Date 21/9/15

(1)

UNIT-VI

V - 1) objectives of facts controllers in a ps n/w
VI - 2) Explain about midpoint regulation in
VII - 3) Explain a... objectives of shunt controller
VIII - 4) Explain about UPFC

objectives of series compensation

Shunt compensation

Objectives of shunt compensation
- ***Im power transfer
- power oscillation damping
- Improvement of SSSL & TSSL

Static VAR compensators
- TCR *Im
- TSC

Comparision between SVC & STATCOM

* Static shunt compensation:-

A shunt reactor (or) capacitor is used for shunt compensation.

Objectives:-

(i) To improve v/g profile.
(ii) *Im To increase power transfer.
(iii) To improve steady state (power transfer) & transient state stability (reduce of power oscillation damping)
(iv) To improve voltage stability on radial lines.
(v) To control reactive power over lines in a large system to reduce power losses.

Methods of controllable VAR Generation
- midpoint v/g regulation
- SVC

STAT com

Variable impedance type → SVC → TCR+TSC

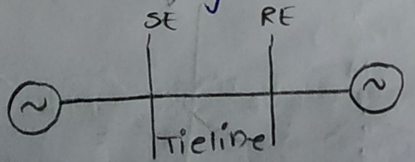
* Midpoint v/g regulation (MPVR):-

Advantages:-

(i) Better v/g profile (improving)
(ii) Increased power transfer
(iii) To damp power oscillations
(iv) Increase in transient state stability & steady state stability limits.

reactors (R)
capacitor (C)

(v)



SE - Sending End
RE - Receiving End.

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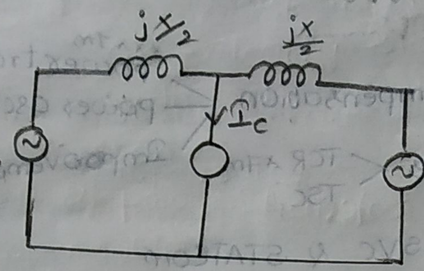
① Better v/g profile:-

Improvement of v/g - reactor, power transfer, capacitor

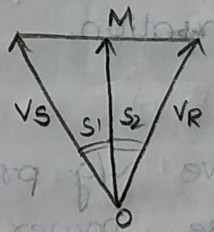
(2)

According to midpoint v/g



(Resistance is neglected)

The phasor diagram without compensation is shown in figure.



Phasor diagram (without compensation)

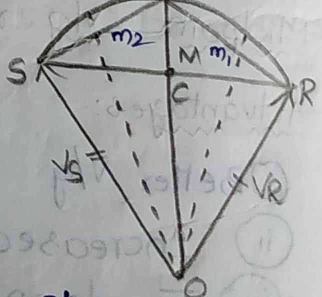
let $|V_s| = |V_r| = V$

where

OM gives the minimum v/g on the line at the midpoint.

let a shunt compensator be located at midpoint & is so controlled that the v/g there is maintained constant at $|V_s| = |V_r| = V$.

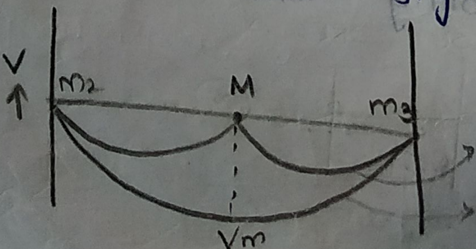
Reactor is used as compensating element in midpoint v/g regulation.



Phasor diagram with compensator

ΔOSC and ΔORC are isosceles & concurrent.

minimum v/g occurs at $\frac{1}{4}$th & $\frac{3}{4}$th of the line i.e OM_2 & OM_3 as shown in fig.



→ without shunt compensator

→ Flat v/g profile with shunt compensator

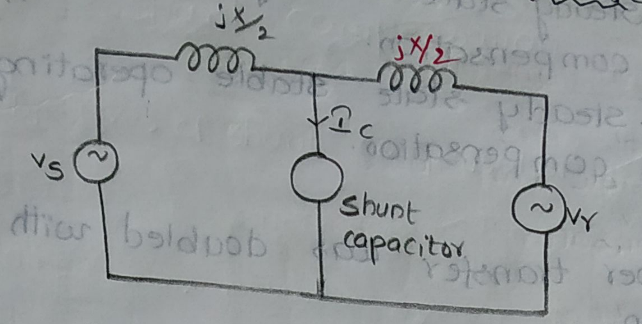
OM_2 & OM_3 are greater than minimum v/g V_m without shunt compensator.

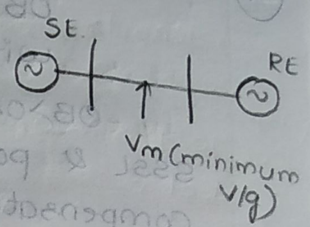
Flat v/g profile (or) better v/g profile is obtained using shunt

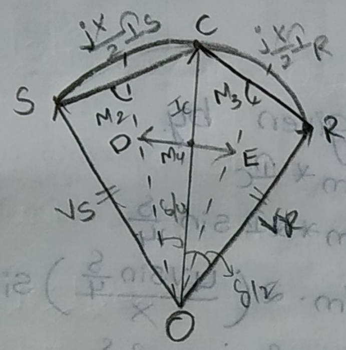
***Imp

3

(ii) Improvement of power transfer (SSSL)







For power transfer capacitor is used as compensating element I_c loads V_m by $90°$ due to capacitor as compensating device Δ'les OSC & ORC are isosceless & concurrent.

Min v/g is wrt M_2 on M_3 so the angles shifted from $\frac{\delta}{2}$ to $\frac{\delta}{4}$.

$$P = P_s = V_s I_s \cos\frac{\delta}{4}$$

(same every where)

substituting this value in

$$P = V_s I_s \cos\frac{\delta}{4} \text{ we get}$$

$$P = \frac{4V^2}{X}\sin\frac{\delta}{4}\cos\frac{\delta}{4} \doteq \frac{2V^2}{X}\sin\frac{\delta}{2}$$

In $\Delta ODE = I_s = I_r = I$

$$\underset{SE}{P = VI\cos\phi} = \underset{RE}{\frac{V^2}{X}\sin\delta}$$

M_4 is a mid point, $\frac{I_c}{2} = I\sin\frac{\delta}{4}$

Necessary for compensation $\boxed{I_c = 2I\sin\frac{\delta}{4}}$

In ΔOSC, $SM_2 = V_s\sin\frac{\delta}{4} = \frac{X}{4}I_s$

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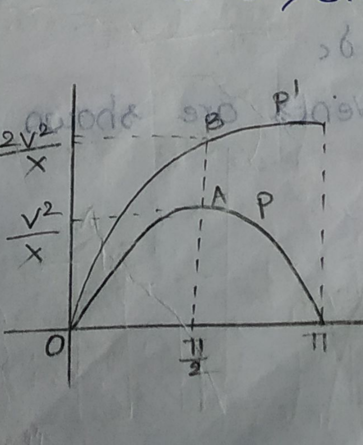


OA – Steady state stability region without compensation.

OB – Steady state stable operating region with compensation.

OB > OA

SSSL & power transfer was doubled with compensation.

Rating of compensation is given by

$$Q_{compensation} = V_m * I_C$$

V_m = minimum v/g that occurs at mid point

$$= V_m * 2I \sin\frac{\delta}{4}$$

$$= V_m \cdot 2\left(\frac{4V\sin\frac{\delta}{4}}{X}\right)\sin\frac{\delta}{4}$$

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

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

* Improvement of transient state stability limit (TSSL) (equal area criterian).

Without midpoint v/g regulation, $P = \frac{V^2}{X}\sin\delta$ —(1)

with midpoint V/g regulation, $P' = \frac{2V^2}{X}\sin\frac{\delta}{2}$ —(2)

let the system be operating with an initial power of P_0

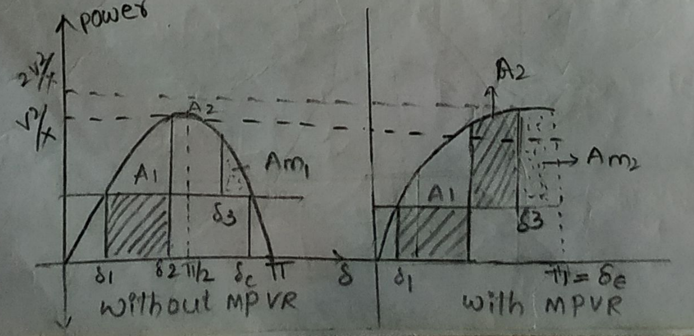
let an short circuit fault occur which makes power transfer zero.

let the fault be cleared after a delay time given by an δ_c

These events are shown in the following

2 causes.

power angle curves → swing curve → TSSL



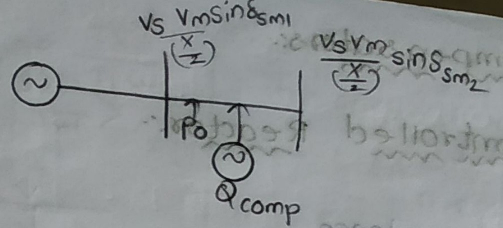
A1 = accelerating area

A2 = deaccelerating area

$A_{m_2} > A_{m_1}$

TSSL is improved

(5)



fault clearingtime is less when compared to without
↑ Area is more.

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Power Oscillation damping:-

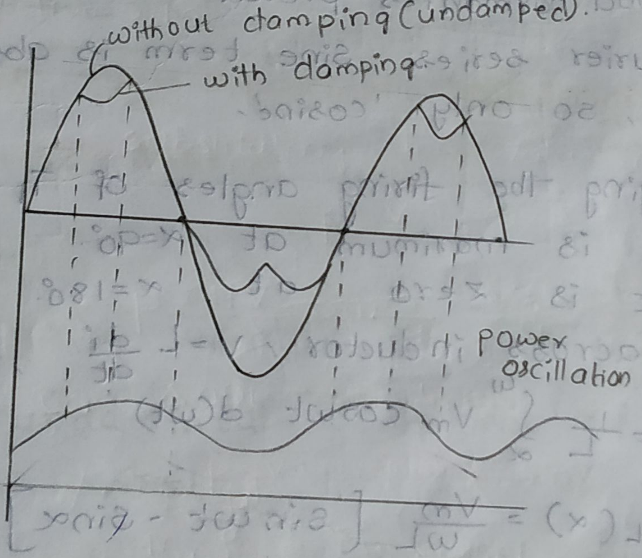
System is stable, $P_0 = P_i$

$P_i \rightarrow (\sim) \rightarrow P_0$

Due to disturbance let 'p' falls temporarily.

$P_0 < P_i$ ~ The machine accelerator, δ increases.
$\frac{d\delta}{dt} > 0$, power increases.

$P_0 > P_i$ ~ The machine deaccelerates, δ decreases & power reduces.



$P_0 < P_i$ → During accelerating period shunt compensator (reactor) absorb leading reactive power so that V_m increases & hence P_0 increases. This reduces the rate of δ & so the rate of increase of power.

$P_0 > P_i$ → During deaccelerating period, shunt compensator (capacitor) absorbs lagging reactive power. so V_m decrease & hence P_0 reduces like this oscillation of power & δ are damped.

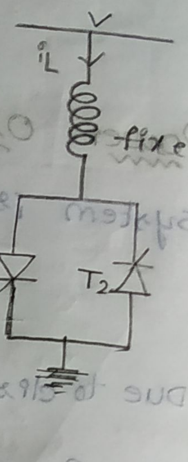
** Vimp.

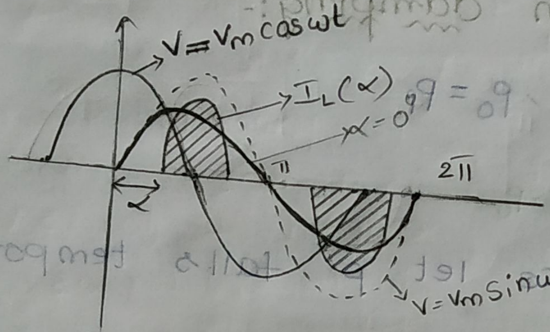
(6) Static VAR compensators:.

** 14m

(1) Thyristor controlled Reactor:. < TCR < Imp / TSC Cap - FC-TCR

It is a variable impedance type compensator.





$V = V_m \sin(90° - \omega t)$ lagging nature

$V = V_m \cos \omega t$.

- only odd harmonics present. (AC)
- In fourier series sine term is absent for n=odd, so only 'cosine'.

By varying the firing angles of T_1 & T_2 reactor current is maximum at $\alpha = 90°$.
current is zero at $\alpha = 180°$.

vlg across inductor, $V = L\frac{di}{dt}$, $i_L = \frac{1}{L}\int v\,dt$

$$= \frac{1}{L}\int_{\alpha}^{\omega} V_m \cos\omega t \; d(\omega t)$$

$$i_L(\alpha) = \frac{V_m}{\omega L}\left[\sin\omega t - \sin\alpha\right]$$

(1) $b_1 = \frac{2}{\pi}\int f(t)\sin n\omega t \; d(\omega t)$

$$= \frac{2}{\pi}\int_{\alpha}^{\pi-\alpha} \frac{V_m}{\omega L}(\sin\theta - \sin\alpha)\sin\theta \, d\theta \quad (\because \omega t = \theta)$$

$$= \frac{2V_m}{\pi\omega L}\int_{\alpha}^{\pi-\alpha}(\sin^2\theta - \sin\theta\sin\alpha)\,d\theta$$

$$= \frac{2V_m}{\pi\omega L}\int_{\alpha}^{\pi-\alpha}\left(\frac{1-\cos 2\theta}{2}\right)d\theta - \int_{\alpha}^{\pi-\alpha}\sin\theta\sin\alpha\,d\theta$$

$$= \frac{2V_m}{\pi\omega L}\left(\frac{1}{2}(\theta)_{\alpha}^{\pi-\alpha} - \left(\frac{\sin 2\theta}{4}\right)_{\alpha}^{\pi-\alpha} - \sin\alpha(-\cos\theta)\right.$$

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$$= \frac{2V_m}{\pi \omega L}\left[\frac{1}{2}(\pi-\alpha-\alpha) - \left(\frac{\sin 2(\pi-\alpha)}{4} - \frac{\sin 2\alpha}{4}\right)\right.$$

$$\left. - \sin\alpha\left[-\cos(\pi-\alpha) + \cos\alpha\right]\right]$$

$$= \frac{2V_m}{\pi \omega L}\left[\frac{1}{2}(\pi-2\alpha) - \frac{\sin(2\pi-2\alpha)}{4} + \frac{\sin 2\alpha}{4}\right.$$

$$\left. - \sin\alpha\left(\cos\alpha + \cos\alpha\right)\right]$$

$$b_1 = \frac{2V_m}{\pi\omega L}\left[\frac{\pi}{2} - \alpha - 2\sin\alpha\cos\alpha + \frac{2\sin 2\alpha}{4}\right]$$

$$= \frac{2V_m}{\pi\omega L}\left[\left(\frac{\pi-2\alpha}{2}\right) - \sin 2\alpha + \frac{\sin 2\alpha}{2}\right]$$

$$= \frac{2V_m}{\pi\omega L}\left[\frac{\pi-2\alpha}{2} - \frac{\sin 2\alpha}{2}\right]$$

$$\boxed{b_1 = \frac{V_m}{\omega L}\left(1 - \frac{2\alpha}{\pi} - \frac{\sin 2\alpha}{\pi}\right)}$$

By changing firing angle to control reactor current.

Reactor current

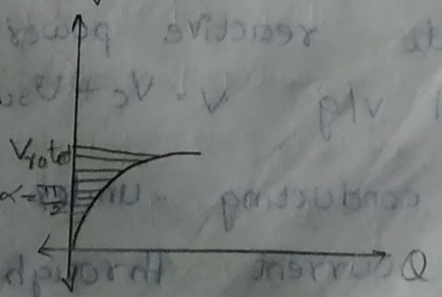
$$i_L = b_1 \sin\omega t$$

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

Fundamental component of harmonic reactor current.

I_q = quadrature current $= I_{LF}(\alpha) - I_C$

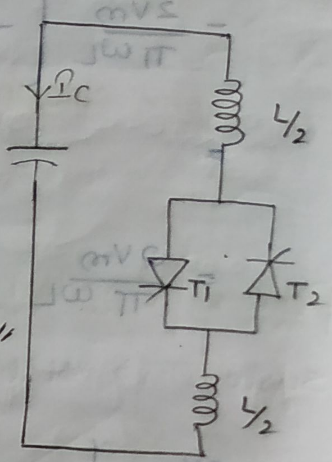
$$Q_C = I_Q V = V\left[I_{LF} - I_C\right]$$



V–Q characteristics.

(Impedance control by using current)

(8) FC-TCR provides compensation for both Inductive & Capacitive elements.



FC-TCR.

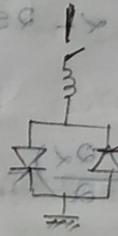
$I_C = B_C V$

$I_L = B_{LF(\alpha)} V$

$\left[B_{LF(\alpha)} = \frac{1}{\omega L}\left[1 - \frac{2\alpha}{\pi} - \frac{\sin 2\alpha}{\pi}\right] \right]$

$B = \frac{1}{X}$

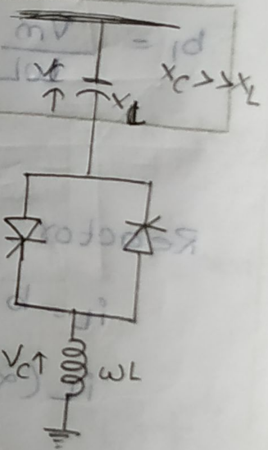
Thyristor switched reactor

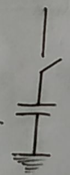


26/9/15 *** Imp

* Thyristor switched capacitor (TSC)

Thyristor switching is faster than mechanical switching.





TSC (mechanical) ← C

- capacitor 'C' will be either in the ckt (or) out of the ckt.

$V = \frac{1}{C}\int i\,dt$.

- TCR & TSC are used to overcome surges.

They provide over current protection.

Here X_L is used to damp surges but not to compensate reactive power

Total v/g $V = V_C + V_{sw} + V_L$

T_1 & T_2 conducting, under steady state conditions, the current through E is obtained as follows.

let $V = V_m \sin\omega t$, $i = C\frac{dv}{dt}$

(9)

current through $C = \frac{V_m}{X_C - X_L} \cos\omega t$ $(\because X_C >> X_L)$

$C = \frac{1}{X_L}$

$$= \frac{V_m}{X_C\left[1 - \frac{X_L}{X_C}\right]} \cos\omega t$$

$$= \frac{V_m}{X_C\left[1 - \frac{1}{n^2}\right]\cos\omega t}$$

degree of compensation

$$\therefore I = \frac{n^2}{n^2-1} \frac{V_m}{X_C} \cos\omega t \qquad \left(\because \sqrt{\frac{X_C}{X_L}} = n\right)$$

V/g across the inductor 'L'

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

$$V_L = L\left(\frac{n^2}{n^2-1} \frac{V_m}{X_C} \cos\omega t\right] \frac{d}{dt}$$

$$= L \frac{V_m}{X_C} \frac{n^2}{n^2-1} (-\sin\omega t)\omega$$

$$= -\omega L \frac{n^2}{n^2-1} \frac{V_m}{X_C} \sin\omega t$$

$$= -\left(\frac{X_L}{X_C}\right) \frac{n^2}{n^2-1} V_m \sin\omega t$$

$$= -\frac{n^2}{n^2-1} \cdot \frac{1}{n^2} V_m \sin\omega t$$

$$V_L = \frac{-1}{n^2-1} V_m \sin\omega t$$

$$Q_C = V I_C = \frac{V^2}{X_C}$$

For transient free operation

$V = V_C$

Drawback:

1. Design parameter n must be designed where it is not require in case of TCR.
2. Cost of TSC is more than TCR.
3. Delta connection of 3 single phase TCR's eliminates Tripplen harmonics.

... parallel ... d

due to charging and discharging of capacitor.

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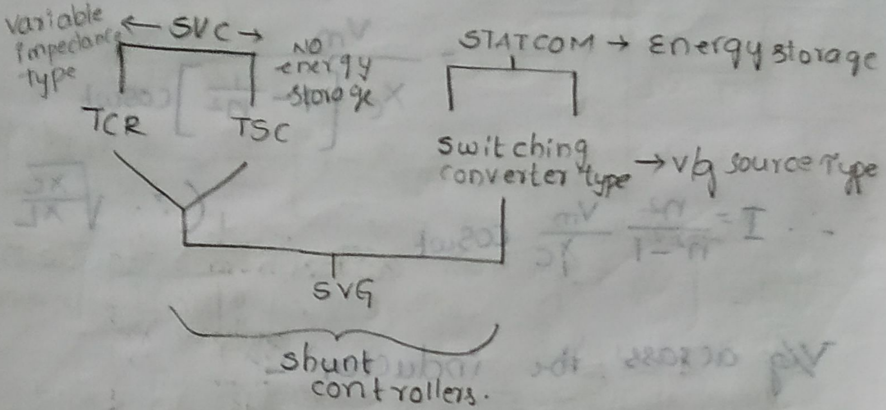
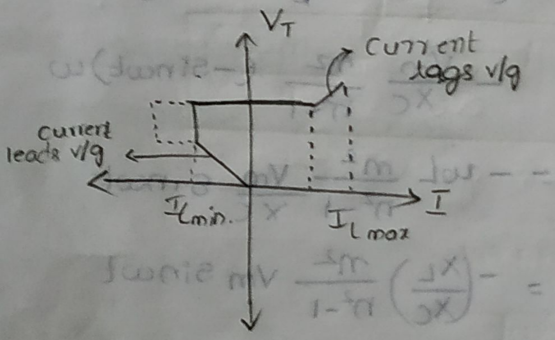
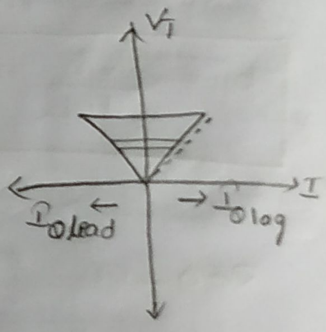
(10) Comparision between SVC and STATCOM:



1) V-I characteristics:- real power



STATCOM



SVC

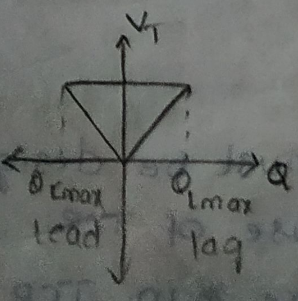
In STATCom, max current will not reduce with v/g.

In SVC max current reduces linearly with the v/g drooping characteristics for SVC.

2) V-Q characteristics:-

$Q \propto V$

$Q = V I_C$

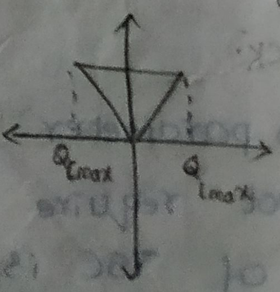


STATCOM

$Q \propto V^2$

$Q = VI$

$= \frac{V^2}{X}$



SVC

- linear Characteristics in STATCOM and exponential characteristics in SVC.
- Reduction of v/g in results in reduction of Q in STATCOM

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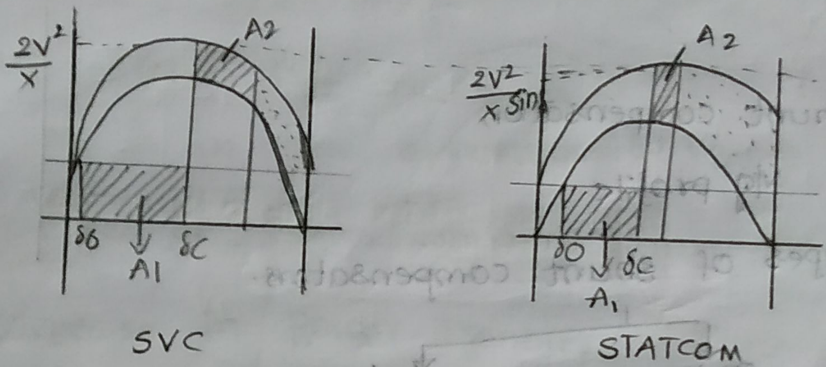
3) Transient stability Enhancement :-



A_1 - Accelerating area
A_2 = Deaccelerating area.

- marginal area is more in STATCOM. δc is more for SVC. After post fault the area not affected by fault is more in STATCOM & the area in SVC is less.
- power carrying capability for STATCOM is more.

(4) Response time :- (ON (or) OFF w.r.t fault condition)

TCR & TSC → upto 2.5 m sec → ½ cycle
TCR → upto 5 msec → 1 cycle

STATCOM - 200 μsec - 350 μsec (Fast response).

(5) Operation with unbalanced v/g's.

STATCOM : o/p v/g will have negative sequence fundamental & a third harmonic v/g.
SVC : unbalanced v/g's, unequal compensating currents in lines.

(6) physical size:

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(12) STATCOM has only one capacitor occupies less space (30-90%) & low installation cost.

SVC requires bank of capacitors & reactors which are large in size & cost is more.

① shunt compensation

V/g profile

Types of shunt compensators.

→ STATCOM
V/g source/switching

→ SVC/Impedance type
TCR+TSC
TSR
SVS

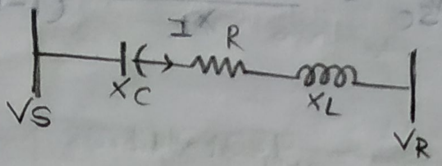
→ Comparision of STATCOM & SVC.

29/9/15 ①

UNIT - VII

Series Compensation

① objectives of series compensation



Net reactive drop $I(X_L - X_C)$

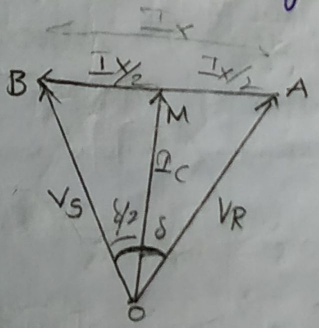
V_C is in phase opposition to V_R.

Objectives of Series compensation:-

(i) Increase in Power Transfer.
(ii) Improvement of steady state & transient state stabilities.
(iii) Improvement of v/g stability in radial lines.
(iv) power oscillation damping.

Improvement of power transfer:- (or) SSSL

The main objectives of series compensation is to decreased the overall effective series impedance from sending end to receiving end.



let $X_C = kX_L$

$k = \frac{X_C}{X_L}$

Degree of series compensation $(0 \le k \le 1)$

Then $X = (X_L - kX_L) = (1-k)X_L$

In $\triangle OAB$, $IX = 2BM = 2V\sin\frac{\delta}{2}$

$\Rightarrow I = \frac{2V}{X}\sin\frac{\delta}{2}$ — ①

power flow at sending end, $P_S = VI\cos\frac{\delta}{2} = V\cdot\frac{2V}{X}\sin\frac{\delta}{2}\cos\frac{\delta}{2}$

$= \frac{V^2}{X}\sin\delta = \frac{V^2}{(1-k)X_L}\sin\delta$ — ②

k=0 ~ uncompensated line

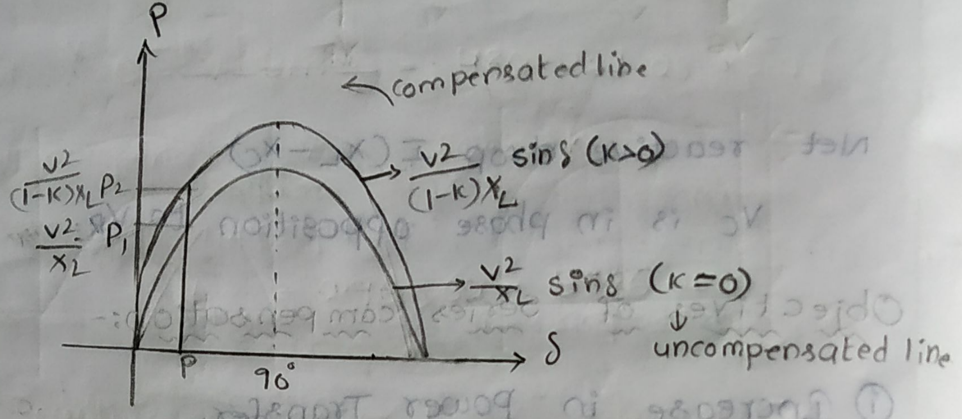
k<1 ~ compensated line

(2)

Reactive power, $Q_{SC} = I^2 X_C$

$$= \frac{4V^2 \sin^2\frac{\delta}{2}}{(X_L^2)(1-K)^2} K X_L$$

$$Q_{SC} = \frac{4V^2 \sin^2 \delta/2}{X_L} \frac{K}{(1-K)^2} \quad \text{---} (3)$$



$\alpha = \pi/2$

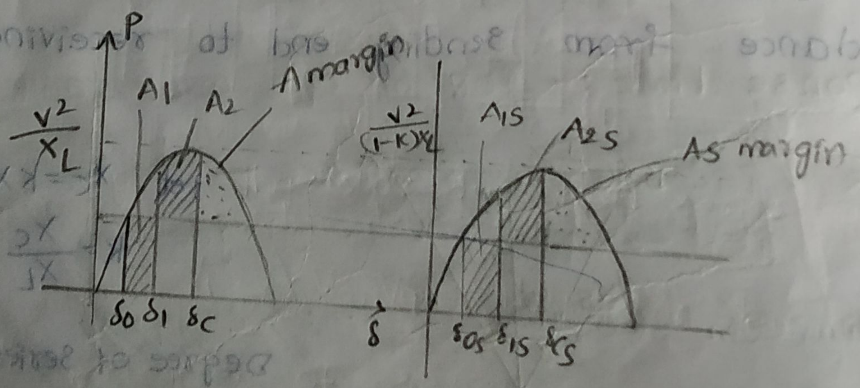
shunt = π

Increase in SSSL

- At any power angle δ power transfer is increased from $PP_1 - PP_2$
- Steady state stability is increased from $\frac{V^2}{X_L}$ to $\frac{V^2}{(1-K)X_L}$

1/10/15

- Enhancement of transient stability:- (iv) power angle curve

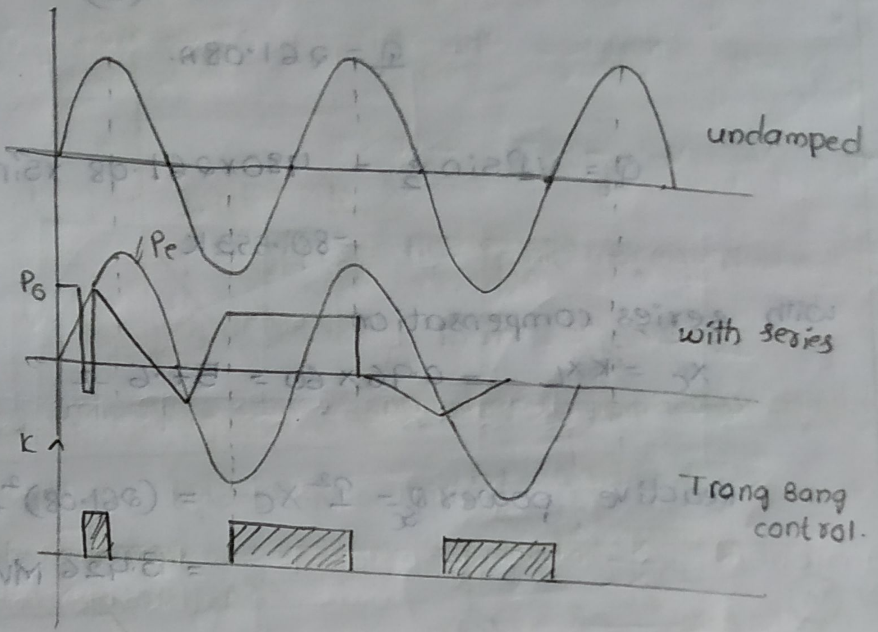


Margin area is more in case of series compensated line & hence transient stability is more.

- Power oscillation damping:-

$P_i - P_e = P_o$

③ By providing the series compensation during periods of acceleration, power oscillation can be damped.



① - For particulars of a series Compensation transmission line with TCSC (Thyristor control series capacitor).

$V = 480V$, $f = 60Hz$, $X_L = 60\Omega$, $P = 96kW$, $\delta = 80°$

The components of TSC are $C = 25\mu F$, $L = 40mH$

(i) Find degree of compensation.
(ii) Compensation of reactance.
(iii) Reactive power flow in the line.

Sol:

Given $V = 480V$, $f = 60Hz$, $X_L = 60\Omega$, $P = 96kW$

$\delta = 80°$

(i) $K = \frac{X_C}{X_L}$

$X_C = 2\pi f C$

$= 2\times\pi\times 60\times 25\times 10^{-6}$

$X_C = 9.247 m\Omega$

$P = VI\cos\frac{\delta}{2}$

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

$(1-K) = \frac{V^2}{PX_L}\sin\delta = \frac{(480)^2}{96\times10^3\times60}\times\sin(80)$

$1-K = 0.0393$

$K = 0.96$

(4)

$P = VI\cos\frac{\delta}{2} \Rightarrow 96\times10^3 = 480\times I \cos\left(\frac{80}{2}\right)$

$I = \frac{96\times10^3}{480\times\cos\left(\frac{80}{2}\right)}$

$I = 261.08A.$

$Q = VI\sin\frac{\delta}{2} = 480\times261.08 \times\sin\left(\frac{80}{2}\right.$

$= 80.553K$

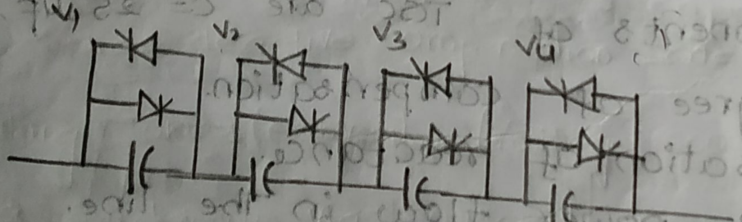
with series compensation

$X_C = KX_L = 0.96\times60 = 57.6\,\Omega$

Reactive power $Q_{SC} = I^2X_C = (261.08)^2 \times$

$= 3.926$ MVA

Variable Impedance type Series compensators:



Thyristor switched series capacitor (TSSC)

$V_1, V_2, V_3, V_4 \rightarrow$ Thyristor bidirectional switches

The degree of series compensation is controlled in a step like manner by increasing (or) decreasing the no. of series capacitors inserted.

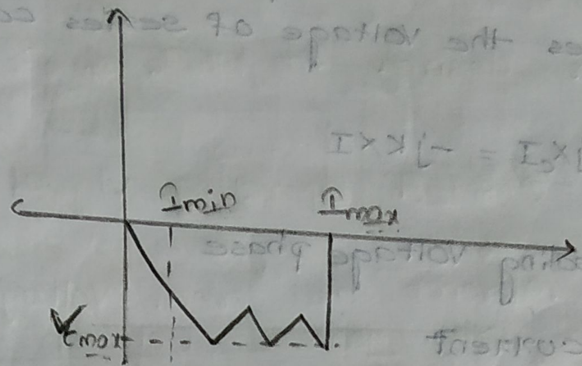
A capacitor is inserted by turning off and it is by passed by turning on the corresponding thyristor valve.

Time delay would be upto 1 cycle. This is called

5

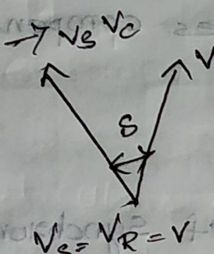
$$\frac{V_C}{I_{min}} = X_{TOTAL}$$

$$V_{C_{max}} = (X_{TOTAL})\, I_{min}$$

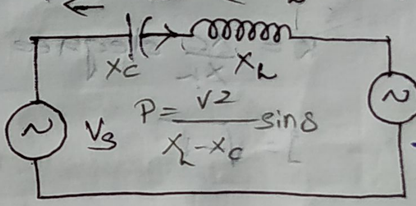


TWO Machine system with a series capacitor compensated line (Basic operation of SSSC)

I V_L V_q = quadrature



(phasor diagram)

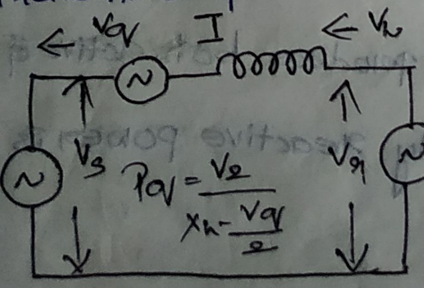


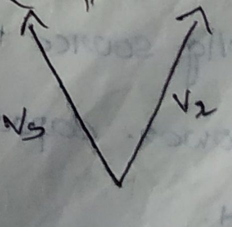
Equivalent ckt diagram with series capacitor

Two machine system

The phasor diagram shows that at a given the line currents, the v/g across the series capacitor forces the opposite polarity across the series line reactor to increase the magnitude of capacitor v/g.

Thus the series capacitor compensation works by increasing the v/g across the impedance of the given line, which inturn increases corresponding current & transmitted power.





Basic two machine systemwith synchronous V/o replacing the series capacitor

5) the steady state power transmission is same if it is a transferred by series compensation provided by a synchronous ~~so~~ ac voltage source, where o/p polarity matches the voltage of series capacitor.

I.e $V_q = V_c = -jX_c I = -jKXI$

Injected compensating voltage phase

I - line current

$X_c \rightarrow$ reactance of series capacitor.

X - line reactance

$K = \frac{X_c}{X_L}$ degree of series compensation.

$j = \sqrt{-1}$

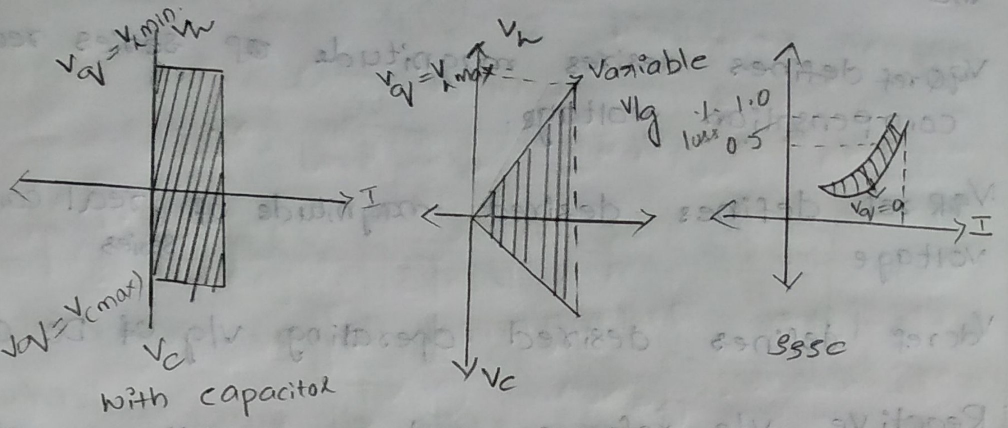
thus by making o/p voltage of synchronous v/g source a function of line current some compensation will be provided as a series capacitor.

the series reactive compensation scheme using a switching power converter (Voltage source converter) As a synchronous v/g source to produce controllable v/g in quadrature with line current. this termed as static synchronous series compensator transmitted power is

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

By using v/g source we can produce both active & reactive power. capacitor only reactive power is increased.

(7) Characteristics:-

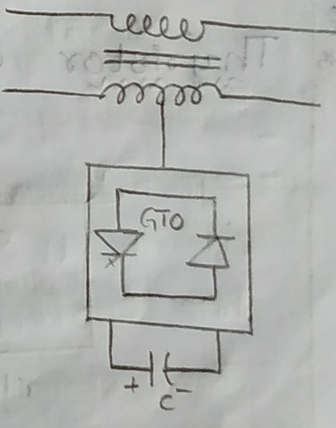


Imp
xxxx
7m
Explain SSSC & TCSC

10/15 Static synchronous series compensator (SSSC).

Definition:

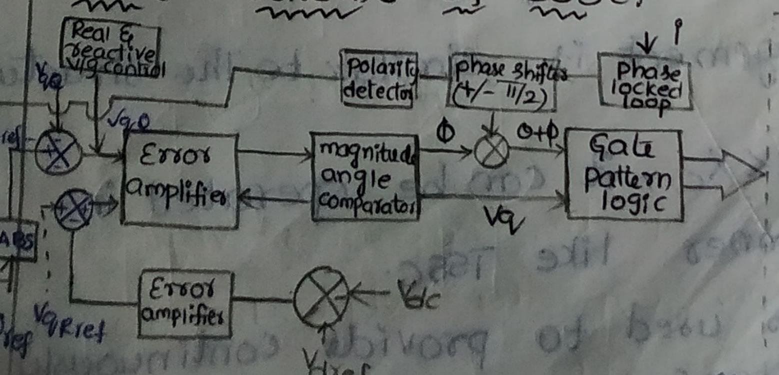
The function of series capacitor is to produce an appropriate v/g at the fundamental ac system frequency in quadrature with Transmission line current in order to increase the v/q across the inductive line impedance & thereby increase the line current & transmitter power.

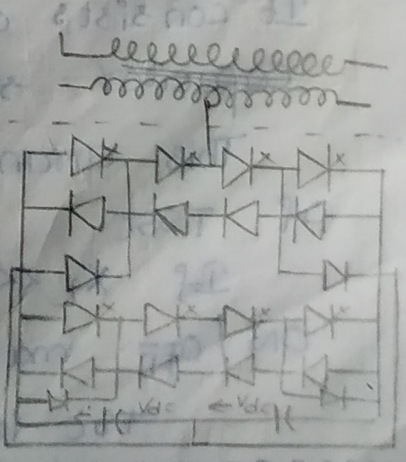


The v/g source converter based shunt compensator is STATCom.

The v/g source converter based series compensator is SSSC.

7m Control Scheme of SSSC:-





connected in parallel to eliminate harmonics

The control is operated from V_{qQ} ref, V_{qR} ref, V_{dc} ref

V_{qQ} ref defines desires magnitude of series reactive compensation voltage.

V_{qR} ref defines desired magnitude of real compensation voltage.
series

V_{dc} ref defines desired operating v/g of DC capacitor.

Reactive v/g reference and real voltage reference determines the real power between V_{dc} & V_q.

Magnitude of V_q & $\theta + \pi$ are used to generate gate drive signal for converter. $(V_q = V_{qQ} + V_{qR})$

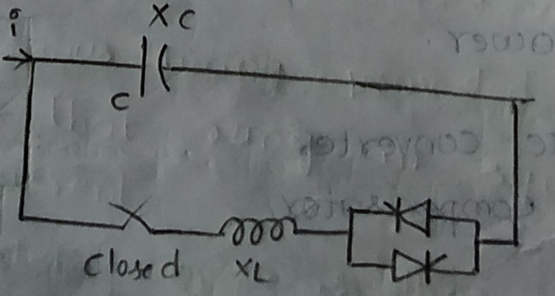
(+ reactive power (leading)
− real power (lagging))

V_q − synchronous voltage source in phase quadrature with the line current improves v/g across the series impedance line.

Im.

why it is used in transmission line & advantages

Thyristor controlled Series capacitor (TCSC):



It consists of a series compensating capacitor