line → injecte

19/8 Static Shunt Compensators - SVC & STATCOM.

Objectives

* SS Transmittable power along the line can be ↑
* Voltage profile can be controlled
* Purpose of reactive comp - to Δ natural elec. cha of the Tr line - compatible with load demand.

* r. Shunt connected
  - fixed (or) MS Reactors - minimise line over voltage under light load conditions.
  - fixed (or) MS C - maintain voltage levels under heavy load conditions.

* ultimate objective - to ↑ transmittable power.

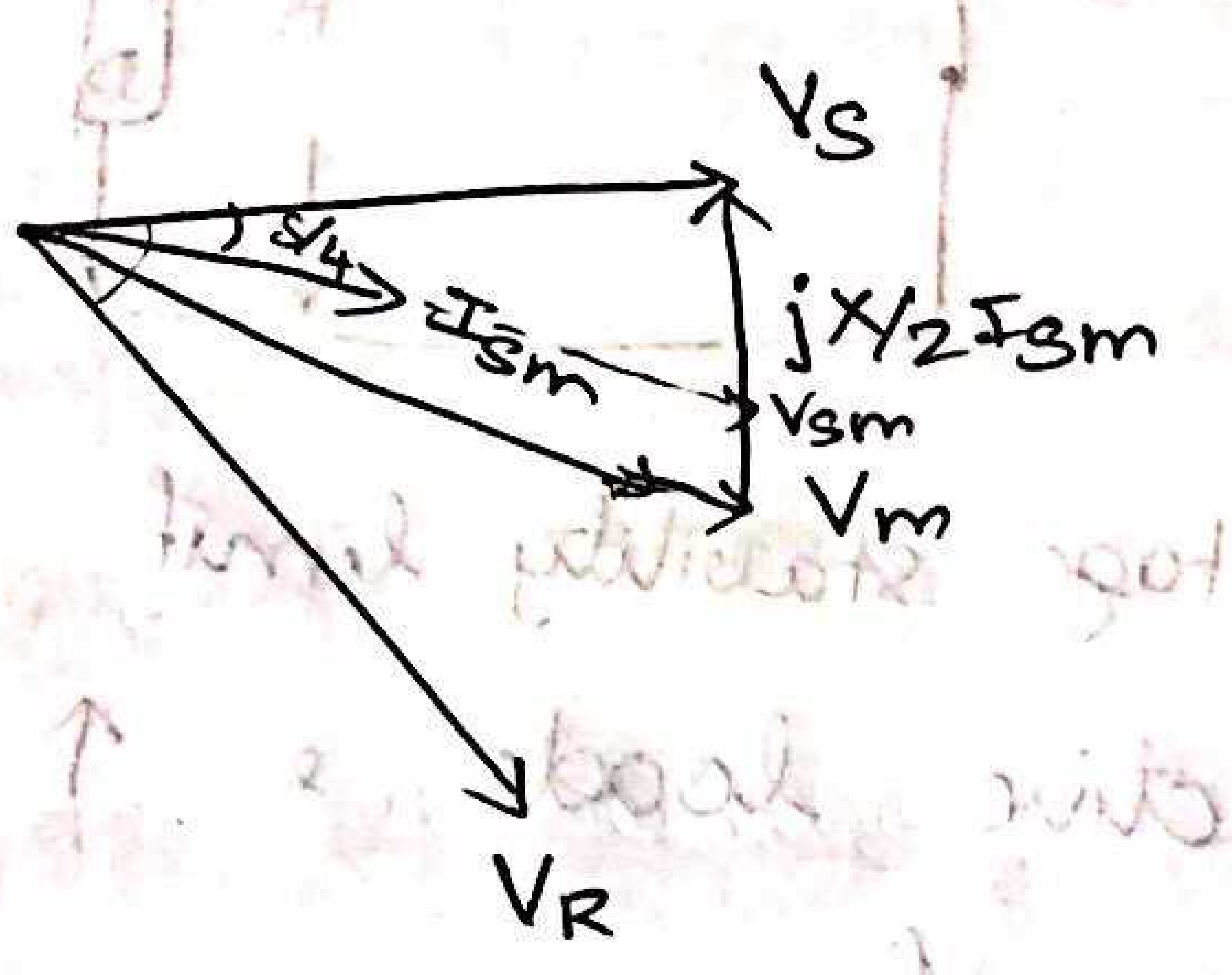
* Voltage regulation - at midpoint - end of the line - V instabil
* dynamic V control to ↑ transient stability + damp powe oscillations.

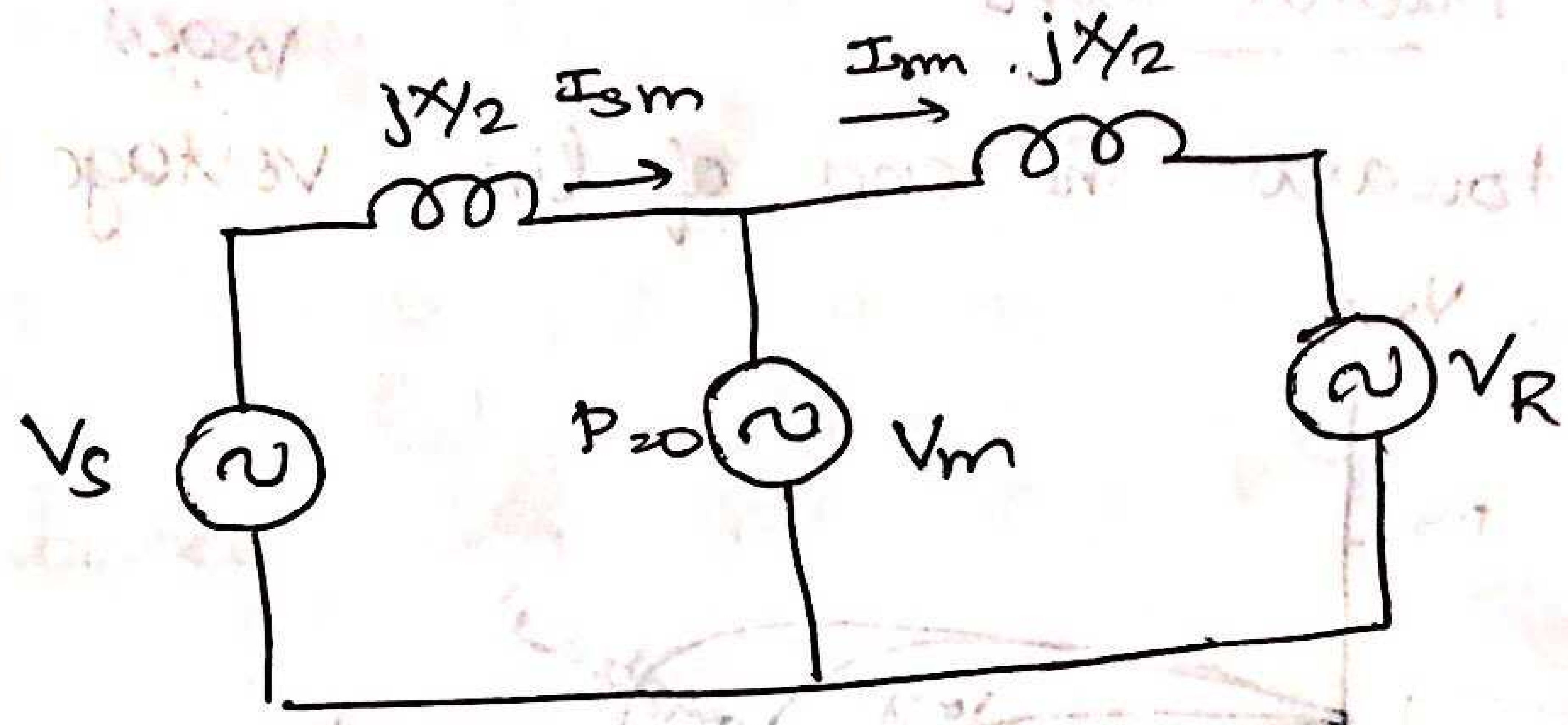
Location of SVC - important

* long Tr line - one SVC - midpoint.
* very long lines - multiple SVC's at regular intervals,

→ Voltage Instability ⇒ Dynamic

1. Midpoint compensation





$|V_S| = |V_m| = |V_R| = V$

$\cos \delta/4 = \frac{V_{sm}}{V_S}$ → $V_{sm} = V \cos \delta/4$ $\quad \sin \delta/4 = \frac{jX/2 \; I_{sm}}{V}$

$I_{sm} = \frac{4V}{X} \sin \delta/4$. $\quad P = \frac{4V^2}{X} \sin \delta/4 \cos \delta/4$.

$P = \frac{2V^2}{X} \sin \delta/2 = \frac{2V^2}{X} \sin \delta/2$ $\quad P = VI \cos \delta/4$

$Q = VI \sin \delta/4. = \frac{4V^2}{X} \sin^2 \delta/4$ $\quad \sin^2\theta = \frac{1-\cos 2\theta}{2}$.

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

→ Location of SVC - impt → midpoint - Voltage sag.

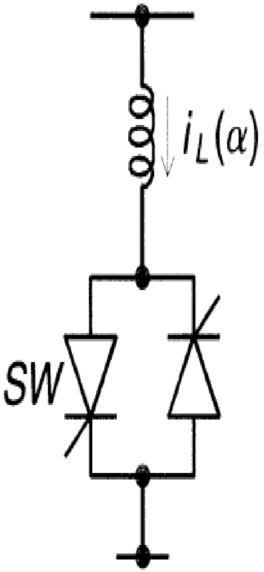
→ so 1 SVC - placed in MP. → multiple SVC's, along the line → costly

Thyristor Control Reactor (TCR)

- Thyristor control reactor (TCR) is the basic building block of SVC(static Var compensator).
- TCR used to absorb the excess reactive power in the system.
- It can’t be used alone, because of the inductive nature of power system load.
- It is normally used with thyristor switched capacitor (TSC), to provide the controlled reactive power generation.
- Single-phase thyristor-controlled reactor (TCR) is consists of a fixed (usually air-core) reactor of inductance L, and a bidirectional thyristor valve (or switch).

Thyristor Control Reactor (TCR)

- Currently available thyristors have 4KV to 10KV voltage rating and current rating is 3KA to 6KA amperes.
- To meet the required blocking voltage and current in real power system, the series and parallel connection of thyristor is used (thyristor valve).
- A thyristor valve can be brought into conduction by simultaneous application of a gate pulse to all thyristors of the same polarity.



Thyristor Control Reactor (TCR)

- High voltage rating

  It can be established by connecting thyristor in series and giving synchronized pulse.

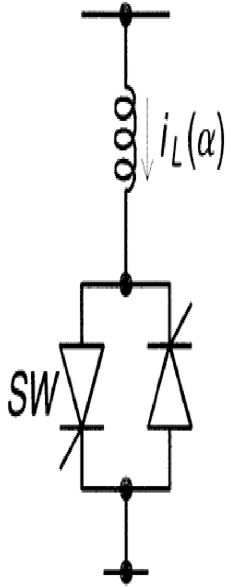
- High current rating

  It can be established by parallel connection of thyristor valve and giving synchronized pulse.

- The valve will automatically block immediately after the ac current crosses zero, unless the gate signal is reapplied.

Thyristor Control Reactor (TCR)

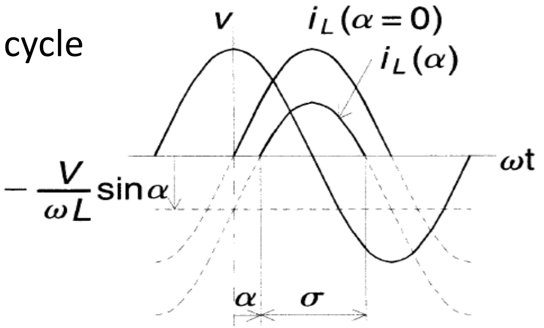
- Reactive power absorbed by TCR is proportional to the current flowing through inductor($I_L(\alpha)$)
- The current in the reactor can be controlled from maximum (thyristor valve closed) to zero (thyristor valve open) by the method of firing delay angle control
- Firing angle of TCR is varying from 90^0 to 180^0.
- It can't able to varying from 0^0 to 180^0, unlike AC voltage controller

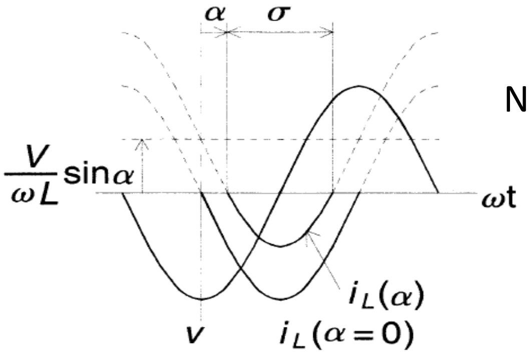


Thyristor Control Reactor (TCR)

- The current in the reactor can be controlled from maximum (thyristor valve closed) to zero (thyristor valve open) by delaying the firing angle
- The closure of the thyristor valve is delayed with respect to the peak of the applied voltage in each half-cycle, and thus the duration of the current conduction intervals is controlled.

Positive half cycle





Negative half cycle

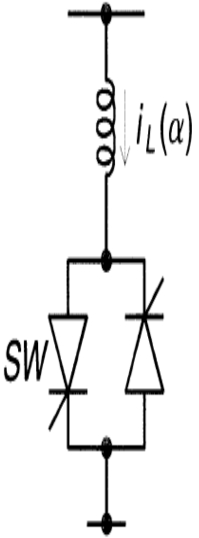
Thyristor Control Reactor (TCR)

Current flowing through inductor when valve is conduction

- let applied voltage $v(t) = V_m \cos\omega t$
- During positive half $i_L(\alpha) = \frac{1}{L}\int_{\alpha}^{\omega t} v(t)dt$

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

- This equation is valid only for at is ωt varying from $\alpha \le \omega t \le \pi - \alpha$
- From the expression is find that current is by an offset of $-\frac{V_m}{\omega L}\sin(\alpha)$)
- Similarly for negative half

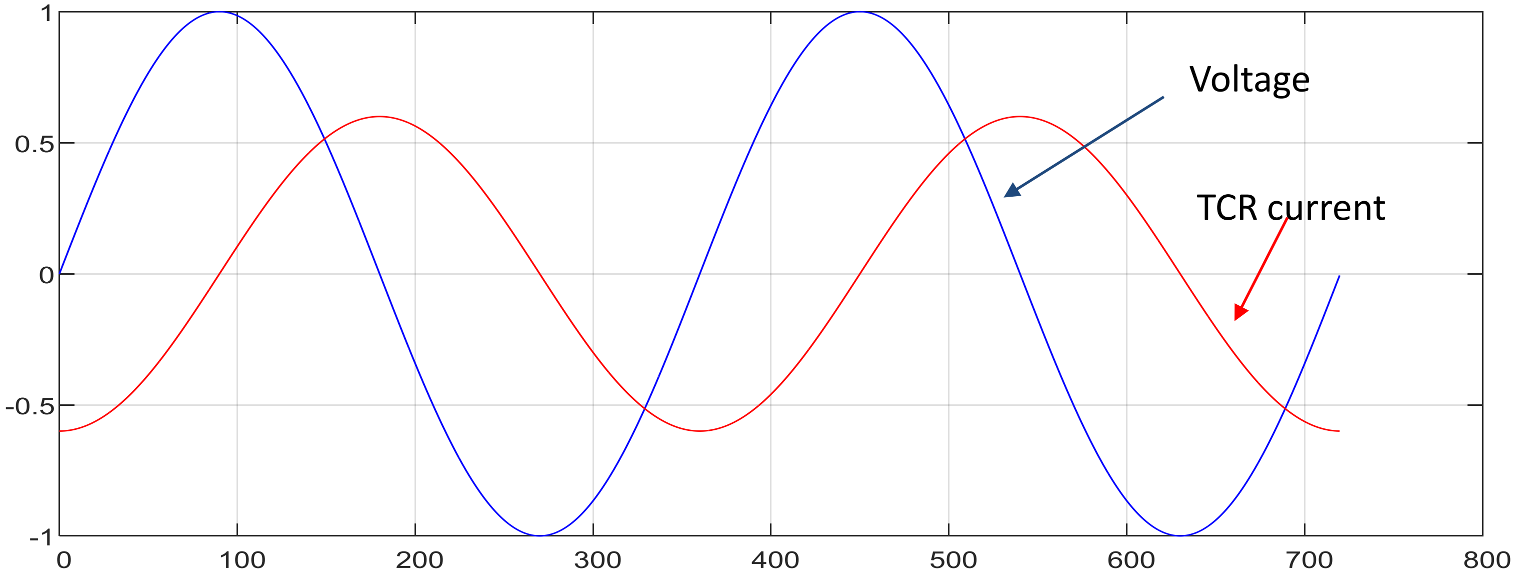


Thyristor Control Reactor (TCR)

- The delay angle is α, then the conduction angle $\sigma = 2\pi - \alpha$
- Thus, as the delay angle a increases, the correspondingly increasing offset results in the reduction of the conduction angle of the valve, and the consequent reduction of the reactor current.
- At the maximum delay of α=$\pi/2$, the offset also reaches its maximum of $V_m/\omega L$, at which both the conduction angle and the reactor current become zero.
- Should be note that the two parameters, delay angle $\alpha$and conduction angle σ are equivalent and therefore TCR can be characterized by either of them.

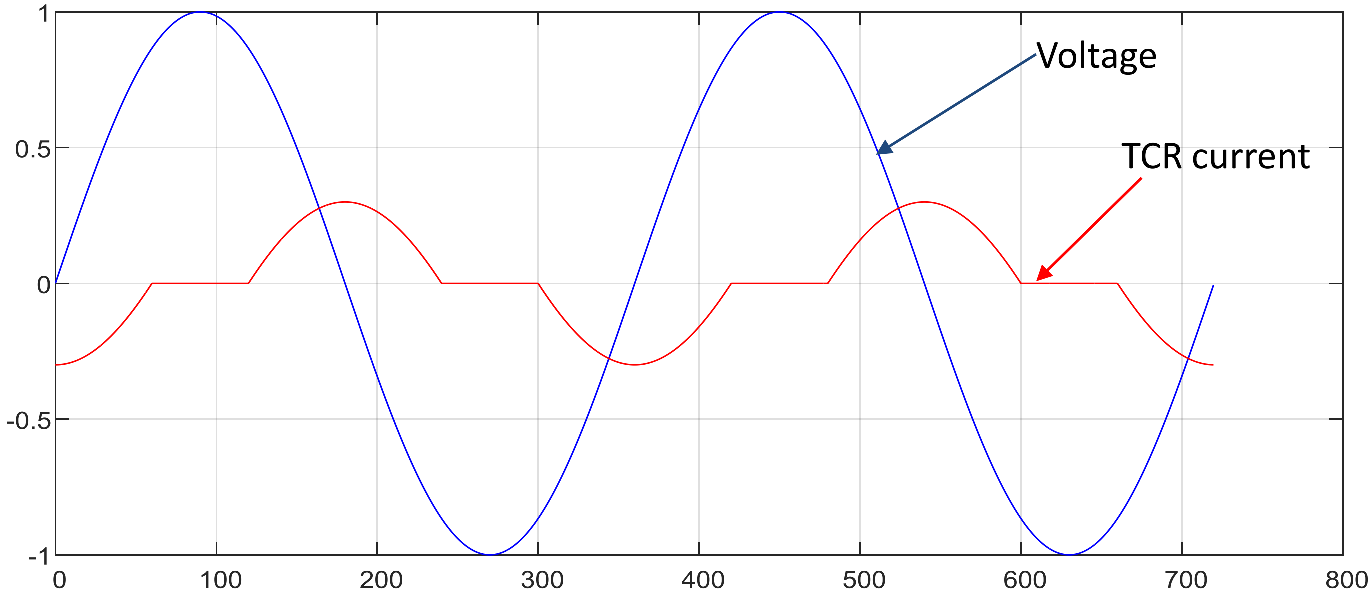
Thyristor Control Reactor (TCR)

- firing angle α =0 (measured from peak of source voltage)



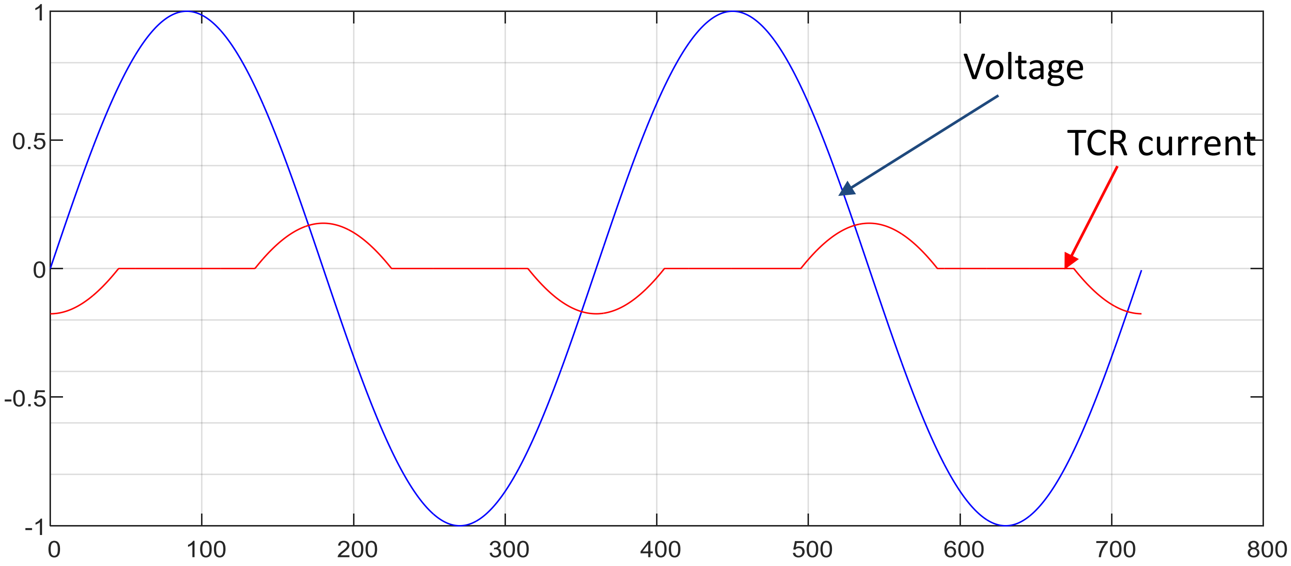
Thyristor Control Reactor (TCR)

- firing angle α =30dgree



Thyristor Control Reactor (TCR)

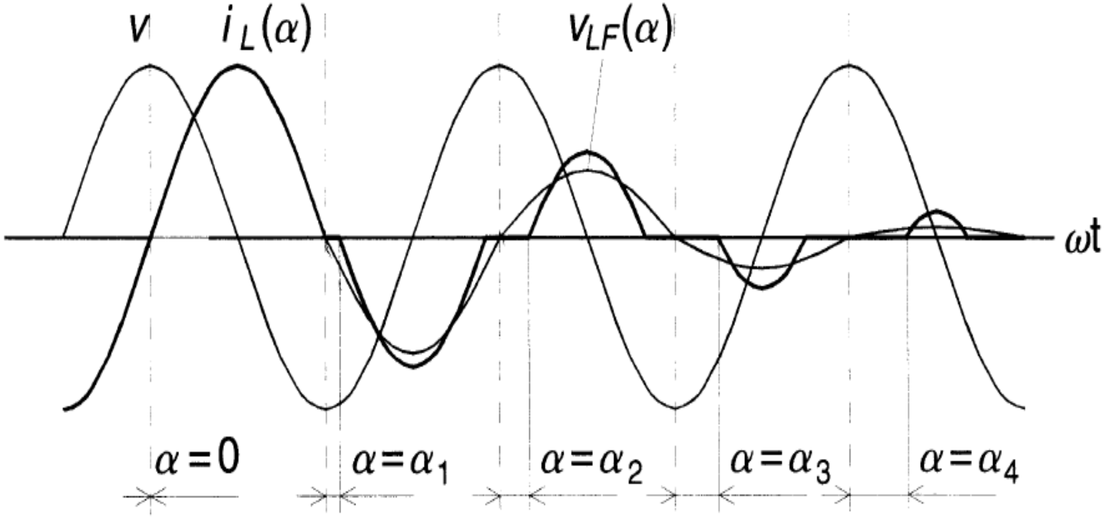
- firing angle α =45dgree



Thyristor Control Reactor (TCR)

- By continuous varying of firing angle

$0<\alpha_1<\alpha_2<\alpha_3<\alpha_4$



Thyristor Control Reactor (TCR)

- Mathematical analysis

Reactor current in positive half cycle is $i_L(\omega t) = \frac{V_m}{\omega L}(\sin(\omega t) - \sin(\alpha))$ when $\alpha \leq \omega t \leq \pi - \alpha$ and other wise zero

- Now find the fundamental component by using furrier series expansion

$$i_L(\omega t) = \sum_1^{\infty} a_n \cos(n\omega t) + b_n \sin(\omega t)$$

$$i_{L1}(\omega t) = a_1 \cos(n\omega t) + b_1 \sin(\omega t)$$

$a_1 = 0$ (odd symmetry or quarter wave symmetry)

$$b_1 = \frac{2}{\pi} \int_{\alpha}^{\pi-\alpha} i(\omega t) \sin(\omega t)\, d\omega t$$

Thyristor Control Reactor (TCR)

$$b_1=\frac{2}{\pi}\int_{\alpha}^{\pi-\alpha}\frac{V_m}{\omega L}\,(\sin(\omega t)-\sin(\alpha))\sin(\omega t)\,d\omega t$$

$$b_1=\frac{2}{\pi}\frac{V_m}{\omega L}\int_{\alpha}^{\pi-\alpha}(\sin(\omega t)^2-\sin(\alpha)\sin(\omega t))\,d\omega t$$

After simplification

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

there for

$$i_{L1}(\omega t)=\frac{2}{\pi}\frac{V_m}{\omega L}\left[\frac{\pi-2\alpha}{2}-\frac{1}{2}\sin(2\alpha)\right]\sin(\omega t)$$

Peak Current

$$I_{L1p}(\alpha)=\frac{V_m}{\omega L}\left[1-\frac{2\alpha}{\pi}-\frac{1}{\pi}\sin(2\alpha)\right]$$

Thyristor Control Reactor (TCR)

- $I_{L1p}(\alpha)=\frac{V_m}{\omega L}\left[1-\frac{2\alpha}{\pi}-\frac{1}{\pi}\sin(2\alpha)\right]$

  $i_{L1p}(\alpha)=V_m B_L$

  B_{tcr} is the TCR admittance

Where $B_L = B_{Lmax}\left[1-\frac{2\alpha}{\pi}-\frac{1}{\pi}\sin(2\alpha)\right]$

$$B_{Lmax}=\frac{1}{\omega L}$$

Now the expression of admittance in conduction angle σ where $\alpha=\frac{\pi-\sigma}{2}$

$$B_L = B_{Lmax}\left[\frac{\sigma}{\pi}-\frac{\sin\sigma}{\pi}\right]$$

Thyristor Control Reactor (TCR)

$i_{L1p}(\alpha)=V_m B_L$

Where $B_L = B_{Lmax}\left[1-\frac{2\alpha}{\pi}-\frac{1}{\pi}\sin(2\alpha)\right]$

$\alpha\uparrow \Rightarrow$ TCR admittance $(B_L)\downarrow \Rightarrow I_{L1}(\alpha)\downarrow \Rightarrow$ Reactive power absorbed ↓

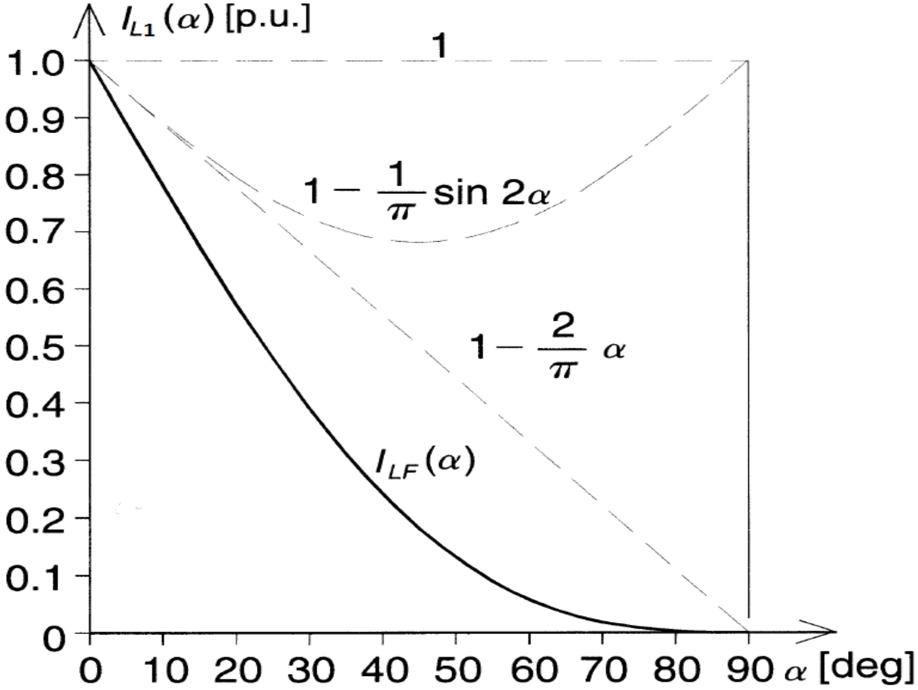
$\alpha\downarrow \Rightarrow$ TCR admittance $(B_L)\uparrow \Rightarrow I_{L1}(\alpha)\uparrow \Rightarrow$ Reactive power absorbed ↑

so by varying firing angle (α) smooth control of reactive power absorption is achieved by TCR

Thyristor Control Reactor (TCR)

TCR fundamental current

- $I_{L1p}(\alpha) = \frac{V_m}{\omega L}\left[1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin(2\alpha)\right]$



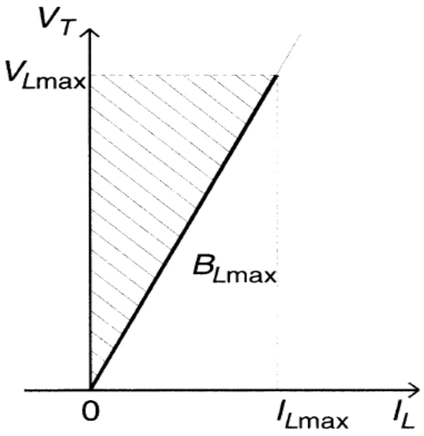
Thyristor Control Reactor (TCR)

- In practice, the maximal magnitude of the applied voltage and that of the corresponding current will be limited by the ratings of the power components (reactor and thyristor valve) used.
- A practical TCR can be operated anywhere in a defined V-I area, the boundaries of which are determined by its maximum attainable admittance, voltage, and current ratings.

V_{Lmax}=Voltage limit

I_{Lmax}= Current limit

B_{Lmax}= Maximum admittance of TCR

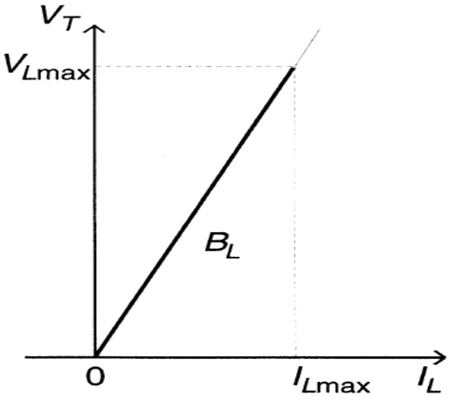


Thyristor Control Reactor (TCR)

- If the TCR switching is restricted to a fixed delay angle, usually $\alpha = 0$, then it becomes a thyristor-switched reactor (TSR) (it have only two option either fully on or fully off).
- The reactive current will be proportional to the applied voltage
- TSRs can provide a reactive admittance controllable in a step-like manner.

TCR may be used alone but TSR can never be used alone it is always conjunction with TCR

B_L= admittance of reactor



Thyristor Control Reactor (TCR)

- When α > 0 ,results in a non sinusoidal current waveform in the reactor.
- i.e. it have fundamental current, with some harmonics.
- Due to the half wave symmetry, only odd harmonics are present .
- The amplitudes of these are a function of angle α,

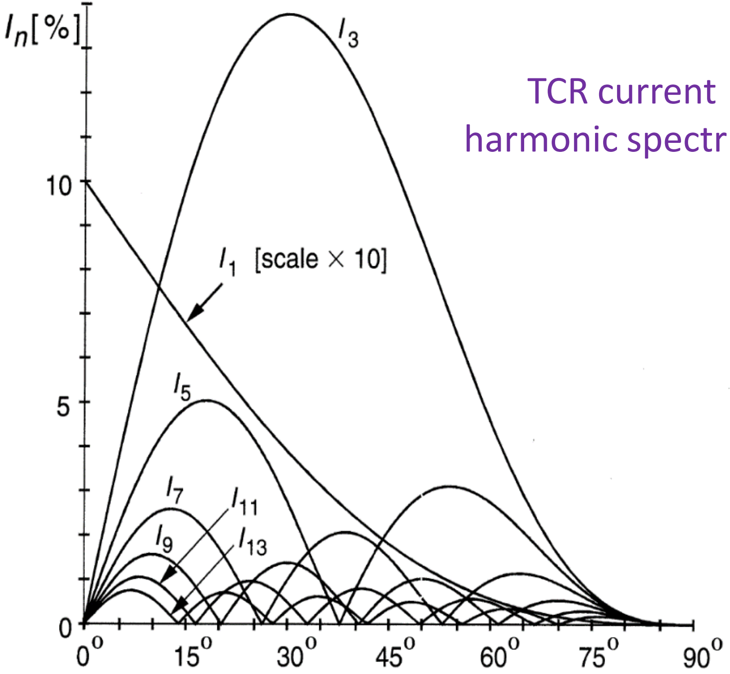
$$I_{Ln}(\alpha)=\frac{V_m}{\omega L}\frac{4}{\pi}\left[\frac{\sin(\alpha)\cos(n\alpha)-n\cos(\alpha)\sin(n\alpha)}{n(n^2-1)}\right]$$

Where n=2k+1 , k=1,2,3,…

Thyristor Control Reactor (TCR)

- Dominant harmonic present is 3rd around 15% of the fundamental
- To reduce the harmonic content inter connection multiple TCR as desired manner such as

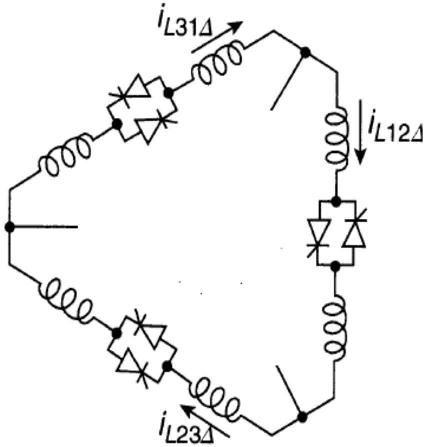
1. Delta connection of three phase TCR
2. Multi pulse delta connected three phase TCR
3. Segmented TCR



TCR current harmonic spectrum

Thyristor Control Reactor (TCR)

- In a three-phase system, three single-phase thyristor-controlled reactors are used, usually in delta connection.
- Under balanced conditions, the triple-n harmonic currents(3rd, 9th, 15th, etc.) circulate in the delta connected TCRs and do not enter the power system.
- The reactor are bifurcated on either side of AC voltage so if a short circuit occurs across one of the reactors then high voltage across reactor is prevented by the other reactor.

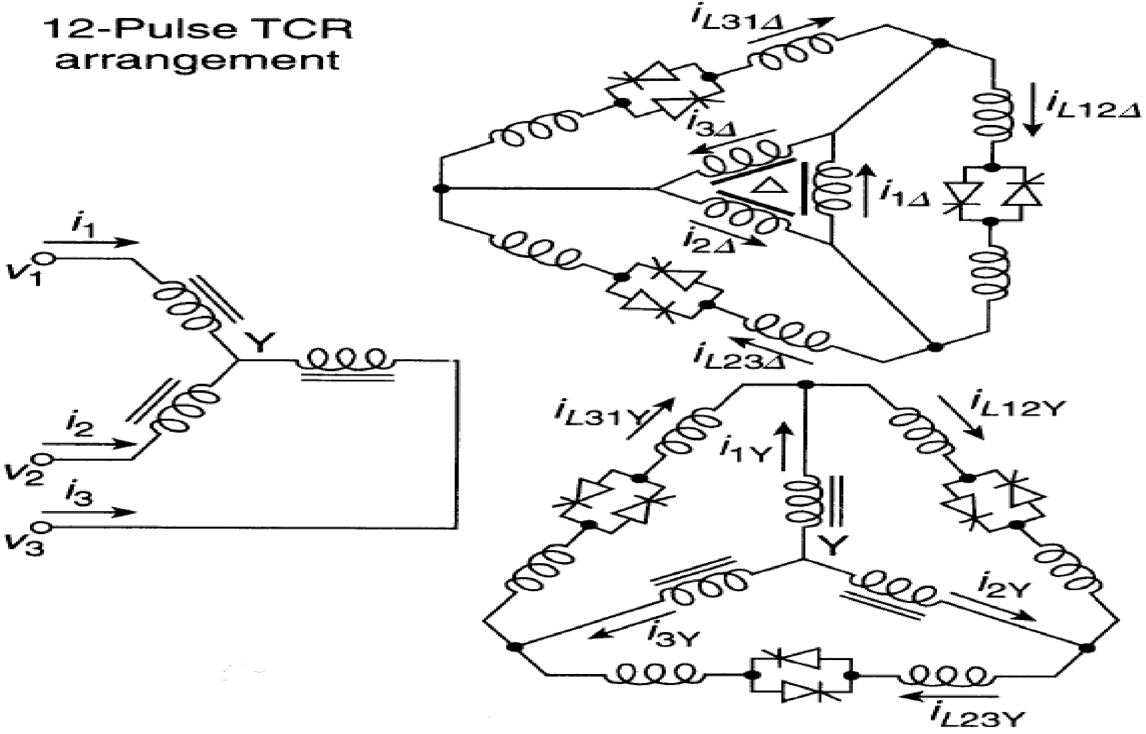


Thyristor Control Reactor (TCR)

- 6 pulse TCR have the all non-triplent harmonic 5,7,11,13,17,19….
- By using 12 pulse TCR the harmonic spectrum is improved
- It have two set TCR are connected delta format with transformer have two secondary in star and delta
- By using 12 pulse transformer 5, 7,17,19,29… harmonics removed from the current.
- It have draw back it will increases the cost of the system and also complex control circuit required
- If required to suppress more harmonic, then replace 12 pulse by 18,24,48… pulse transformers

Thyristor Control Reactor (TCR)

12-Pulse TCR arrangement

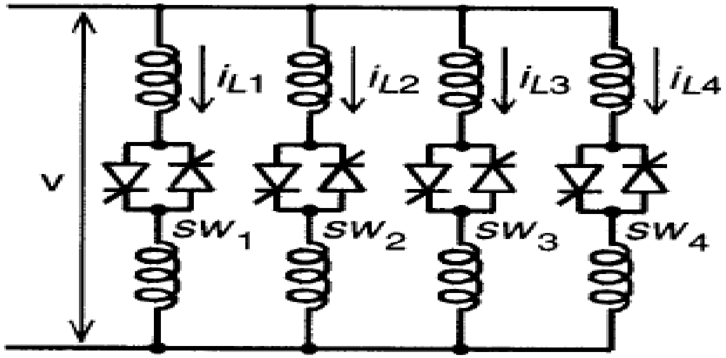


Segmented TCR

- In order to reduce the harmonic another method is segmented TCR (parallel connected TCR)
- This method used for high power applications.
- Each TCR will absorbs "Q_{total} /m" , where n is the number of TCR.
- There fore the magnitude of harmonic current reduce by a factor of "1/m".
- It is the combination of TCR with TSR.
- Only one of the m reactors is delay angle controlled, and each of the remaining m - 1 reactors is either fully "ON' or fully "off" depending on the total reactive power required.
- losses associated with this scheme are generally lower than those characterizing a TCR with equivalent rating due to the reduction in switching losses.

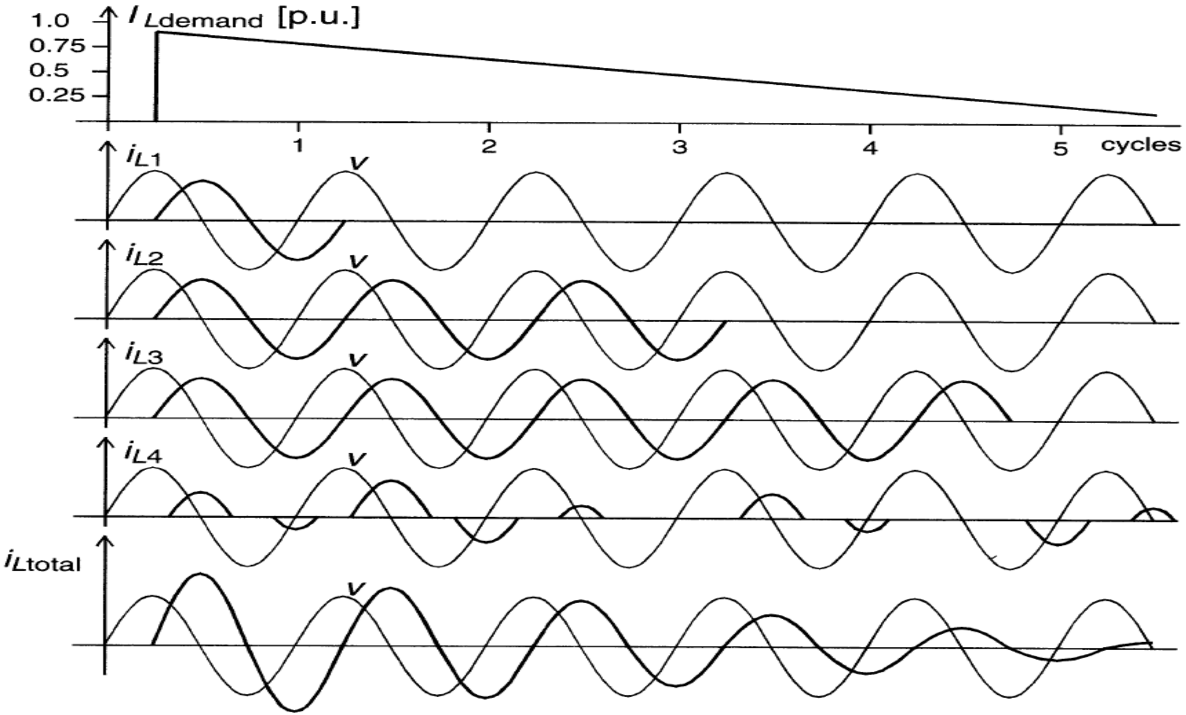
Segmented TCR

- Segmented TCR by using four TCR
- 4th TCR is only operating as thyristor control reactor all other operating as thyristor switched reactor(TSR)



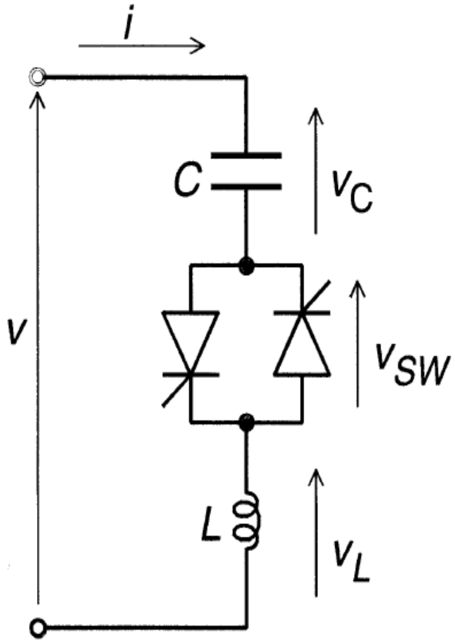
$$i_{Ltotal} = i_{L1} + i_{L2} + i_{L3} + i_{L4}$$

Segmented TCR



Thyristor Switched Capacitor (TSC)

- A single-phase thyristor switched capacitor (TSC) consists of a capacitor, a bidirectional thyristor valve, and a relatively small surge current limiting reactor.
- This reactor is needed primarily to limit the surge current in the thyristor valve and it may also be used to avoid resonances with the ac system impedance at particular frequencies.



Thyristor Switched Capacitor (TSC)

- Under steady-state conditions, when the thyristor valve is closed

  For a given voltage $v = V sin\omega t$ the branch current is

$$i(\omega t) = \frac{V sin\omega t}{X_L + X_c} \Rightarrow \frac{V sin\omega t}{j\omega L + \frac{1}{j\omega c}}$$

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

let $n = \frac{1}{\sqrt{\omega^2 LC}}$

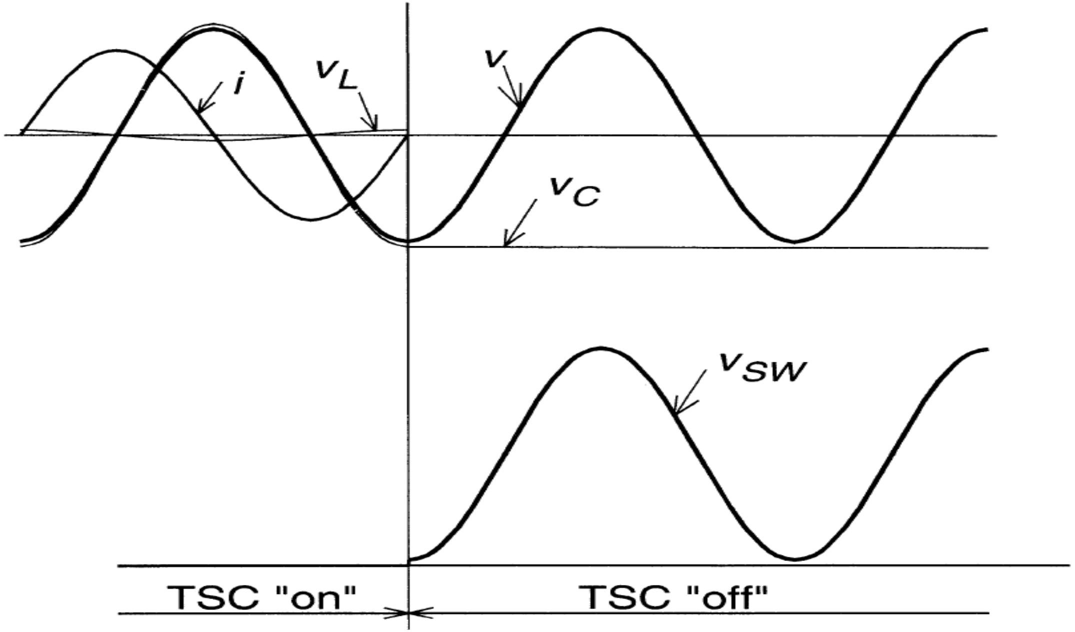
$$i(\omega t) = V \frac{n^2}{n^2 - 1} \omega C cos\omega t$$

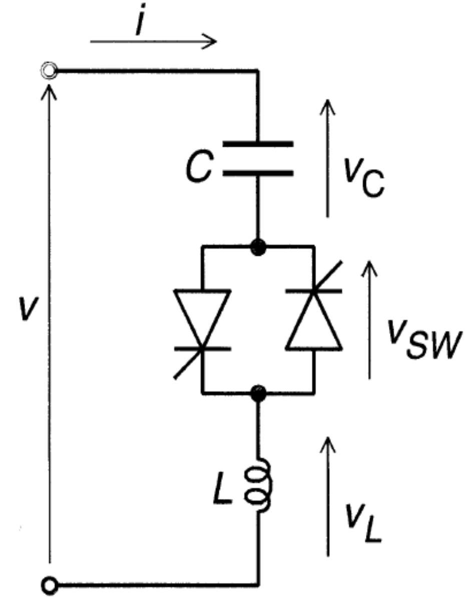
Thyristor Switched Capacitor (TSC)

- The TSC branch can be disconnected ("switched out") at any current zero by prior removal pulse for the thyristor valve.
- At the current zero crossing, the capacitor voltage is at its peak value.
- The disconnected capacitor stays charged to this voltage
- Consequently, the voltage across the non conducting thyristor valve varies between zero and the peak-to-peak value of the applied ac voltage,

voltage across the capacitor $V_c = V \frac{n^2}{n^2-1}$

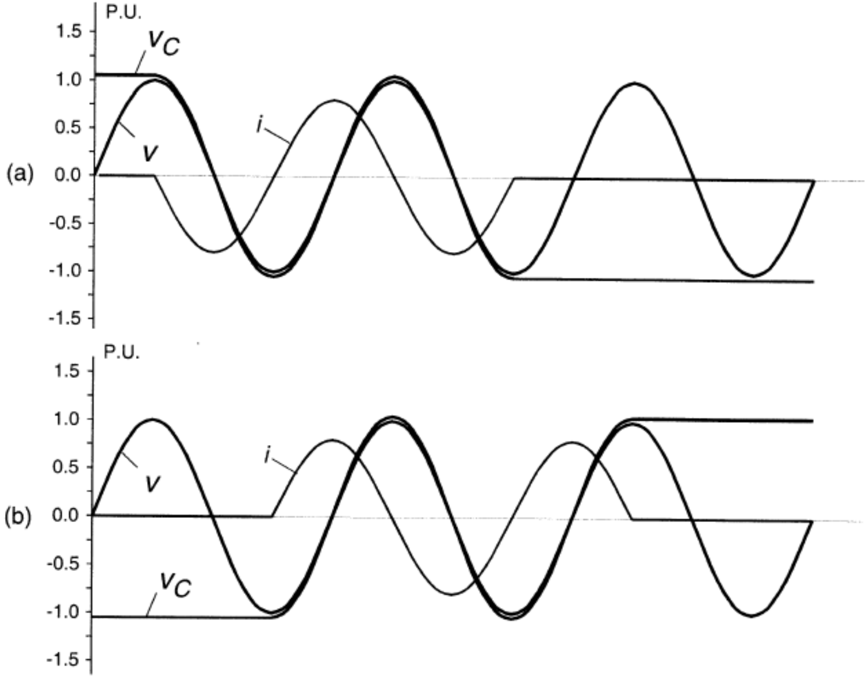
Thyristor Switched Capacitor (TSC)





Thyristor Switched Capacitor (TSC)

- If the voltage across the disconnected capacitor remained unchanged, the TSC bank could be switched in again, without any transient, at the appropriate peak of the applied ac voltage for a positively (a) and negatively (b) charged capacitor



Thyristor Switched Capacitor (TSC)

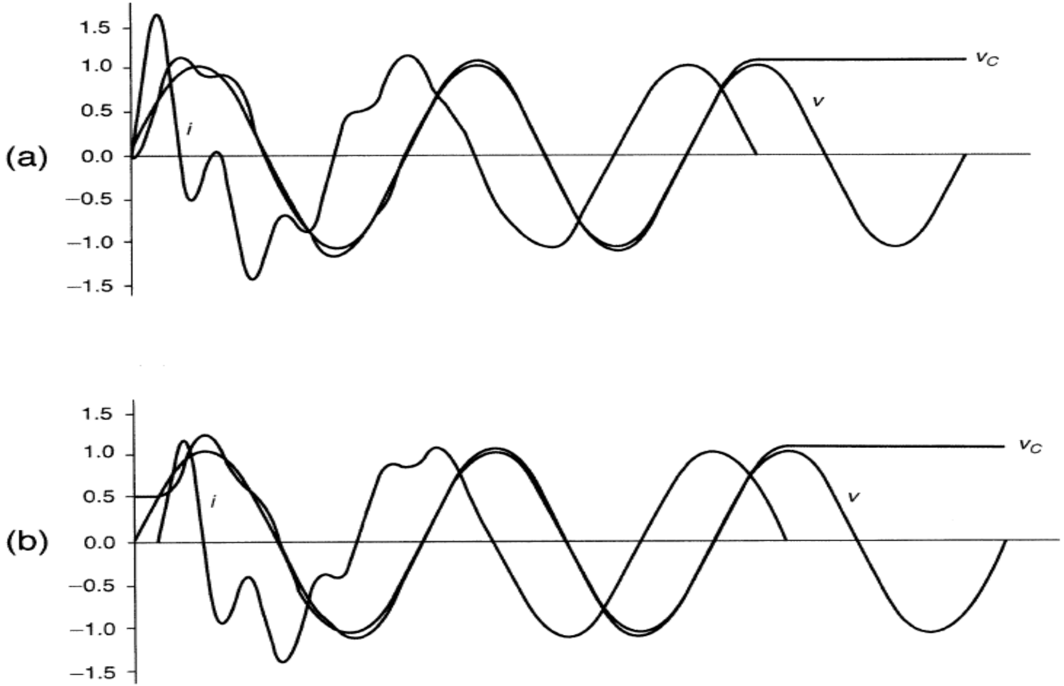
- Normally, the capacitor bank is discharged after disconnection.
- Thus, the reconnection of the capacitor may have to be executed at some residual capacitor voltage between zero and V_c.

To minimize the transient disturbance if the thyristor valve is turned on at those instants at which the capacitor residual voltage and the applied ac voltage are equal, that is, when the voltage across the thyristor valve is zero.

- The switching transients obtained with a fully and a partially discharged capacitor.

Thyristor Switched Capacitor (TSC)

- (a) fully discharged
- (b) partially discharged



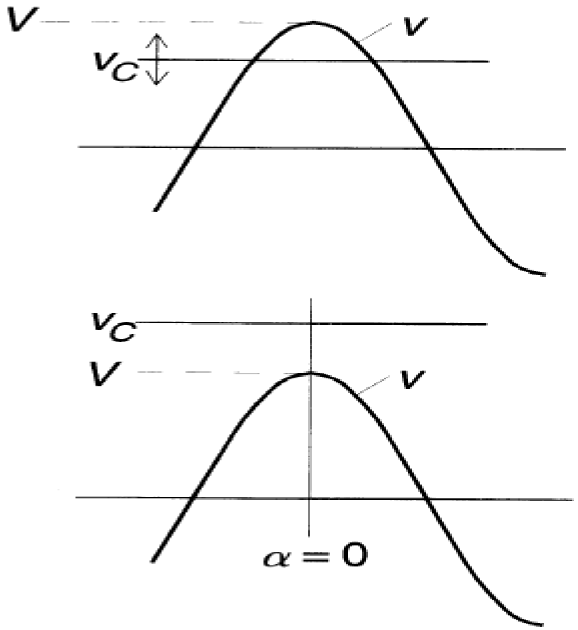
Thyristor Switched Capacitor (TSC)

- These transients are caused by the nonzero $\frac{dv}{dt}$ at the instant of switching.
- If without the series reactor, would result in an instantaneous current of i= $C\frac{dv}{dt}$, in the capacitor.
- The limiting reactor will slow down the rate of change surge current.
- The interaction between the capacitor and the current limiting reactor, with the damping resistor, produces the oscillatory transients.

Thyristor Switched Capacitor (TSC)

The conditions for "transient-free" switching of a capacitor by two simple rules

1. if the residual capacitor voltage is lower than the peak ac voltage ($V_c < V$), then the correct instant of switching is when the instantaneous ac voltage becomes equal to the capacitor voltage
2. if the residual capacitor voltage is equal to or higher than the peak ac voltage ($V_c > V$), then the correct switching is at the peak of the ac voltage at which the thyristor valve voltage is minimum.

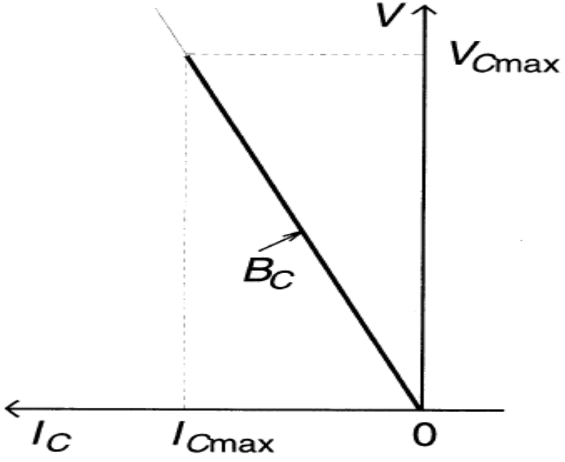


Thyristor Switched Capacitor (TSC)

- The maximum possible delay in switching in a capacitor bank is one full cycle of the applied ac voltage, that is, the interval from one positive (negative) peak to the next positive (negative) peak.
- So firing delay angle control is not applicable to capacitors.
- The capacitor switching must take place at that specific instant in each cycle at which the conditions for minimum transients are satisfied.
- For this reason, a TSC branch can provide only a step like change in the reactive current (maximum or zero).

Thyristor Switched Capacitor (TSC)

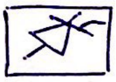
- The current in the TSC branch varies linearly with the applied voltage according to the admittance of the capacitor.
- The maximum applicable voltage and the corresponding current are limited by the ratings of the TSC components (capacitor and thyristor valve).
- To approximate continuous current variation, several TSC branches in parallel with small rating.



V_{Cmax}=Voltage limit
I_{Cmax}= Current limit
B_{Cmax}= Maximum admittance of TSC

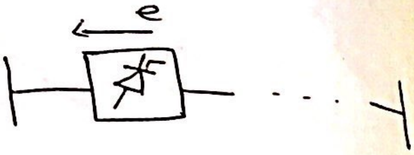
voltage regu

control both P & Q



Basic types of FACTS controllers - General Classification

Series connected controllers : variable Z - C or X



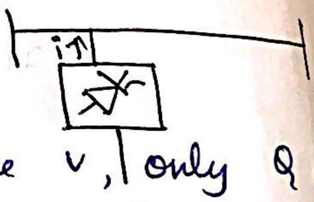
- * inject V in series with the line
- * X × I = implies injected V in the line.
- * As long as V is in phase quadrature with I_L, - only supplies (or) consumes Q.
- * some other phasor - includes P as well.

$R = \frac{V}{I}$

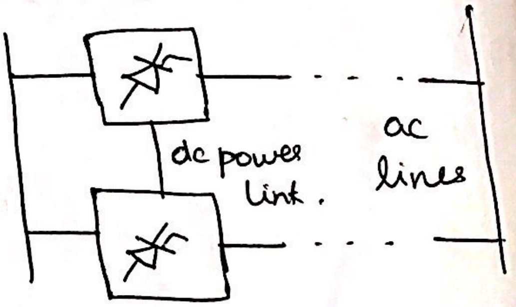
$\frac{V}{R} = I$

Shunt connected controllers : variable Z (or) var. source

- * inject I into the s/m at the point of connection
- * $\frac{V}{Z}$ = implies injected I into the line.
- * As long as I is in quadrature with line V, only Q



Combined series - series controllers



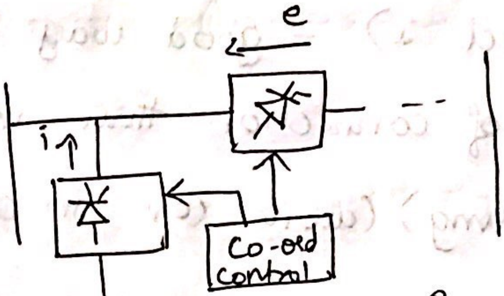
- * combination of separate series controller, controlled in a co-ordinated manner in a multiline t/r s/m.
- * independent series reactive compensation, But also transfer along the lines.

* Real P transfer capability of unified S-S controller - Interline P flow controller, possible to balance both P + Q

* hence maximise the utilisation of the Tr s/m.

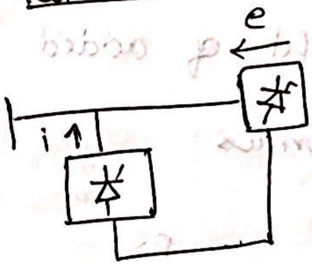
* unified - dc terminals of all controller converters are connected together ~~to form~~ for P transfer.

Combined series - shunt controller.



* combination of separate series + shunt controller - controlled in a co-ordinated manner. (UPFC)

* inject both V & I -



* when unified, P exchange via power link.

Classification based on PE devices

* Variable Z type * Voltage src Converter type

based on whether it is inserting Z (or) VS to the s/m

Variable Impedance type - insert Z

* SVC - shunt compensator * TCPST - Combined sh & se.

* TCSC - series (Active capacitor) ↳ Power angle regulator)

VSC type

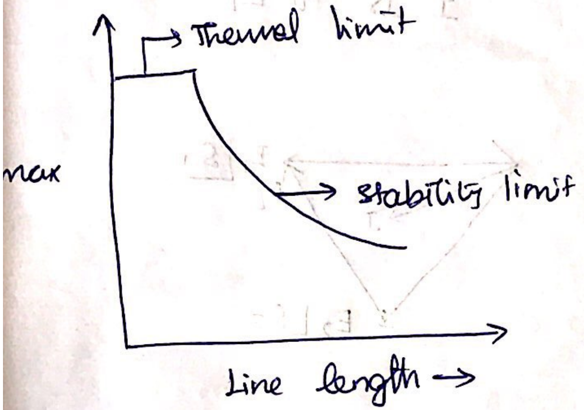
* STATCOM - Static Syn Comp - Shunt

* SSSC - Static Syn Series Comp

* IPFC - Comb - series - series * UPFC - comb shunt + series

What limits the loading capability

Power transfer capacity as a fn. of line length



* Thermal
* Dielectric
* Stability

* achieve max loading capability.

Thermal : OH line fn (temp ↱ 40°C >, wind conditions, condn of conductor, ground clearance

* nominal rating - worst ambient condn.
* off line computer programs that calculates line's loading cap based on amb temp & recent loading history
* on-line monitoring devices -
* tr line rating ↑, transformer should also be considered.
* upgrading a line to a higher capacity, require structured upgrading also.
* converting a single ckt to double ckt line.
* control power flow - FACTS.

Dielectric : gn operating V = ±10%.

* transient & dynamic V should be within limits.
* Modern gapless arresters, powerful thyristor controlled V suppressors - ↑ in V capability
* FACTS - OV & Pflow.

Stability - Transient, SS, Dynamic, δ Collapse, V collapse

Sub-synchronous resonance.

12/8/18 Relative importance of controllable parameters

* control of line Z - X - means of current control
* control of angle - control of P.
* Injecting a voltage in series with line, injection of Q in ⊥r to I flow provide powerful means of controlling the line I + hence P when the angle is not large.
* some other phasor - control both P & Q in the line
* Combination of the line Z control with a series controlle voltage regulation with a shunt controller - cost effective to control both P & Q