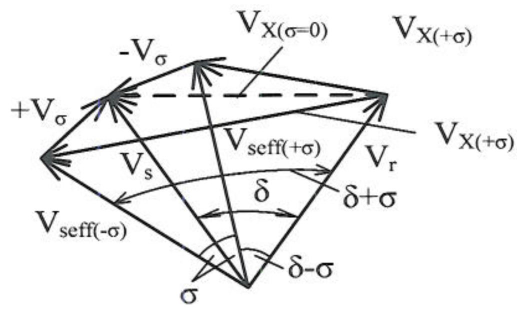
The basic concept is explained again with the help of the two-machine system in which a phase shifter is inserted in series with the line as illustrated in Fig B.5. It can be seen from the figure that a small voltage Vσ with an angle σ is added with receiving end voltage in such a way that the overall 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:

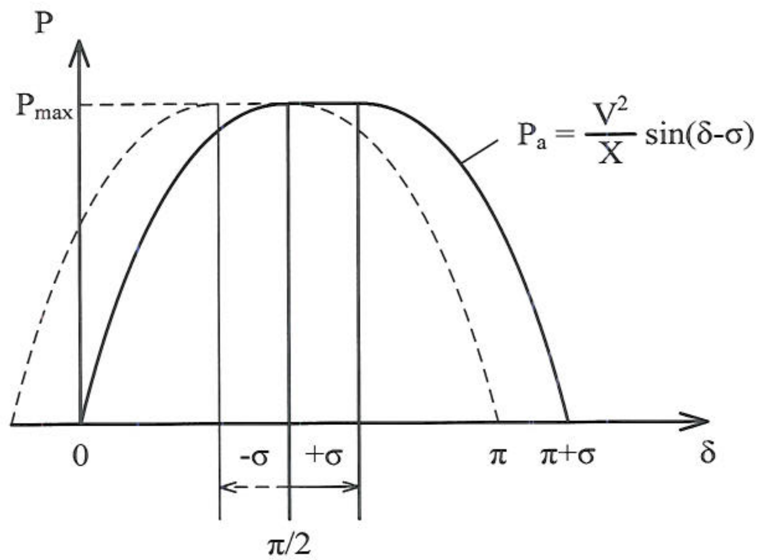
$$P = \frac{V^2}{X} \sin(\delta - \sigma)$$

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.*

[4.49]







b) Discuss modular operating strategy of Thyristor switched capacitor and Thyristor control reactor (TSC+TCR) and its effectiveness in reducing over all capacity of VAR sources.

[7]

A basic single-phase TSC-TCR arrangement is shown in Fig. B.14. 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 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:

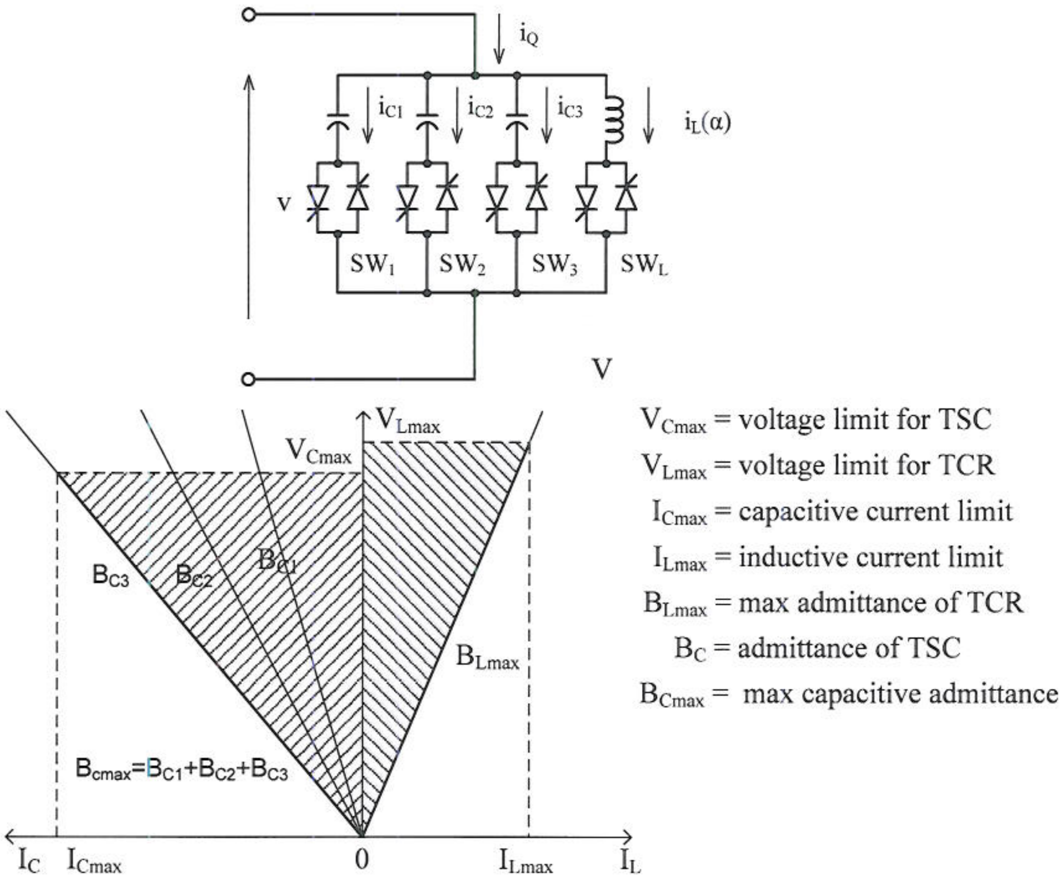


Fig B.14: TSC+TCR topology and associated V-I characteristic

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 Q_{cmax}/n range, where Q_{cmax} 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 var output of the TSC (negative) and that of the TCR (positive) equals the capacitive output required. In the subsequent intervals the output is

[4.49]

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 loss versus loading characteristic for fixed capacitor and Thyristor control reactor (FC+TCR) type static var compensator (SVC). How does the 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 B.15 shows its loss characteristics.

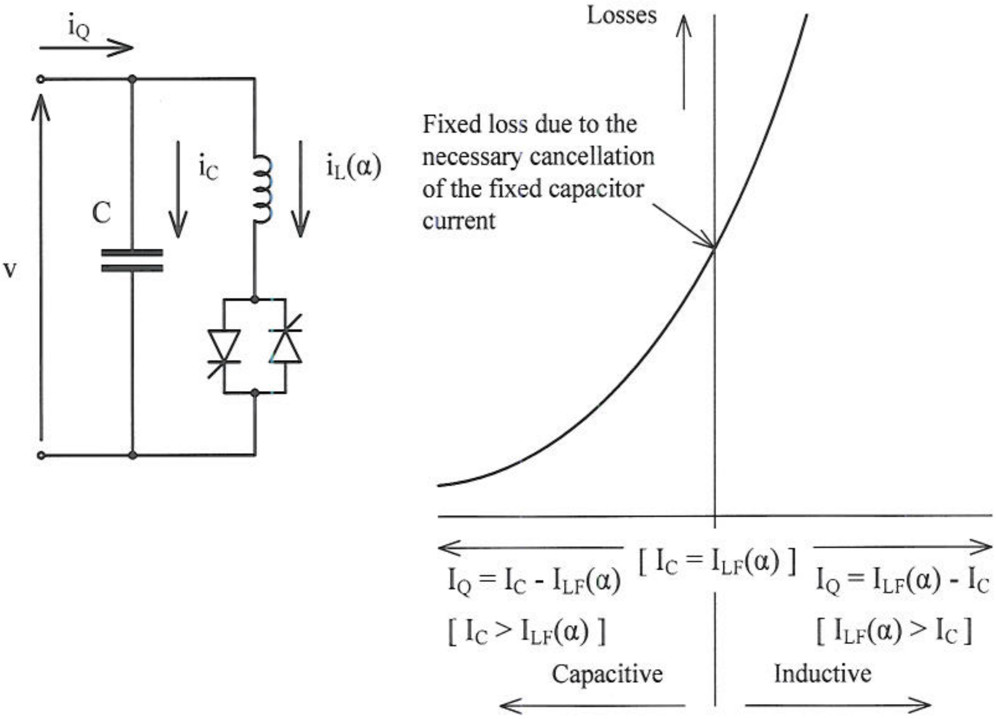


Fig. B.15: Loss characteristics of FC+TCR type of var generator

5

a) What is meant by the loadability of an AC power transmission line? With the help of a loadability curve of an uncompensated transmission line, explain various factors that affect transmission system loadability.

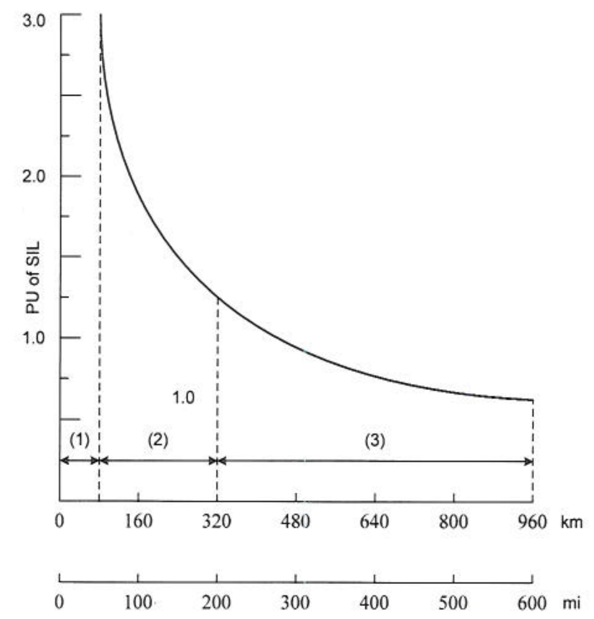
[8]

The loadability of a transmission line in an interconnected system of operation is defined as the amount of MW that can be transferred without violating operational constraints such as thermal, voltage and stability limits. [1]

The loadability of a transmission line can easily be explained with the help of St. Clair curve. This curve, shown in the figure, 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)

[4.49]



(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.3: Transmission Line loadability curve

Thermal

The heat produced by current flow in a transmission system has two undesirable effects:
Annealing and gradual loss of mechanical strength of the aluminium conductor caused by continued exposure to temperature extremes
Increased sag and decreased clearance to ground due to conductor expansion at higher temperatures
The second of the above two effects is generally the limiting factor in setting the maximum permissible operating temperature. At this limit, the resulting line sag approaches the statutory ground clearance. The maximum allowable conductor temperatures based on annealing consideration is 127 degree Celsius for aluminium conductor. The allowable maximum current (i.e. the ampacity) is dependent on ambient temperature, wind velocity. The thermal time constant is of the order of 10 to 20 minutes. Therefore the distinction is always made between short time rating during contingency and normal continuous rating. It is once again an empirical relation to assume thermal limit of a 50-mile long line to be 3.0 times the surge impedance loading (SIL) as shown in the St. Clair curve. In practice this varies perhaps by a factor of 2 to 1 due to variable environment, condition of the conductor and loading history. The nominal rating is generally decided on a conservative basis with the worst case operating scenario considered. The worst case scenario might not occurs in years, means a considerable amount of capacity is not utilised for most of the operating life of the line. Although some utility assign winter and summer loading, still the line remains unutilised for most of the time. It is important to assess the loadability of a line based on ambient conditions and loading history by off line computer program. Given the current state of the art in GPS and fibre optic technology for data handling and communication, online assessment of thermal loading limit on a day to day or even in an hour to hour basis is possible. This information certainly would optimise the usage of the thermal capacity.

Voltage (dielectric): *Insulation is the most important factor in EHV/UHV transmission. The lines are designed with conservative margin. A line can be subjected to 10% extra voltage above nominal one, provided transient (lightning and switching) and dynamic over voltage conditions are managed through*

[4.49]

proper protection equipment such as arresters or thyristor controlled over voltage suppressors. Most of the time an overloaded line (beyond surge impedance) is under compensated resulting in poor voltage. The poor voltage conditions leads to many problems, increased current flow and hence losses. The FACTS technology could be used to ensure improved voltage profile or even acceptable over-voltage and power flow conditions.

Stability: *There are number of stability issues that restrict the limit on transfer capability. They are transient, small signal (steady state), voltage stability etc. From the power angle relationship it was apparent that the maximum power can flow between two systems when the angular separation is 90 degree. With a 30% margin, the maximum permissible angle is 44 degree.*
[7]

b) Figure 5.1 shows a simple model of an interconnected power system. The voltages 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 29% capacity margin.

i) Find an expression of real power flow across 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 40% 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*

[7]

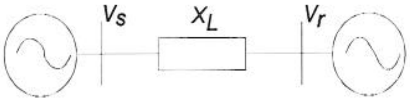


Fig 5.1: A simple interconnected power system model

(i) *Starting from voltage current and power relationship:* $P + jQ = VI^*$, *the students are expected to establish* $P = \frac{V_sV_r}{X_L}\sin\delta$

(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 $P = \frac{V_sV_r}{X_L}\sin\delta$,

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

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

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, $P_{max} = \frac{V_sV_r}{X_L}$, $\quad P'_{max} = \frac{V_sV_r}{(1-K)X_L}$

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

[4.49]

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

$= \frac{1-0.29}{1-0.40} = \frac{0.71}{0.60} = 1.183$

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

$(1 - K) \times 1.183 = 1$

$(1 - K) = \frac{1}{1.183}$

$K = 1 - \frac{1}{1.183} = 0.1549$

% degree of compensation $of \approx 16\%$ *is required to improve the capacity margin to stability level of 40%.*

[4.49]

6.

a) What is loop flow in a meshed system? What consequence does it have on operational efficiency of the network?

[4]

In an interconnected network power flows satisfying ohms law. A particular load point can be reached from a particular generation point through more than one root. The total current flows and hence the power flow will be shared by these paths in inverse proportion to their impedance and power frequency. Some time, the point of delivery may not be located physically far, but because of the interconnection, portion of the power would come in a circuitous root involving many transmission line sections. The power wheels through various sections in a transmission system before reaching the load point. This is known as loop flow. Because of the finite conductivity of the transmission conductors carrying current, I^2R loss is inevitable. The extent of loss depends on the magnitude of current and resistance. For longer paths which are encountered in loop flows, losses are more. The reactive power loss proportional to I^2X, has also to be supplied either from the sending or from the receiving end of the contract if the other arrangement of compensation with in the network is not made. All these lead to higher operational losses and the cost of these losses are a significant proportion of total cost of operation. If loop flow is avoided by proper design of the transmission system, or retrofitting it with FACTS controller, significant price reduction can be achieved that can easily be passed on to the customers.

b) What are the structural and functional differences between a static var compensator (SVC) and a static synchronous compensator (STATCOM)?

[5]

Static var compensators (SVC) are the forerunners of todays FACTS controllers. Developed in the early 1970s for arc furnace voltage unbalance compensation, they are being used in transmission systems in large scale for years. Simple Thyristor is at the heart of this class of device. A typically shunt connected static var compensator composed of thyristor controlled reactor (TCR) and fixed capacitor (FC) or Thyristor switched Capacitor (TSC) and TCR. The var output can be varied in a controlled way between the maximum inductive current and capacitive current rating. The voltage at the point SVC is connected is regulated through SVC by defining proper slope defined within the maximum current (inductive and capacitive) limits by control circuit. Beyond these ranges the SVC behaves as a passive device, i.e beyond capacitive maximum limit, it acts as a simple capacitor and beyond inductive limits it acts as a pure inductor. Outside its control range, reactive power injected to or absorbed from the system is proportional to the square of the system voltage.

Static synchronous compensator (STATCOM) is also a controllable shunt reactive power source or sink. It is relatively new concept and topology. The device utilizes voltage sourced converter (VSC) technology. For reactive power compensation, a capacitor is adequate on the DC side. STATCOM has an additional features that when equipped with energy storage source , it can exchange real power with the system. The STATCOM provides reactive power compensation which is independent of system voltage in a wide range (0.2 p.u. to 1.1 p.u.) unlike SVC. STATCOM results in higher power transfer capacity of the system than that of SVC of comparable rating. The transient stability margin improvement capacity of STATCOM is also larger than that of SVC. The dynamic response of SVC is sluggish over that of STATCOM because of thyristor firing delay. This results in limited band width of control. The steady state characteristic in the control range is identical .[Students can alternatively answer this question through VI characteristics of both the devices]

c) Discuss how the control slope, either in STATCOM or SVC, can be altered to provide effective voltage regulation.

[6]

In many applications, the static compensator is not used as a perfect terminal voltage regulator rather terminal voltage is allowed to vary in proportion with the compensating current. There are several reasons for this:

The linear operating range of a compensator with given maximum capacitive and inductive ratings can be extended if a regulation 'droop' is allowed. The regulation droop means the terminal voltage is allowed to be smaller than the nominal no load value at full capacitive compensation and conversely is allowed to be higher than the nominal value at full inductive compensation.

Perfect regulation (zero droop or slope) could result in poorly defined operating point, and a tendency of oscillations, if the system impedance exhibited a flat region (low impedance) in the operating frequency range of interest.

A regulation 'droop' or slope tends to enforce automatic load sharing between static compensators as well as other voltage regulating devices normally employed to control transmission voltage.

The desired terminal voltage versus output current characteristic of the compensator can be established by a minor control loop using the previously defined auxiliary input as shown schematically in Fig 6.1. A signal proportional to the amplitude of the compensating current kI_Q with an ordered polarity (capacitive current is negative, and inductive current is positive) is derived and summed to the reference V_{Ref}. The effective reference $V_{Ref}{}^*$, controlling the terminal voltage thus becomes

$$V_{Ref}{}^* = V_{Ref} + kI_Q$$

'k' is the regulation slope

$$k = \left(\frac{\Delta V_{Cmax}}{I_{Cmax}}\right) = \left(\frac{\Delta V_{Lmax}}{I_{Lmax}}\right)$$

Where ΔV_{Cmax} is the deviation in terminal voltage from its nominal value at maximum capacitive output current ($I_{Qmax}=I_{Cmax}$) and ΔV_{Lmax} is the deviation in terminal voltage from its nominal value at maximum inductive output current ($I_{Qmax}=I_{Lmax}$)

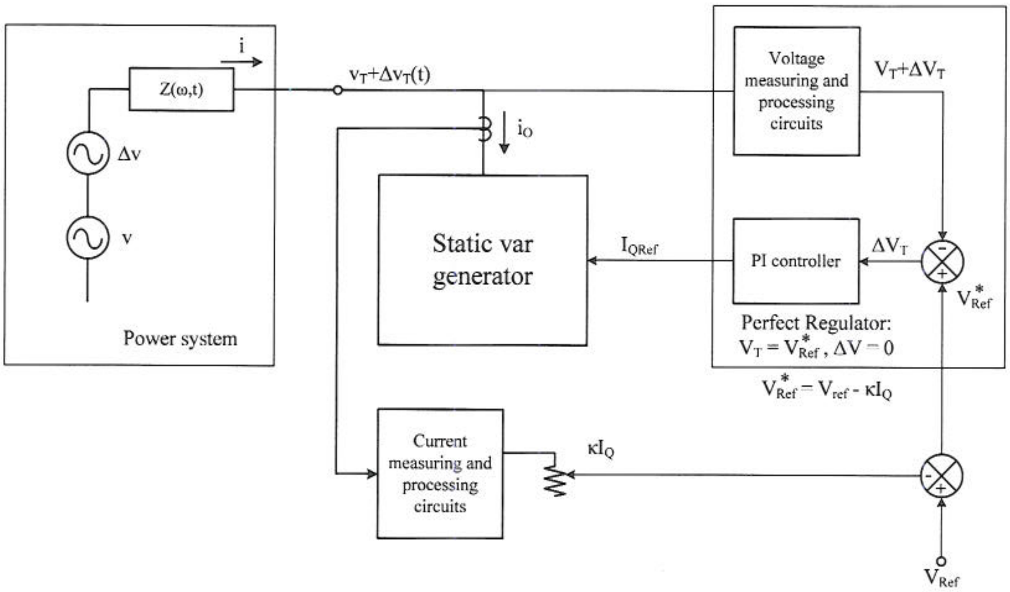


Fig 6.1 Implementation of V-I slope by a minor control loop changing the reference voltage in proportion to the line current

It can be seen that $V_{Ref}{}^*$ is controlled to decrease from the nominal (as set) value (no compensation) with increasing capacitive compensating current and conversely it is controlled to increase with increasing inductive compensating current until limits in either direction is reached. As a consequence the amplitude

[4.49]

of the terminal voltage, V_t, is regulated along a set of linear slope over the control range of the compensator. For terminal voltage changes outside of the linear control range, the output current of the compensator is decided by the V-I characteristic of the var generator used. The current will stay at maximum value for voltage sourced converter and will change like that in passive inductor and capacitor for variable impedance type var generator.

The terminal voltage change with compensation because of system changes in slow and steady state is determined by the regulation slope of the linear range and independent of type of var generator. Outside this linear range STATCOM and SVC would act differently. The dynamic characteristic of the two compensators are also different.

d) Discuss various technical benefits of the FACTS controllers.

[5]

The students are expected to expand each of the following points through two to three sentences

- *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*