LECTURE NOTES
ON
Flexible AC Transmission Systems(FACTS)

EDITED BY
DR. RAJKISHORE SWAIN

ASSOCIATE PROFESSOR

GOVT. COLLEGE OF ENGINEERING, KALAHANDI,
BHAWANIPATNA

MODULE- I

FACTS

FACT Concept and General system considerations.

→ For economic reason, the electric supply system are widely interconnected to improve ~~new~~ reliability of power supply and to reduce the cost of electricity.

→ The purpose of the transmission network is to pool power plants and load centers in order to minimize the total power generation capacity and fuel cost. Another advantage of interconnection is to divesify the loads, availability of sources and fuel cost.

If we construct a radial lines, more generation resources would be needed to serve ~~the~~ the loads with maintaining same reliability but later stage the cost of generation would be high. Due to lack of transmission capability more generation is required. The most important paradism is optimum balance between generation and transmission by using advanced methods of analysis which integrate transmission planning into integrated value based transmission.

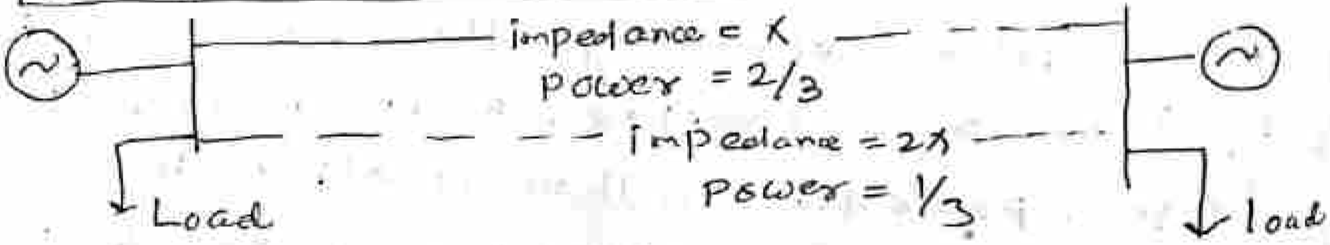
If we increase the power transmission capability, the power system becomes more complex. If we increase the large power flow with inadequate control, excessive reactive power ~~in~~ in various part of the system, large dynamic swing between different part of the system, and thus the full potential utilization cannot be utilized.

The recent power system are operated mechanically controlled. The mechanical switching device cannot operated frequently. Mechanical device tend to wear out very quickly compared to static device. The system is really uncontrolled with dynamic and steady state operation. Power system planners and Engineers have using a variety of ingenious technique to make the system work effectively, but at a price of providing greater operating margin and redundancies

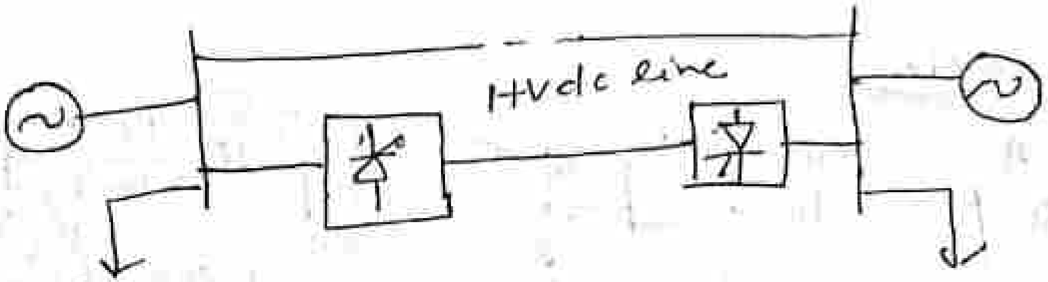
Flow of power in AC system :-

In most important things is that, the electrical generation and load must balance at all times. If generation is less than the load, the voltage and frequency drop. If sufficient amount of generation is available active power flow from surplus area to deficit area and it flows through all parallel path available which frequently involves extra high voltage and medium voltage lines.

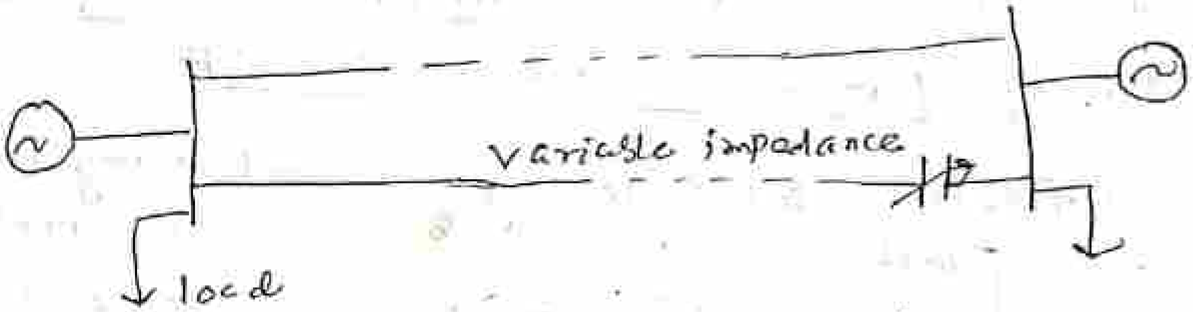
power flow in parallel path :-



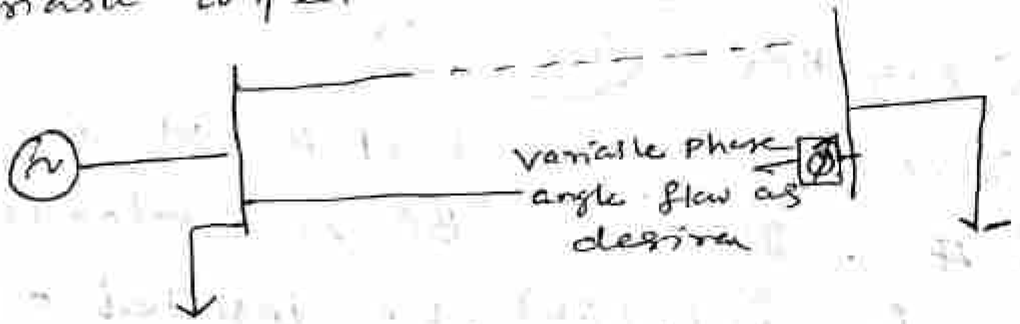
This indicates that power will flow from surplus area to deficit area without any control. Only importance to vary impedance of transmission lines. Impedance is inversely proportional power flow.



In HVDC power power system, power is electronically controlled. If adequate converter capacity is provided, the HVDC line is fully utilised with its thermal capacity. Due to high speed control, parallel ac lines to maintain stability. It is preferred (for HVDC line to use for long distance.



This type of power flow is used by series type FACT controller with controlling variable impedance.



This type of power flow is possible by phase angle control or series injection of appropriate voltage

POWER flow in a Meshed System:-

* Example

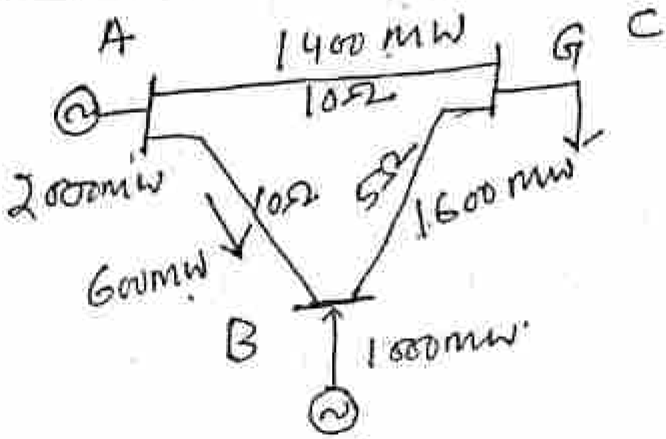


Fig 1 (a)

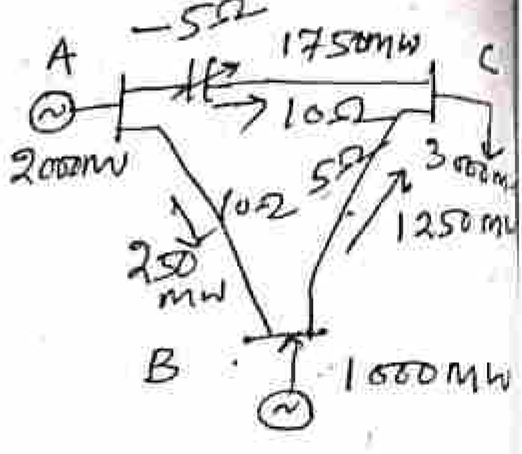


Fig 1 (b)

Fig 1(a) indicates two generators feeding power to load centers. Suppose three transmission lines AB, BC and AC having rating 1000MW, 1250 MW and 2000MW

Concept

~~AB~~Line	Upper loading	Existing loading
AB	1000 MW	600MW
BC	1250 MW	1600MW
AC	2000	1400
	4250 MW	3600 MW

Generation:- 3000MW

Generation decrease at B at increase at A. The line BC is overloaded. In figure 1.1(b), we inserted a capacitor whose reactance $-j5\Omega$ to reduce line reactance from 10Ω to 5Ω with synchronous frequency. The modified power in the transmission line

AB = 250 MW

BC = 1250 MW

AC = 1750 MW

4250 MW

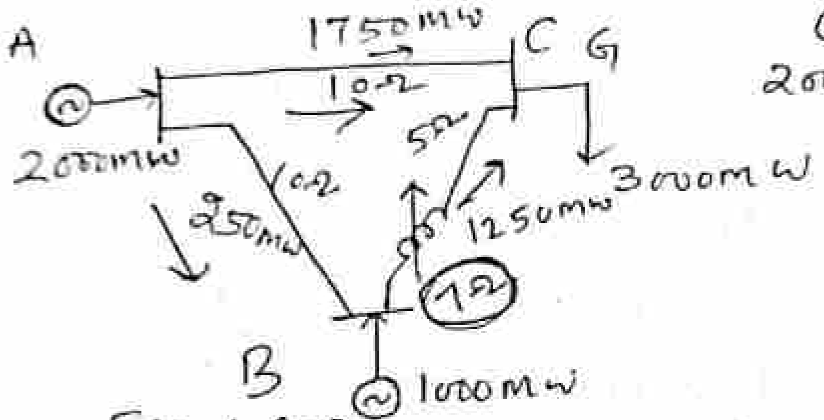


Fig 1 (c)

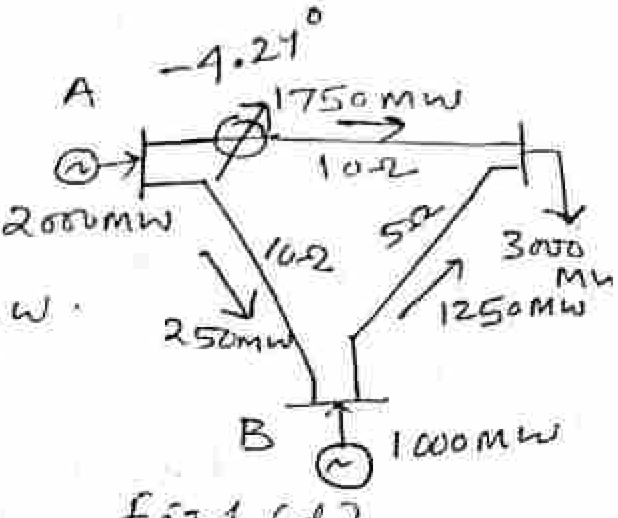


Fig 1 (d)

* Wide range of load and generation scheduling is possible of series capacitor ~~is adjustable~~.
capacitor could be modular and mechanically switched, the number
capacitor operations could be severely restricted

* If capacitor is mechanically switched, there is severely wear on a mechanical component

* If the capacitor is mechanically operated, there is chance to occur resonance that is called sub synchronous Resonance (typically 10-50 HZ for 60 HZ system). If such resonance persists, it will damage the shaft

* In case of outage of one lines, under emergency condition and load demand becomes very high, in this situation power flow oscillation at low frequency (typically 0.3 - 3 HZ) has occurred which the generator lose the

Synchronism.

In order to establish Thyristor Controlled series capacitor (TCSC) which will give better benfits like to reduc subsynchronous resonance, damp out lo frequency oscillation in power flow and also enhance the stability of the netwo

In fig 1.(C), TR reactor (inductor) in se with the line ~~AB~~ BC. It is partly mechan and partly thyristor-controlled which give steady-state power flows as wel as damp unwanted oscillations.

Another option is that thyristor-contr phase angle regulator could be instal to reduce the total phase-angle diff along the line from 8.5° to 4.26°

What limits the loading capability

There are three kinds of limitation

- Thermal
- Dielectric
- Stability

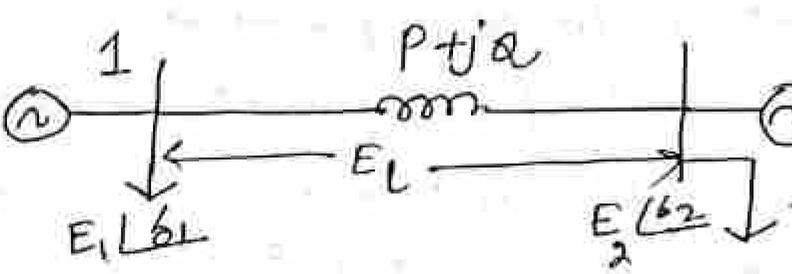
Thermal:— It is a function of the ambient temperture, wind condition, structure of conductor and ground clearance.

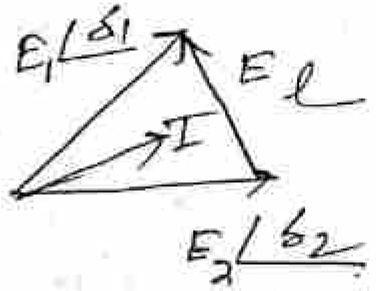
Dielectric :- If we increase the voltage by ± 10% or higher. Dynamic and transient overvoltage analysis is done whether the line is within the limit. Modern gapless arrester or line insulator with internal gapless arrester or powerful thyristor controlled overvoltage arrester at the substation can enable significant increase in the line and substation overvoltage capability.

Stability :- There are various stability issues which limit the transmission capability. The issues are

1 → Trasient Stability
2 → Dynamic Stability
3 → Steady State Stability
4 → voltage collapse
5 → Subsynchronous resonance.

Power Flow and Dynamic stability considerations of a Transmission interconnection.





$I = \frac{E_L}{X}$ which lags E_L by 90°

→ The current flow on the line ~~ϕ~~ can be controlled by controlling $\boxed{E_L \text{ or } X \text{ or } \delta}$

Example

[500KV, 2000A line has three phase power 18
200km,
voltage drop = 60KV]

Series compensation (of 25%)

$(V_L\ I_R\ \mathrm{O}\ X_R)$

$0.25 \times \underline{60} \times \underline{2000} = 3\underline{0\,\mathrm{mVA}}$

for 3 phase $= 30 \times 3 = \boxed{90\,\mathrm{mVA}}$ (Series eq

$\frac{90}{\cancel{1800}_{20}} = \frac{1}{20} \times 100 = \boxed{5\%}$

$\frac{5}{\cancel{100}_{5}} \times \cancel{60}^{3}$

Contigency :-

[contigency analysis is used to calcu

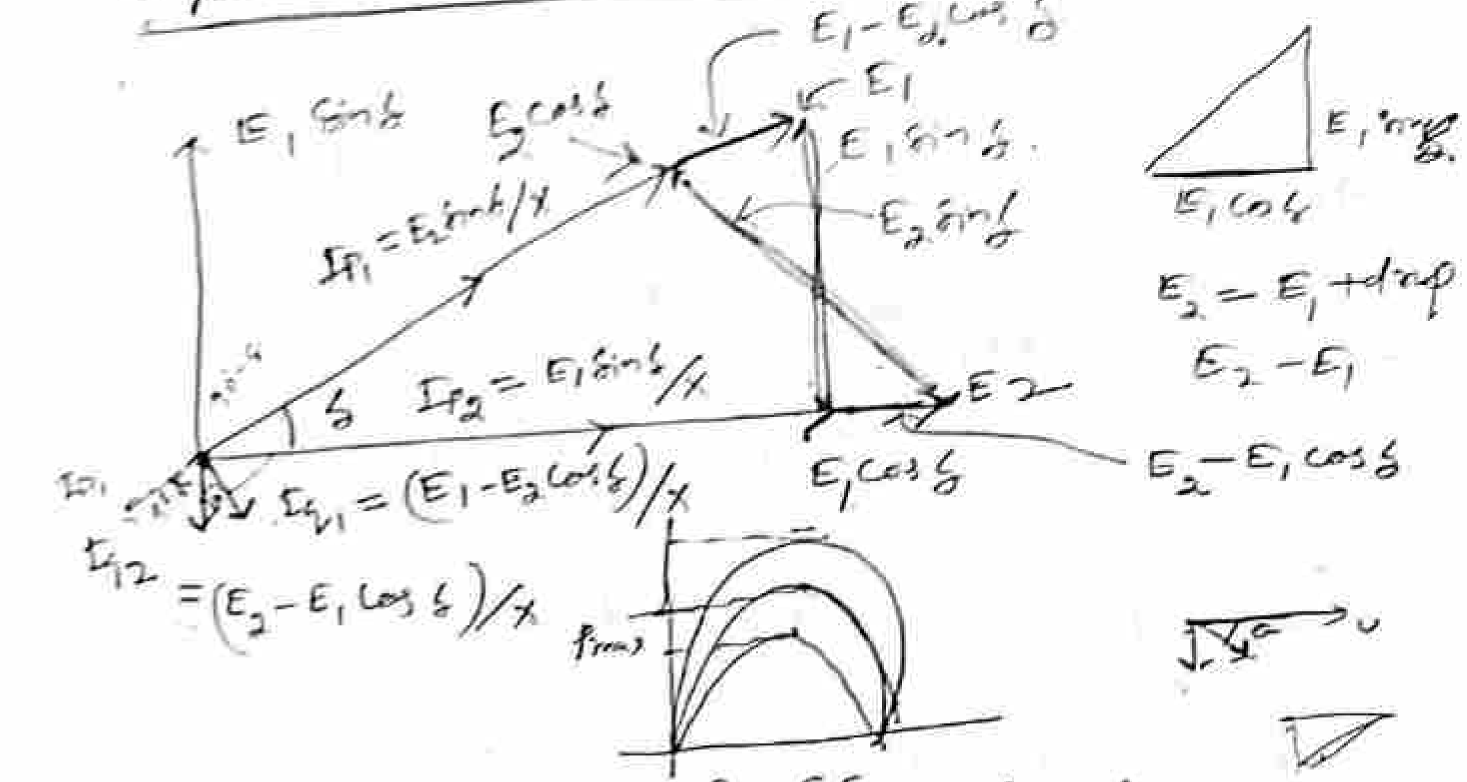
\# Series connected equipment has to ~~designe~~ to carry ~~[illegible]~~ (Contigency overloads) that the equipment may ~~too~~ have to sa 100% overload capability.

\# If the angle between the bus voltage is smal the current flow largely represent the active power.

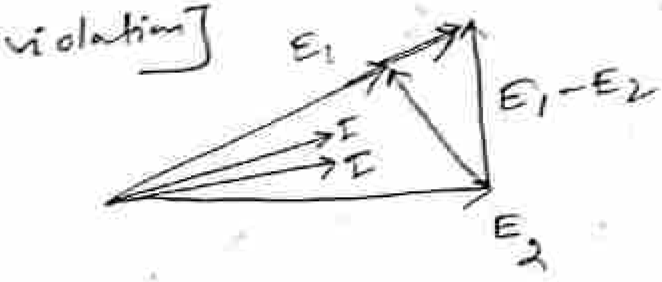
\# increasing or decreasing the Inductive imped of a line will greatly affect the active power flow. Thus impedance control is a real control of current control, wh can be the cost-effective means of controlling the power flow.

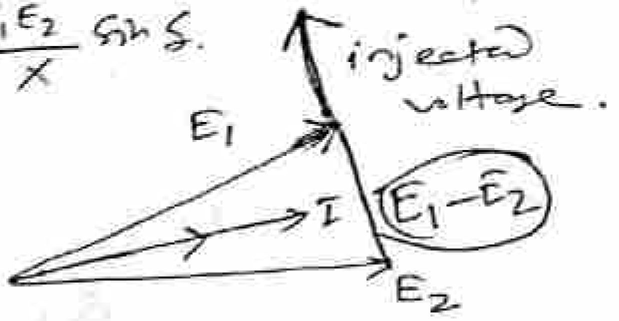
~~By~~ appropriate [illegible]

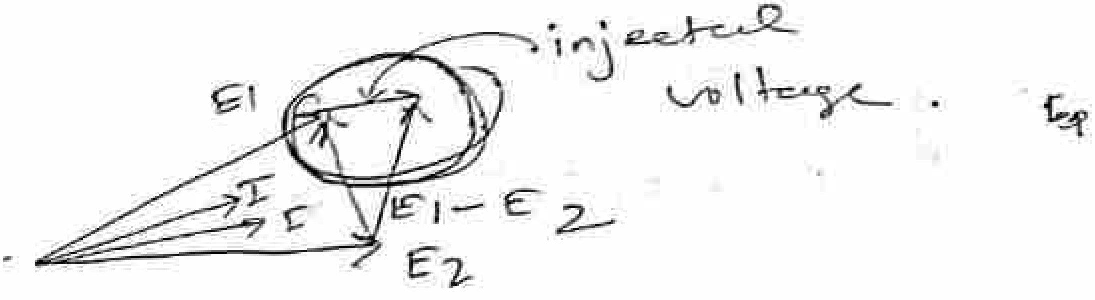
It can be used real control of power flow or angle control for stability.



$$P = \frac{E_1 E_2}{X} \sin\delta.$$







Active component of the current flow at E_1 is $I_{P_1} = (E_2 \sin\delta)/X$

Reactive component of the current flow at E_1 is

$$I_{q_1} = \frac{(E_1 - E_2 \cos\delta)}{X}$$

Active power $P_1 = E_1 \cdot (E_2 \sin\delta)/X$

Reactive power at the E_1 end

$$\boxed{Q_1 = E_1 (E_1 - E_2 \cos\delta)/X}$$

Active component of the current flow E_2 is

~~$I_{q_2} = (E_2 - E_1 \cos\delta)/X$~~

$$I_{p_2} = E_1 \sin\delta / X$$

Reactive compomet of the current flow at E_2 is $I_{q_2} = (E_2 - E_1 \cos\delta)/X$

active power at the E_2 end

$$P_2 = E_2 (E_1 \sin\delta)/X$$

Reactive power at the E_2

$$\boxed{Q_2 = E_2 (E_2 - E_1 \cos\delta)/X}$$

Naturally P_1 and P_2 are same

$$P = E_1 E_2 \sin\delta / X$$

from the figure it is analyzed that active power increasing to a maximum value with an increase in δ to 90°, then power falls with further increase in and finally to zero at δ = 180°.

To maintain proper stability margi for transient and dynamic stability and it ensure that the system

does not collapse

power flow can also be controlled by regulating the magnitude of voltage phasor E_1 ~~and~~ or voltage phasor E_2, no significant change by changing driving phasor $E_1 - E_2$. only power flow can be controlled by phase angle.

Regulation of the magnitude of phasor voltage E_1 or E_2 has much more influence over the reactive power flow control then active power flow.

current and power flow can also changed by injecting voltage in series with the line. Injected voltage is phase quadrature with the current in phase with driving voltage.

voltage injected in series can be phasor with variable magnitude and phase relationship with line voltage.

It is seen that varying the amplitude and phase angle of the voltage injected in series both active and reactive power can be controlled.

Relative importance of controllable param

- Control of the impedance, with a thyristor controlled series capacitor can provide a powerful means of current control.

- Control of X or the angle substantially provide the control of active power.

- phase angle control which controls the driving voltage, provide a powerful means of controlling current flow and hence active power flow.

- Injecting a voltage in series with the lin and perpandicular to current flow, can increase or decrease the magnitude of current flow.

- Injecting voltage in series with the line and with any phase angle with respect to driving voltage can control the magnitu and the phase of the line current.

Basic Types of FACT controller:-

1. Series controller
2. Shunt Controller
3. Combined series-series controller
4. Combined Series-shunt controller

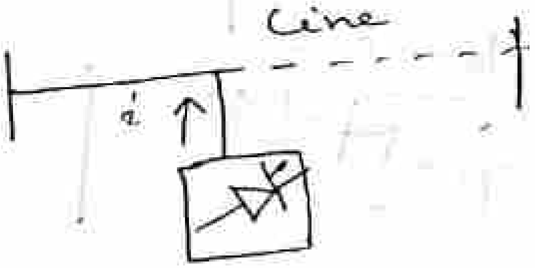
Series controller:-

(a) Variable impedance, capacitor, reactor and power electronics based variable source are the main parameter of series controller.

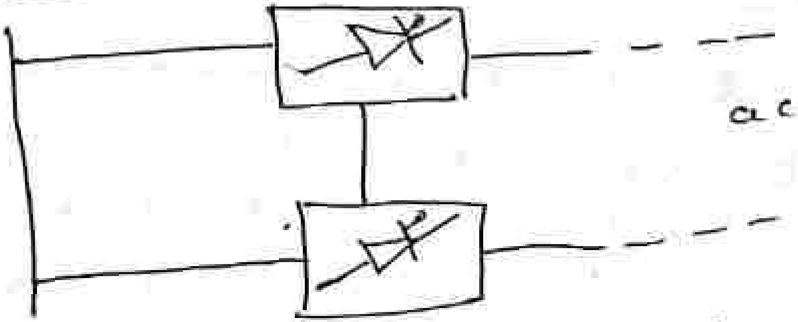
(b) It elliminates subsynchronous resonance and harmonic frequency.

(C) Series controller supplies or consume variable reactive power.

Shunt controller:- Like series controller, shunt controller may be variable impedance ~~impe~~ controller or combination of these. Shunt controller injects current into the line. Injected current is in phase quadrature with line voltage. Shunt controller only supplies or consume variable reactive power.

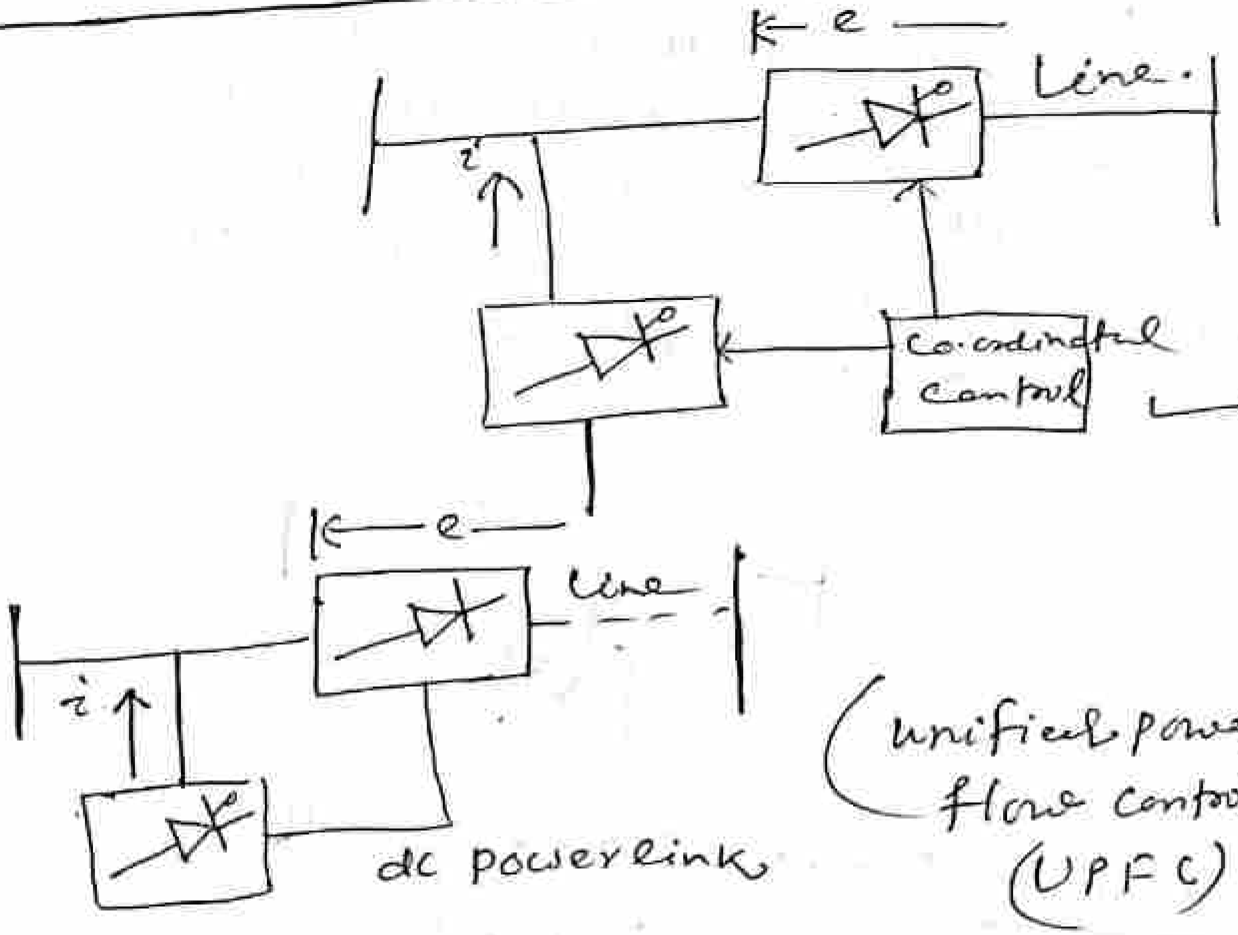


Combined series - series controller:-



→ In a multiple transmission system, separate series controller are provided. In series controller provide independent series reactive compensation for each line bu also transfer real power among the line via the power link. The real power transfe capability of the unified series-series controller, referred to as Interline Power flow controller. The benefits of IPFC to manage both real and reactive power flow in the line and better utilization of the transmission system.

Combined Series-Shunt controllers:-



(unified power flow controller) (UPFC)

Combined shunt and series controllers inject current into the system with the shunt part of the controller and voltage in series in the line with series part of the controller. When the shunt and series controller are unified, the real power exchange between the series and shunt controller can be established via power link.

Relative importance of Different type of controllers.

0. The major importance of series controller is to control current or power flow and damp oscillations. Series controller is basically used contigency and dynamic overload.

*. Shunt controller is a current source which draws or inject current into the line. The major role of shunt controller is inject reactive current and active current for a smooth voltage control and damping voltage oscillations. shunt control is the most effective way of improving the voltage profile.

*. Power electronics device like thyrister with gate turn-off capability are used FACT controller.

Brief description and definition of FACT controller # —

Flexibility of electric power transmission: The ability to accomodate in the electric transmission system or operating conditions while maintaining sufficient steady state and transient margins.

Flexible AC Transmission systems (FACTS)

✓Alternating current transmission system incorporating power electronics-based and other static controllers to ~~[illegible]~~ enhance controllability and increase power transfer capability.

Shunt connected controller

(STATCOM)

Static Synchronous compensator :- A static synchronous generator operated as a shunt connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage.

STATCOM is one of ~~to~~ the key root of FAC Controller. It is a voltage source or current converter.

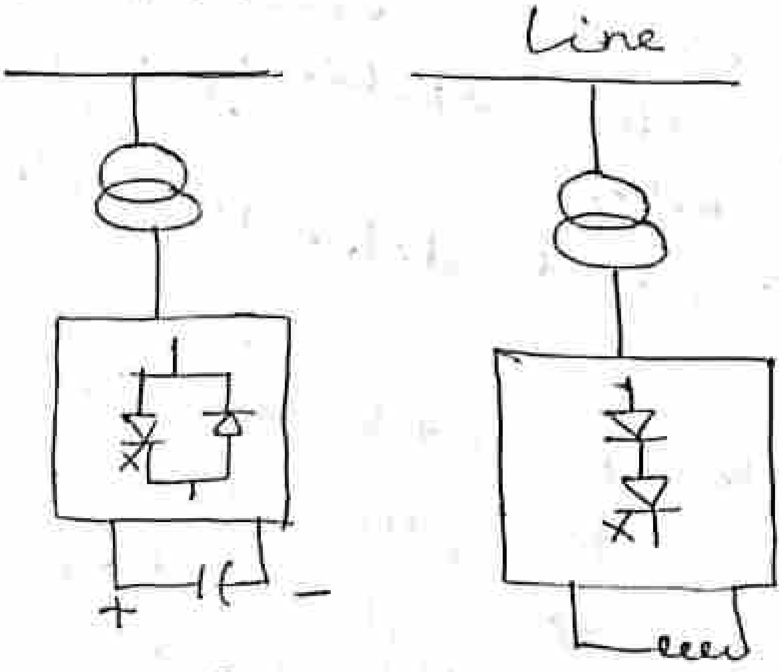


Fig 2(a)

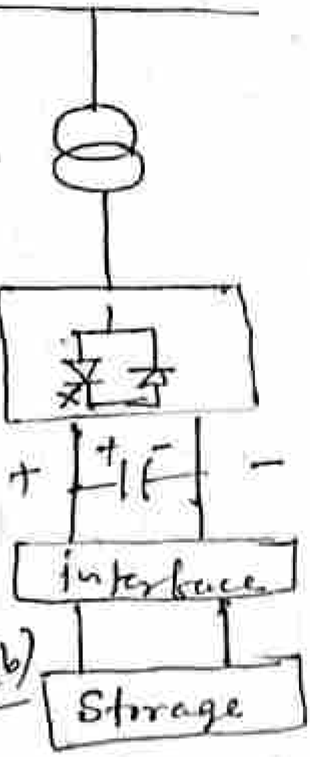


Fig 2.(b)

In voltage source converter, its ac output voltage is controlled such that required reactive current flow for any ac bus voltage by dc capacitors voltage ~~is~~ which is automatically adjusted. STATCOM can be designed to act as active filter to absorb harmonics. It act as active power source as recommended by IEEE.

Static Synchronous Generator (SSG).

A static self-commutated switching power converter supplied from a appropriate electric energy source and operated to produce a set of adjustable multiphase output voltages, which may be coupled to an ac power system for the purpose of exchanging ~~independently controllable~~ real and reactive power.

#The term SSG, is realizing for any source of energy including a battery, flywheel, superconducting magnet, large dc storage capacitor,

Battery Energy Storage System (BESS)

A chemical-based energy storage system using shunt connected, voltage source converters capable of rapidly adjusting the amount of energy which is supplied to or absorbed from an ac system.

The one line diagram in which

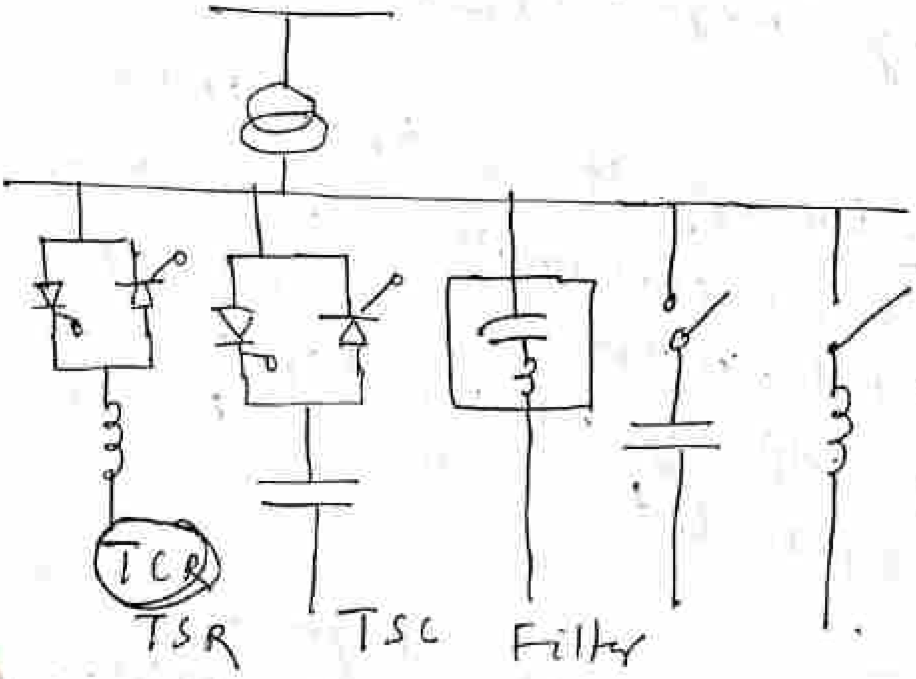
√The BESS storage unit size would tend to be small (a few tens of MWHs), and if the short time converter rating was large enough, i could deliver MWs ~~a~~. with high (MW/MWh ratio for transient stabicity. The converte can also simultaneously absorb or delive reactive power within the converter's MVA capacity.)

(SMES)

Superconducting magnetic Energy storage

A superconducting electromagnetic energy st device containing electronic converters that rapidly inject or absorbs real or reactive power or dynamically controls power flow in ac system.

√Static Var compensator:— A shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or induct current so as to maintain or control spec parameter of the electrical power system.



fib 2(c)

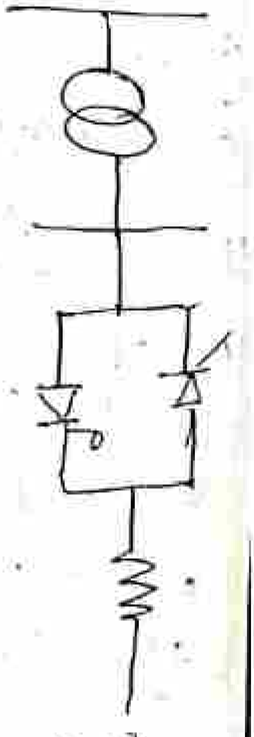


Fig. 2(d)

→ SVC is operated on thyristor without gate turn-off capability.

→ Thyristor-switched reactor is used for absorbing reactive power

→ Thyristor-switched capacitor is used for supplying reactive power.

→ TCR TSR is a subset of ~~svc~~ SVC.

TCR

→ The effective reactance is varied in continous manner by partitial-conduction control of the thyristor value

TSR

→ The effective reactance is varied in stepwise manner by full or zero conduction operation of thyristor valve

TSC → A shunt connected, thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full or zero conduction operation of the thyristor value.

Static var generator or Absorbor (SVG)

It is static device that is capable of controlled capacitive or inductive current from an electrical power system and generating or absorbing reactive power. It is considered as a thyristor-controlled reactor and thyristor switched capacitor which are shunt connected.

Thyristor controlled Braking Resistor.
(TCBR)

A Shunt connected thyristor-switched resi which required stabilization of a powe system and minimize power acclerati during disturbance.

Series connected controller :-

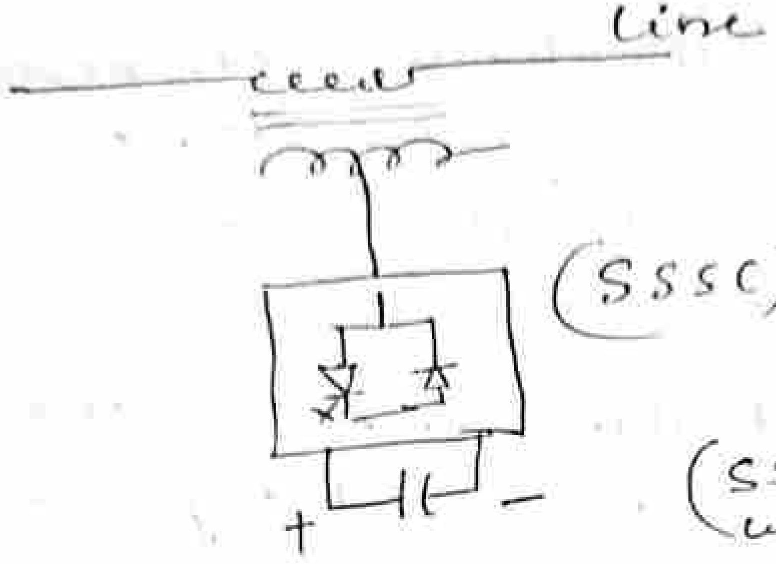
(a) Static synchronous series compensator (SS

1. SSSC is one of the most important FACT controller. It is equivalent to STATCOM.

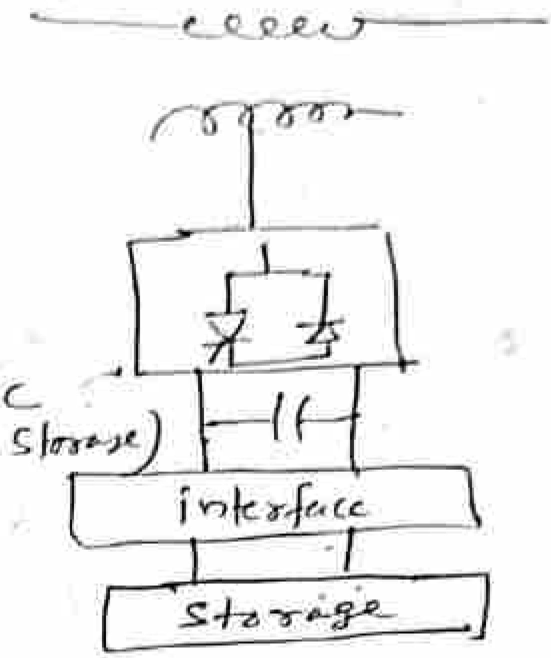
2. SSSC is a static synchronous generator which operated without external electr energy, whose output voltage in quadrature with it so that overall real voltage drop across the line will be increasing or decreasing along the transm line.

3. The SSSC may include transiently rated energy storage or energy absorbing devi to increase the dynamic behaviours of the power system. It is basically used for increase or decrea overall voltage drop across the line.

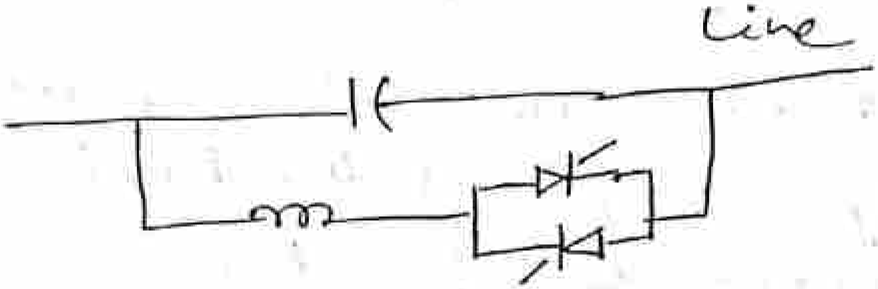
3/ It is a voltage
or



(SSSC)

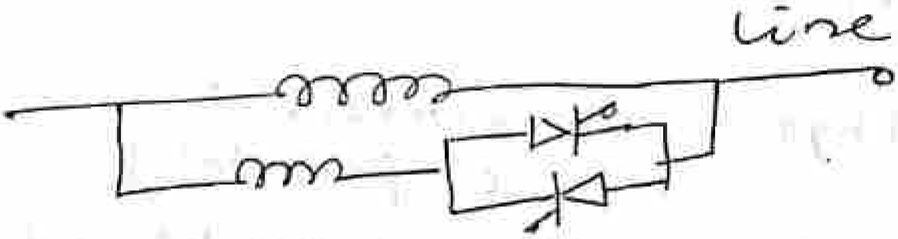


(SSSC with storage)



Thyristor controlled series capacitor
(TCSC)

Thyristor switched series capacitor (TSSC)



Thyristor controlled series reactor
(TCSR)

Thyristor-switched series Reactor (TSSR)

1. SSSC can only inject variable voltage, which is 90° leading or lagging the current.

IPFC (Inter line power flow controller)

→ When two or more SSSC are coupled via common dc link to facilitate bi-directional flow of real power between the ac terminals of the SSSCs.

TCSC :— A thyristor controlled react is parallel with series capacitor in or to provide (smoothly) variable series capacitive reactance.

- When TCR firing angle is 180°, the reactor become non-conducting, seri capacitor is ~~non conducting~~ has it norm value impedance.
- When TCR firing angle is 90°, reactor becomes fully conducting and the total impedance become inductive because the reactor impedance is designed to be much lower than the series capacitor impedance.

TSSC (Thyristor-switched series capacitor)

A capacitive reactance compensator which consists of series capacitor bank shunt by a thyristor switched reactor to provi a (stepwise control) of series capacitive reactance. The concept of switching inductors at firing angle of 90° or 180° but without firing angle control & the cost could be reduce.

TCSR (Thyristor controlled series react

A inductive reactance compensator which consists of a series reacto shunted by a thyristor controlled reactor in order to provide smoothly variable series inductive reactance.

When firing angle of thyristor controlled reactor is 180°, it stops conducting and the uncontrolled reactor acts as fault current limiter. As the firing angle ~~ed~~ below 180°, the net inductance decreases until firing angle of 90°.

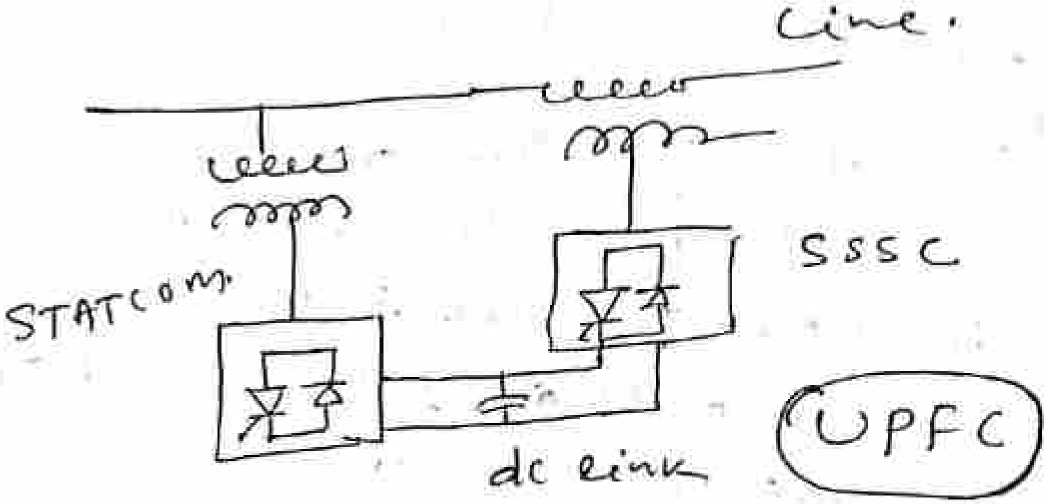
TSSR*: — An inductive reactance compensator which consist of series reactor shunted by a thyristor controlled switched reactor in order to provide a stepwise control of series inductive reactance.

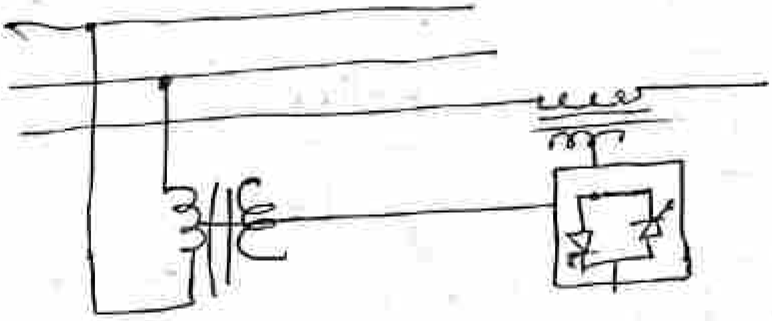
Combined Shunt and Series Controllers: —

Unified power flow controller

A combination of static synchronous compensator (STATCOM) and a static series compensator (SSSC) which are coupled via common dc link, which allow bi directional real power flow between series output terminals of the ~~S~~ SSSC and the shunt output terminals of the STATCOM, and are ~~co~~ controlled to provide concurrent real and reactive series line compensation without an external energy

Source. The UPFC by means of angu
unconstrained series voltage injection, is
able to control, concurrently or selecti
transmission line voltage, impedance, an
angle, alternatively the real and reacti
power flow in the line. The UPFC ma
also provide independently controllable s
reactive compensation.





(TCPAR) Thyristor-Controlled Phase
angle Regulator (TCPA

In UPFC which combines a STATCOM
and an SSSC, the active power for
the series unit (SSSC) is obtained
form the line itself via the shunt
unit STATCOM. This is complete

Controller for controlling active and reactive power control through the line, as well as line voltage control.

Thyristor Controlled Phase Angle Regulator (TCPAR)

The perpendicular series voltage is made variable with variety of power electronics topologies. A circuit concept that can handle voltage reversal can provide phase shift either direction. This controller is also refered to as Thyristor-controlle phase Angle Regulator.

MODULE- II

Static Shunt compensators: SVC and STATCOM

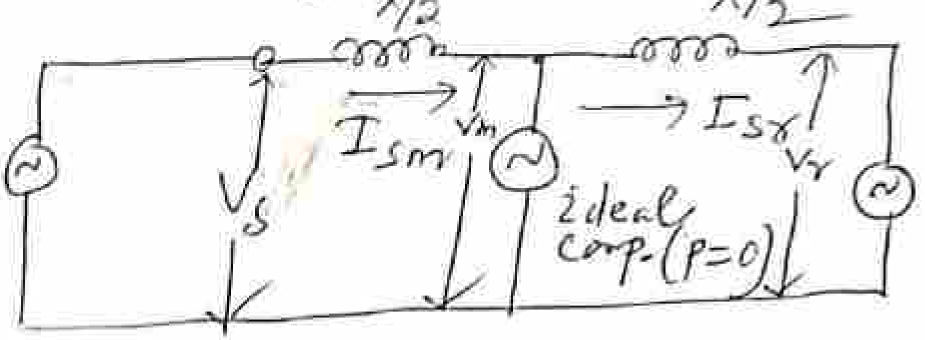
1. — The purpose of reactive compensation is to change natural ectrical characteristic of the transmission line to make it more compatible with the prevailing load demand.

2 → The shunt connected, fixed or mechanically switched reactors are applied to minimize line overvoltage under light load condition.

→ Shunt connected capacitors applied to maintain under heavy load condition.

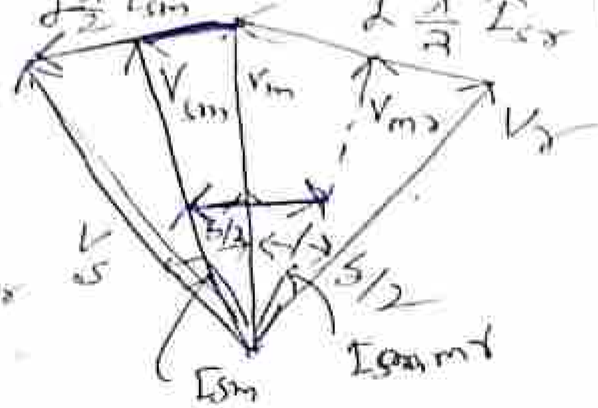
→ The shunt connected var compensation in a transmission system is to increase transmittable power. This will improve the steady state transmission characteristics as well as the stability of the system.

- Var compensation is thus used for voltage regulation etc.
- To prevent voltage instability
- To increase transient stability
- Damp power oscillations.



→ The compensator is a sinusoidal ac voltage source in phase with midpoint voltage V_m.

So $V_m = V_s = V_r = V$



$V_s = V_m + j\frac{X}{2}I_{sm}$

$V_m = V_r + j\frac{X}{2}I_{sr}$

$V = 2V\cos\frac{\delta}{4}$

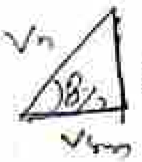
$I = \frac{4V}{X}\sin\frac{\delta}{4}$

$V \cdot \frac{4V}{X}\sin\frac{\delta}{4}\cdot ~~\cos\frac{\delta}{2}~~$

$V ~~= 2IV~~$

$2V\cos\frac{\delta}{4}\cdot\frac{4V}{X}\sin\frac{\delta}{4}$

$\frac{8V^2}{X}\frac{2}{1}$



$\frac{X}{2}I_{sm}$

$j\frac{X}{4}I_{sm} = V_m\sin\frac{\delta}{4}$

$I_{sm} = \frac{4V_m}{X}\sin\frac{\delta}{4}$

$V_{sm} = = V_{mr} = V\cos\frac{\delta}{4}$ ✓

$I_{sm} = I_{mr} = I = \frac{4V}{X}\sin\frac{\delta}{4}$

Power $P = V_{sm}I_{sm} = V_{mr}I_{mr}$

$= V\cos\frac{\delta}{4}\cdot\frac{4V_m}{X}\sin\frac{\delta}{4}$

$= \frac{4V^2}{X}\,\frac{2\cos\frac{\delta}{4}\cdot\sin\frac{\delta}{4}}{2}$

$$\boxed{P = \frac{2V^2}{X}\sin 2\cdot\frac{\delta}{4_2} = \frac{2V^2}{X}\sin\frac{\delta}{2}}$$

$V\cdot I\sin\frac{\delta}{4}$

$V\cdot\frac{4V}{X}\sin\frac{\delta}{4}\cdot\sin\frac{\delta}{4}$

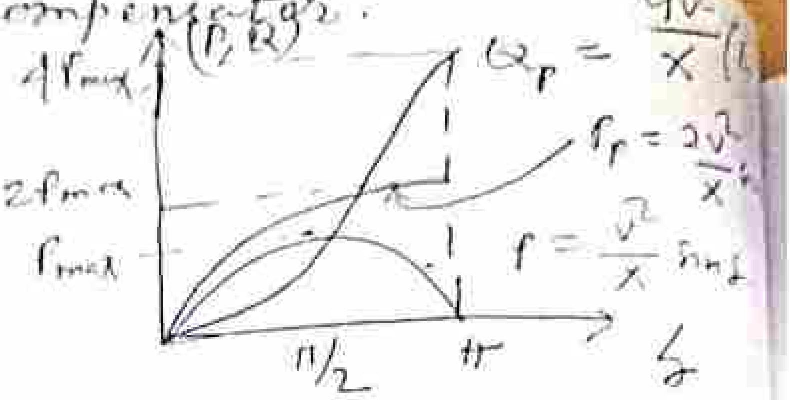
$\frac{4V^2}{X}\sin^2\frac{\delta}{4}$

$\frac{4V^2}{X}\frac{(1-\cos\frac{\delta}{2})}{2}$

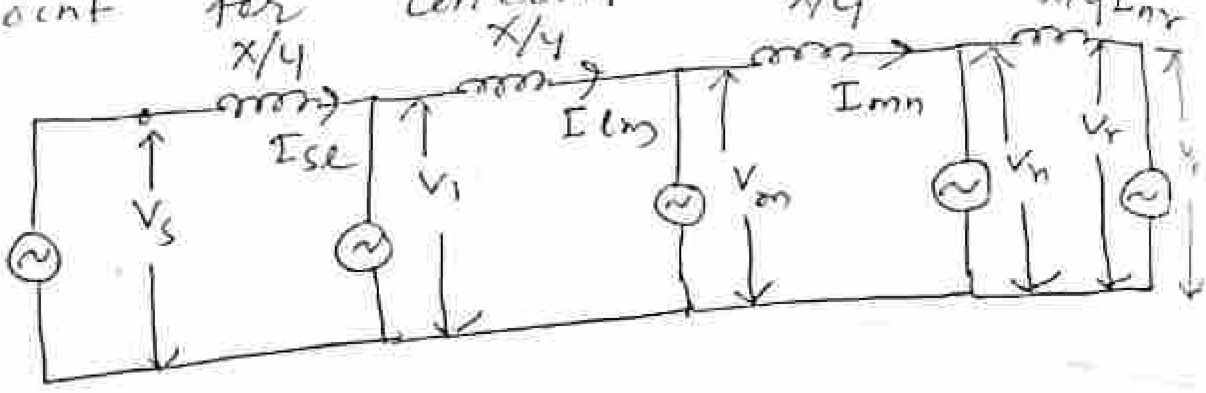
$Q = VI\sin\frac{\delta}{4} = \frac{4V^2}{X}\left(1-\cos\frac{\delta}{2}\right)$

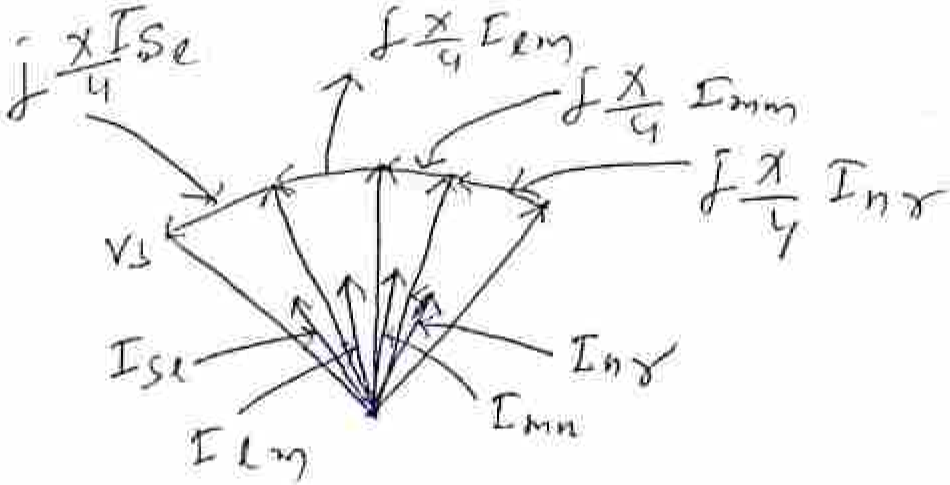
midpoint shunt compensation can significantly increase the transmittable power at the expense of a rapidly increasing reactive power demand on

the midpoint compensator.

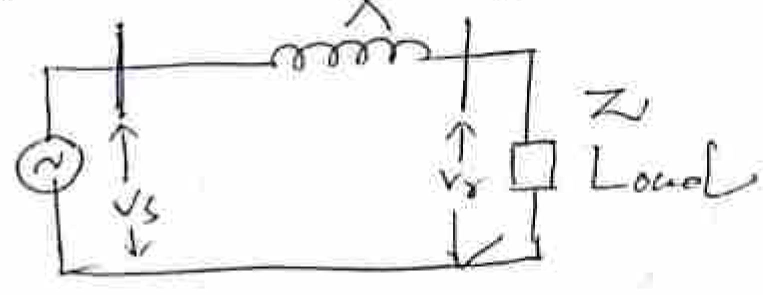


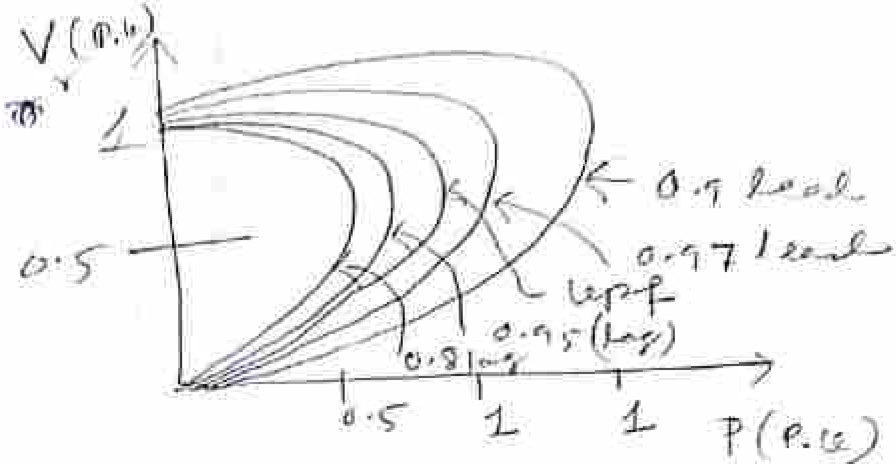
The midpoint of the transmission line is the best location for the compensator voltage sage is the largest at the mid point for uncompensated line.





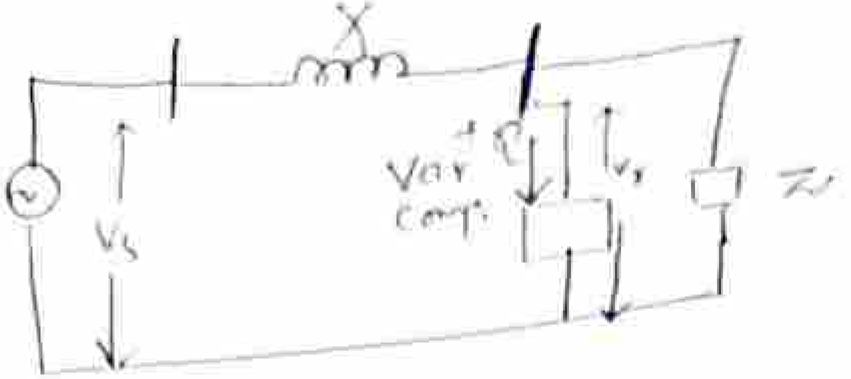
End line voltage support to prevents voltage instability.

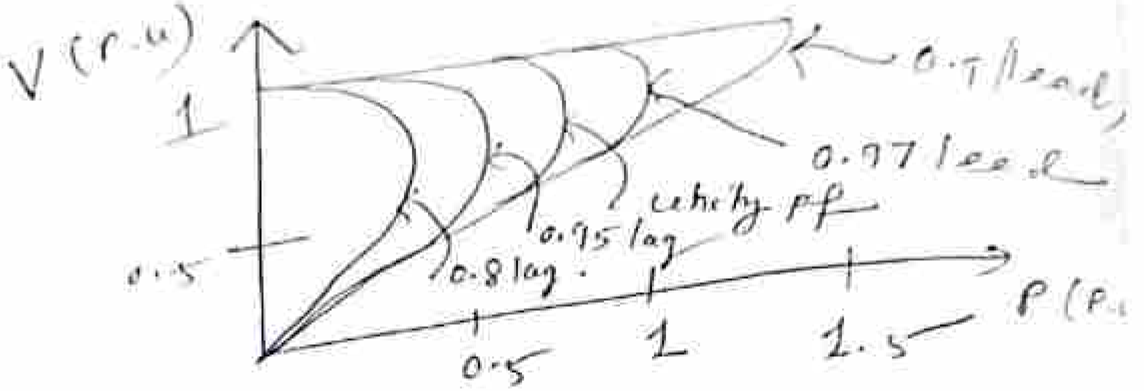




In this figure, load is passive type which consume power P at voltage V is connected to mid point in place of the receiving part of the system. without compensation the voltage at the mid point would vary with the load and load powerfactor.

→ A simple radial system with line reactance X and load impedance Zr. The figure shows the normalized terminal voltage V_r versus power P plot at various load pf ranging from 0.8 lag and 0.9 lead. The "nose point" of each plot given a specific power factor represents the voltage instability corresponding to that system condition. It is clearly represent that voltage instability limit decreases with inductive load and increases with capacitive load.



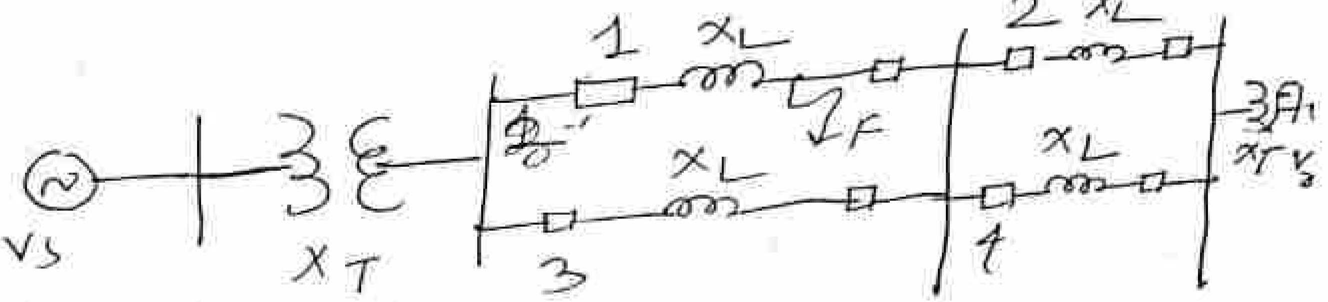


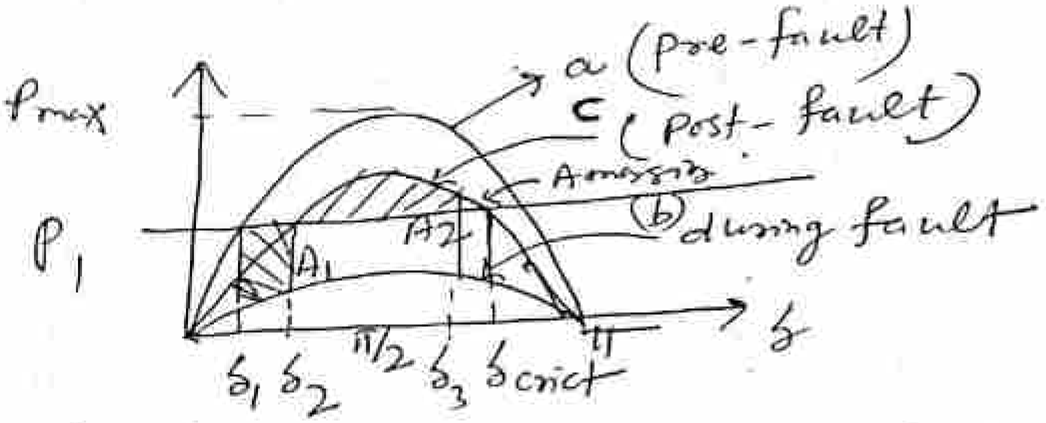
By connecting shunt reactive power Compensa can effectively increase the voltage Stabili limit by supplying the reactive load and regulating the terminal voltage $(V - V_r)$ = It is evident that from a radial line, t end of the line, where the largest voltage variation is experienced, ~~at the best locati~~ The best location of for the compensa is midpoint is the most effective locati for the line interconnecting two ac Syste

EX:- When a large load area is suppli from two or more generation plants with independent transmission line. This frequent happens when the locally generated pow becomes inadequate to supply growing load area and additional Power is imported over a separate transmission li The loss of one of the power source could suddenly increase the load demand on the remaining part of the system, cause sever voltage depression that could result in an ultimate voltage collapse.

Improvement of Transient Stability

→ Shunt compensation ~~eff~~ will able to change power flow in the system during dynamic disturbance so as to increase the transient stability limit and provide effective power oscillation damping.





Pre fault :- The system is characterised by P-δ curve "a" and operating at angle δ_1 and transmitt Power P_1

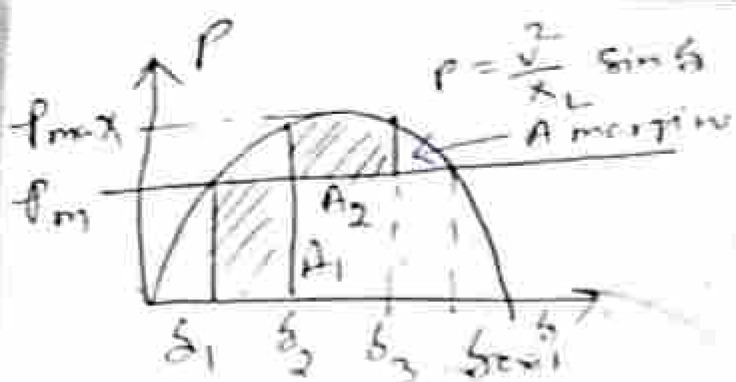
During fault :- Fault occurs at Segment "1"

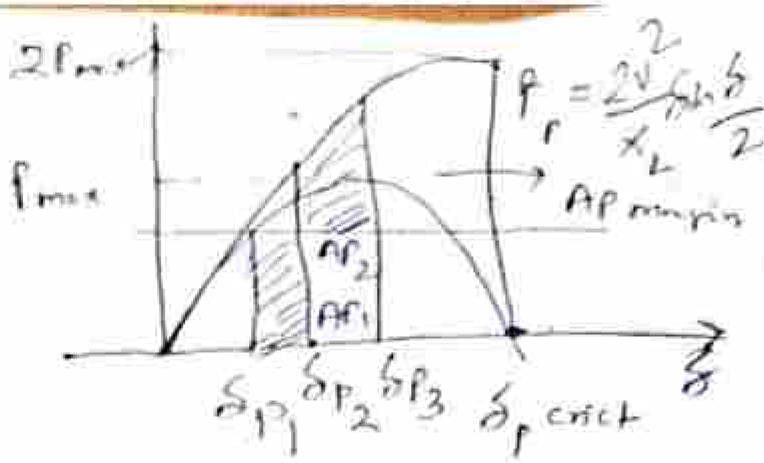
The transmitted electrical power decreases significantly while mechanical input power

remains constant, so generator accelerate
the transmission angle increases from δ_1 t
The sending end generator absorbs ac
energy represented by area A_1

After fault clearing, the transmitted powe
exceeds the mechanical input and sendi
end generator starts decclerating. The a
δ further increase due to stor
Kinetic energy. The maximum angle
reached δ_3 where deacclerating energy
area A_2 becomes equal to accelerati
energy represent by area A_1 ($\therefore A_1 =$
The limit of transient stability i
reached at $\delta_3 = \delta_{crit}$ beyond whic
acclerating energy is not equal to de
energy. The synchronism between se
end and receiving end could not
restored. The area A_{margin} between δ_3 a
δ_{crit}, represents the "transient Stabi
margin" of the system.

#— Since appropriately controlled shunt
compensation can provide effective vol
support, it can increase the transmis
capability of the post fault system
and thereby enhance transient stabi





[P_m at angle δ_1 and δp_1 respectively.)

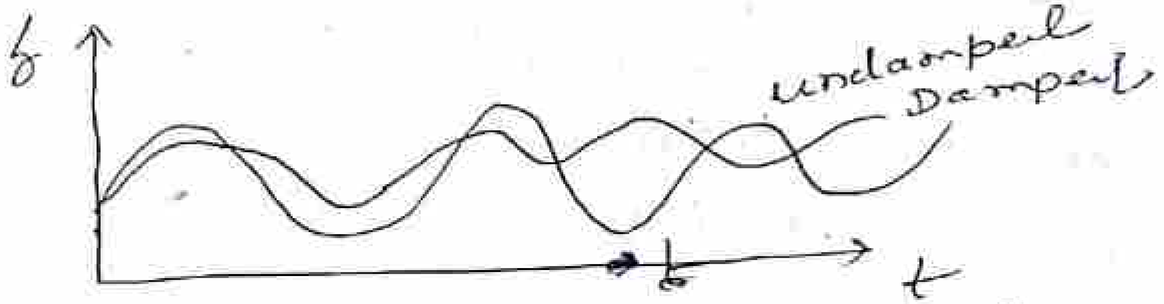
During fault, the transmittable electric power becomes zero which the mechanical input power to the generators remain constant (P_m). The sending end generator accelerates from steady-state angles δ_1 and δp_1 to angle δ_2 and δp_2. The accelerating ~~area~~ energy to represent by area A_1 and AP_1. After fault clearing, the transmitted electric power exceeds the mechanical input power and sending end machine deaccelerates, but accumulated kinetic energy further increases until a balance between the accelerating and deaccelerating energies, corresponding to area A_1, AP_1 and A_2, AP_2 reached at δ_3 and δp_3. The margin of transient stability is δp_{crit}. It is clearly show that substantial increase in the stability margin by using midpoint compensation.

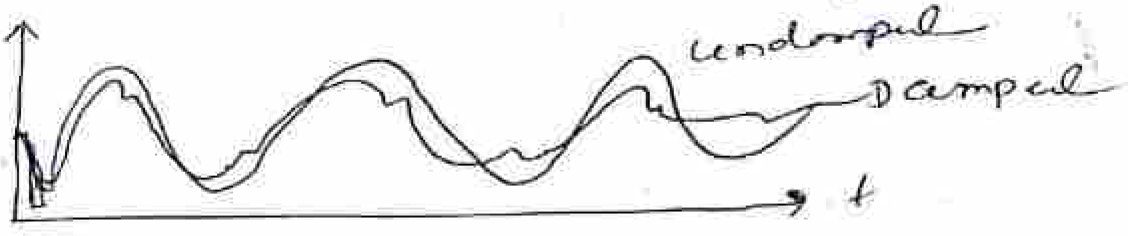
power oscillation damping

Power oscillation is a sustained dynamic in case of underdamped power system, any disturbance happen, the machine angle is to deviate its steady state value at natural frequency. So requirement is to applied shunt compensation, therefore point voltage of the transmission line, counteract the acclerating and deaccleration swing of the disturbed machine.

\# When the generator acclerates and angle δ increases $\left(\frac{d\delta}{dt} > 0\right)$, the elec power must be increased to compen for the excess mechanical input po

\# When the generator deacclerates an angle δ decreases $(d\delta/dt < 0)$, the ele power must be decreased to balan the insufficient electrical power.





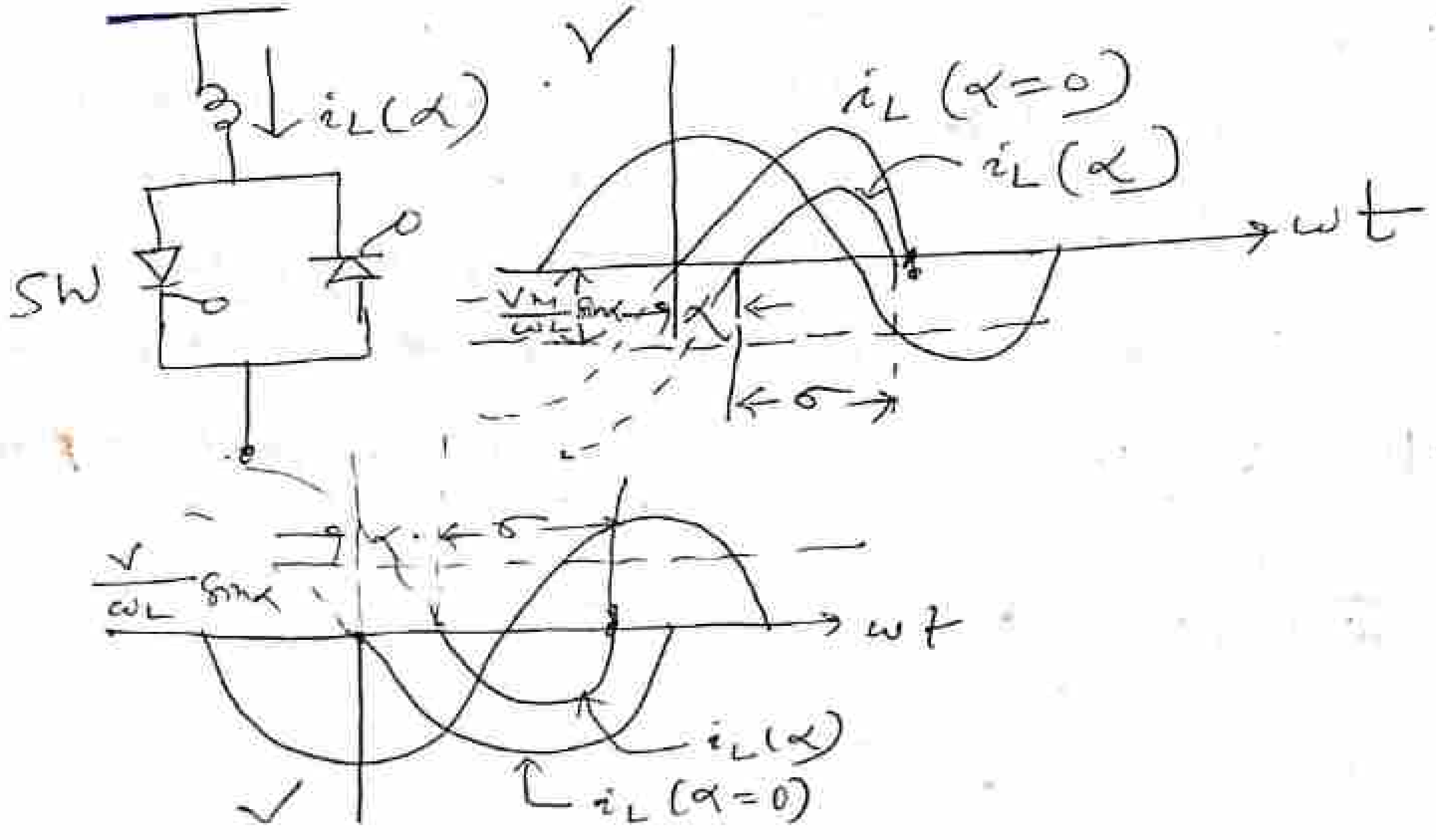
Var output is controlled in a "bang-bang" manner.

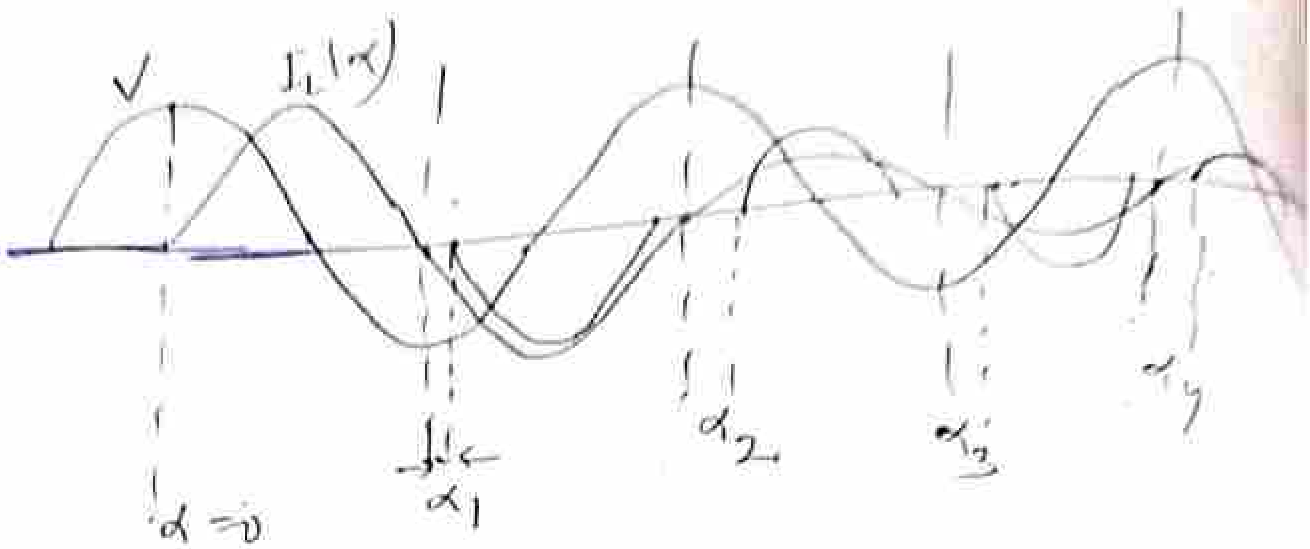
Compensator must be able to recapture synchronism immediately fault clearing.

#. The compensator regulate the bus voltage and improved transient stability and power oscillation damping enhancement

Best suitable location of var compensator is in the middle in case of transmission line connecting two system, for radial line feed to a load the best location is at the load end.

Thyristor - controlled and Thyristor switched Reactor (TCR and TSR)





1. When $\alpha = 0$, the sw closes at maximum of the applied voltage and reactor curre will be same as steady state. When the firing angle α $(0 \leq \alpha \leq \pi/2)$, the current in the reactor can be expressed $\underline{v(t) = V\,\text{si}}$

$$v = L\frac{di}{dt}$$

$$\text{i.e.}\quad i = \frac{V}{L}\int_{\alpha}^{\omega t} dt = \frac{V}{\omega L}(\sin\omega t - \sin\alpha)$$

$$\alpha \leq \omega t \leq \pi - \alpha.$$

$$\boxed{\text{When } \alpha = 0 \quad \frac{V}{\omega L}\sin\alpha \text{ is offset.}}$$

As delay angle α increases, increasing offset result which reduction of conduction angle σ of the valve, consequent reduction of reactor curr

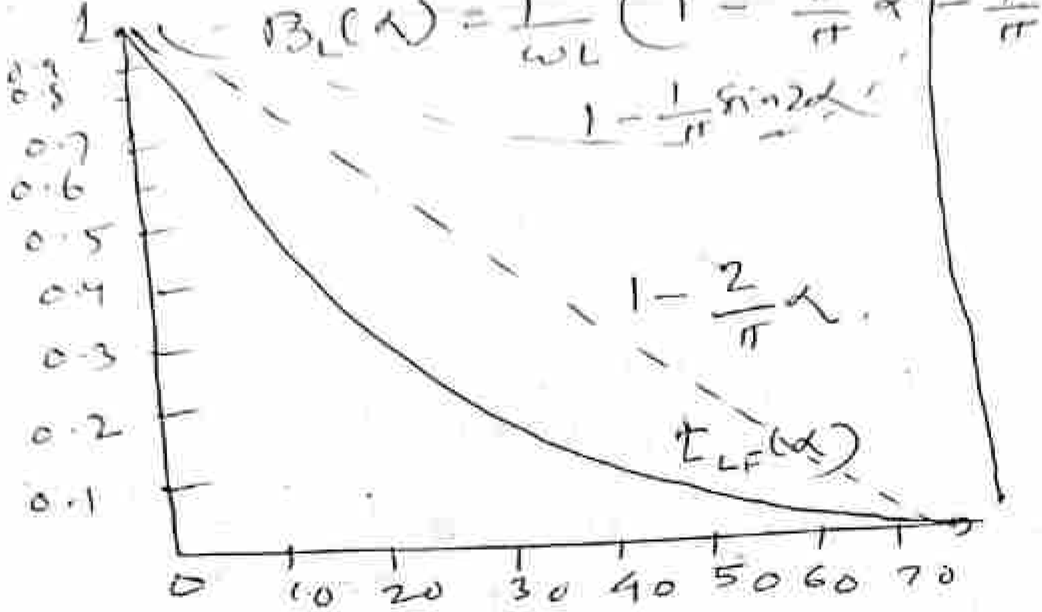
When $\alpha = \pi/2$ reactor current is zer

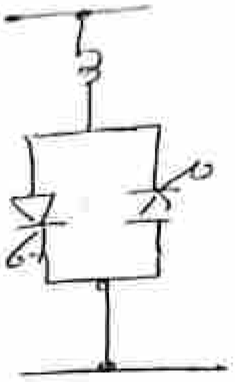
$$I_{LF}(\alpha) = \frac{V}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right)$$

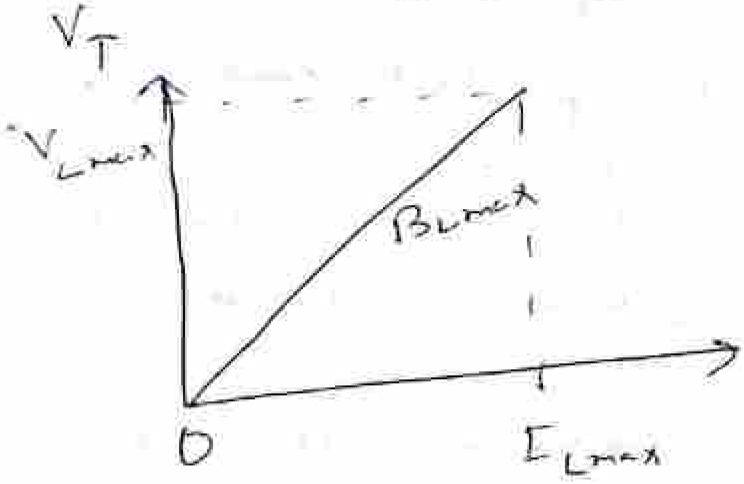
TCR can controlled the fundamental current continuously from zero to maximum as if it was variable reactive admittance

The effective reactive admittance $B_L(\alpha)$ for the TCR

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







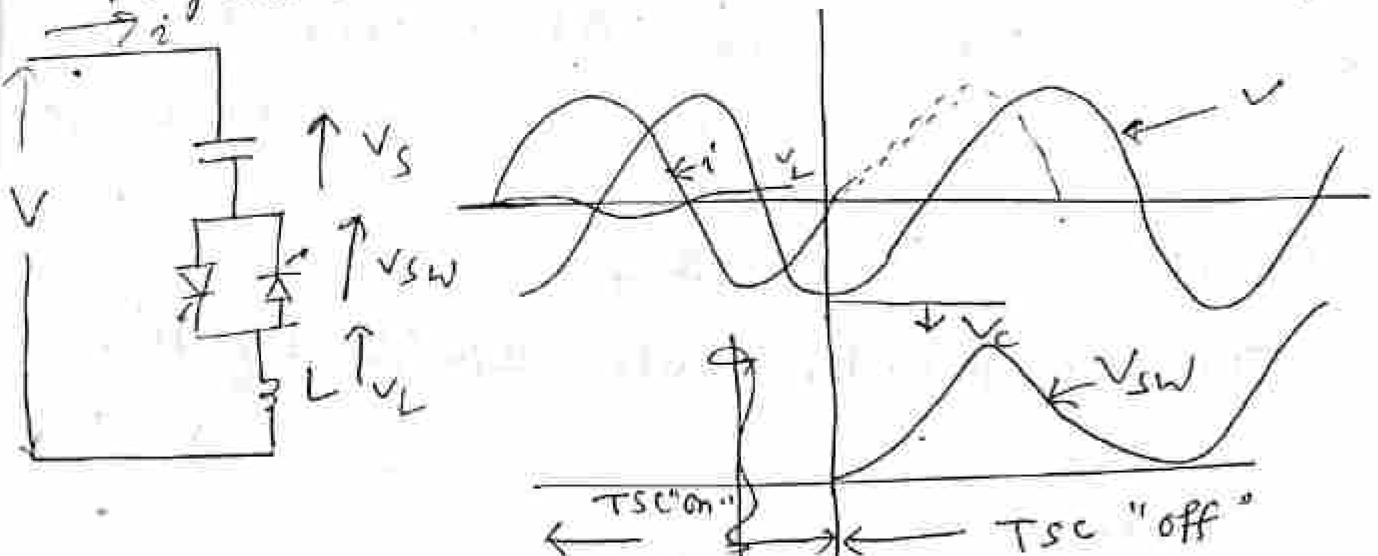
V_{Lmax} = voltage limit

I_{Lmax} = current limit

B_{Lmax} = max admittance of TCR

B_L = admittance of reactor

Thyristor - switched capacitor (TSC)



$$i(\omega t) = V \frac{n^2}{n^2-1} \omega C \cos\omega t$$

$$n = \frac{1}{\sqrt{\omega^2 L C}} = \sqrt{\frac{x_C}{x_L}} = \frac{\frac{1}{\omega C}}{\omega L} = \sqrt{\frac{1}{\omega^2 L}}$$

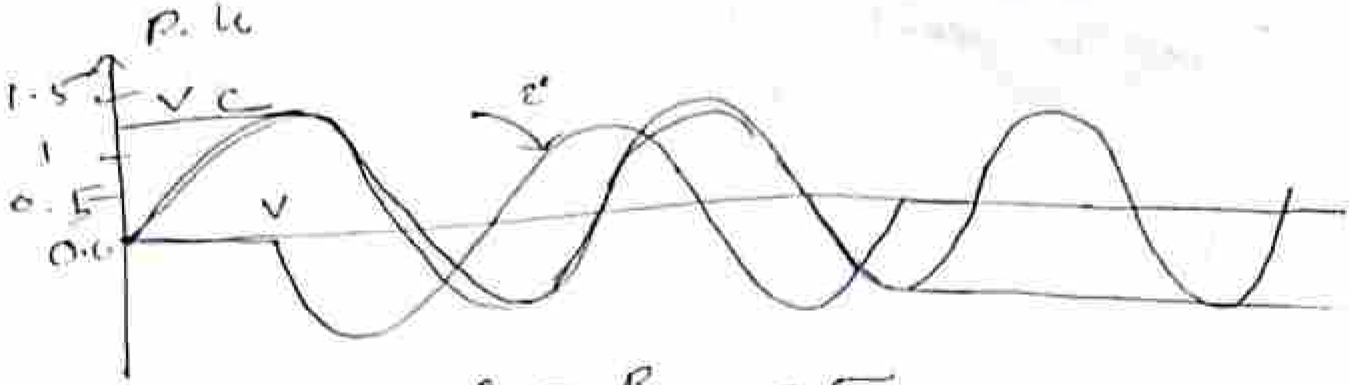
The amplitude of voltage across the capaci
is $V_c = \frac{n^2}{n^2-1} V$.

→ TSC consists of a capacitor, a bidirectional thyristor valve, and a relatively small surge current limiting reactor. This reactor is primarily to limit the surge current, ~~limiting reactor.~~

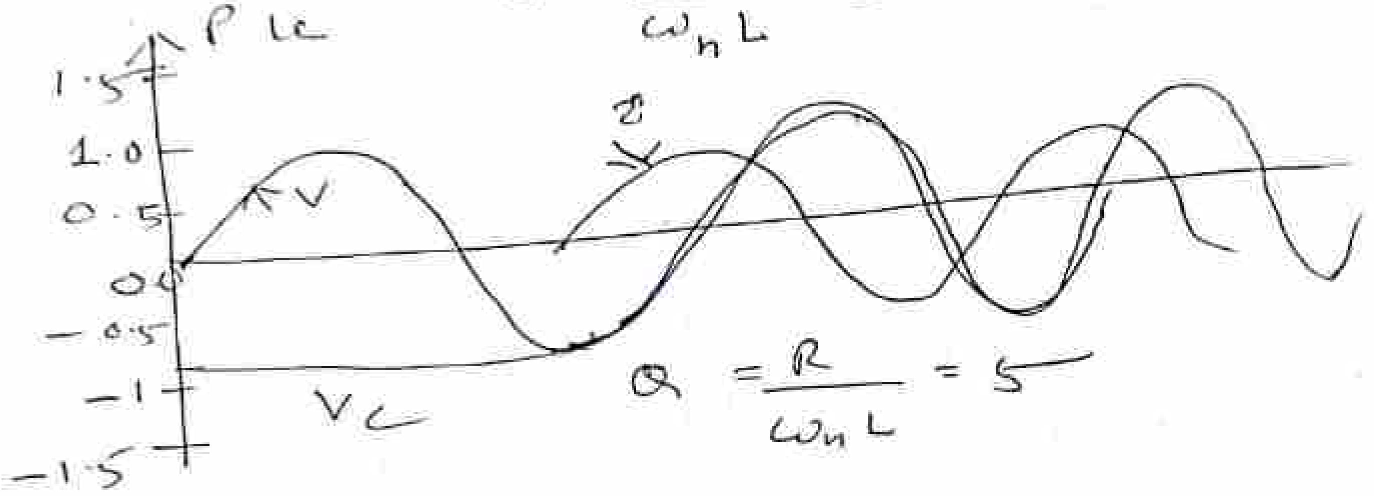
under steady state condition when the thyristor valve is closed and the TSC branch is connected to sinusoidal ac voltage source, $v = V\sin\omega t$

→ When gate signal removal, the TSC branch can be disconnected at any current zero. At current zero crossing, the capacitor volt is $V_{C,i=0} = V\frac{n^2}{n^2-1}$

→ The capacitor hold charge by this

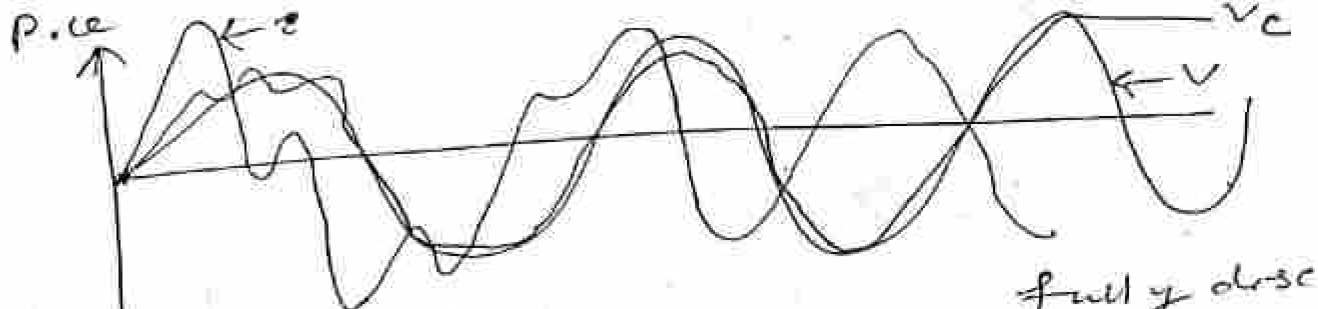


$$Q = \frac{R}{\omega_n L} = 5$$

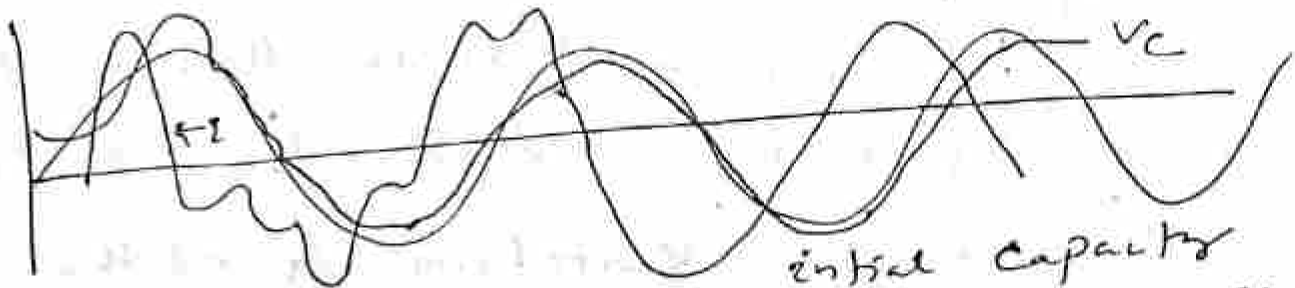


$$Q = \frac{R}{\omega_n L} = 5$$

The capacitr is discharged after disconnectn. The residual capacitr voltage remains from zero to $\frac{Vn^2}{n^2-1}$. At this instant if TSC valve is on, the residual voltage across capacitr is equal to supply voltage [illegible].



fully discharged



initial capacitr ~~[illegible]~~ charge 0.5 pu are transient are caused by non zero $\frac{dv}{dt}$ at instant of switching ~~capacitor~~ without series reactor. would result i instaneous current $\boxed{i_c = c\frac{dv}{dt}}$

The interaction between capacita the current limiting reactor, with the damping resistor, produce the oscillat switching transient. The switching transient is greater for fully discharged than partially discharged because applied voltage has max $\frac{dv}{dt}$ of applied voltage has max at the zero crossing point.

<u>Transient free</u>

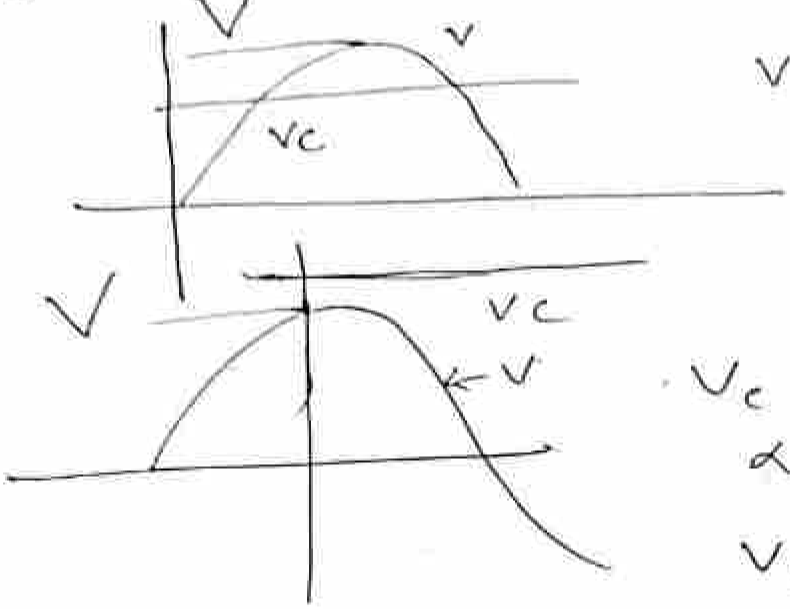
$\boxed{If\ V_c < V}$

① If the residual capacitor voltage, lower than the peak ac voltage, th correct switching is <u>instaneou</u> ~~[illegible]~~ ac voltage equal to capa ~~capacitor~~ voltage.

② $V_c \geqslant V$

If the residual capacitor volt is equal to or higher than the peak ac voltage, then the ~~current~~

of the ac voltage at which the thyristor valve voltage is minimum.



$V_c \leq V$

$V_c = V$

$V_{sw} = 0$

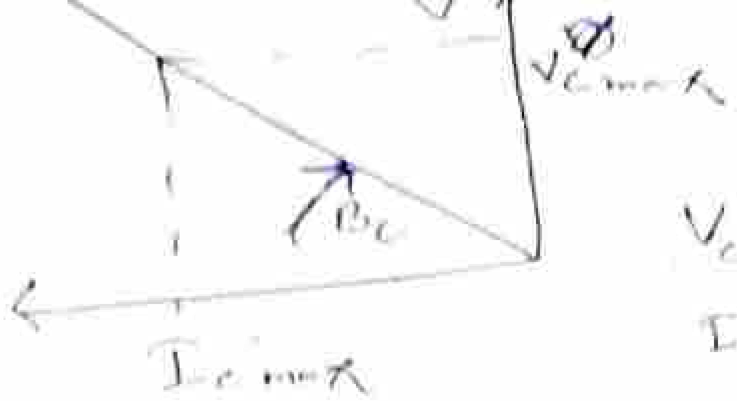
$V_c > V$

$\alpha = 0$

$V_{sw} = \min$

→ The maximum possible delay in switching in capacitor bank is one full cycle of the applied ac voltage,

→ firing delay angle control is not applicable to capacitor because capacitor switching must take place at that specific instant on each cycle at which the condition for minimum transient are satisfied, when the voltage across the thyristor valve is zero. The current in the TSC branch varies linearly with applied volt according with admittance of the capacitor,

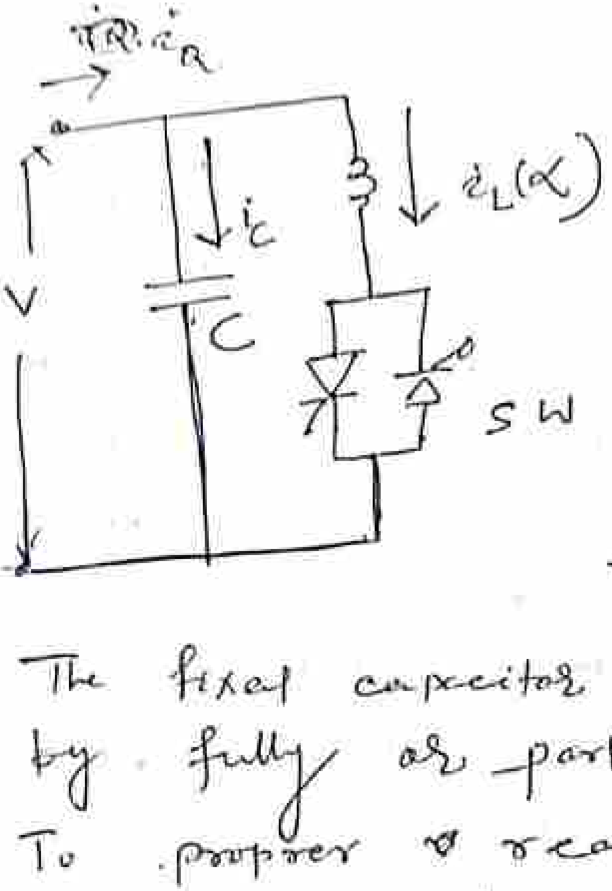


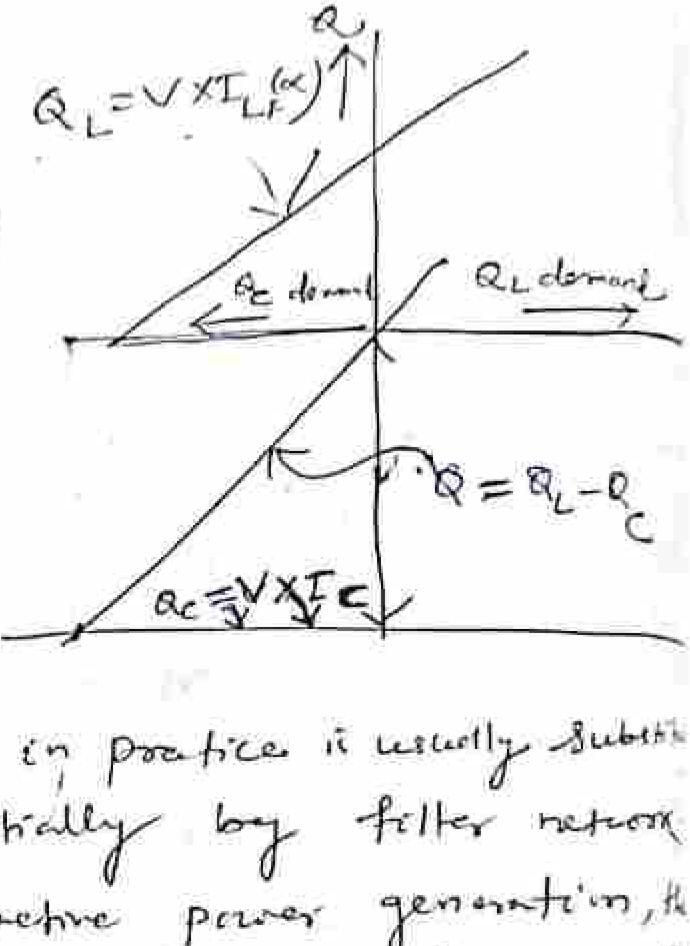
V_{cmax} = voltag

I_{cmax} = curre

B_C = admit
of the

Fixed capacitor, Thyristor-controlled Reactor type
Var Generator





The fixed capacitor in practice is usually substit by fully or partially by filter network. To proper reactive power generation, the capacitive reactance at the fundamental frequency.

\# The constant capacitive var generation Q_C of the fixed capacitor is opposed by the variable var absorption Q_L of the thyristor controlled reactor, to generate total var output (Q)

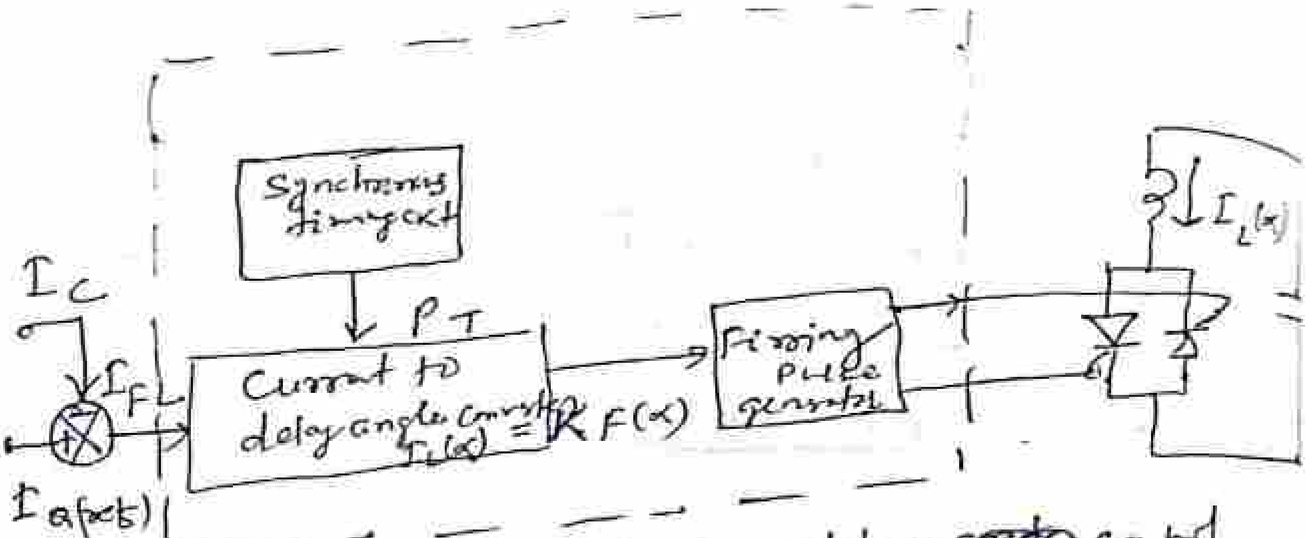
#At the maximum capacitive var output the thyristor controlled reactor is off ($\alpha = 90$). By decreasing the firing angle α, the reactor current increases which decreases the capacitive output. (At zero var output, the capacitive and inductive current becomes equal and thus the capacitive and inductive vars cancel each other.

#By decreasing the firing angle α, the inductive current becomes larger than the capacitive current, resulting in net inductive var output.

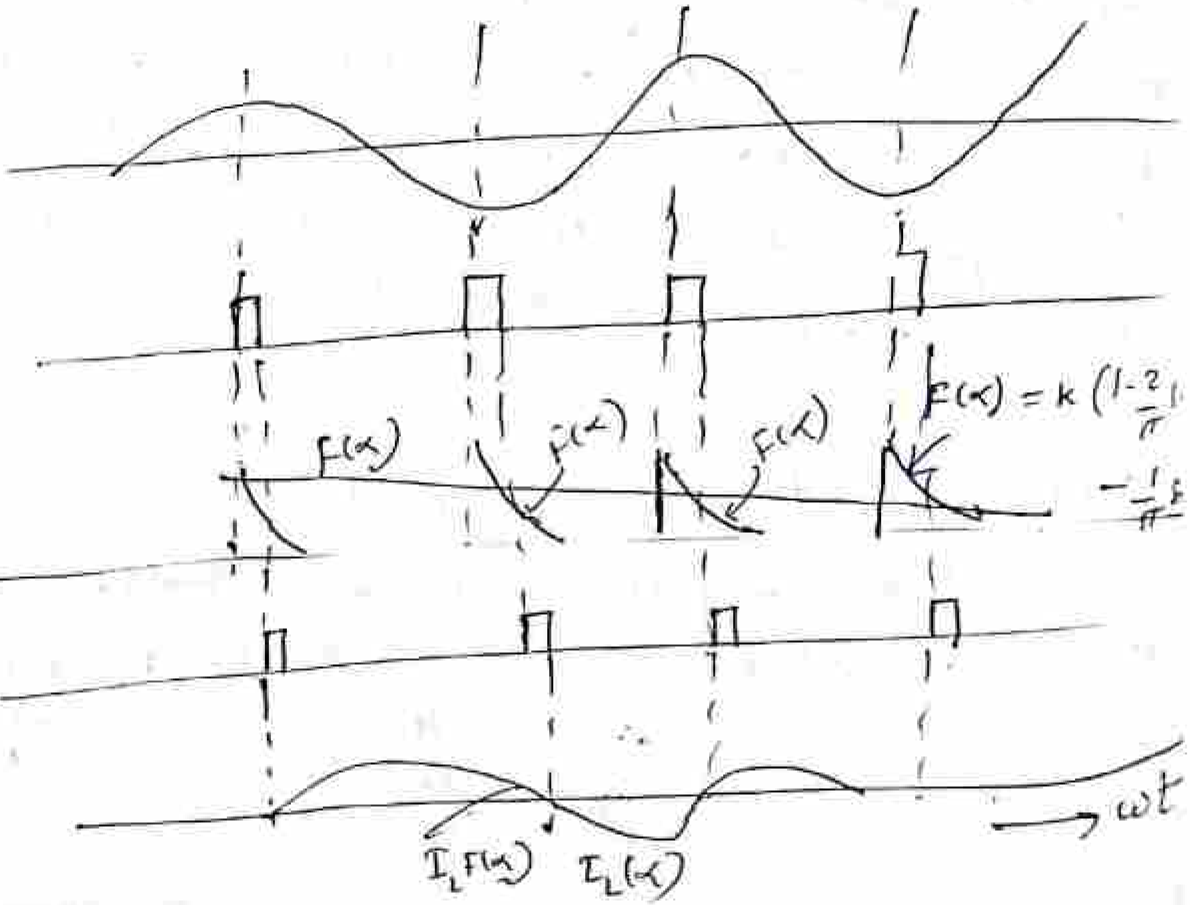
#At zero delay angle, the TCR conducts current over the full 180 degree, resulting in maximum inductive var output that is equal to the difference between var generated by capacitor and those absorbed by reactor.

#one function is synchronous timing. This function is usually provided by a phase locked loop circuit that runs in synchronism with the ac system voltage and generates appropriate timing pulse with respect to peak voltage.

The second function is the reactive cu to firing angle conversion. The mathem relationship have been developed between fundamental TCR current $I_{LF}(\alpha)$ and delay α. One is analog function generator producing in each half-cycle a scale electrical signal that represents the I_L versus a relationship.



Thyristor firing delay ~~angle~~ control



→ The third function is the computation of the required fundamental reactive current I_F by total output current I_Q (sum of fixed capacitor and the TCR current) defined by the amplitude reference input I_{Qref} to the var generator control. This is simple done by substracting the amplitude of the generator control, I_C from I_{Qref}. ~~Capacitor~~.

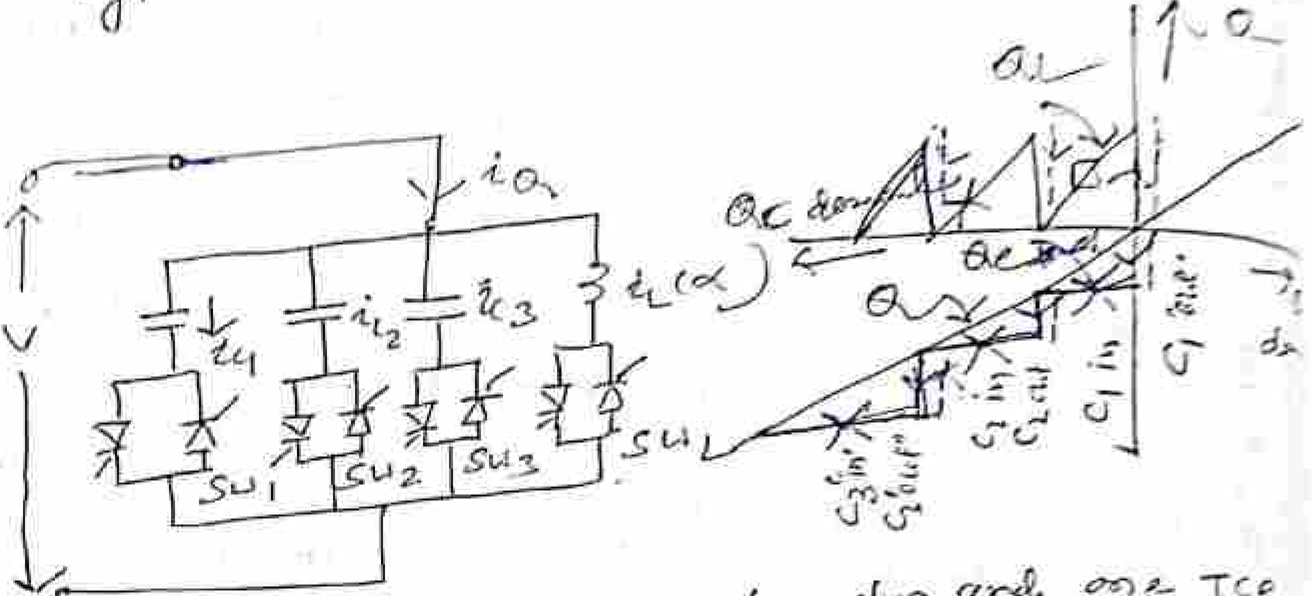
→ The fourth function is the thyristor firing pulse generation. This is accomplished by the firing pulse generator circuit which produce the necessary gate current pulse for the thyristor to turn on in response to the output signal provided by the reactive current to firing angle converter. The gate drive circuits are sometimes at ground potential with magnetic coupling to the thyristor gates, more often, they are at potential level of thyristors.

~~Thy~~ The dynamic performance of the var generator is limited by the firing angle delay control, which results in a time lag or transport lag with respect to input reference signal. The actual transfer function FC-TCR type var generator can be expressed with transport lag

$$G(s) = K e^{-T_d s}$$

$$G(s) = K \frac{1}{1+T_d s}$$

Thyristor - switched capacitor, Thyristor-controlled Type - var Generator. (TSC - TCR)



This consists of n TSC branches and one TCR. The total capacitive output range is divided in n interval. In first interval, the output of the var generator is controllable in zero to Qcmax/n range, Qcmax is total rating provided by all TSC branch. Suppose one capacitor bank is on, TCR current is set by appropriate firing angle, so that the sum of var output of TSC (negative) and TCR current (positive) equal the capacitive output required.

In 2nd, third ..... nth interval the output is controllable in Qcmax/n to 2 Qcmax/n, $\frac{2\,Q_{cmax}}{n}$ to 3 Qcmax/n . . .

$(n-1)\,Q_{cmax}/n$ to Q_{cmax} simply by switching in the second, third ... and nth capacitor bank and using the TCR to absorb the surplus capacitive vars.

#when we switch the capacitor bank switching in and out within one cycle of the applied ac voltage, the maximum surplus var in the total output range can be restricted to that produced by one capacitor bank, so theoritically TCR should have the same var rating as TSC. At the end point switching condition, the var output of TCR is larger than that TSC inorder to provide overlap between switching in and ~~a~~ switching off var levels.

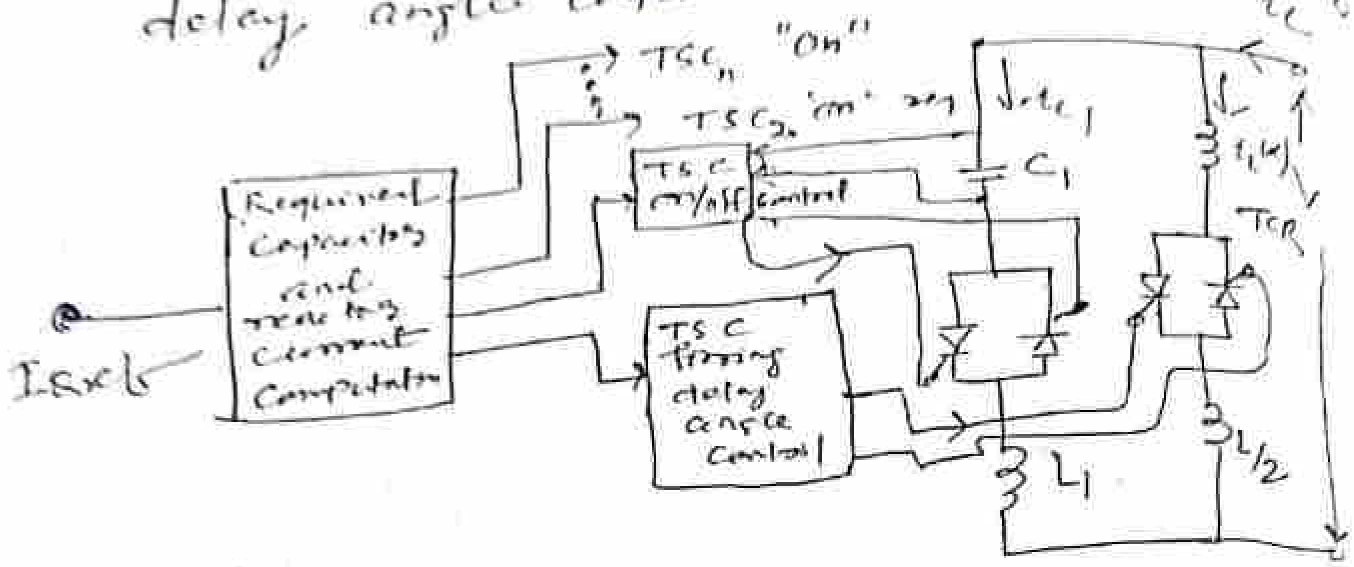
#The capacitive var Q_c is changed step wise in TSC. with the surplus var, the inductive var output of TCR, Q_L is used to cancel the surplus capacitive var.

A suitable control strategy for the TSC-TCR type var generator is shown below. Its 3 major functions are

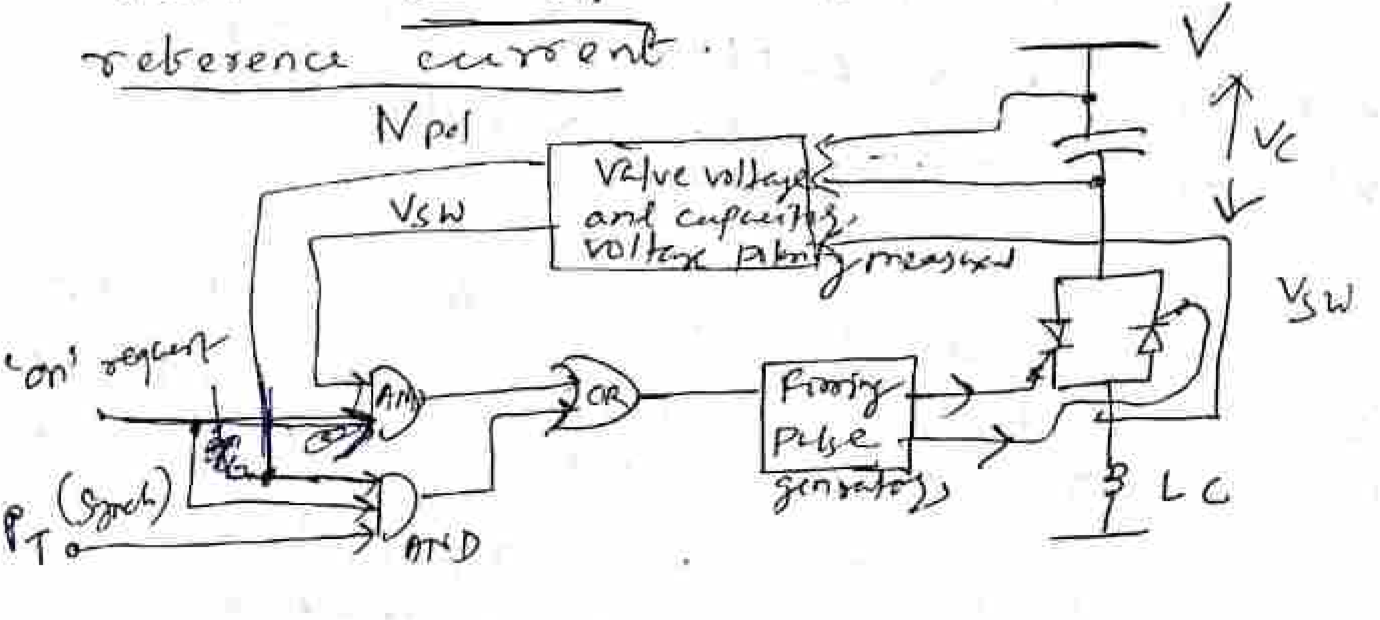
1. Number of TSC branch ~~separate~~ required and provide capacitive current which is cancel by inductive current of TCR.

2. TSC switching current is the transient free.

3. Varies the current in the TCR by firing delay angle control.



The input current reference [Qref representing the magnitude of the requested output current is divided by the (scal amplitude I_c of the current that i TSC branch would draw at the given amplitude V of the ac voltage. The current I_{LF} is decided by diffence between $\Sigma \cdot I_{cn}$ ~~[illegible]~~ and ~~[illegible]~~ reference current.



"on" = 1 $V_{sw} = 1$

or

"on" = 1 and $P_T = 1$ and $V_{pol} = 1$

$V_{sw} = 1$ and $V_c = V$

$P_T = 1$ when $V = V$

$V_{pol} = 1$ when sign V = sign V_C

This switching phenomenon is established either switch the capacitor bank when the voltage across the thyristor value becomes zero or when the thyristor value voltage is at minimum.

→ The first condition can be meet if the capacitor residual voltage is less than the peak ac voltage and the letter condition is satisfied at those peak voltage ~~is less~~ ~~than peak ac voltage and the letter condn~~ ~~is satisfied at these~~ has the same residual voltage of the capacitor. polarity as the residual voltage of the capacitor.

→ The actual firing pulse generation for the thyristor in the TSC value is similar to that used for TCR with exception that a continuous gate drive is usually provided to maintain to maintain continuity in conduction when the current is transfer form one thyristor string carrying current of one polarity.

The third function is TCR firing delay control is identical to that used in fixed capacitor, TCR scheme. The tot output current $i_Q = i_c + i_L$, the curre i_c drawn by the switched capacitor bank and current i_L drawn by the thyristor-contr reactor.

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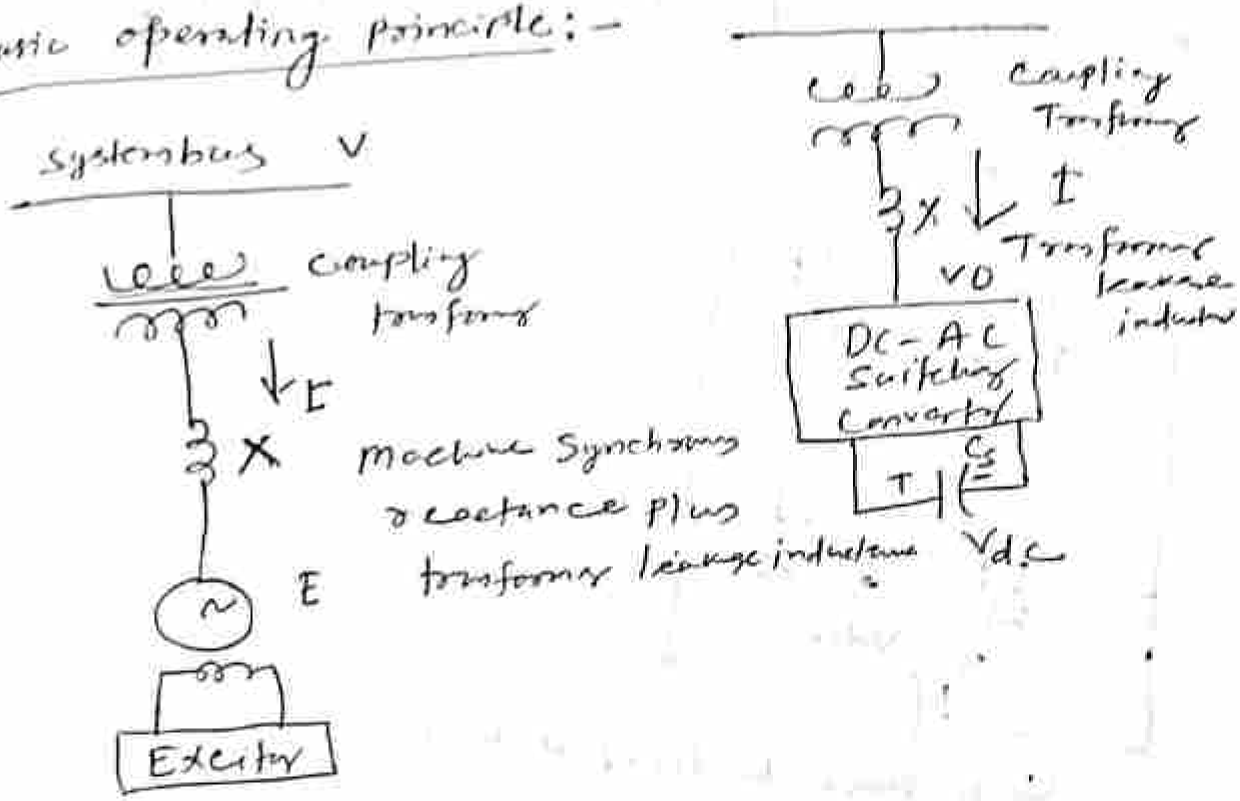
MODULE- III

Switching Converter-type Generators

Converters employed in FACT controllers are the voltage-source type.

Basic operating principle:-

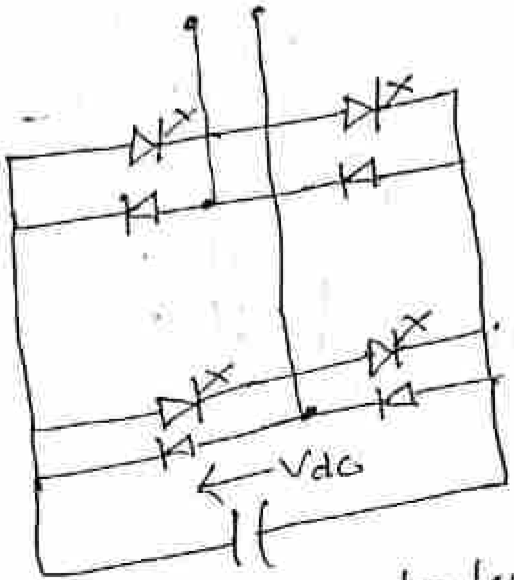


The reactive current I drawn by the synchronous compensator is determined by the magnitude of system voltage V, internal voltage E, X is the total circuit reactance.

$$I = \frac{V - E}{X}$$

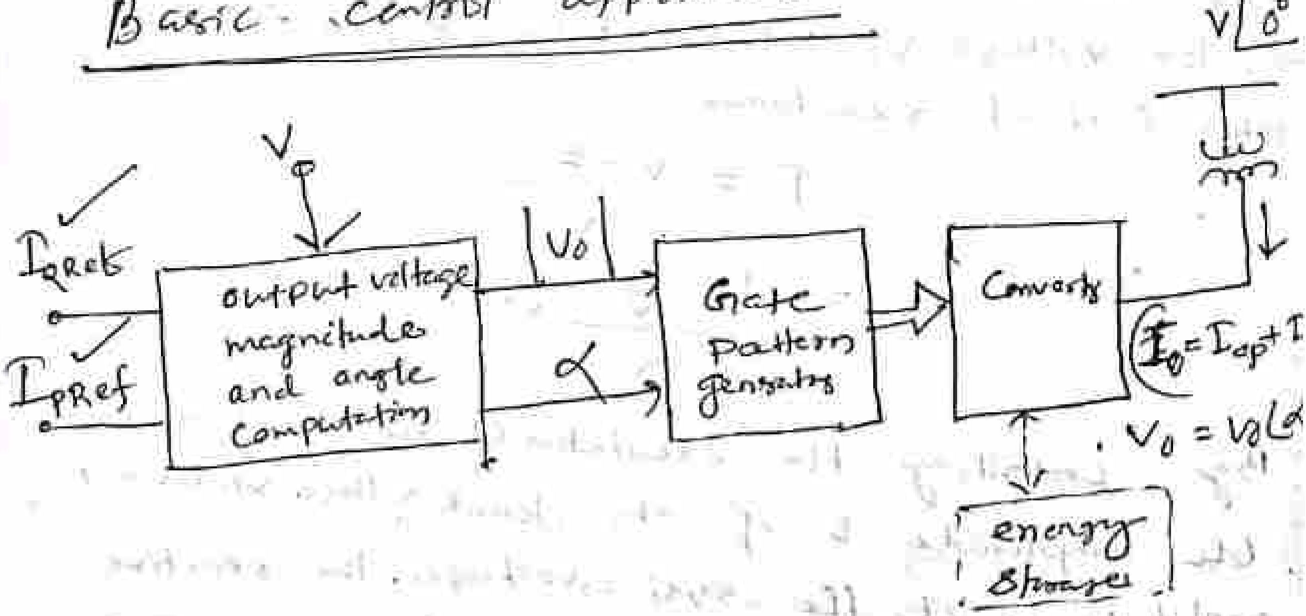
$$Q = \frac{1 - \frac{E}{V}}{X} V^2)$$

By controlling the excitation of the machine, hence the amplitude E of its internal voltage relative to the amplitude V of the system voltage, the reactive power flow can be controlled. Increasing E above V results in a leading current. Decreasing E below V (i.e operating under excited) produce a lagging current, the machine ~~[illegible]~~ ~~[illegible]~~ as reactor (inductor) by the ac system. If the excitation of the mach is controlled so that the corresponding reactive output maintains or varies a specific parameter of the ac system, then the machine functions as a rotating synchro compensator.



Single phase two level H-bridge.

Basic control approach



→ A static generator converter comprises a large number of gate-controlled semiconductor power swit (GTO) thyristor.

→ The gating commands for these device

are [illegible] control. The reference signal are provide the external or system control.

→ The internal control is an integral part of the converter. It's main function is to operate the converter power switch so as to generate fundamental output voltage waveform with demanded magnitude and phase angle in synchronism with ac system.

→ The internal control achieves this by computing the magnitude and phase angle of the required output voltage from $I_{Q_{Ref}}$ and I_{PRef} provided by the external control and generating a set of coordinated timing waveform, which determine the on and off periods of each switch in the converter corresponding to the wanted output voltage.

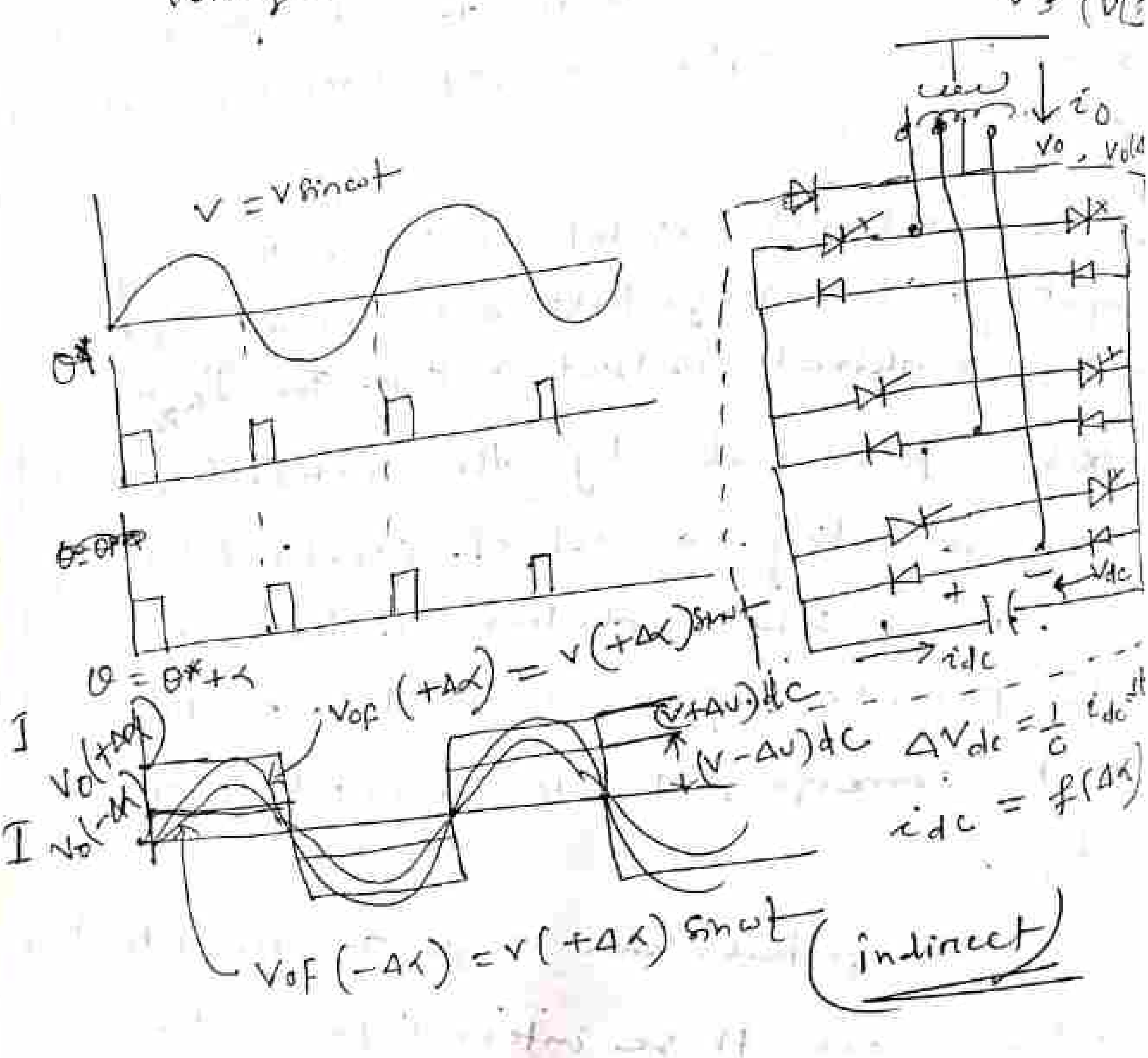
→ The magnitude and angle of the output voltage are those internal parameters which determine the real and reactive current the converter draws from.

→ The magnitude of ac output voltage is indirectly proportional to the

Two control approach is

The reactive output current can be controlled indirectly via controlling dc capacitor voltage (which in turn is controlled by the angle of the output voltag

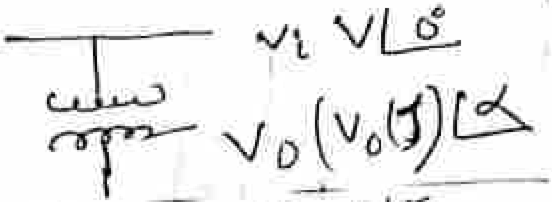
Directly by the internal control mech of the converter in which case the dc voltage is kept constant.

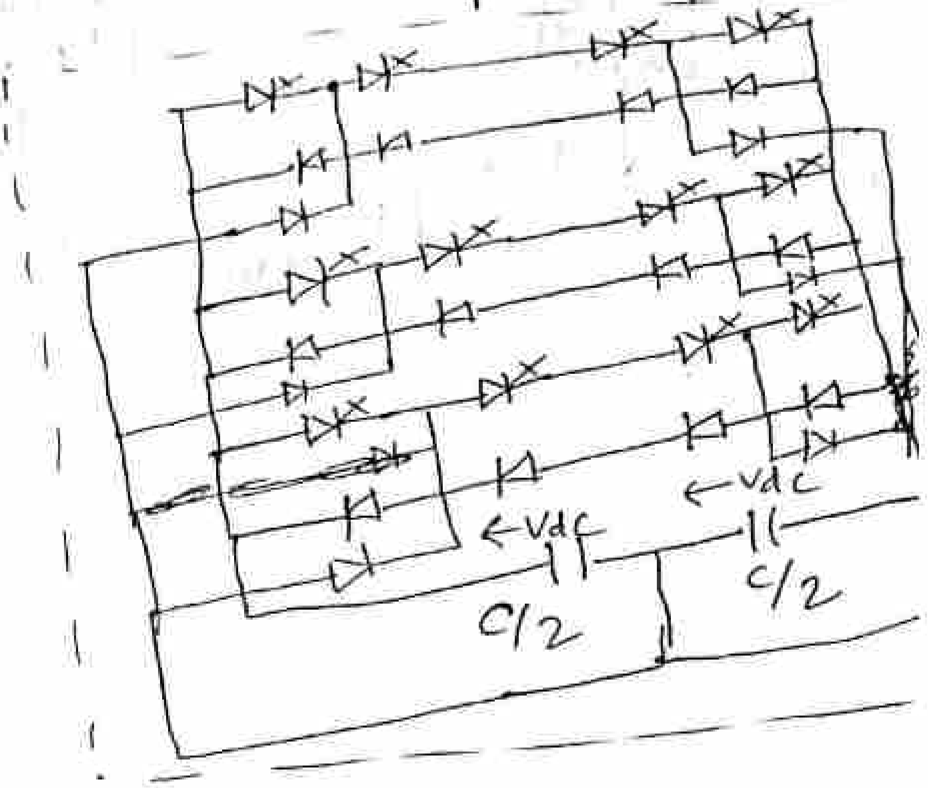


$\Delta V_{dc} = \frac{1}{C} \int i_{dc}\, dt$

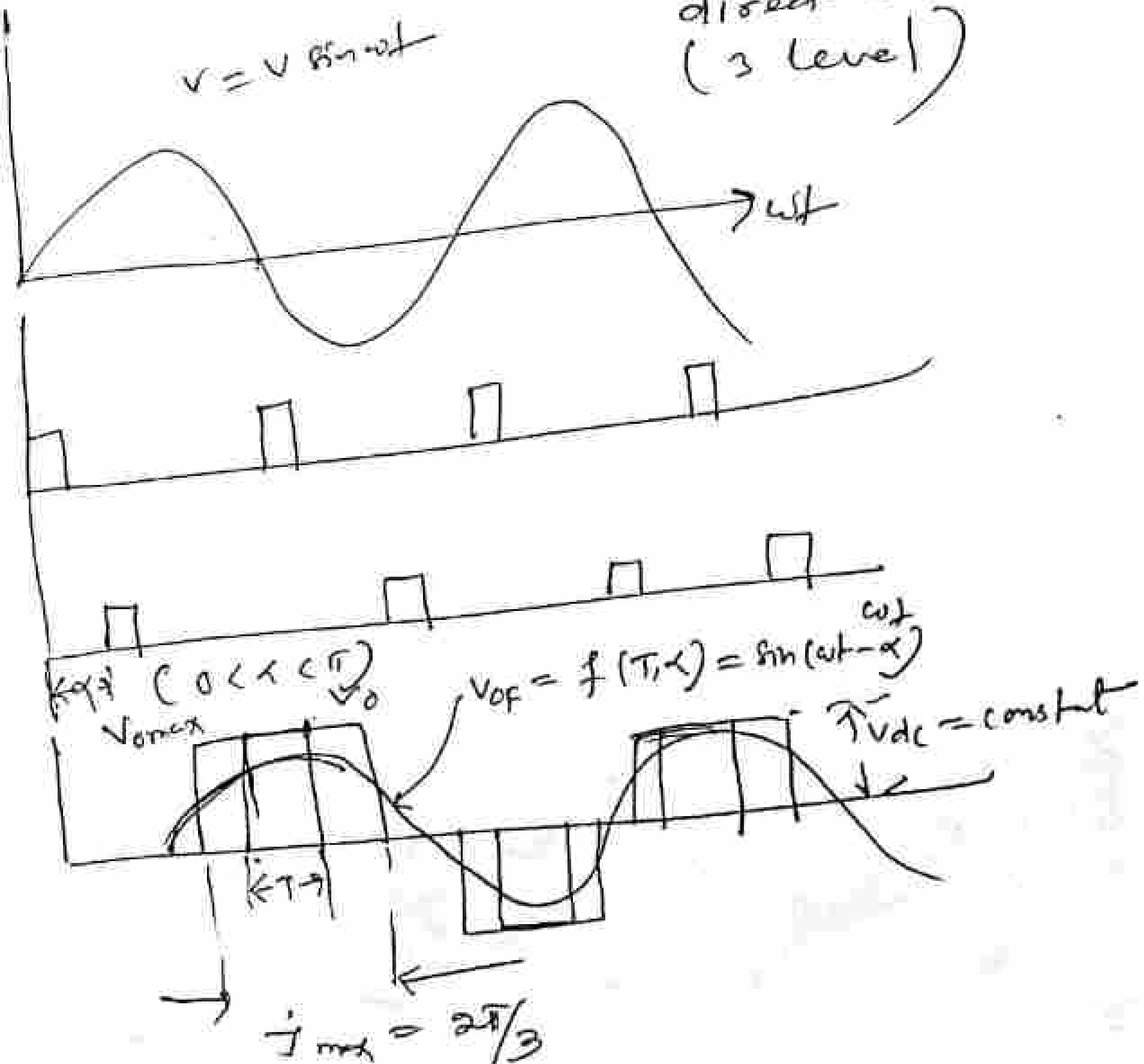
$i_{dc} = f(\Delta\alpha)$

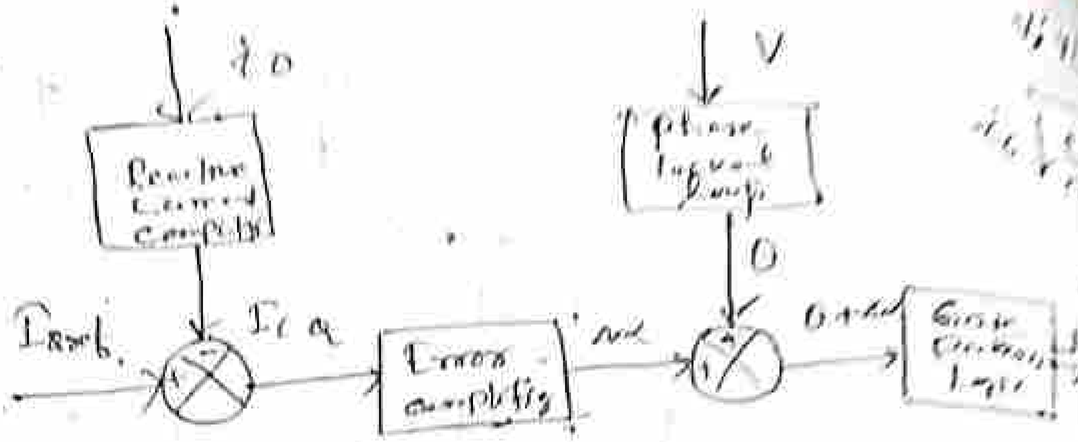
(indirect)





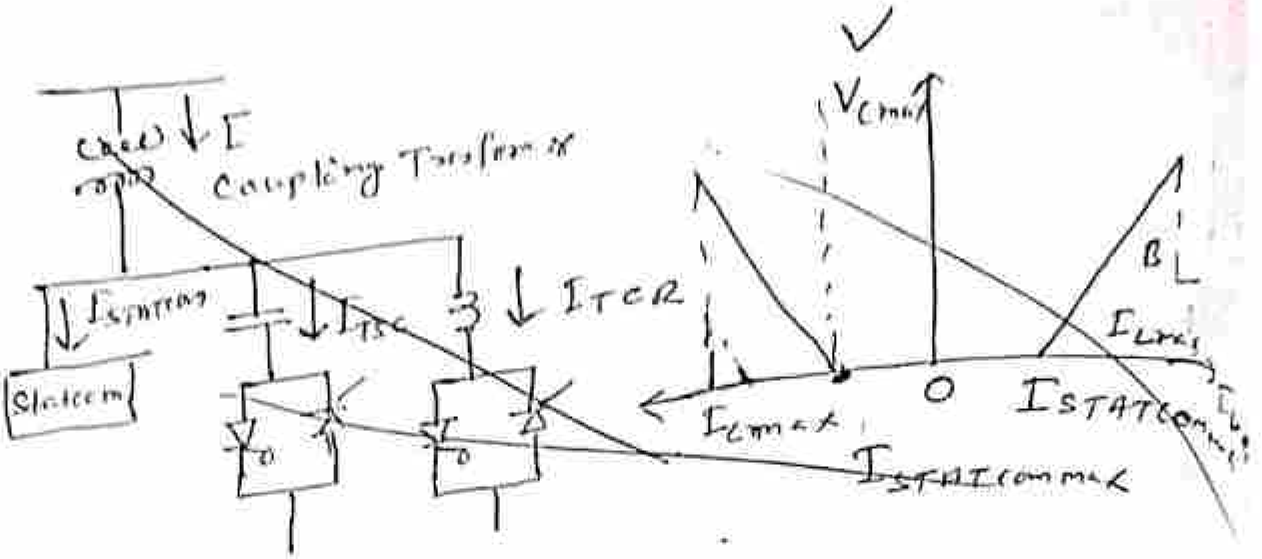
direct control
(3 level)





Iref
id
Reactive Current Computer
Id
Error amplifier
V
Phase Locked Loop
θ
Gate Control Logic

Static VAR compensator SVC and STATCOM.

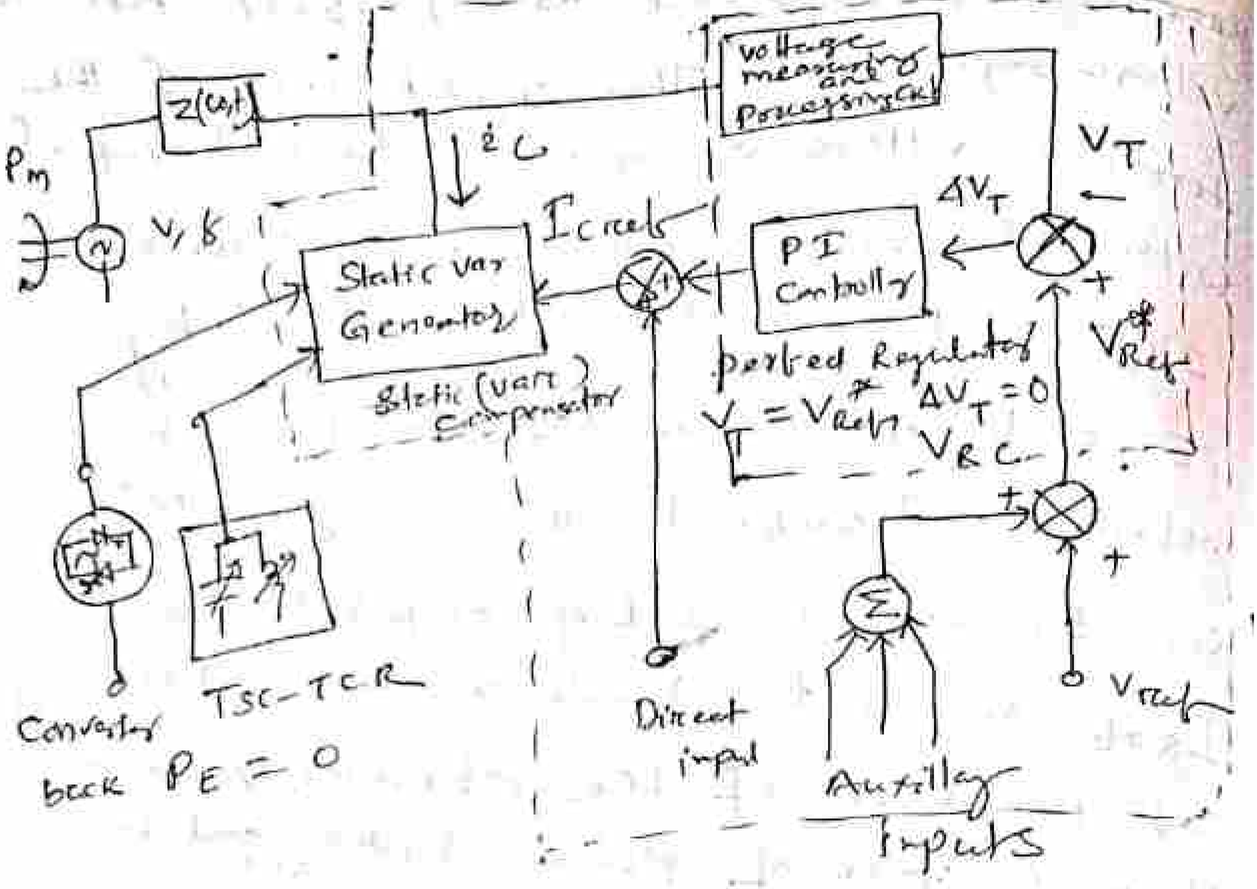


The power system, at the terminal of the compensator is represental by a generator with a generally varying sotor angle δ, internal voltage v, source impedance z, that is the function of angular frequency ω and time. The terminal voltage V_T of the power system can characterized by a generally varying amplitude V_T and angular frequency ω.

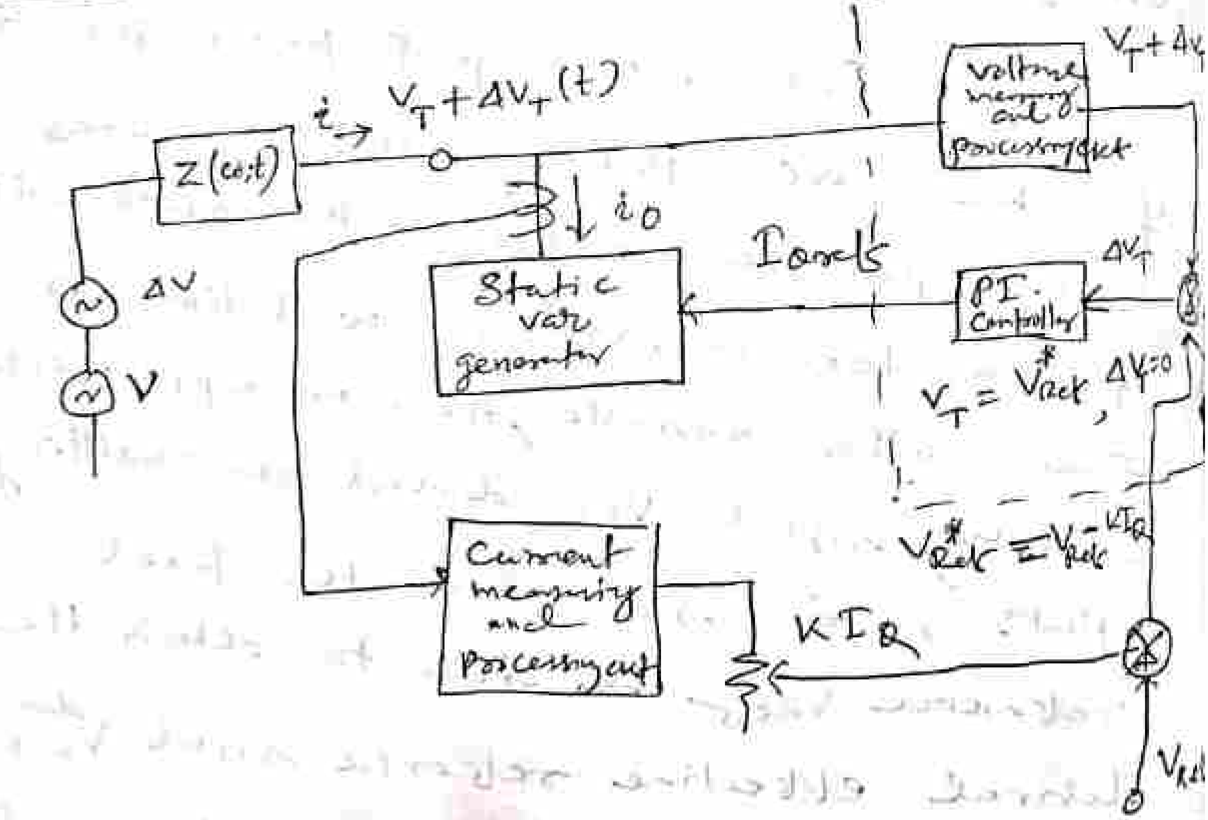
The output of the static var generator is controlled so that the amplitude I_0 of the reactive current I_0 drawn from the power system follows the current reference I_{Qref}. In static compensator control, the var generator is operated as a perfect terminal voltage regulator. The amplitude V_T of the terminal voltage v_T is measured and compared with the voltage reference V_{Ref}; the error ΔV_T is processed and amplified by PI controller to provide the current reference I_{aref} for the var generator, so, I_O is closed-loop controlled via I_{aof} so that $\hat{V}_T$ is maintained precisely at the level of the reference voltage V_{Ref} in face of power system and load change

silicon
\\192.168.1.12   Sit In 17

For making proper compensation of the ac power system requires some specific variation in the amplitude of the terminal voltage with time or some other variable, then an appropriate correcting signal V_{RC} derived from auxillary inputs, is summed to the fixed reference V_{Ref} in order to obtain the desired effective reference signal V^*_{Ref} that closed-loop controls the terminal voltage V_T



Regulation slope :-

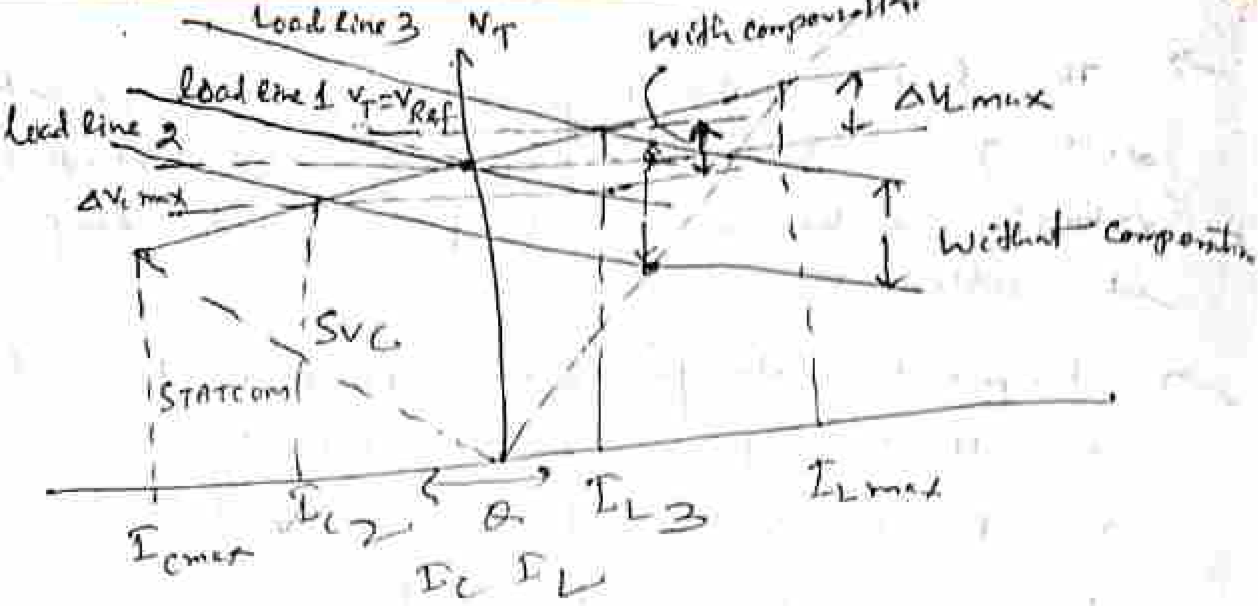


→ The linear operating range of a compensator with given maximum capacitive and inductive ratings can be extended if a regulation "droop" is allowed.

→ Regulation "droop" means that the terminal is allowed to be smaller than nominal no load value at full capacitive. Conversely it is allowed to be higher than the nominal value at full inductive compensation.

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

* 3. A regulation "droop" or slope tends to enforce automatic load sharing between static compensator as well as other voltage regulating device normally employed to control transmission voltage.
Ref



#A signal proportional to the amplitude of the compensating current KI_Q with an ordered polarity i.e capacitive current is negative and inductive current is positive is down to the reference V_{Ref}. The effective V^*_{Ref} controlling the terminal voltage thus become

$$V^*_{Ref} = V_{Ref} - \underline{K} I_Q$$

K is the regulation slope,

$$K = \frac{\Delta V_{Cmax}}{I_{Cmax}} = \frac{\Delta V_{Lmax}}{I_{Lmax}}$$

ΔV_{Cmax} = deviation of the terminal voltage from its nominal value at maximum output current. ($I_{Qmax} = I_{Cmax}$)

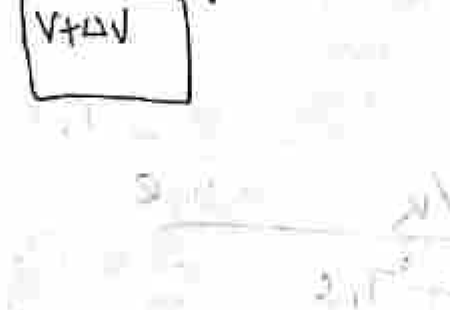
ΔV_{Lmax} = deviation of the terminal voltage from its nominal value at maximum inductive output current. ($I_{Qmax} = I_{Lmax}$)

I_{Cmax} = maximum capacitive Compensating current.

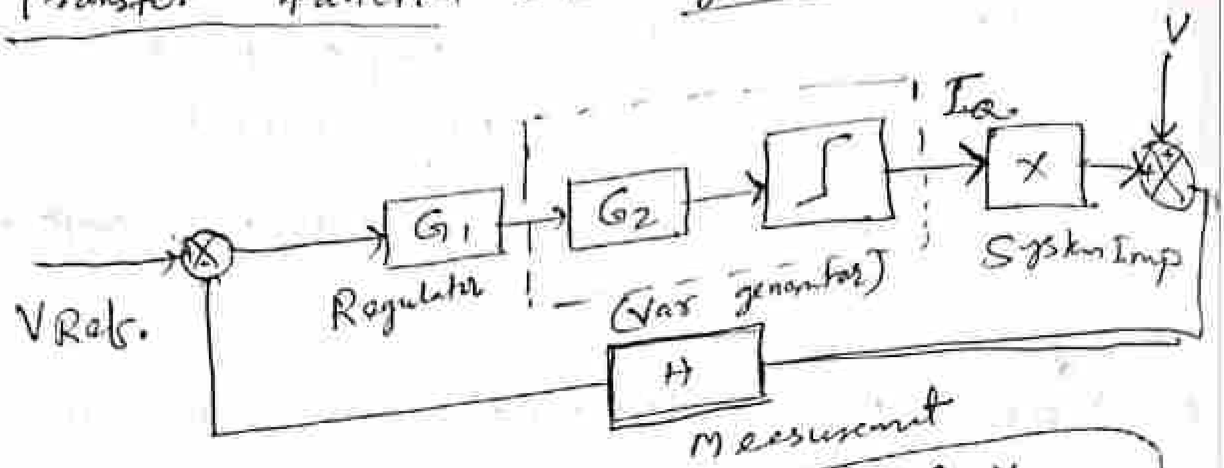
I_{Lmax} = maximum inductive compensating Current.

* ΔV_{REF}^{*} is controlled to decrease form the nominal value with increasing capacitive compensating current and conversely it is controlled to increase with increasing inductive compensating current until the maximum capacitive or inductive compensating current reached.

* The amplitude of the terminal voltage V_T is regulated along a set linear slope over the control range of the compensator. For terminal voltage changes outside of the linear control range, the output of the compeneator is determined by the basic V-I characteristic ~~to~~ of the var generator used.



Transfer function and dynamic performance



$$\boxed{V_T = V\frac{1}{1+G_1G_2HX} + V_{Ref}\frac{G_1G_2X}{1+G_1G_2HX}}$$

The dynamic behaviour of the compensator in the compensating range can be characterized by the basic transfer function.

This block diagram is drawn directly from the control scheme. Since the objective is to establish how well terminal voltage is regulated against system voltage, $V_{Ref} = 0$ and consider small variation only. The amplitude variation of the terminal voltage ΔV_T against the amplitude variation of the power system voltage ΔV can be expressed

$$\frac{\Delta V_T}{\Delta V} = \frac{1}{1+G_1G_2HX} = \frac{1}{1+GHX}$$

$$G_1 = \frac{1/K}{1+T_1S}$$

$$G_2 = e^{-T_dS}$$

$$G = G_1G_2 = \frac{1/K}{1+T_1S}e^{-T_dS}$$

T_1 = main time constant of the P-I controller

signal) T_2 = amplitude measuring circuit time constant.

T_d = transport lag of the var generator.
(typically 2.5 ms for TCR)

K = regulation slope. $H = \frac{1}{1+T_2 S}$

It should be pointed out that practical compensator control often employ filters in the signal processing circuits which may introduce additional time constant in the transfer function. Sometimes phase correcting (lead/lag) circuit are also employed.

Under steady state condⁿ $(s \to 0)$

$$\frac{\Delta V_T}{\Delta V} = \frac{1}{1+\frac{X}{K}}$$

Slope become smaller $(K \to 0)$, the terminal voltage remain constant, independent of the system voltage variation $\left(\frac{\Delta V_T}{\Delta V} \to 0\right)$
Similarly, with increasing slope $(K \gg X)$ the terminal voltage becomes unregulated.
$\left(\frac{\Delta V_T}{\Delta V} \to 1\right)$

Dynamic behaviour of the compensator is a function of the power system impedance That is time response and stability control is dependent on the system impedance. Control is normally optimized for the maximum system impedance. The system impedance variation and the attainable worst case response time are considerable dependent on the achievable frequency bandwidth of the compensator which is ultimately limited by the transport lag of the var generator employed.

MODULE- IV

Static Series compensator

GCSC, TSSC, TCSC, SSSC

→ Reactive shunt compensation is highly effective in maintaining the desired voltage profile along the transmission line interconnecte two buses of the ac system and providing support to the end voltage of radial lines in the face of increasing power demand.

→ Reactive shunt compensation when applied at sufficiently close intervals along of the line, if a large enough angle between the two end voltage could be established. However, shunt compensation is ineffective in controlling the actual transmittal power which, at a defined transmission voltage, is ultimately determined by the series impedance and the angle between the end voltage of line.

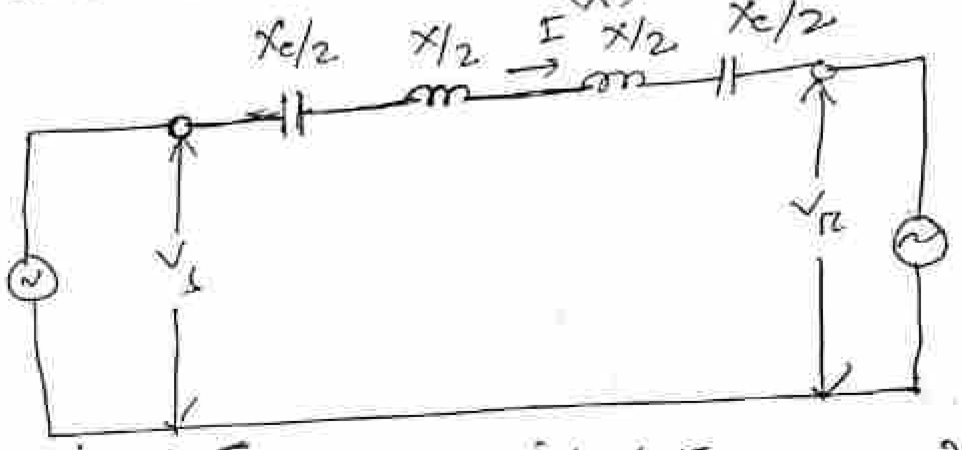
→ It was always recognized that ac power transmission over long lines was primarily limited by the series reactive impedance of the line. Series capacitive compensation was introduced decades ago to cancel a portion of the reactive line impedance and thereby increase the transmittable power, Series compensation is highly effective in both controlling power flow in the line and improving stability.

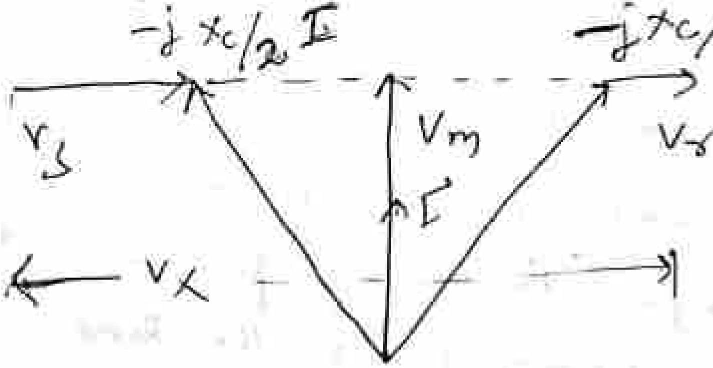
controllable series line compensation is controlling the power flow in the lines preventing loop flow with use of fast controls minimizing the effect of system disturbances, thereby reducing traditional stability margin requirements.

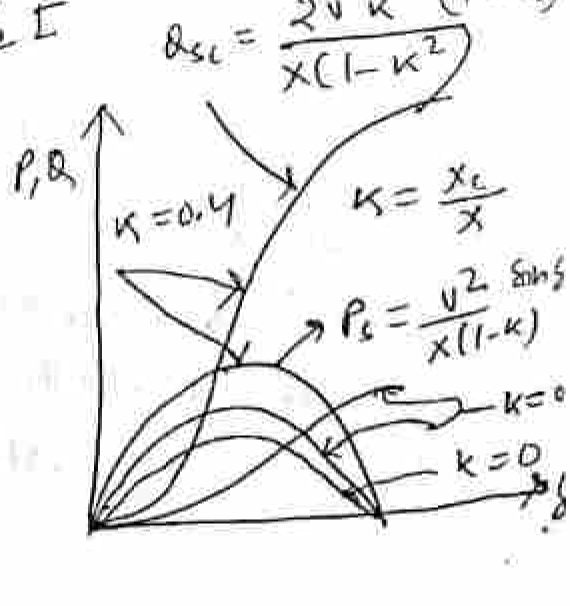
→ The effect of series compensation on the basic factors, maximum power transmission, steady state power transmission, transient stability voltage stability and power oscillation damping will be examined.

Concept of series capacitive compensation :—

The overall concept of series capacitive compensati is to decrease the overall effective series transmiss impedance from sending end to receiving end i.e X in the $P = \left(\frac{V^2}{X}\right)\sin\delta$ relationship







Note that for the same end voltage the magnitu of the total voltage across series line inductance $V_x = 2V_{x/2}$ is increased by the magnitude of the opposite voltage, V_c, developed across the series capacitor. The effective transmission impedance with series capacitive compensation.

$$X_{eff} = X - X_C$$

$$X_{eff} = (1-K)X$$

$$K = \frac{X_C}{X} \qquad 0 \leq K \leq 1$$

Assuming $V_s = V_r = V$, the current in the compensated line, and the corresponding real power transmitted

$$I = \frac{2V}{(1-K)X}\sin\frac{\delta}{2}$$

$$P = V_m I = \frac{V^2}{(1-K)X}\sin\delta$$

$$Q_c = I^2 X_c = \frac{2V^2}{X}\frac{K}{(1-K)^2}(1-\cos\delta)$$

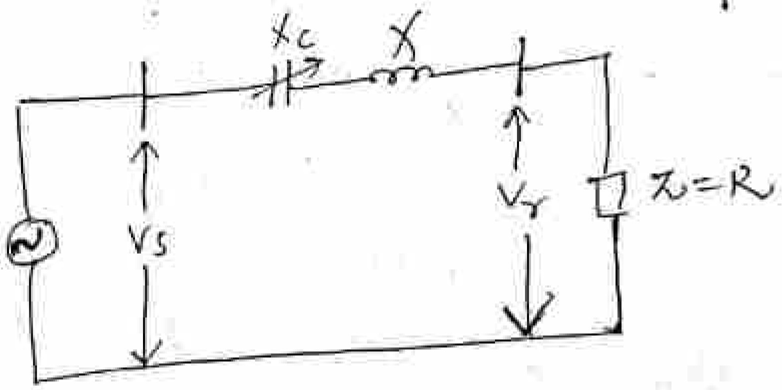
→ It can be observed that the transmittable power rapidly increase with the degree of series compensation K. The reactive power supplied by the series capacitor also increases sharply with K and varies with angle δ

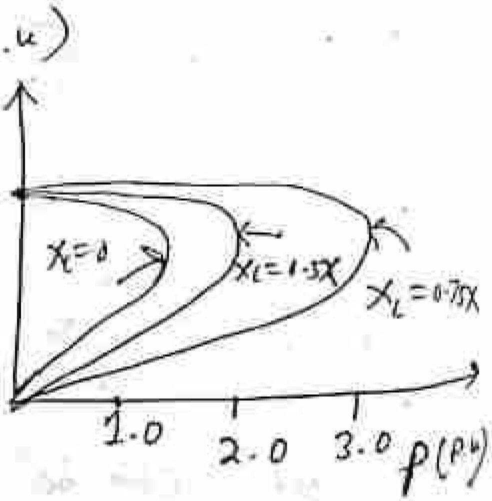
→ The actual explanation ~~of~~ of that the impedance of the series compensating capacitor cancel a portion of the actual - line reactance and the effective impedance ~~rotoral~~ is reduced.

→ indirectly we increase the current in the given series impedance of the actual physical line, the voltage across this impedance must be increased.

→ Switching power converter used in the shunt connected STATCOM; applied as a voltage source in series with the line, serves the functional capabilities of series capacitive compensation and also provide additional options for power flow control.

Voltage stability





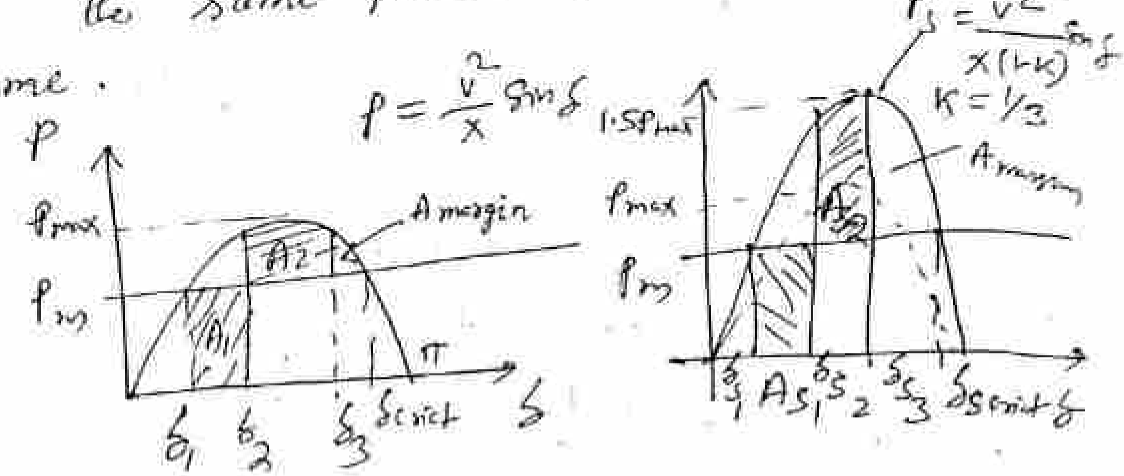
→ Series capacitive compensation can also be used to reduce the series reactive impedance to minimize the receiving-end voltage variation and possibility of voltage collapse.

Consider a radial system with feeder line reactance X, series compensating reactance X_C' and load impedance Z. The corresponding terminal voltage V_r versus power P plots, with unity pf at 0, 50 and 75% series capacitive compensation. The "nose point" at each plot given for a specific compensation level represents the corresponding voltage instability.

Both shunt and series capacitive compensation can effectively increase the voltage stability limit. Shunt compensation does it by supplying the effective load demand and regulating terminal voltage. Series capacitive compensation does it by canceling a portion of the line reactance and in effect in stiff voltage for the load. For increasing the voltage stability limit of overhead transmission, series compensation is much more effective than shunt compensation of the same MVA rating.

Improvement of Transient Stability.

In series compensated case that the pre fault and post fault systems remain the same, suppose that the systems with and without series capacitive compensation, transmit the same power P_m. Assume that both the uncompensated and series compensated systems are subjected to the same fault for the same period of time.



1. prior to the fault both of them transmitt power P_m at angle δ_1 and δ_{S1} respectively

2. During fault, transmitted electrical power becomes zero while the mechanical input power to the generator remains constant, P_m

3. The sending-end generator accelerates from the steady-state angle δ_1 and δ_{S1} to angle δ_2 and δ_{S2} respectively; when the fault clears.

4. The accelerating energies are represented by area A_1 and A_{S1}.

5. After fault clearing, the transmitted electric power exceeds the mechanical input power and therefore the sending-end machine deaccelerates. However, the accumulated Kinetic energy further increases until a

ance between accelerating energy and decelerating energies, represented by area A1 and A_2 and A_{S1} and A_{S2} respectively, is reached at the maximum angular swing δ_3 and δ_{S3} respectively.

The area between the P versus δ curve and the constant P_m line over the intervals defined by angle δ_3 and δ_{crit}, and δ_{S3} and δ_{Scrit} respectively, determine the margin of stability, represented by area A_{margin} and $A_{Smargin}$.

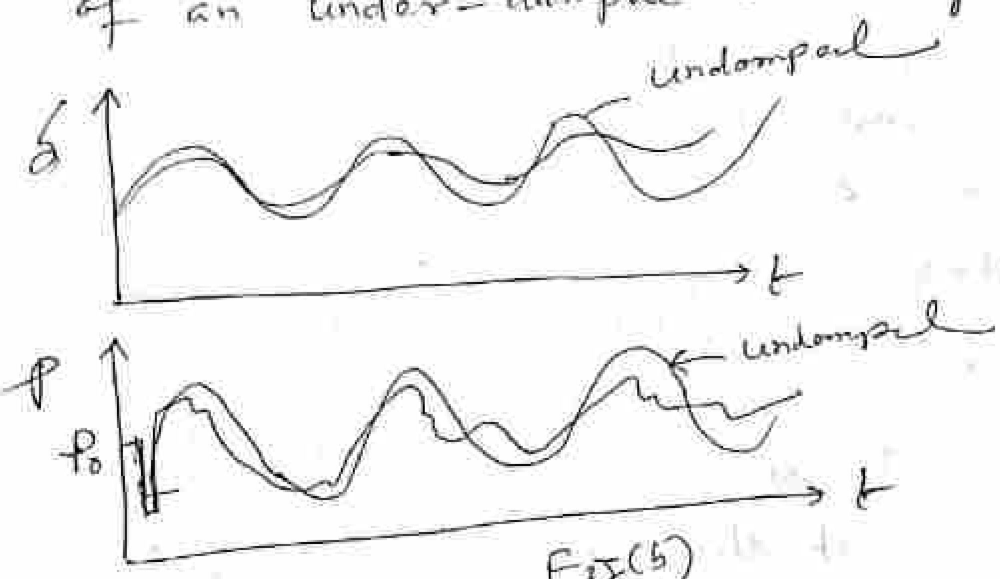
→ It is clearly shows a substantial increase in the transient stability margin, the series capacitive compensation can provide by partial cancellation of series impedance of the transmission line. The increase of transient stability margin is proportional to the degree of series compensation.

power oscillation Damping :-

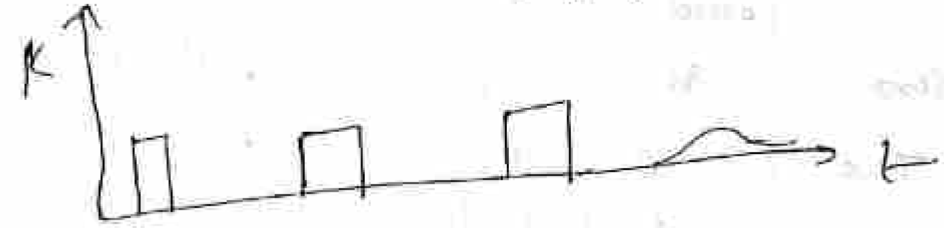
→ Series compensation can be applied effectively to damp power oscillations.

→ When the rotational oscillating generator accelerates and angle δ increases $\left(\frac{d\delta}{dt} > 0\right)$, the electric power transmitted must be increased to compensate for the excess mechanical input power. When the generator decelerates and angle δ decreases $\left(\frac{d\delta}{dt} < 0\right)$, the elect. Power must be decreased to balance the insufficient mechanical input power.

The required variation of the degree of series compensation, variation of the transmission angle δ and transmitted power P versus time of an under-damped oscillating system.



Fig(b)



Undamped and damped oscillation of angle δ around steady-state value δ_0. Fig(b) shows the undamped and damped oscillation of ~~angle δ around the steady state value~~ ~~δ_0~~ electric power P around the steady state value P_0. Waveform c shows the applied variation of degree of series compensation K. K is maximum when $\frac{d\delta}{dt} > 0$ and it is zero when $\frac{d\delta}{dt} < 0$. When K is maximum, the effective line impedance is minimum, the electric power transmitted over the line is maximum.

When K is zero

the effective line impedance is maximum and power transmitted over the line is minimum. The illustration shows that K is controlled in a "bang-bang manner." This type of control is the most effective for damping large oscillations. Damping relatively small power oscillation, particularly with a relatively large series compensation

Subsynchronous oscillation Damping

Sustained oscillation below the fundamental system frequency can be caused by series capacitive compensation. This phenomenon referred to as subsynchronous resonance (SSR)

→ Theoretical survey reveals that interaction between series capacitor compensated transmission line, oscillating at the natural resonant frequency and mechanical system of a turbine generator set or torsional mechanical oscillation can result negative damping with the consequent mutual reinforcement of electrical and mechanical oscillation

A capacitor in series with the total circuit inductance of the transmission line forms a series resonant circuit with the natural frequency of $f_e = \frac{1}{2\pi\sqrt{LC}} = f\sqrt{\frac{X}{}}$

where X_c = reactance of series capacitor
X = total reactance of the line at fundamental power frequency

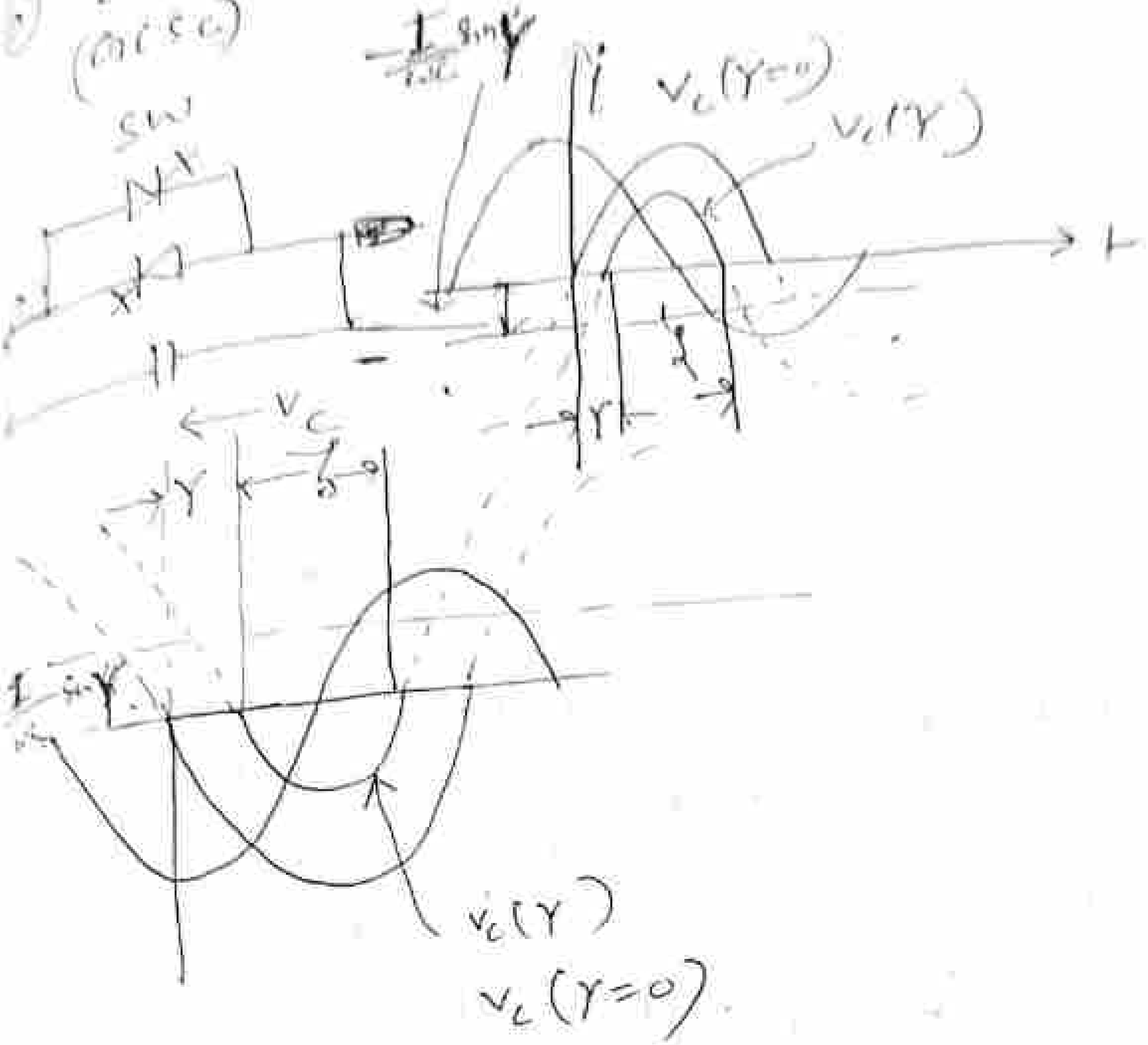
So, $K = \frac{X_c}{X}$ is usually 25% to 75%, the electrical resonant frequency f_e is less than the power frequency f, so f_e is a subharmonic frequency.

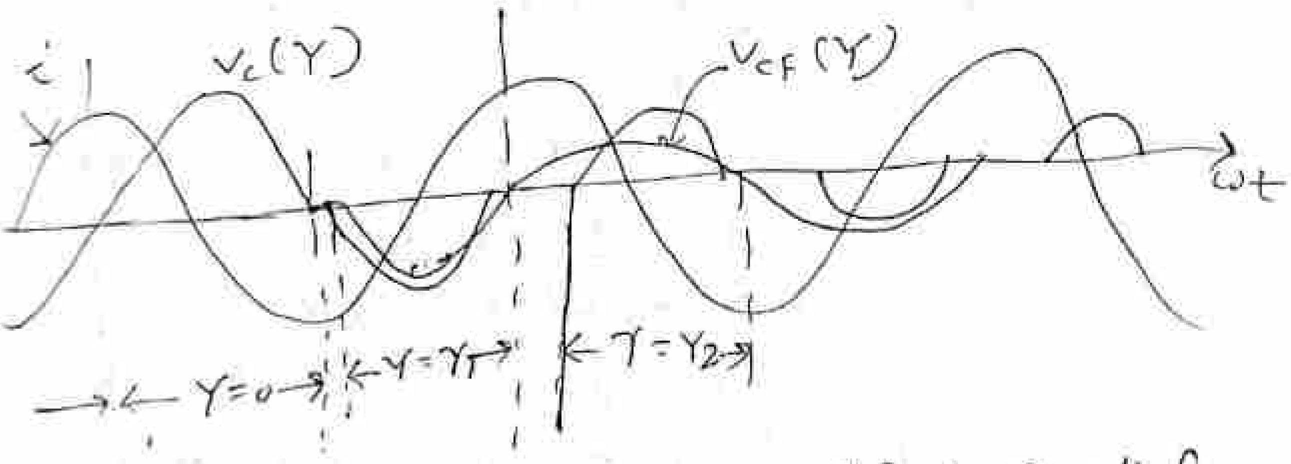
$f_e < f$

If the electrical circuit is brought into oscillation then the subharmonic component of the line current results in a corresponding subharmonic field in the machine which rotates backwards relative to the mainfield, producing an alternating torque on the rotor ~~backwards~~ at the difference $f - f_e$. If the difference frequency coincide with one torsional resonance of the turbine-generator set, mechanical torsional oscillation is excited, which in turn further excites the electrical resonance. This condition is defined as subsynchronous resonance.

variable impedance type series compensator

i) GTO Thyristor - controlled series capacitor (GCSC)





It is consist of fixed capacitor in parallel with GTO thyristor valve (or switch) that has the capability to turn on and off uppon command.

→ The objective of GCSC scheme is to control the ac voltage v_c across the capacitor at given current i. when GTO value, sw is

Closeds, the voltage across the capacitor valve is zero, and the valve is open, the voltage appears maximum.

→ The on and off the valve is carried out in each half cycle in sychronism with the ac system frequency, when controlling the capacitor voltage.

→ The turn-off instant of the valve in each half cycle is controlled by a delay angle γ $(0 \leq \gamma \leq \pi/2)$ with respect to the peak of the line current.

→ When the opening of the valve is delayed by the angle γ with respect to the crest of the line current, the capacitor voltage can be expressed with a defined line current $i(t) = I\cos\omega t$

$$V_c(t) = \frac{1}{C}\int_{\gamma}^{\omega t} i(t)\,dt = \frac{I}{\omega C}(\sin\omega t - \sin\gamma)$$

→ The valve open at γ and [illegible] to close at the first voltage zero. is valid for the interval $\gamma \leq \omega t \leq \pi - \gamma$.

→ The term $(I/\omega C)\sin\gamma$ is simple a γ dependent constant by which the sinusoidal voltage at $\gamma = 0$ is offset, shifted down for positive and up for negative voltage half-cycle.

→ GTO valves automatically turns on at the instant of voltage zero crossing, this process ually controls the non-conducting interval of the GTO valve. The turn off delay angle defines the prevailing blocking angle ζ, ζ = π − 2γ. As the turn-off delay angle γ increases, the correspondingly increasing offset results in reduction of the blocking angle ζ of the valve, and consequent reduction of capacitor voltage. At the maximum delay of γ = π/2, the offset also reaches its maximum of I/ωC, at which both the blocking angle and the capacitor voltage becomes zero.

→ The magnitude of the capacitor voltage can be varied continuously by this method of turn-off delay angle control from maximum (γ = 0) to zero (γ = π/2)

→ The TCR is a switch in series with a reactor, the GCSC is switch is shunt with capacitor

→ The TCR is supplied from ~~current~~ voltage source (transmission ~~line current~~ bus voltage), the GCSC is supplied from current source (transmission line current)

→ The TCR valve is stipulated to close current zero, the GCSC at voltage zero.

→ The TCR is controlled by a turn-on

delay with respect to crest of the applied voltage, ~~[illegible]~~ which defines the conduction interval of the valve. The GCSC is controlled by turn-off delay with respect to the peak of the line current, which defines the blocking intervals of the valve

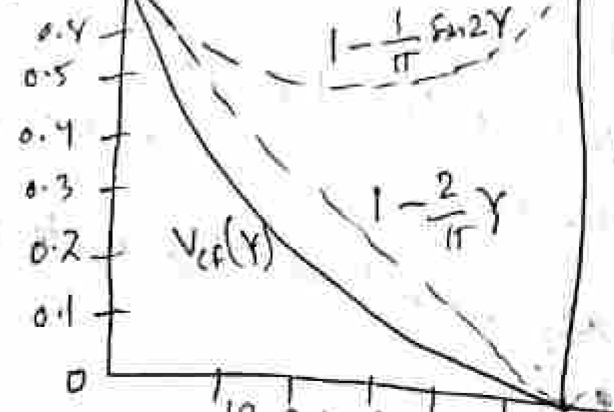
→ The TCR controls the current in a fixed inductor from a constant voltage source, thereby presenting a variable reactive admittance as the load to this source. The GCSC controls the voltage developed by a constant current source a fixed capacitor, thereby presenting a variable reactive impedance to this source.

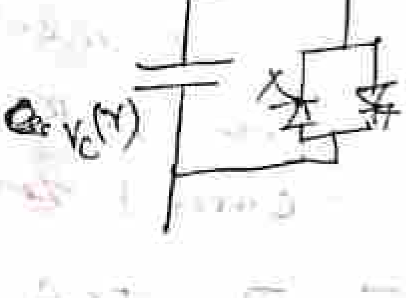
The amplitude $v_{CF}(\gamma)$ of the fundamental ~~voltage~~ capacitor voltage can be expressed as a function of angle γ

$$v_{CF}(\gamma) = \frac{I}{\omega C}\left(1 - \frac{2}{\pi}\gamma - \frac{1}{\pi}\sin 2\gamma\right)$$

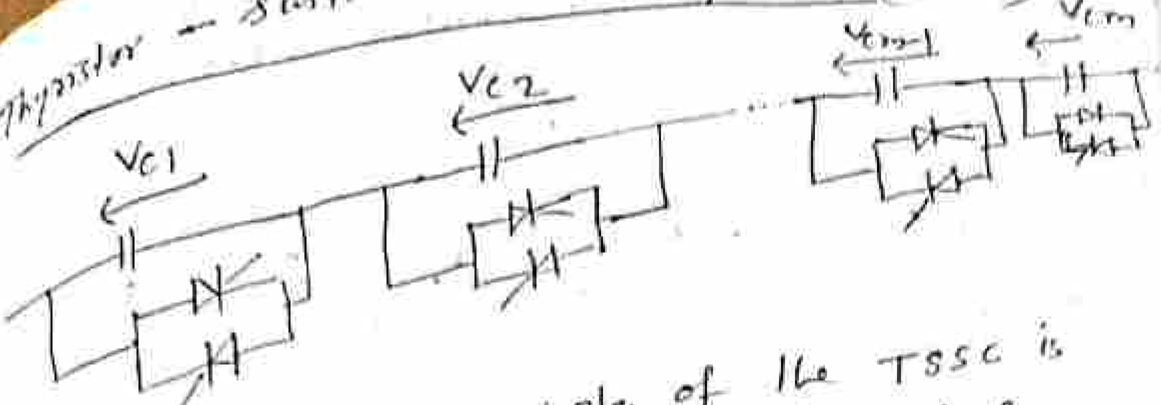
I is the amplitude of line current, C is the capacitance of GTO-thyristor controlled capacitor

$$X_C(\gamma) = \frac{1}{\omega C}\left(1 - \frac{2}{\pi}\gamma - \frac{1}{\pi}\sin 2\gamma\right)$$





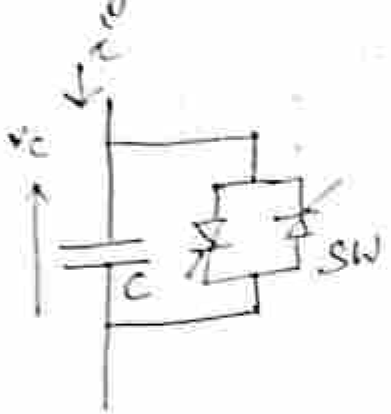
Thyristor - Switched Series Capacitors (TSSC)

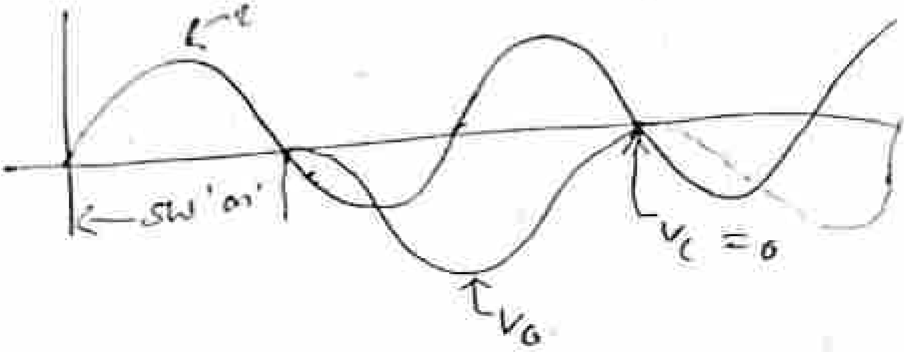


→ The operating principle of the TSSC is straightforward; the degree of series compensation is controlled in a step like manner by increasing or decreasing the number of series capacitors inserted. A capacitor is inserted by turning off, and it is ~~p~~ bypassed by turning on the corresponding thyristor valve.

→ A thyristor valve commutates naturally that is turn-off when the current crosses zero. Thus a capacitor can be inserted into the line by the thyristor valve only at the zero crossing of the line current. The insertion takes place at line current zero, a full half-cycle of the line current will charge the capacitor from zero to maximum and the successive opposite polarity half-cycle of the line current will discharge it from this maximum to zero.

→ The capacitor insertion at line current zero, necessiated by the switching limitation of the thyristor valve, results in a dc offset voltage which is equal to the amplitude of the ac capacitor voltage. In order to minimize the initial surge current in the valve and the corresponding circuit transient, the thyristor valve can be turned on for bypass only when the capacitor voltage is zero.

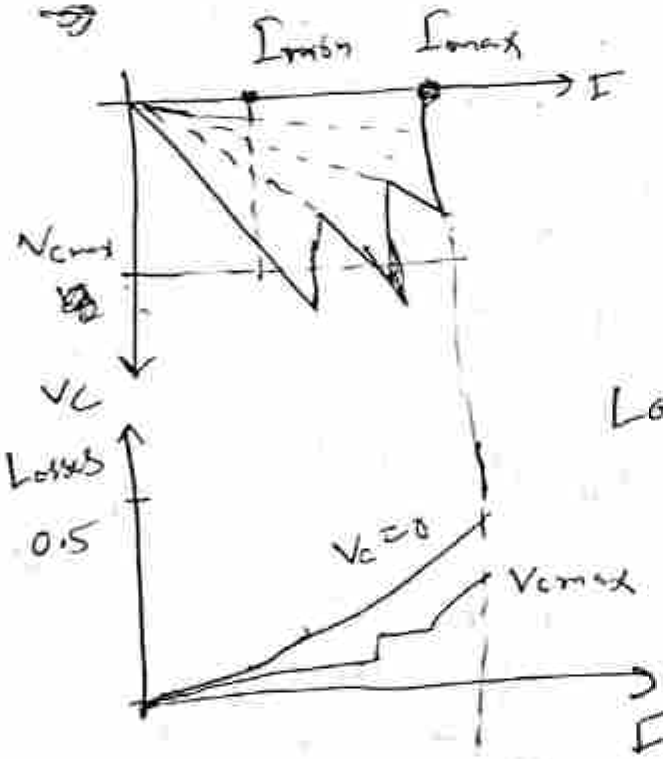


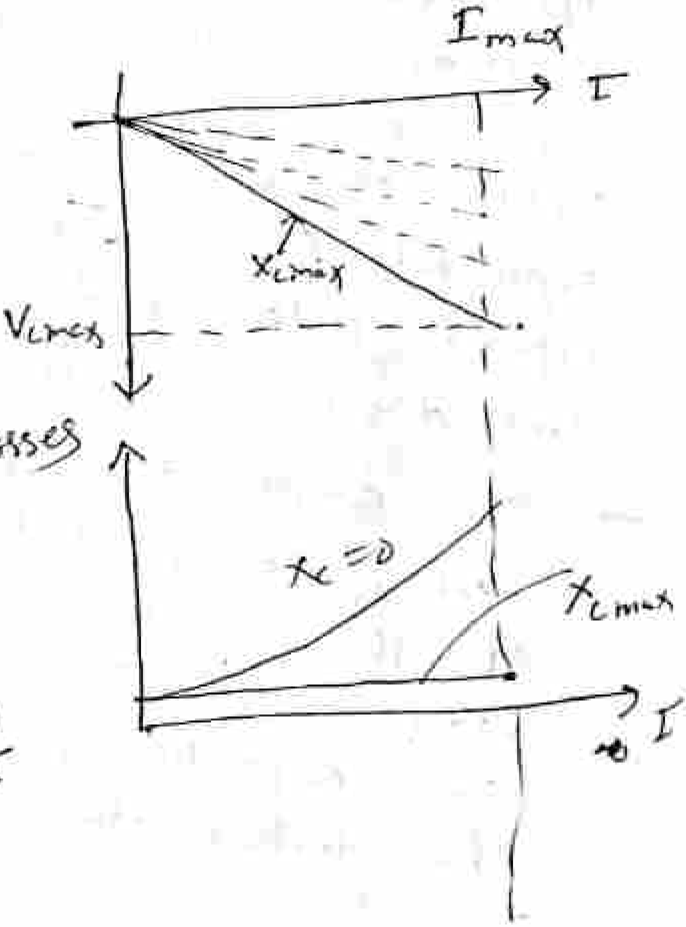


→ The TSSC can control the degree of series compensation by either inserting or bypassing series capacitor but it can not change the natural characteristic of the classical series capacitor compensated line.

→ High degree of series capacitor ~~compensated~~ compensation could cause subsynchronous resonance. TSSC switching could be modulated to counteract subsynchronous oscillations. Long switching delays encountered.

⇒





V-I characterstic

The componsating mode the reactance of the capacitor bank is chosen so as to produce, on the average, the rated compensating voltage $V_{cmax} = 4 X_C I_{min}$, in the face of decreasing line current over a defined interval $I_{min} \leq I \leq I_{max}$. As current increasing from I_{min} to I_{max}, to reduce capacitive reactance and thereby maintain compensating voltage with increasing line current. There is a loss percent of the rated var, result is that zero voltage injection and for maintaining maximum rated voltage injection.

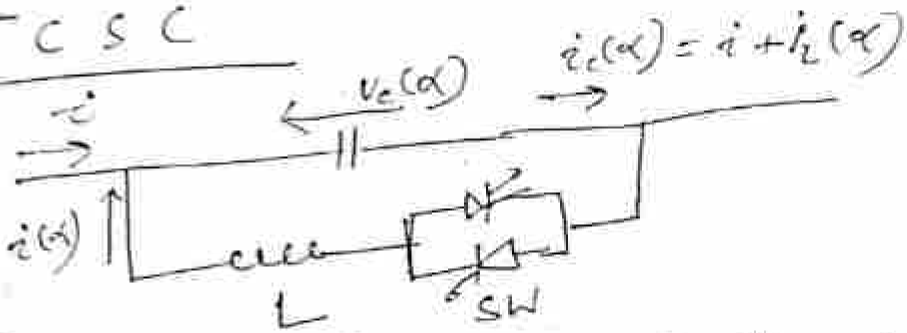
In the impedance compensation mode, the TSSC is applied to maximum rated compensating reactance at any line current up to rated maximum. In this capacitive compensation mode, the capacitive ~~compensation~~ impedance is chosen to provide the maximum series compensation at rated current $4X_C = \frac{V_{cmax}}{I_{max}}$ that TSSC can vary in a step-like manner by bypassing on or more capacitor banks. The loss versus line current characteristic ~~[illegible]~~ for this compensation mode for zero compensating impedance (all capacitor banks are bypassed by the thyristor valves) and for maximum compensating impedance (all valves are off)

Application :-

1→ TSSC would be protected against excessive currents and voltage surges either by external protection

2 - Constraints imposed by physical device limitation on the turn-on condition of thyristor. ($\frac{di}{dt}$ duty and surge current magnitude) would necessitate in practice

TCSC



It is consist of series capacitive compensator shunted by Thyristor - Controlled Reactor.

The basic idea behind the TCSC scheme is to provide a continuously variable capacitor by means of partially cancelling the effect compensating capacitance by the TCR. A steady state impedance of the TCSC is that a parallel LC circuit, consisting of fixed impedance, X_C and a variable inductive impedance $X_L(\alpha)$

$$X_{TCSC}(\alpha) = \frac{X_C X_L(\alpha)}{X_L(\alpha) - X_C}$$

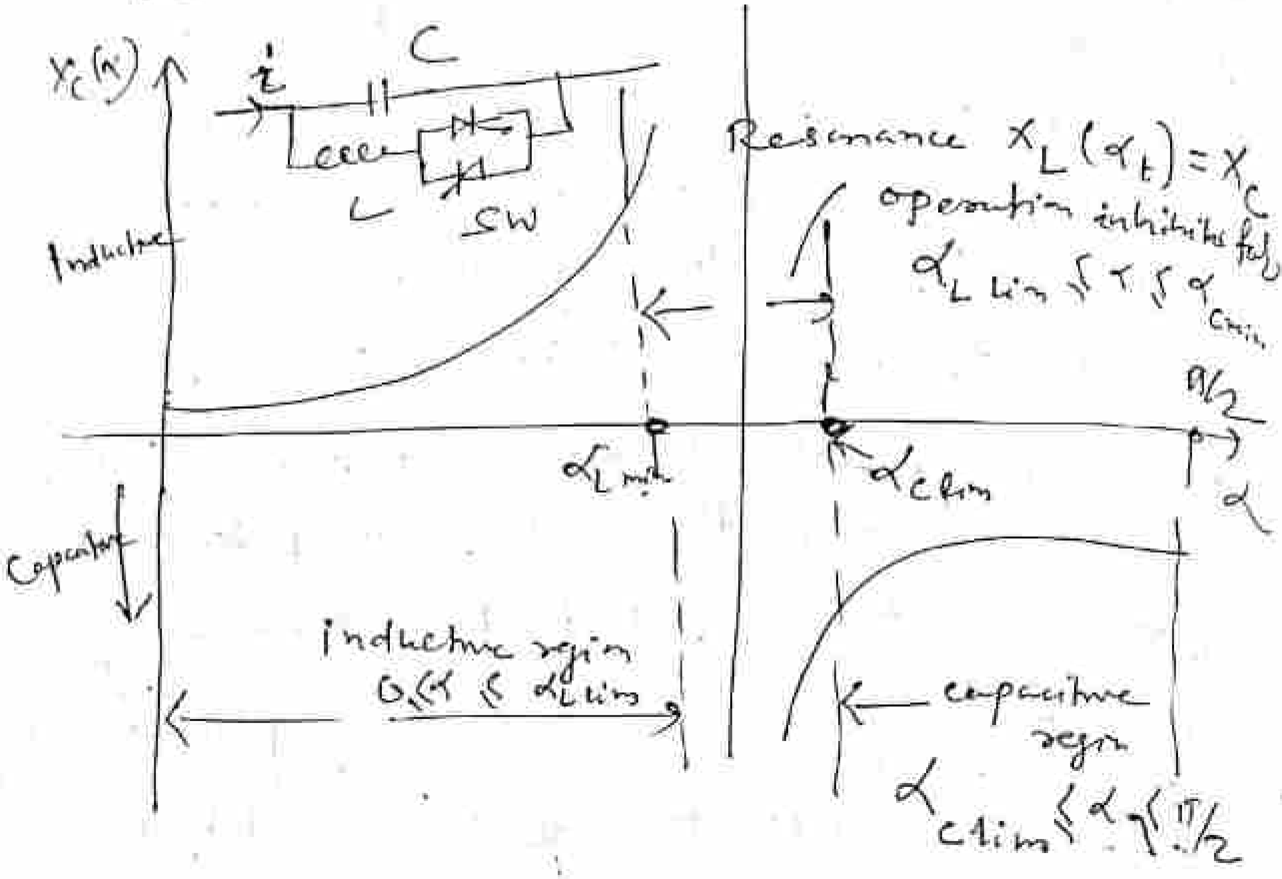
$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin\alpha}$$

$$X_L \leq X_L(\alpha) < \infty$$

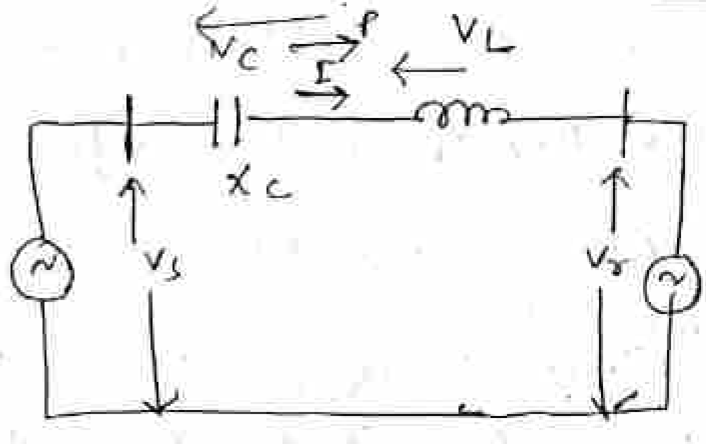
$= \omega L$ and α is the delay angle measured from the crest of the capacitor voltage, the zero crossing of line current.

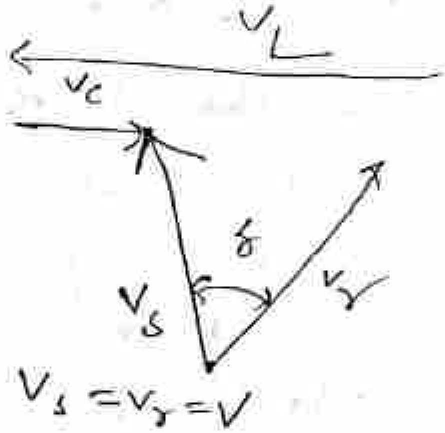
The impedance of the controlled reactor $X_L(\alpha)$ is varied from its maximum toward its minimum (ωL), the TCSC increases its minimum capacitive impedance, $X_{TCSC,min} = X_C = \frac{1}{\omega C}$ until parallel resonance at $X_C = X_L(\alpha)$ is established and $X_{TCSC,max}$ theoritically becomes infinite. Decreasing $X_L(\alpha)$ further, the impedance of the TCSC, $X_{TSC}(\alpha)$ becomes inductive, reaching its minimum value of $\left(\frac{X_L X_C}{X_L - X_C}\right)$ at $\alpha = 0$, where the capacitor is in effect bypassed by the TCR. Therefore, with usual TCSG arrangement in which the impedance of the TCR reactor, X_L, is smaller than that of the capacitor X_C, the TCSC has has two operating range around its internal circuit resonance one is $\alpha_{Clim} \leq \alpha \leq \pi/2$ range, where $X_{TSC}(\alpha)$ is capacitive, the other is the $0 \leq \alpha \leq \alpha_{Llim}$ range where $X_{TCSC}(\alpha)$ is inductive

The steady state model of the TCSC described above is based on the characterstic of the TCR established in an SVC environment, where the TCR is is supplied from a constant voltage source.



Static Synchronous Series compensator (SSSC





The basic operating principle of the SSSC can be explained with reference to the conventional series capacitive compensation. The phasor diagram clearly shows that at a given line current the voltage across the series capacitor forces the opposite polarity voltage ~~source~~ across series line reactance to increase by the magnitude of the capacitor voltage. Series capacitive compensation works by increasing the voltage across the impedance of the given physical line, which in turn increase the line current and the transmitted power.

$$V_s = V_c = -jX_c I = -jKXI$$

V_c = injected compensating voltage Phasor, I is the line current, X_c is the ~~[illegible]~~ reactance of the series capacitor, X is the line reactance $K = \frac{X_c}{X}$ is the degree of series compensation and $j = \sqrt{-1}$

output voltage ~~source~~ of the synchronous voltage source a function of line current

However, the contrast to the real series capacitor, the SVS is able to maintain to constant compensating voltage in the presence of variable line current, or control the amplitude of injected compensating voltage independent of amplitude line current.

→ For normal capacitive compensating output voltage lags the line current by 90°. For SVS; the o/p voltage

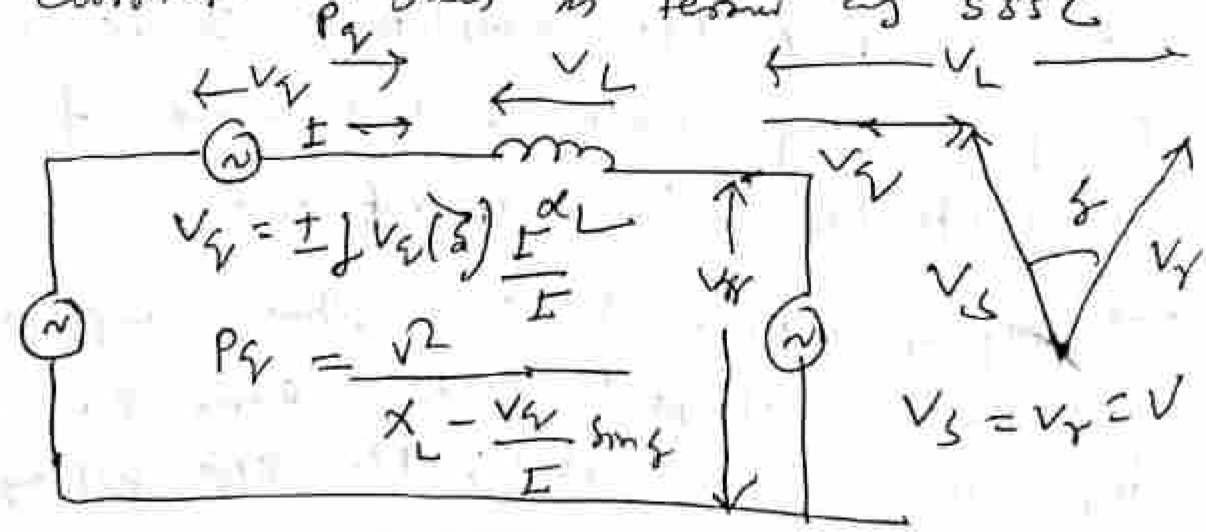
Can be reversal by simple control action to make it lead or lag the line current by 90°. In this case, the injected voltage decreases the voltage across the inductive line impedance and series compensation has the same effect as if the reactive line impedance was increased.

$$V_q = \pm j\, v_q(\zeta) \frac{I}{I}$$

The generalised expression of injected voltage V_q, can simple

~~$V_q =$~~

$v_q(\zeta)$ = magnitude of injected voltage ($0 \le v_q(\zeta) \le V_{q\max}$) and ζ is chosen control parameter. The series reactive compensation scheme using a switching power converter (Voltage source converter) as a synchronous voltage source to produce controllable voltage in quadrature with line current. This is termed as SSSC



$$V_q = \pm j\, v_q(\zeta) \frac{I}{I} \angle \alpha_L$$

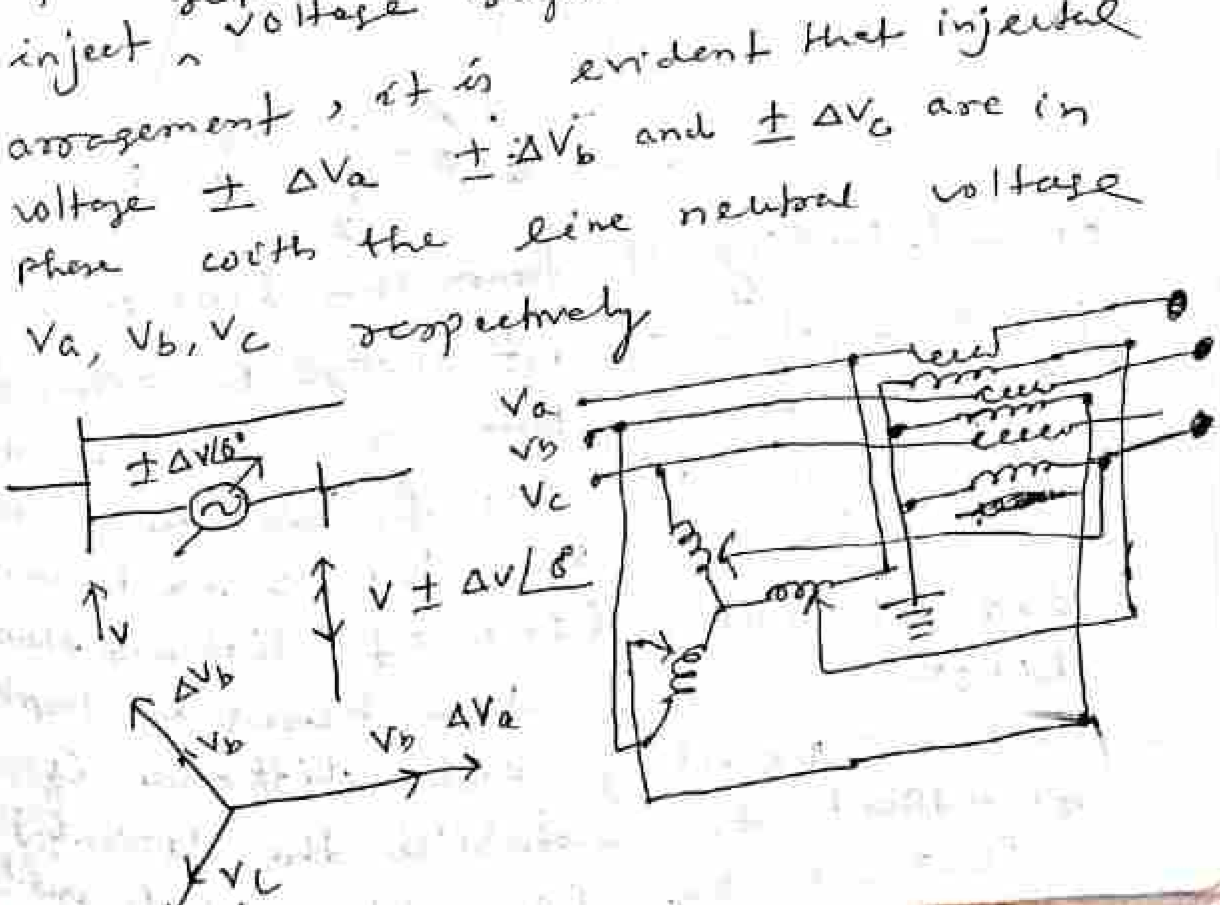
$$P_q = \frac{V^2}{X_L - \frac{V_q}{I} \sin\zeta}$$

$V_s = V_r = V$

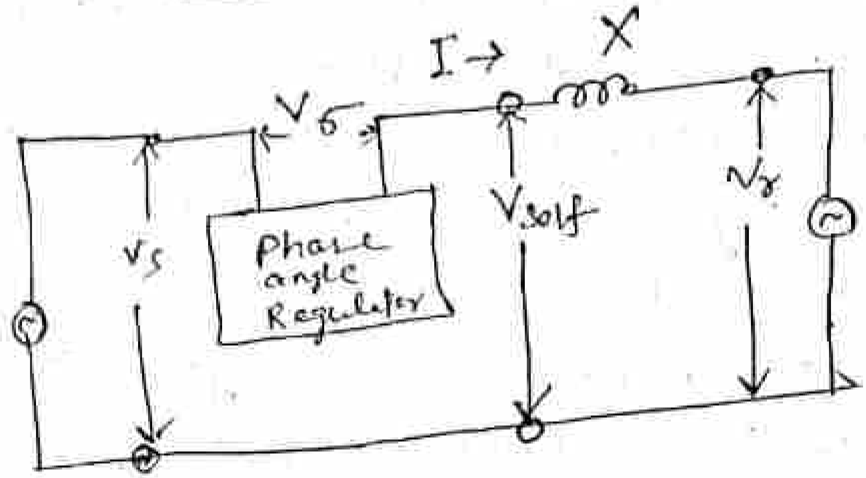
Voltage and phase angle Regulation

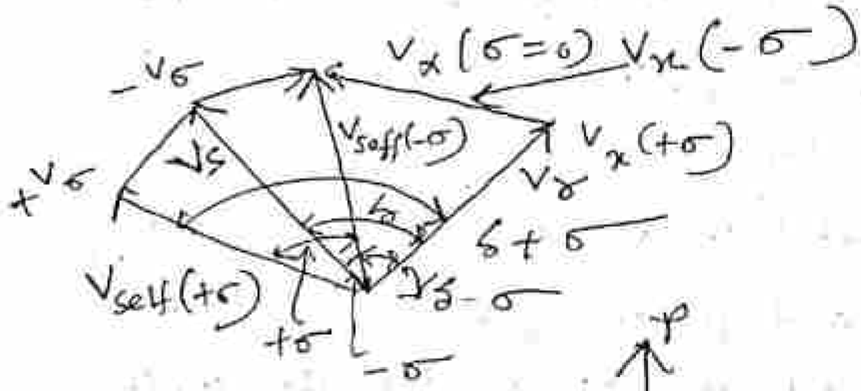
The basic concept of voltage and phase angle regulation in the addition of an appropriate in phase or a quadrature component to the prevailing terminal (bus) voltage in order to chang its magnitude or angle to the value specified. voltage regulation is theoritically achieved by a synchronous, in phase with voltage source with controllable amplitude ± ΔV in series with ac system

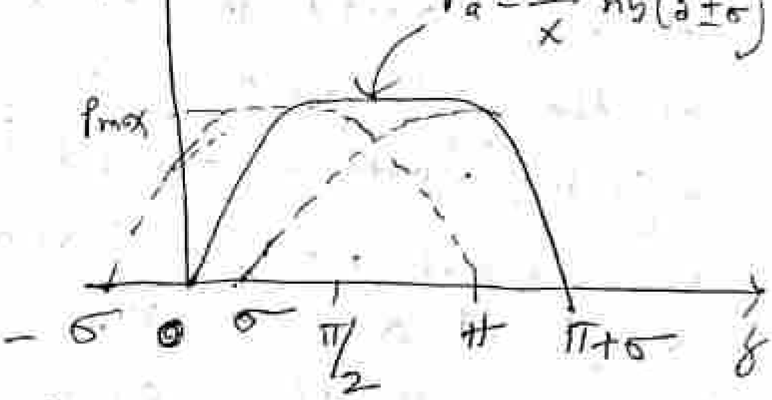
→ An adjustable voltage is provided by means of a tap changer from a three phase auto transformer for the primary of the series insertion transformer which inject required voltage regulation. From this arrangement, it is evident that injected voltage $\pm \Delta V_a$ $\pm \Delta V_b$ and $\pm \Delta V_c$ are in phase with the line neutral voltage V_a, V_b, V_c respectively



Power flow control by phase Angle Regulator.







optimal loading of transmission line in practical power system can not always be achieved at the prevailing transmission angle. Such cases could occur, for example, when power between two buses is transmitted over parallel line of different electric length or when two buses are inserted whose prevailing angle difference is insufficient to establish the desired power flow, In this case phase angle regulator is applied.

- This basic concept of phase angle regulation is represented in terms of two machine model in which phase angle regulator is inserted between sending end generator and transmission line. Phase angle regulator is considered as ac voltage source with controllable ~~voltage~~ amplitude and phase angle.

The effective sending end voltage Vself becomes the sum of the prevailing sending end bus voltage V_s and the voltage V_σ provided by PAR, from the ideal phase angle regulator, the angle of phasor V_σ relative to the phasor V_s is stipulated to vary with σ so that angular change does not result in magnitude change.

$$V_{self} = V_s + \sigma$$

$$|V_{self}| = |V_s| = V_{self} = V_s = V$$

- The basic idea behind the independent angle regulation is to keep the transmitted power at the desired level independent of the prevailing transmission angle δ.

→ Power can be kept at its peak value after angle δ exceeds π/2 by controlling the amplitude of quadrature voltage V_σ so that effective phase (δ−σ) between the sending and receiving end voltage stays at π/2. In this way actual power, so may be increased significantly. With phase angle ~~regulator~~ control arrangement, the effective phase angle between the sending end and receiving end voltage becomes (δ−σ), and with this transmitted power P and the reactive power demands at the ends of the line can simply be expressed as follows.

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

$$Q = \frac{V^2}{X} \left(1 - \cos(\delta - \sigma)\right)$$

In PAR does not increase the transmittable power at its maximum value at any angle δ in the range $\pi/2 < \delta < \pi/2 + \sigma$, in effect shifting the P versus δ curve to the right. It should be noted that P versus δ curve can also be shifted to the left by inserting the voltage of the angle regulator with opposite polarity. In this way, the power transfer can be increased and the maximum power reached at a generating angle less than $\pi/2$ $(\delta = \pi/2 - \sigma)$

If the angle of phasor V_σ relative to phasor V_s is stipulated to be fixed at ± 90°, the phase angle regulator becomes a quadrature Booster (QB) with

$$V_{seff} = V_s + V_\sigma$$

$$|V_{seff}| = V_{seff} = \sqrt{V^2 + V_\sigma^2}$$

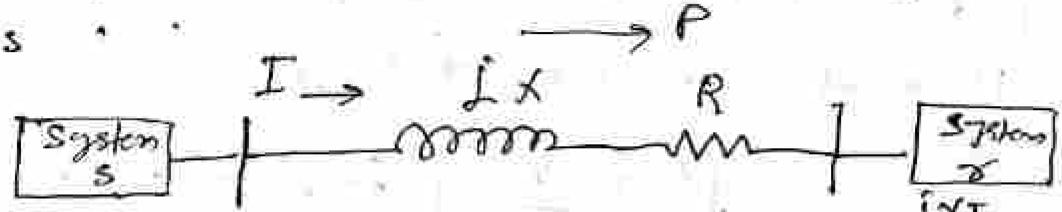
For a quadrature Booster type angle regulator the transmitted power P can be expressed in the following form

$$P = \frac{V^2}{X}\left(\sin\delta + \frac{V_\sigma}{V}\cos\delta\right)$$

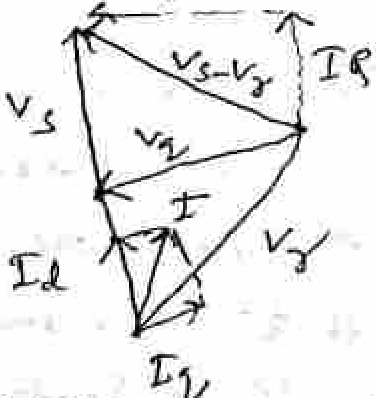
The transmitted power P versus angle δ as a parametric function of the injected quadrature voltage V_σ. It can be observed that the maximum transmittable power increases with injected voltage V_σ, since, in contrast to the proper phase angle regulator, the Quadrature booster increases the magnitude of the effective ~~voltage~~ sending end voltage.

Real and Reactive loop power flow control.

Consider two power system 's' and r connected by a single transmission with reactance X and resistance R. The transmission of power p from 's' to 'r' results in difference in magnitude between the terminal voltage V_s and V_r and also a shift in phase angle. vector difference $V_t = V_s - V_r$ appears across the transmission line impedance $Z = R + jX$, resulting in the line current I. phase V_t is normally considered to be composed of the resistive and inductive voltage drop IR and jIX. For the present consideration of loop power flow it is more meaningful to decomposes V_t into two component, one in phase and other in quadrature with the sending end voltage V_s.



$$V_d = I_d R + j I_q X$$
$$V_q = I_q R + j I_d X$$



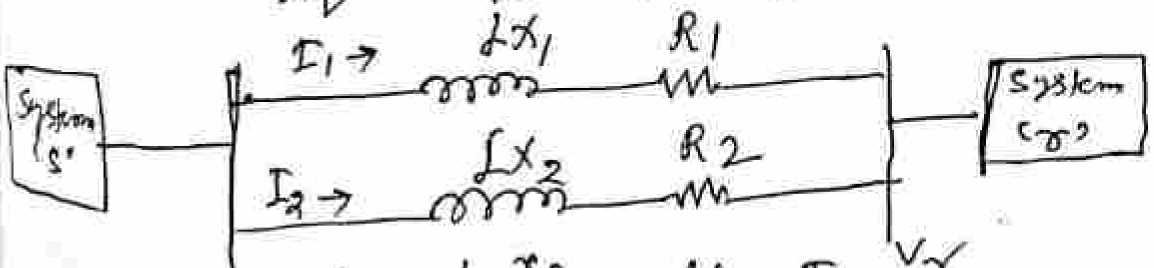
In practice, power systems are normally connected by two or more parallel transmission lines, resulting in one ~~or~~ or more circuit loops with the potential for circulating current flow; Basic circuit consideration indicate that if the $\frac{X}{R}$ ratio for the two line are not equal. If $\frac{X_1}{R_1} \neq \frac{X_2}{R_2}$ then circulating current will flow through the two line. Assuming such an inequality for the two $\frac{X}{R}$ ratio and decomposing both line currents I_1 and I_2 into an in phase and quadrature component with respect to the sending end voltage V_s, then the corresponding in phase and quadrature voltage components for the line V_{1d}, V_{1q} and V_{2d}, V_{2q} can be expressed with circuit resistance and reactance R_1, R_2 and X_1, X_2 the line current component I_{1d}, I_{1q} and I_{2d}, I_{2q} and with the similar component of the assumed circulating current I_{cd} and I_{cq}.

$$V_{1d} = (I_{1d} + I_{cd})R + j(I_{1q} + I_{cq})X_1$$

$$V_{1q} = (I_{1q} + I_{cq})R_1 + j(I_{1d} + I_{cd})X_1$$

$$V_{2d} = (I_{2d} - I_{cd})R_2 + j(I_{2q} - I_{cq})X_2$$

$$V_{2q} = (I_{2q} - I_{cq})R_2 + j(I_{2d} - I_{cd})X_2$$



$\frac{X_1}{R_1} \neq \frac{X_2}{R_2}$ then $I_c \neq 0$