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Shunt Compensation

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➢ *Flexible AC Transmission System (FACTS):*

Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability

➢ *FACTS Controller:*

A power electronic-based system and other static equipment that provide control of one or more AC smission system parameters.

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Basic types of FACTS Controllers

Based on the connection, generally FACTS controller can be classified as follows:

- Shunt controllers
- Series controllers
- Combined series-series controllers
- ombined series-shunt controllers

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Shunt controllers

The shunt controllers may be variable impedance, variable sources or combination of these. In principle, all shunt Controllers inject current into the system at the point of connection as shown in fig.1. As long as the injected current is in phase quadrature with the line voltage, the shunt Controller only supplies or consumes variable reactive power.

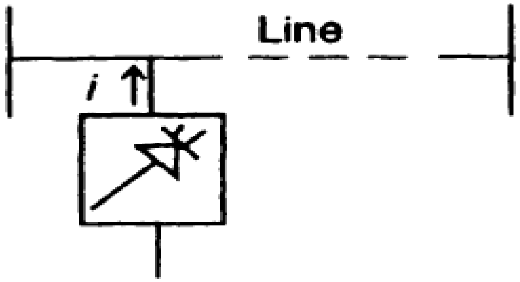

Fig. 1 Symbol of Shunt controller

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Series controllers

The series controller could be a variable impedance or a variable source, both are power electronics based devices to serve the desired needs. In principle, all series controllers inject voltage in series with the line. Symbol of series controller is shown in fig.2.

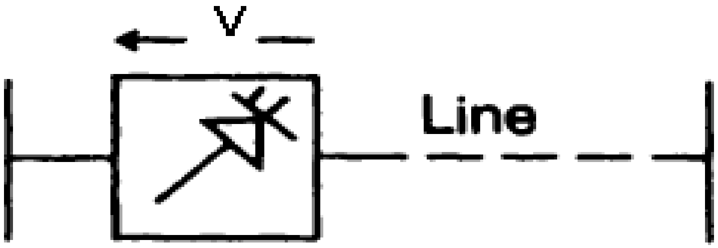

Fig. 2 Symbol of Series controller

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Combined series-series controllers:

Figure 3 shows the symbol of series- series controller. The combination could be separate series controllers or unified series-series controller. Series Controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link- Interline Power Flow Controller.

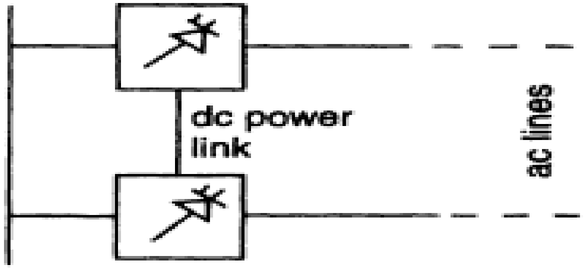

Fig. 3. Symbol of Series- Series controller

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Combined series-shunt controllers

Figure 4 shows the symbol of Series- Shunt controller. The combination could be separated series and shunt controllers or a unified power flow controller. In principle, 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 the series part of the Controller.

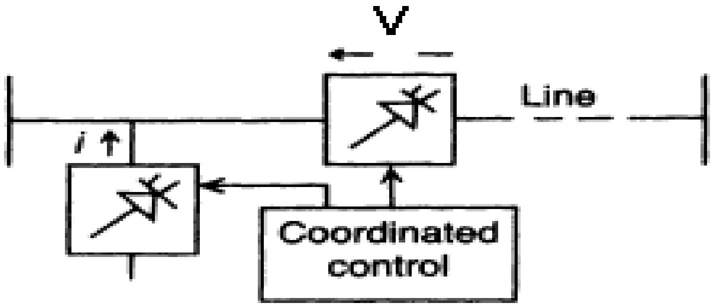

Fig 4 Symbol of Series- Shunt controller

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Choice of the controller

- Series controller controls the current/power flow by controlling the driving voltage.
- To control current/power flow and damp oscillations, series controller is several times more powerful than shunt controller.
- Shunt controller injects current in the line.
- Thus it is used for more effective voltage control & damp voltage oscillations.

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FACTS Controllers

- Injecting the voltage in series with the line can improve the voltage profile.
- But shunt controller is more effective to improve the voltage profile at substation bus.
- For a given MVA, size of series controller is small compared to shunt controller.
- Shunt controllers cannot control the power flow in the lines.
- Series controllers should bypass short circuit nts and handle dynamic overloads.

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FACTS Controllers

- Controllers with gate turn off devices are based on dc to ac converters and exchange active/reactive power with ac lines.
- This requires energy storage device.

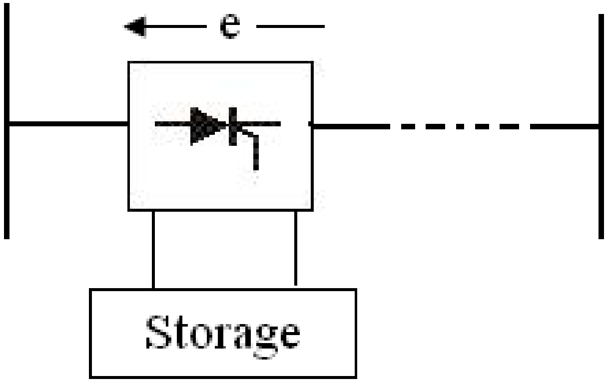

Fig. 5 FACTS controller with energy storage device

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FACTS Controllers

- Energy storage systems are needed when active power is involved in the power flow.
- A controller with storage is more effective for controlling the system dynamics.
- A converter-based controller can be designed with high pulse order or pulse width modulation to reduce the low order harmonic generation to a very low level.
- A converter can be designed to generate the correct waveform in order to act as an active er

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Shunt Controller

- The main object of the shunt facts device to support the reactive power demand.

- It yield to increase the steady-state transmittable power as well as the stability of the system and the voltage profile.

- Shunt Var compensation is thus used for voltage regulation at the midpoint(or some intermediate) to segment the transmission line and at the end of the line to prevent ge instability, as well as for dynamic voltage control crease transient stability and damp power oscillations.

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OBJECTIVES OF SHUNT COMPENSATION

1. Midpoint Voltage Regulation for Line Segmentation.
2. End of Line Voltage Support to Prevent Voltage Instability
3. Improvement of Transient Stability

wer Oscillation Damping

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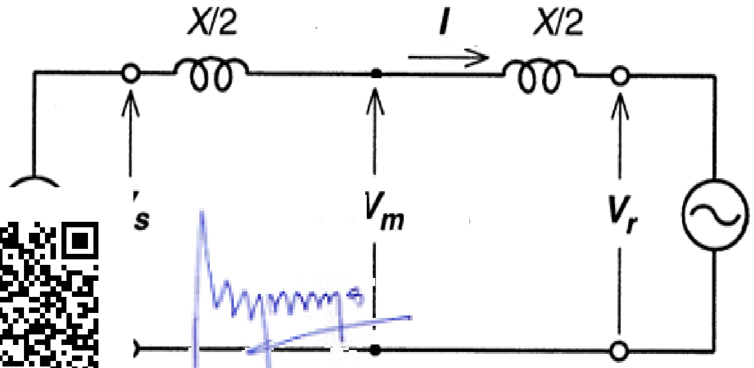
1. Midpoint Voltage Regulation for Line Segmentation.

Consider the simple two-machine (two-bus) transmission model (without any compensation)system as shown in fig. 6(a). The transmission line is represented by the series line inductance. Figure 6(b) shows the phasor diagram of sending and receiving end voltages ($V_s = V_r = V$) and δ is the power angle.



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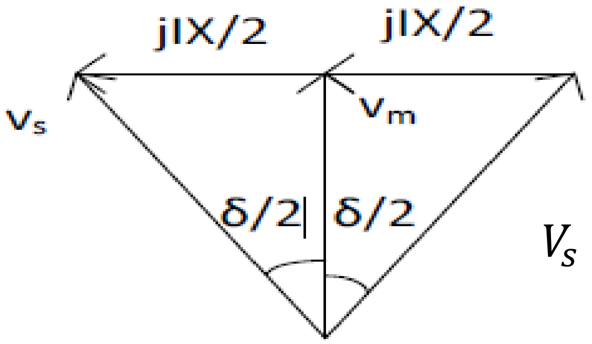
g.6 (a)Two machine model



$V_s = V_r + j\,IX$

Fig.6 (b) Phasor diagram

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1. Midpoint Voltage Regulation for Line Segmentation……

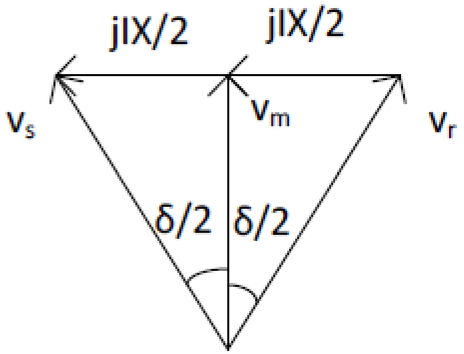
Power at mid point $P_s = V_m\, I$

where $V_m = \dfrac{V_s + V_r}{2}$

$$V_m = \frac{2\,V\cos(\delta/2)}{2}$$

$$I = \frac{V_s - V_r}{jX}$$

$$I = \frac{2\,V\sin(\frac{\delta}{2})}{X}$$



$$Q_s = \mathrm{VI}\sin(\delta/2)$$

$= (V^2 \sin\delta)\,/X$ $\quad Q_s = V^2\,(1 - \cos\delta)\,/X$

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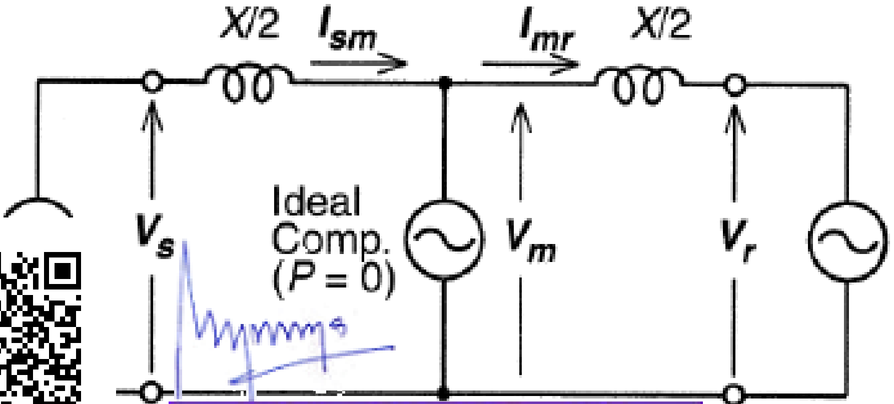
Midpoint Voltage Regulation for Line Segmentation……

The shunt compensator is represented by a sinusoidal AC voltage source in-phase with the midpoint voltage V_m and with an amplitude of the sending and receiving end voltages($V_m = V_s = V_r = V$) as shown in fig.7(a). Phasor diagram is shown in fig.7 (b)



$V_s = V_m + j\, I_m\, X/2$

$V_m = V_r + j\, I_m\, X/2$

Two machine model with shunt compensator

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Midpoint Voltage Regulation for Line Segmentation……

V_{sm} and V_{mr} are voltage at Respective reactance

Power at middle $P_p = V_{sm} I_{sm}$

$$V_{sm} = V_{mr} = V \cos\frac{\delta}{4}; \qquad I_{sm} = I_{mr} = I = \frac{4V}{X}\sin\frac{\delta}{4}$$

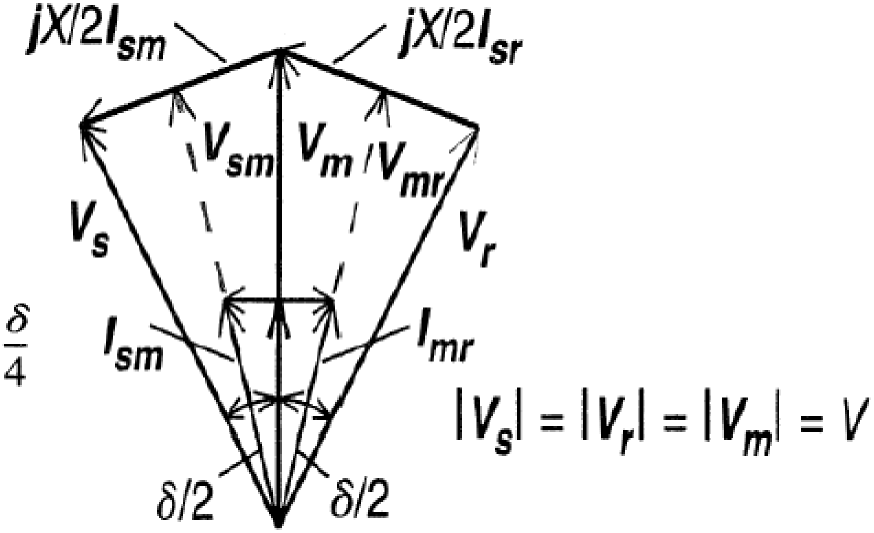

Fig. 7 (b) Phasor diagram

The transmitted power is

$$P = V_{sm} I_{sm} = V_{mr} I_{mr} = V_m I_{sm} \cos\frac{\delta}{4} = VI\cos\frac{\delta}{4}$$

or

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

Similarly

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

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Midpoint Voltage Regulation for Line Segmentation……

The relationship between real power P, reactive power Q, and angle δ for the case of ideal shunt compensation is shown plotted in figure 7(c). It can be observed that the midpoint shunt compensation can significantly increase the transmittable power (doubling its maximum) at the expense of a increasing reactive demand on the nt compensator.

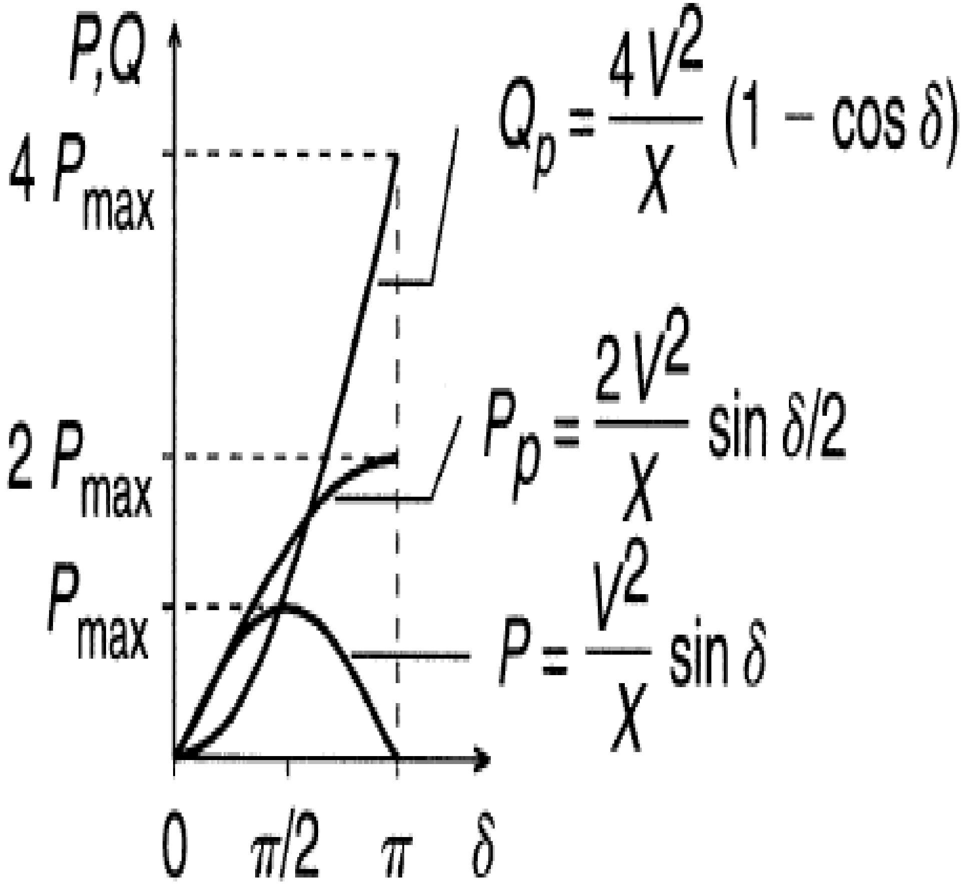

Fig.7 (c) The relationship between real power P, reactive power Q, and angle δ for the case of ideal shunt compensation

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Why midpoint ?

- It is the best location for the compensator because the voltage sag along the uncompensated transmission line is the largest at the midpoint.

- It breaks the transmission line into two equal segments for each of which the maximum nittable power is the same.

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Why Midpoint....

- To get the better voltage profile, transmission line segmentation can be expanded to the use of multiple compensators, located at equal segments of the transmission line.
- Also the transmittable power would double with each doubling of the segments.
- In ideal case the constant voltage profile will be the [illegible] as number compensator increase.

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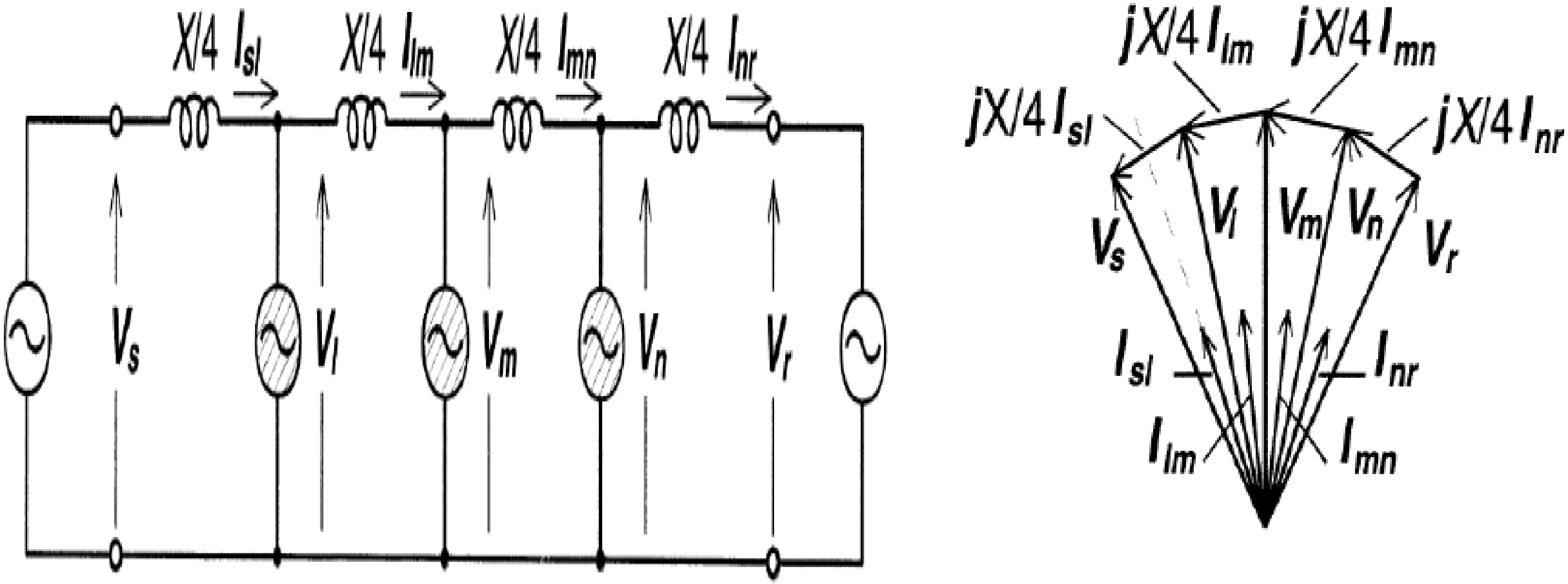
4 Segmentation



machine system with ideal reactive compensators maintaining constant transmission voltage ne segmentation and associated phasor diagram.

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Segmentation disturbance in transmission system

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- Highly complex
- Large expensive for to be practical,
- The stability and reliability requirements under appropriate contingency conditions are also considered.
- However, the practicability of limited line segmentation.

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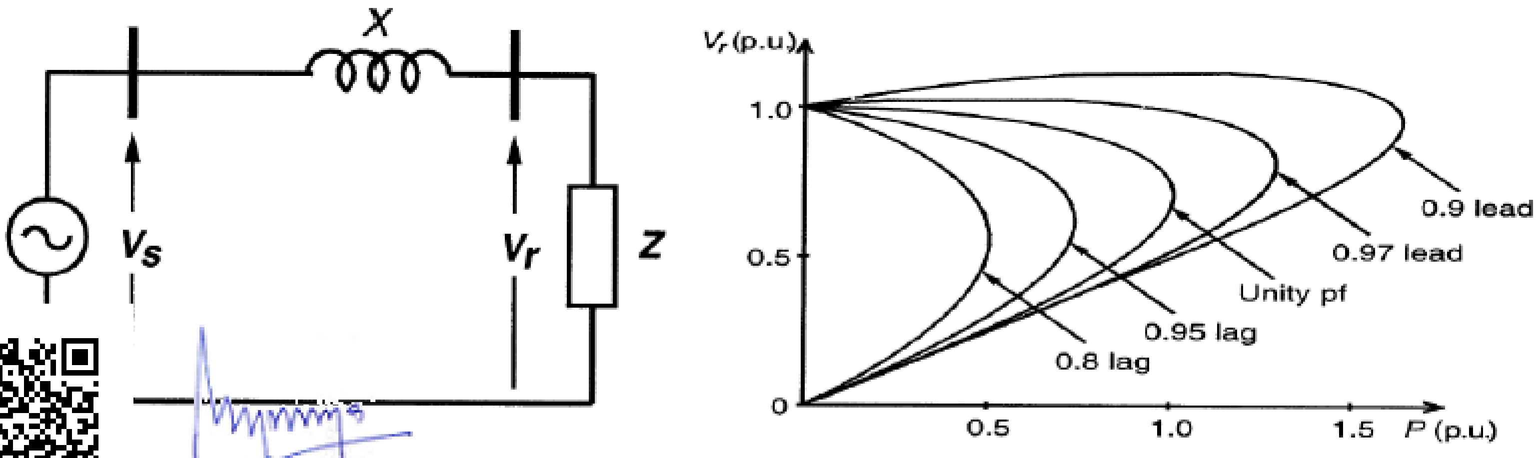
2. End of Line Voltage Support to Prevent Voltage Instability

A simple radial system with feeder line reactance of X and load impedance Z is shown in Figure 9 (a) together with the normalized terminal voltage V_r versus power P plot at various load power factors, ranging from 0.8 lag and 0.9 lead. The "nose-point" at each plot given for a specific power factor represents the voltage instability corresponding to that system condition. Voltage stability limit decreases with inductive loads and increases with capacitive loads.



(a)Variation of voltage stability limit of a radial line with load and load power factor

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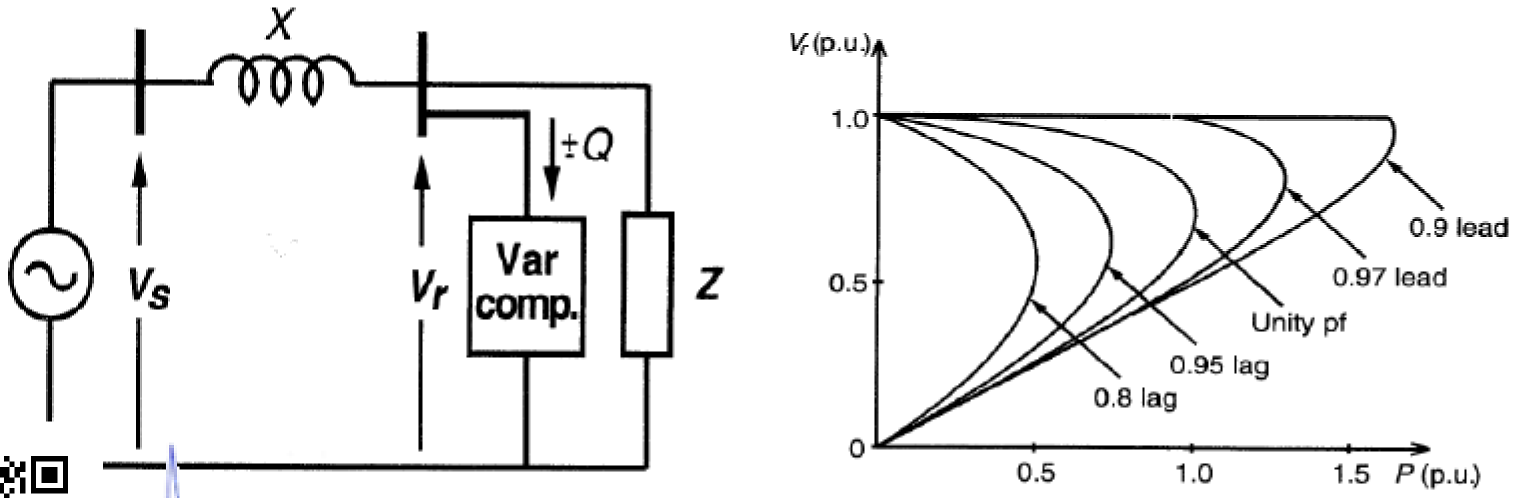
End of Line Voltage Support to Prevent Voltage Instability.....

Figure 9(b) shows the shunt reactive compensation can effectively increase the voltage stability limit by supplying the reactive load and regulating the terminal voltage.



) Variation of voltage stability limit of a radial line with load and load power factor with shunt sation.

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3. Improvement of Transient Stability

- ➢ Reactive shunt compensation can significantly increase the maximum transmittable power.

- ➢ Shunt compensation will be able to change the power flow in the system under dynamic disturbances.

- ➢ The potential effectiveness of transient stability improvement can be conveniently evaluated by the equal area criterion.

meaning of the equal area criterion is explained the aid of the simple two machine (the receiving is an infinite bus)as shown in fig.(10).

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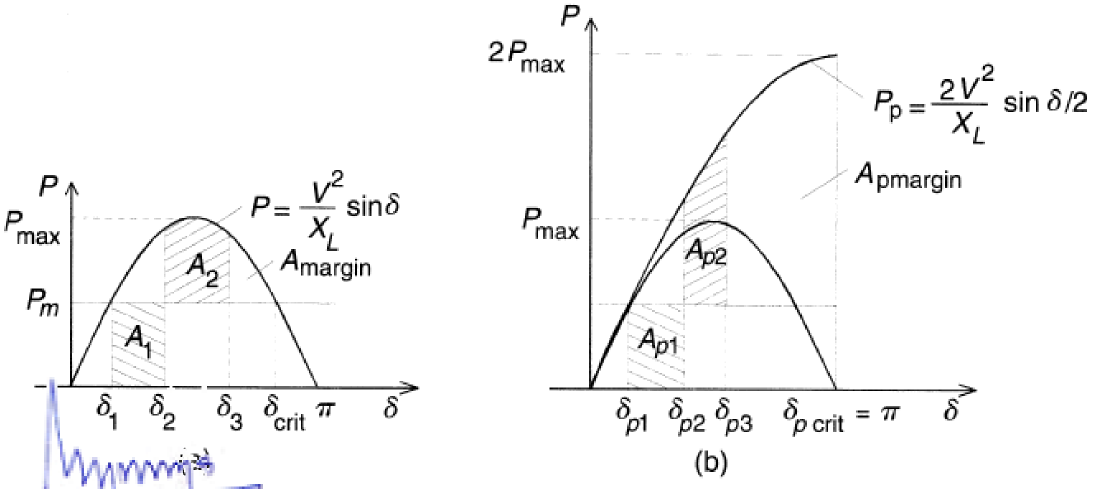
Improvement of Transient Stability……

- Assume that both the uncompensated and the compensated systems are subjected to the same fault for the same period of time.

- Prior to the fault both of them transmit power P_m(mechanical) at angles δ_1 and δ_{p1} respectively.

- During the fault, the transmitted electric power becomes zeros and the mechanical power constant.



)) Equal area criterion to illustrate the transient stability margin for a simple two machine without compensation (a), and with an ideal midpoint compensator (b).

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Improvement of Transient Stability……

- Results the sending-end generator accelerates from the steady state angles δ_1 and δ_{p1} to angles δ_2 and δ_{p2} .
- The accelerating energies are represented by areas A_1 and A_{p1}.

After fault clearing

- Electric power exceeds the mechanical input power and the sending end machine decelerates.
- The accumulated kinetic energy further increases until a balance between the accelerating and decelerating energies.
- Corresponding areas for energy balance is A_1 , A_{p1} and A_2 , A_{p2} and it is reached at δ_3 and δ_{p3}
- The constant P_m line over the intervals defined by angles δ_3 and δ_{crit} and δ_{pcrit} .

ermine the margin of transient stability, that is ,the "unused" nted by areas A_{margin} and $A_{pmargin}$.

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4.Power Oscillation Damping

In the case of an under-damped power system, any minor disturbance can cause the machine angle to oscillate around its steady-state value at the natural frequency.

The angle oscillation results in a corresponding power oscillation. Sufficient damping can be a major problem in some power systems and in some cases, it may be the limiting factor for the transmittable power. It is necessary the applied shunt compensation and thereby the of the transmission line, to counteract the accelerating swings of the disturbed machines.

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4.Power Oscillation Damping……

- When the rotationally oscillating generator accelerates and angle δ increases ($d\delta/dt > 0$), the electric power transmitted must be increased to compensate for the excess mechanical input power.

- Conversely, when the generator decelerates and angle δ decreases ($d\delta/dt < 0$), the electric power must be sed to balance the insufficient mechanical input

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Power Oscillation Damping……

Figure 11(a) shows the undamped and damped oscillations of angle δ around the steady-state value.

Figure 11(b) shows the undamped and damped oscillations of the electric power P around the steady-state value P.

Figure 11(c) shows the reactive power output Qo of the shunt-connected var compensator. The capacitive (positive) output of the compensator increases the midpoint voltage and hence the ed power when ($d\delta/dt > 0$) and it those when ($d\delta/dt < 0$).

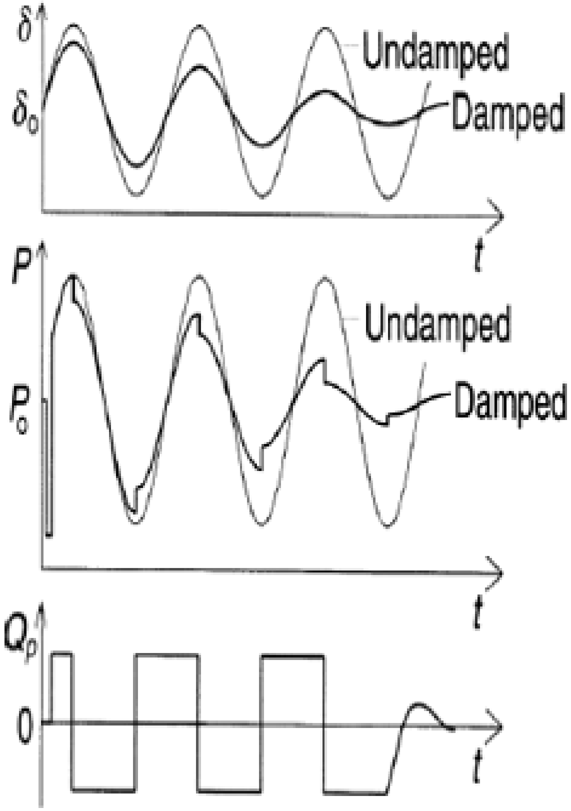

Fig.11 Waveforms illustrating power oscillation damping by reactive shunt compensation: (a) generator angle, (b) transmitted power and (c) var output of the shunt compensator.

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Different Shunt controllers are:-

(A)Variable Impedance based type:-

1. Thyristor Controlled Reactor (TCR)
2. Thyristor Switched Reactor (TSC)
3. Fixed Capacitor, Thyristor Controlled Reactor (FC-TCR)
4. Static Var Compensator (SVC)

(B)VSC based type

atic Synchronous Compensator
TATCOM)

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1. Thyristor Controlled 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.

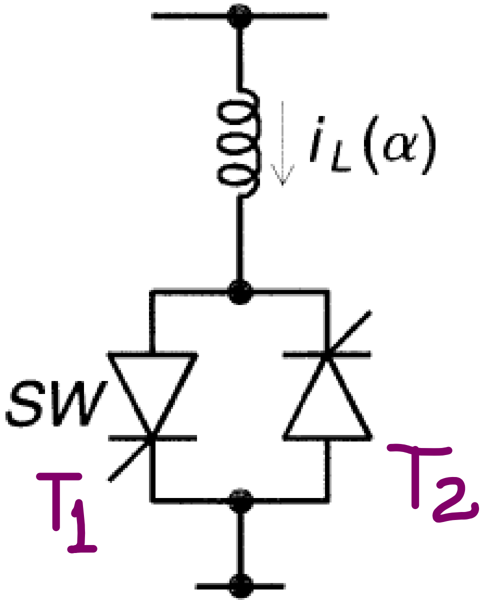

Fig. 12 Thyristor Controlled Reactor

- It can't be used alone, because of the inductive nature of power system load. It is normally used thyristor switched capacitor (TSC), to e the controlled reactive power generation.

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Figure 12 shows the 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).

- 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 ristor is used (thyristor valve).

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- A thyristor valve can be brought into conduction by simultaneous application of a gate pulse to all thyristors of the same polarity.

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.

e will automatically block immediately after the ac crosses zero, unless the gate signal is reapplied.

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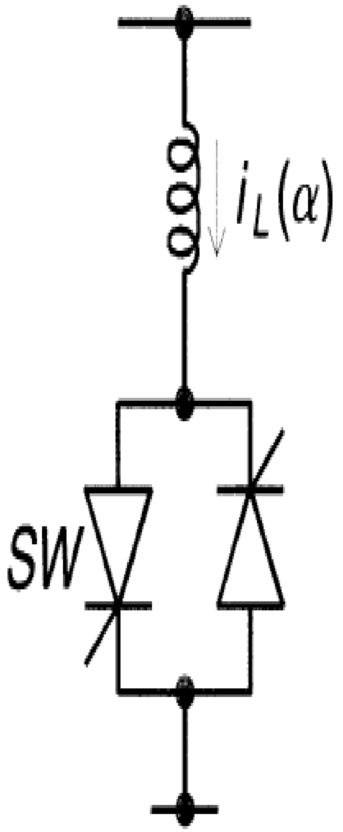
- Reactive power absorbed by TCR is proportional to the current flowing through inductor ($I_L(\propto)$).



- 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.

- g angle of TCR is varying from 90^0 to . It can't able to varying from 0^0 to unlike AC voltage controller.

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Thyristor Controlled Reactor (TCR)…..

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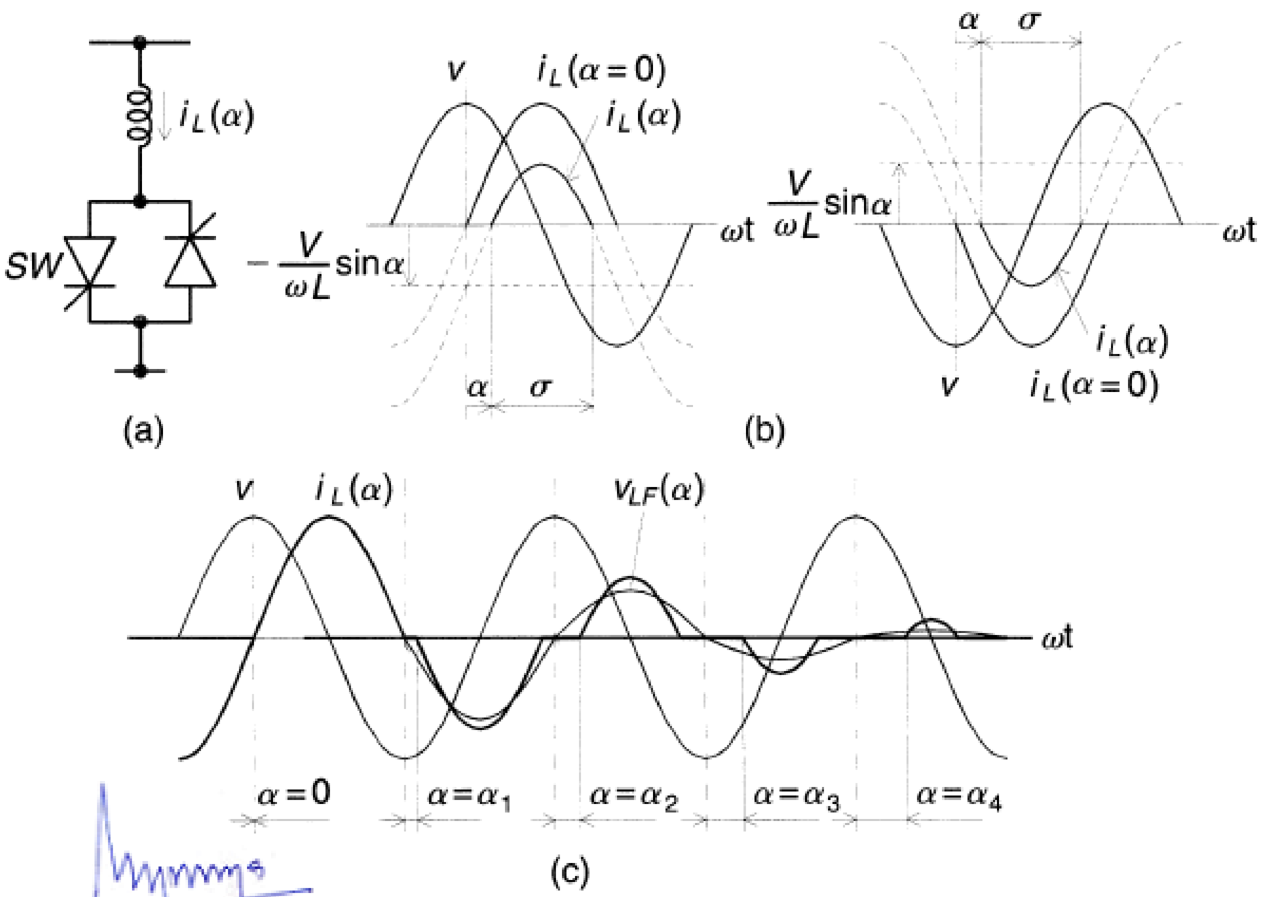
Positive half cycle

Negative half cycle



asic thyristor-controlled reactor (a), firing delay angle control (b) and operating ms (c).

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- The current in the reactor can be controlled from maximum (thyristor valve closed) to zero (thyristor valve open) by delaying the firing angle as shown in fig. 13
- 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 tion intervals is controlled.

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Current flowing through inductor when valve is conduction

Let applied voltage v(t) = V_m cos ωt

During positive half $i_L(\alpha) = \frac{1}{L} \int_{\alpha}^{\omega t} v(t)dt$

$$i_L(\alpha) = \frac{Vm}{\omega L}(\sin(\omega t)-\sin(\alpha))............(1)$$

This equation is valid only for at ωt varying from $\alpha \leq \omega t \leq \pi - \alpha$

From the expression is find that current is by an offset of - $\frac{V_m}{\omega L}$ sin(α)

arly for negative half cycle, the sign of the terms in
ion 1 becomes opposite.

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The delay angle is α, then the conduction angle $\sigma = 2\pi - \alpha$. Thus as the delay angle α 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 $\alpha = \frac{\pi}{2}$, the offset also reaches its maximum of $\frac{V_m}{\omega L}$, at which both the conduction angle and the reactor current become zero. It should be noted that the two parameters, delay angle α and conduction angle σ, are equivalent and therefore TCR can be characterized by either of them.

n of TCR current at α=0 and $\alpha=30^0$ are shown in fig. 14(b).

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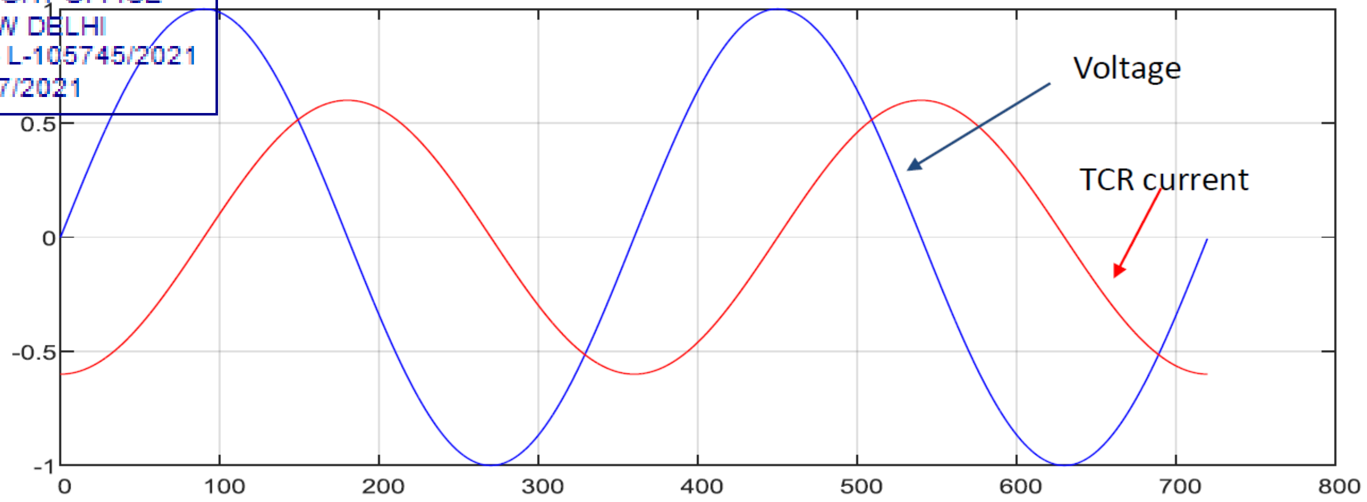

Fig. 14 (a)Firing angle α =0 (measured from peak of source voltage)

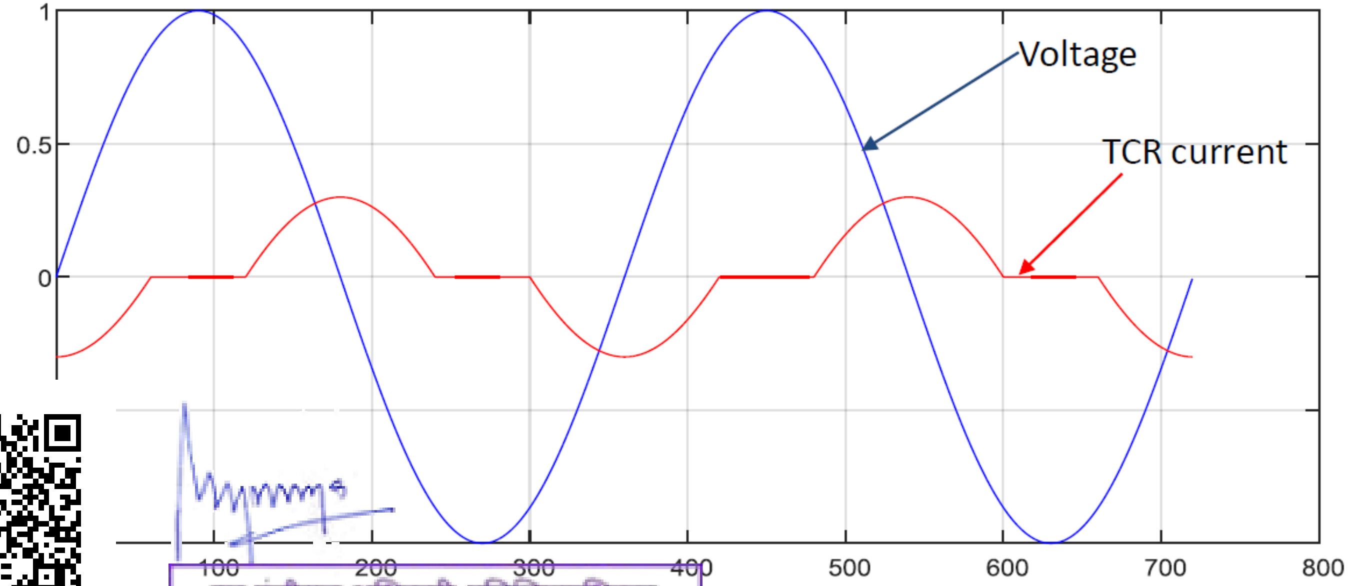

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Fig.14(b) Firing angle α = 30^0

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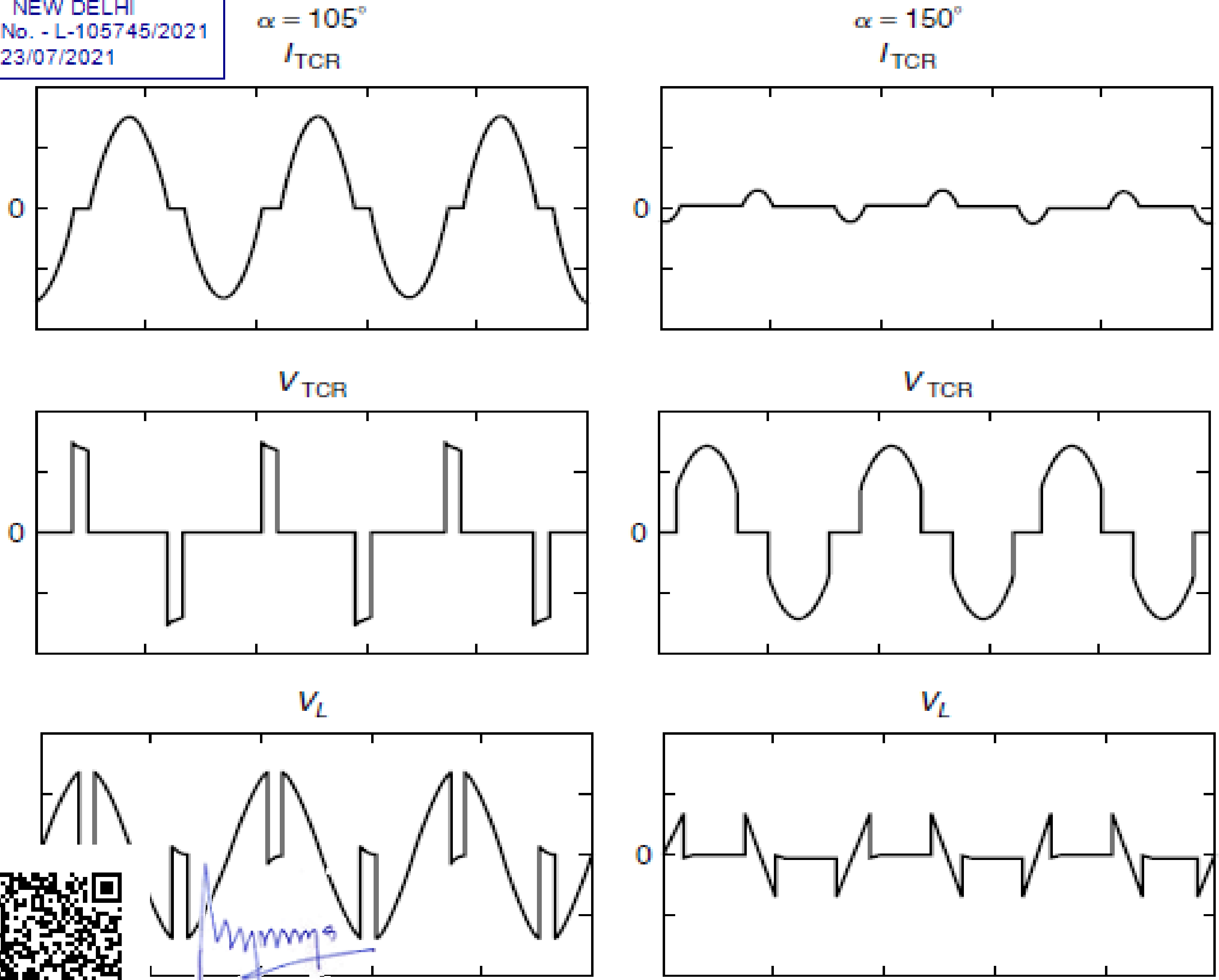

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Fig. 15 Current and voltages for different α in a TCR.

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Reactor current in positive half cycle is $i_L(\omega t)$ = $\frac{Vm}{\omega L}$ (sin (ωt)-sin(α)) when $\alpha\ \leq \omega t \leq\ \pi$ - α and otherwise zero.

Now find the fundamental component by using Fourier 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)

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

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

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

After simplification

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

Therefore

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

Peak Current

$$i_{L1m}(\alpha) = \frac{V_m}{\omega L}\left(1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin(2\alpha)\right)$$

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

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

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 $\alpha = \frac{\pi - \sigma}{2}$

$$B_L = B_{Lmax}\left(\frac{\sigma}{\pi} - \frac{\sin\sigma}{\pi}\right)$$

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Thyristor Controlled Reactor (TCR)…….

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

$\alpha \uparrow \Rightarrow$ TCR admittance $(B_L) \downarrow \Rightarrow \mathrm{I}_{L1}(\alpha\ ) \downarrow \Rightarrow$ Reactive power absorbed $\downarrow$

$\alpha \downarrow \Rightarrow$ TCR admittance $(B_L) \uparrow \Rightarrow \mathrm{I}_{L1}(\alpha\ ) \uparrow \Rightarrow$ Reactive power absorbed $\uparrow$

arying firing angle (α) smooth control of reactive bsorption is achieved by TCR.

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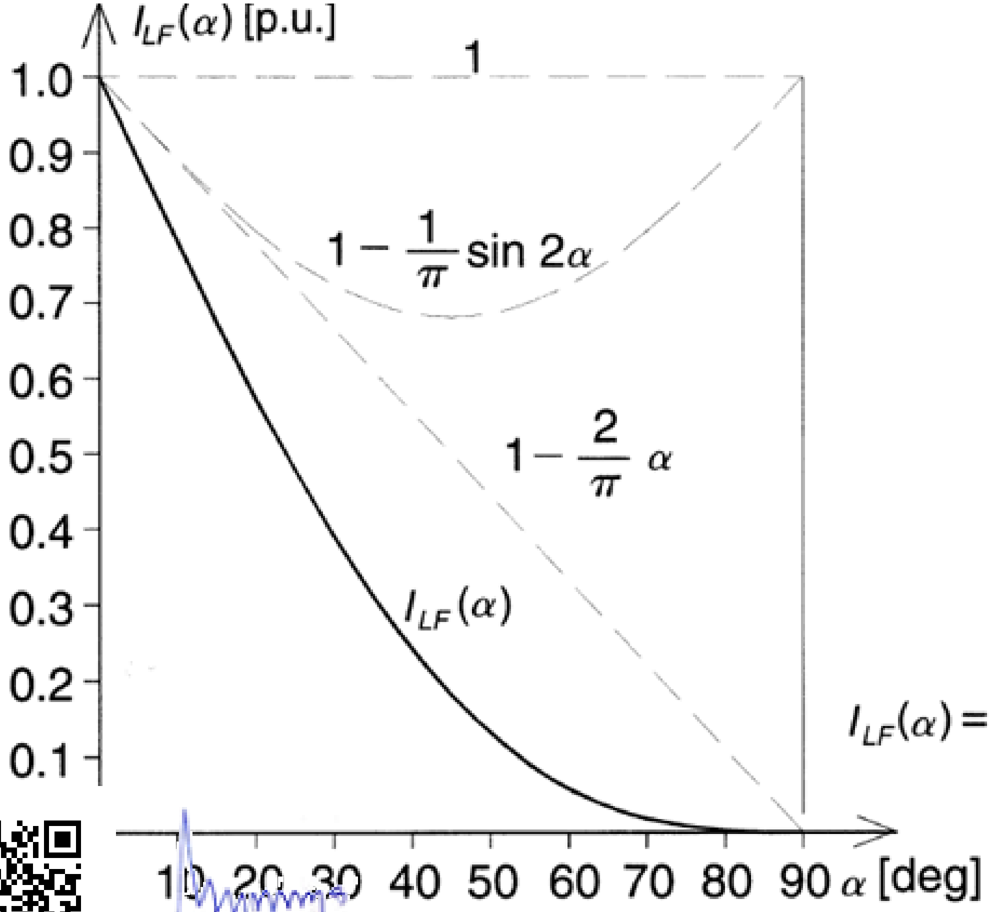
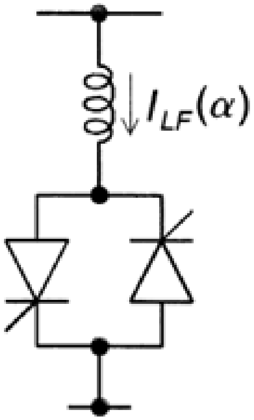
Thyristor Controlled Reactor (TCR)…….





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

Amplitude variation of the fundamental TCR current with the delay angle α

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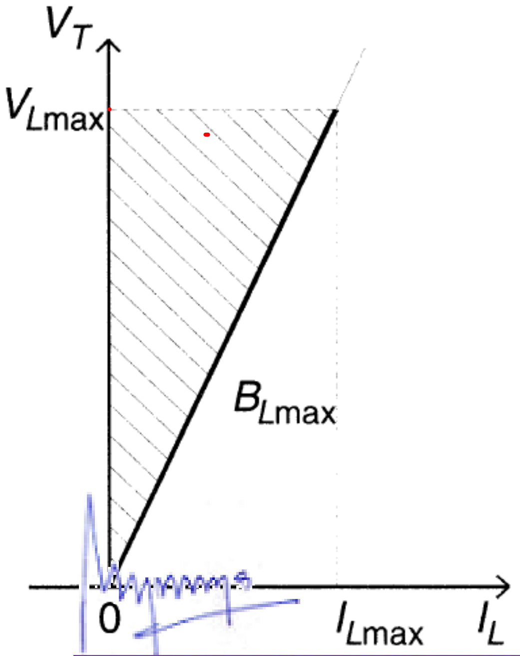
In practice, the maximal magnitude of the applied voltage and that of the corresponding current will be limited by the ratings of the power components (reactor and thyristor valve) used.

A practical TCR can be operated anywhere in a defined V-I area shown in fig. 17, 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

Fig. 17 V-I characteristics of TCR

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- If the TCR switching is restricted to a fixed delay angle, usually α= 0, then it becomes a thyristor-switched reactor(TSR) (it have only two option either fully on or fully off). V-I characteristics of TSR is shown in fig.18.
- 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

tion with TCR

admittance of reactor

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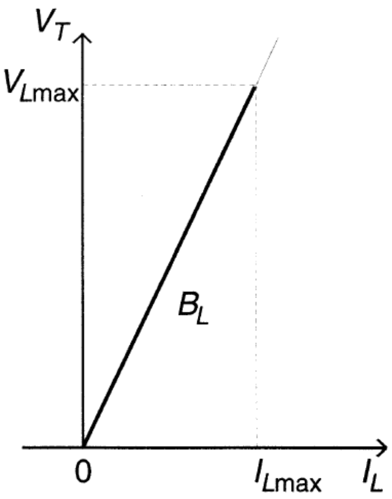

Fig. 18. V-I characteristics of TSR

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- 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

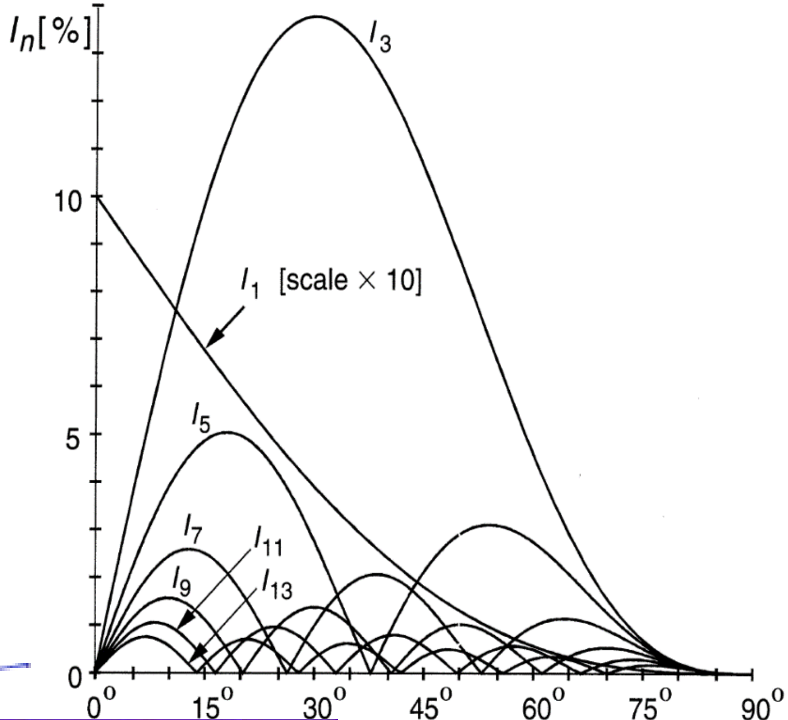

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Fig. 19 TCR current harmonic spectrum

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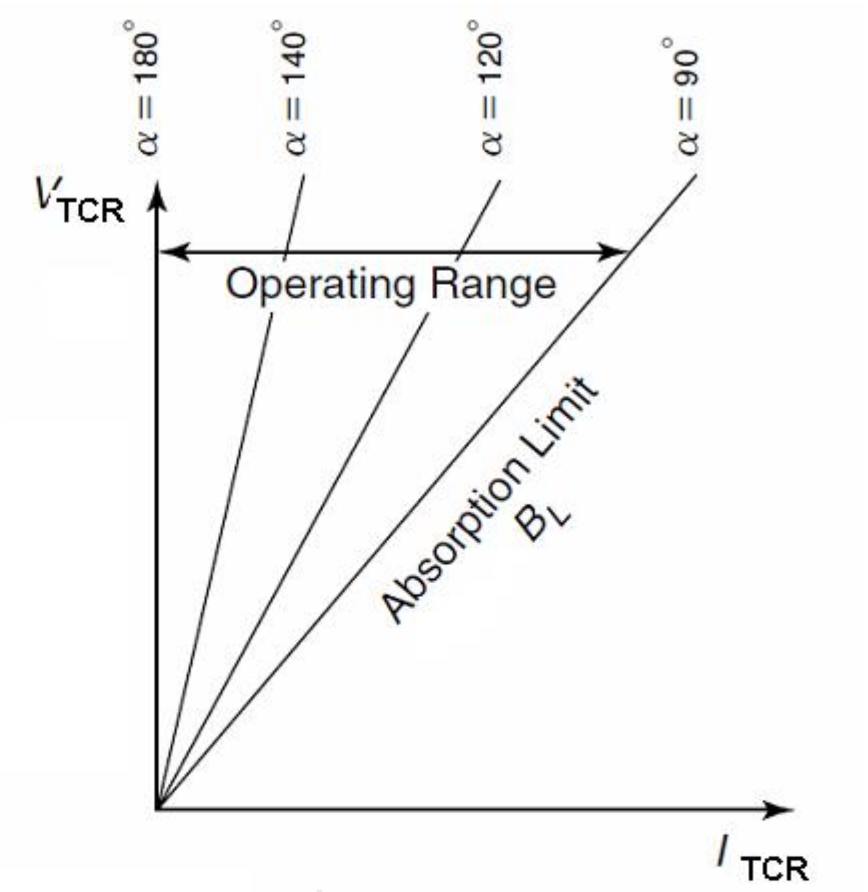
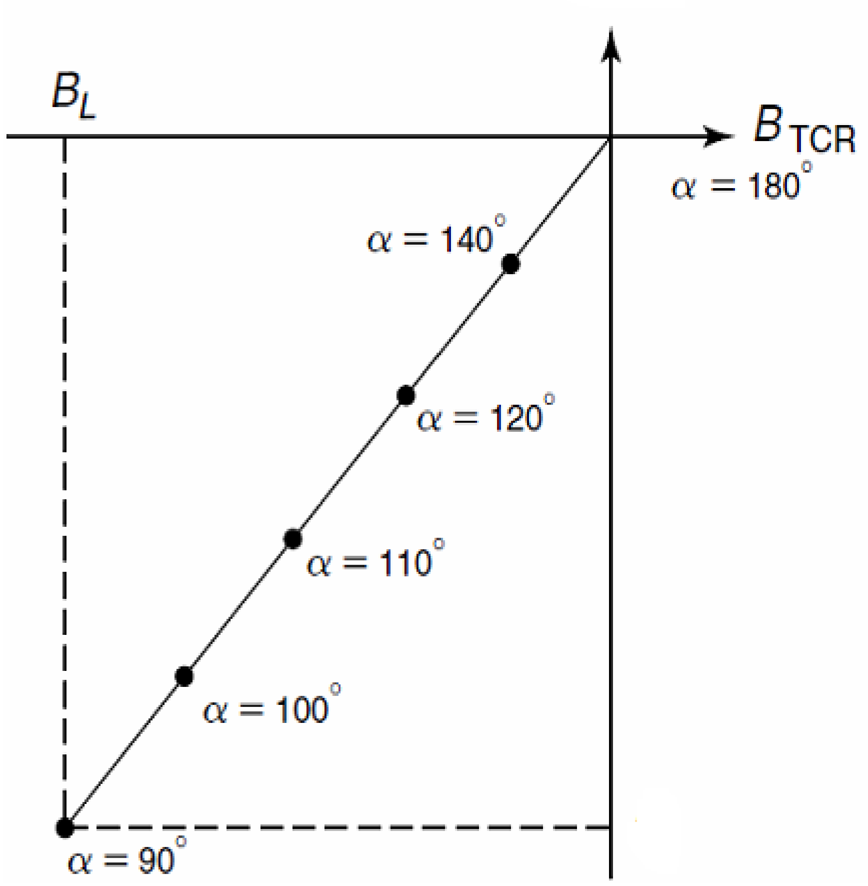
TCR operating Characteristic





. TCR v-I Characteristic

Fig. 21.TCR susceptance characteristic

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- In a three-phase system, three single-phase thyristor-controlled reactors are used, usually in delta connection as shown in fig.22
- 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 across one of the reactors igh voltage across reactor is ted by the other reactor.

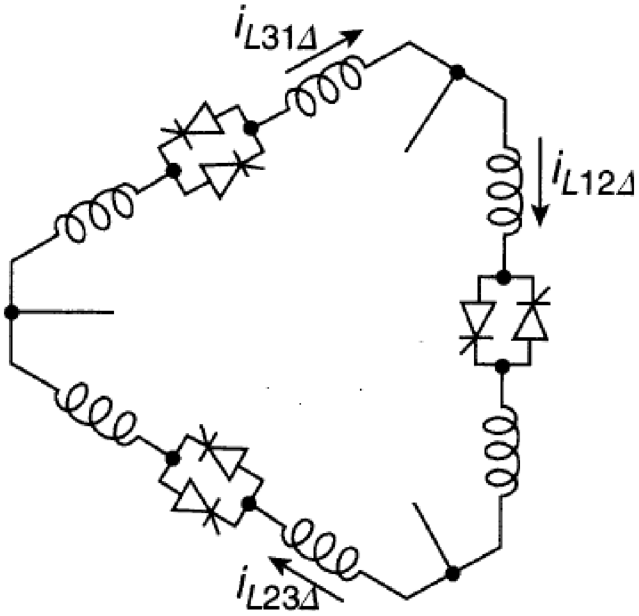

Fig. 22. Three phase delta connected TCR

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- 6 pulse TCR have the all non-triplen 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 4,48… pulse transformers

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

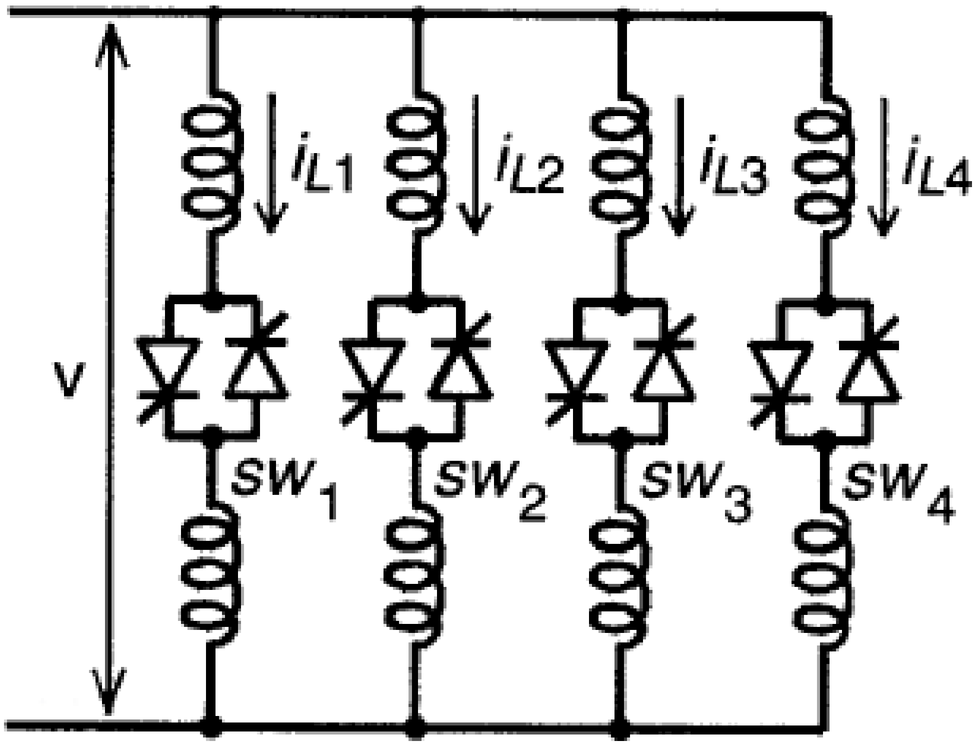

Fig. 23. $i_{Ltotal} = i_{L1} + i_{L2} + i_{L3} + i_{L4}$

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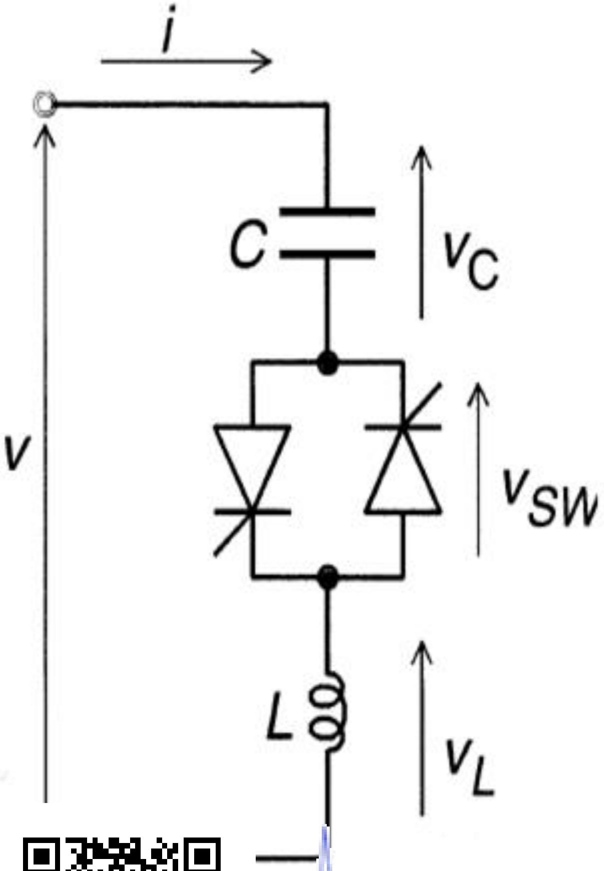
2. Thyristor Switched Capacitor



A single phase thyristor switched capacitor (TSC) is shown in figure 24. It 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 under abnormal operating (e.g. control malfunction causing capacitor switching at a "wrong time," when transient free switching conditions are not satisfied) it may also be used to avoid resonances with the ac system impedance at particular frequencies.

Under steady state conditions, when the thyristor valve is closed and the TSC branch is connected to a sinusoidal ac voltage source, v =V sin ωt, the current in the branch is given by

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

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Under steady state condition, when the thyristor valve is closed

For a given voltage

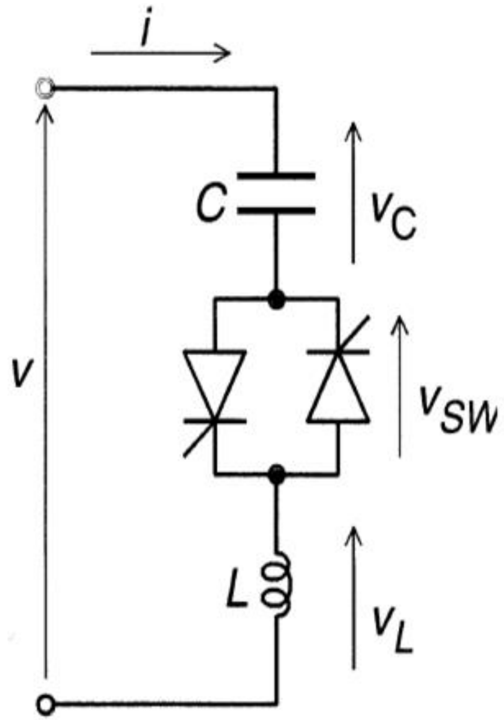
v =V sin ωt

Voltage across capacitor V_c =V sin $\omega t \frac{1/j\omega C}{j\omega L + 1/j\omega C}$

$$V_c = V \sin \omega t \left(\frac{1}{1-\omega^2 LC}\right)$$

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

$$V_c = V \sin \omega t \left(\frac{1}{1-\frac{1}{n^2}}\right)$$



does not affect circuit operation but it is just there to control ren

ude of the voltage across the capacitor is

$$V_c = V \sin \omega t \left(\frac{n^2}{n^2-1}\right)$$

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Thyristor Switched Capacitor……

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 and consequently, the voltage across the non conducting thyristor valve varies between zero and the peak-to-peak value of the applied ac voltage,

The amplitude of the voltage across the capacitor is

$$V_C = \frac{n^2}{n^2 - 1} V$$

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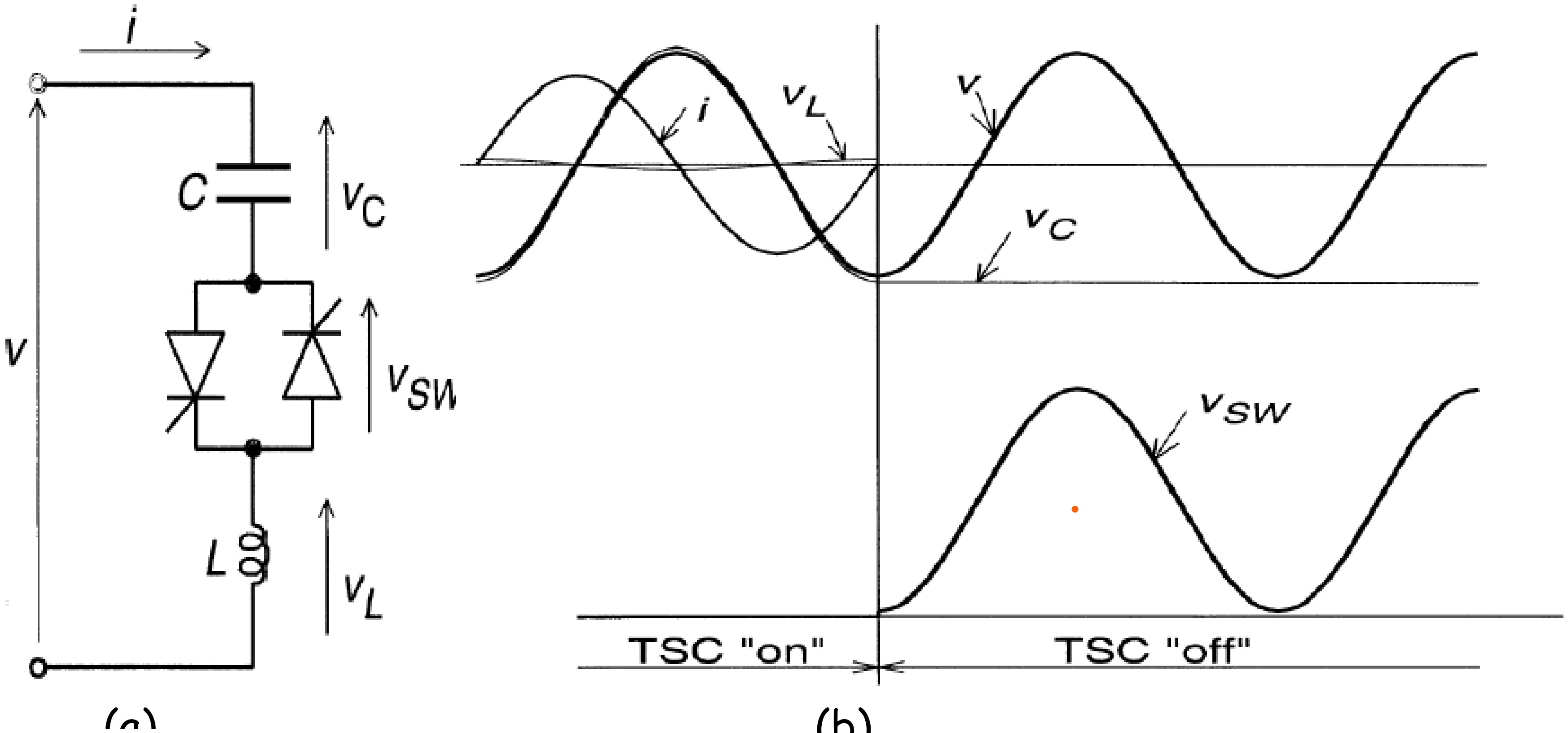
Thyristor Switched Capacitor……



(a)

(b)

N --→ Capacitor C gets connected

FF --→ Capacitor C gets disconnected

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ig.25. Basic thyristor-switched capacitor (a) and associated waveforms (b).

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Thyristor Switched Capacitor…….

If the voltage across the disconnected capacitor remain unchanged the TSC bank could be switch in again without any transient at the appropriate peak of the applied AC voltage for (a) positively and (b)negatively ed capacitor as shown ure 26.

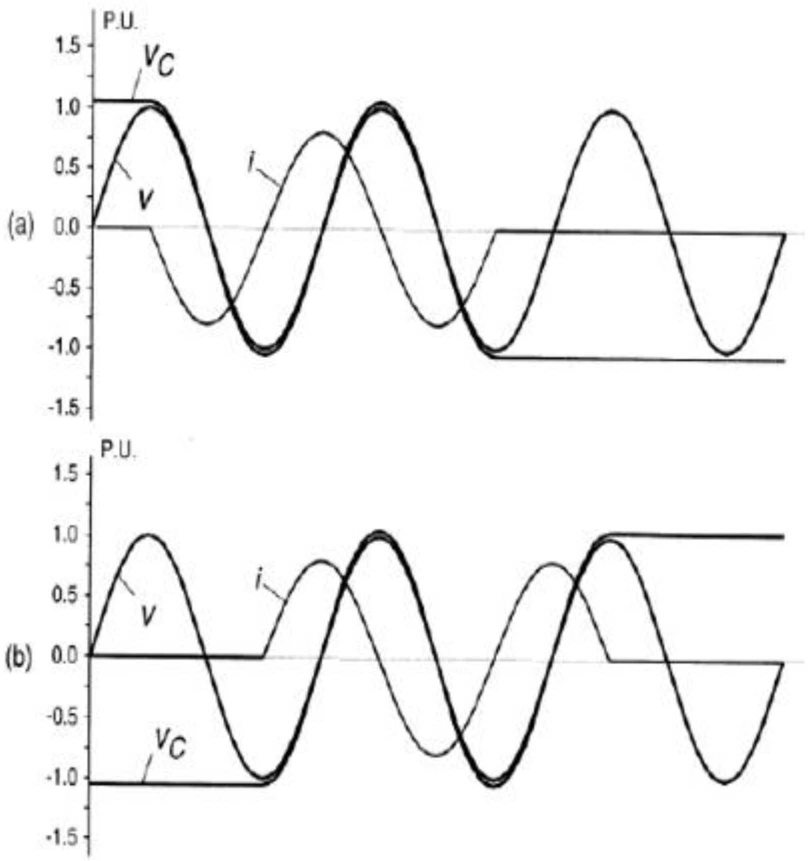

Fig. 26 Waveforms illustrating transient-free switching by a thyristor switched capacitor.

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Thyristor Switched Capacitor…….

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 Vc. 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. Figure 27(a) and (b) the switching transients ith a fully and a partially capacitor

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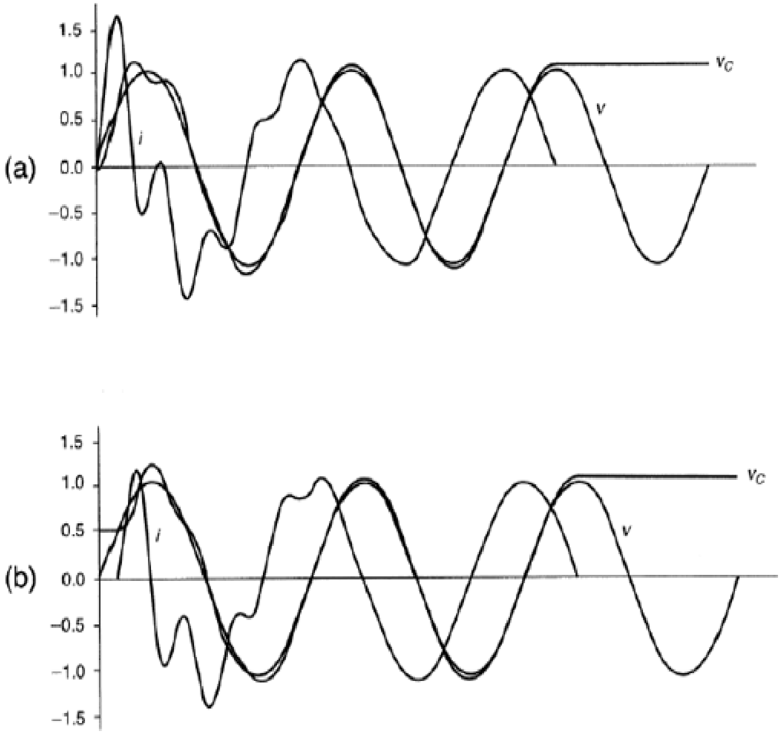

Fig 27. Waveforms illustrating the switching transients with the thyristor switched capacitor fully (a) or partially discharged (b).

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Thyristor Switched Capacitor…….

These transients are caused by the nonzero dv/dt at the instant of switching. which, without the series reactor, would result in an instantaneous current of ic = C dv/dt in the capacitor. (This current represents the instantaneous value of the steady- state capacitor current at the time of the switching.) The interaction between the capacitor and the current (and di/dt) limiting reactor, with the damping resistor, produces scillatory transients visible on the current and e waveforms.

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Thyristor Switched Capacitor…….

The conditions for "transient-free" switching of a capacitor are summarized in Figure 28 . As seen, two simple rules cover all possible cases:

(1) if the residual capacitor voltage is lower than the peak ac voltage (Vc < V), then the correct instant of switching is when the instantaneous ac voltage becomes equal to the capacitor voltage; and

(2) if the residual capacitor voltage is equal to or higher than the peak ac voltage, (Vc > V), then the correct

ng is at the peak of the ac

at which the thyristor valve

is minimum.

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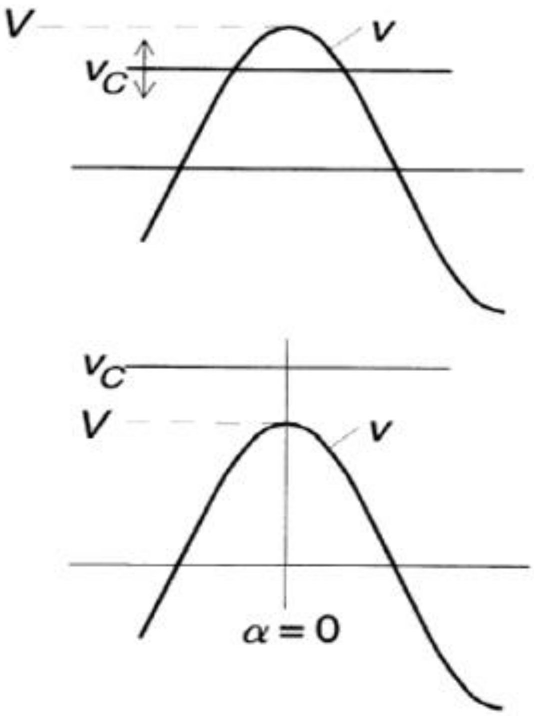

Fig. 28. Conditions for "transient-free" switching for the thyristor-switched capacitor with different residual voltages.

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Thyristor Switched Capacitor…….

- 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 active current it draws (maximum or zero).

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Thyristor Switched Capacitor……

The current in the TSC branch varies linearly with the applied voltage according to the admittance of the capacitor as illustrated by the V-I plot in figure 29.

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 may be employed.

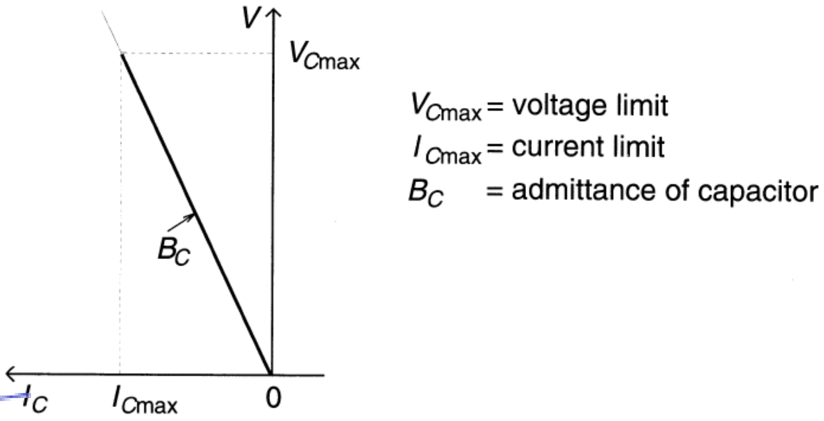

Fig. 29. Operating V-I area of a single TSC.

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3.Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR)

A basic var generator arrangement using a fixed (permanently connected) capacitor with a thyristor-controlled reactor (FC-TCR) is shown functionally in Figure 30.

The current in the reactor is varied by the method of firing delay angle control.

The capacitor always generates the fixed amount of reactive power.

So TCR will absorb the excess reactive power

l manner by varying firing angle.

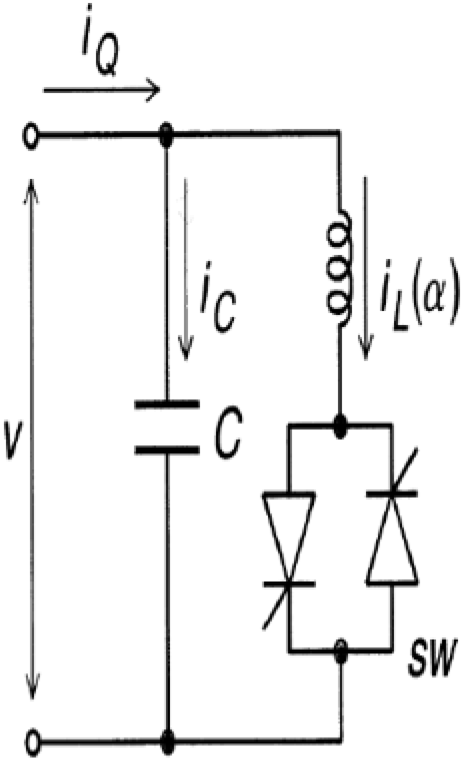

Fig. 30. Basic FC-TCR type static var generator

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Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR).....

- During light load condition the transmission system, it self have the higher reactive power (leading PF).
- So to make unity p.f or better operation of FC-TCR, the TCR rating should be higher than fixed capacitor.
- Normally the capacitors are connected in star format.
- The fixed capacitors having a small inductance in series, hence it acting as passive LC filter.

lter provide capacitive impedance at fundamental ency and generate reactive power in to the system.

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Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR).....

- The LC filter provide lower impedance to selected harmonics (dominant harmonics produced by the TCR) such as 5th, 7th 11th ......

- Each capacitors tuned for different frequency.

- Additional to this LC filter and LC high pass filter also connected with the system as shunt format.

- The fixed capacitor, thyristor-controlled reactor type Var generator may be considered essentially to consist of a variable reactor (controlled by delay angle α) and fixed capacitor.

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Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR).....

- Figure 31 shows the characteristics of FC-TCR.The constant capacitive Var generation (Qc) of the fixed capacitor.
- Variable Var absorption(Q_L) of the thyristor controlled reactor.
- Total Var output(Q) (SVC generation).
- At the maximum capacitive Var output, the thyristor controlled reactor is off ($\alpha = 90^0$ (w.r.t voltage peak))
- ease the capacitive output, the in the reactor is increased by ng the delay angle α.

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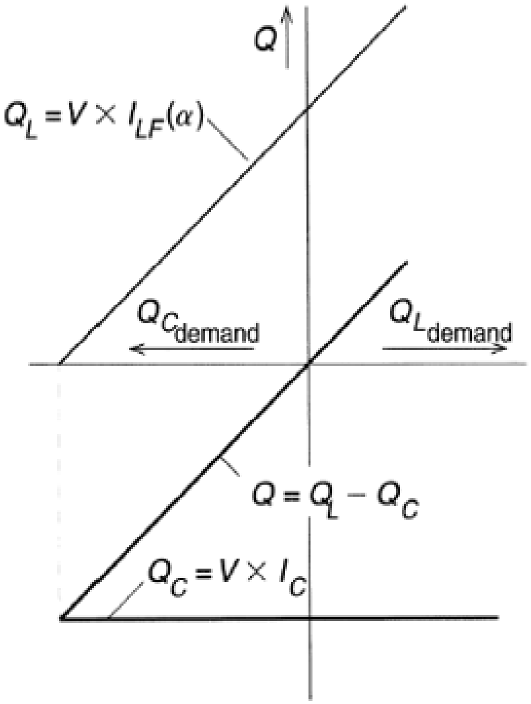

Fig. 31. FC-TCR characteristics

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Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR).....

- At zero Var output, the capacitive and inductive currents are equal (capacitor and inductive Var is cancel out).

- To make net output is inductive Var (inductive current becomes larger than the capacitive current) by further decrease of angle α (assuming that the rating of the reactor is greater than that of the capacitor).

- At zero delay angle, the TCR conducts current over the full 180 degree interval, resulting in maximum inductive Var output.

- It is equal to the difference between the Vars generated by the r and those absorbed reactor.

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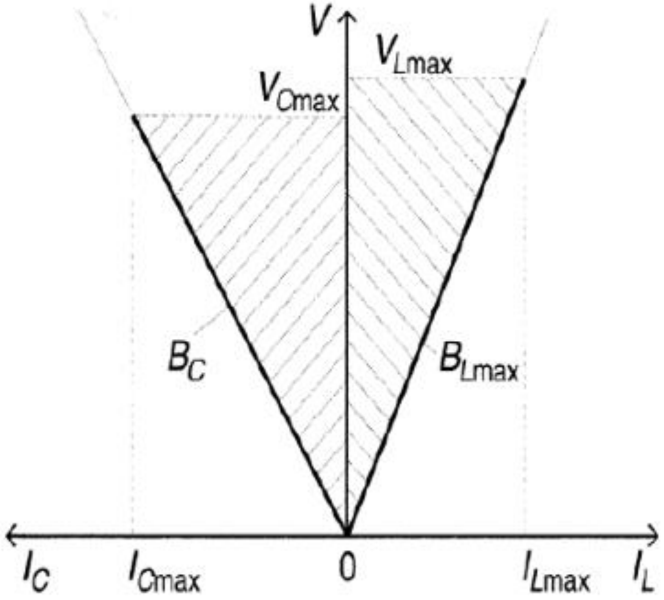
Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR).....



V_{Lmax} = Voltage limit for TCR

V_{Cmax} = Voltage limit for capacitor

I_{Lmax} = Current limit of TCR

I_{Cmax} = Current limit of capacitor

B_{Lmax} = Maximum admittance of TCR

B_c = admittance of capacitor

V-I operating area of the FC-TCR Var generator

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FC-TCR Loss

In practical application additional to dynamic performance, loss also have the important.

In the FC-TCR type Var generator, there are three major elements of the losses encountered

1. Capacitor (or capacitive filter) losses(there are relatively small but constant).
2. Reactor losses(these increase with the square of the current).
3. Thyristor losses(these increase almost linearly with the current).

the total losses increase with TCR current and equently, decrease with increasing capacitive Var ut.

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FC-TCR Loss....

- Figure 33 shows the loss versus var output characteristic of the FC-TCR type static var generator.
- This type of loss characteristic is advantageous when the average capacitive var output is relatively high as, for example, in industrial applications requiring power factor correction.

- It is that disadvantageous when the average var output is low, as mple, in the case of compensation of power ion systems.

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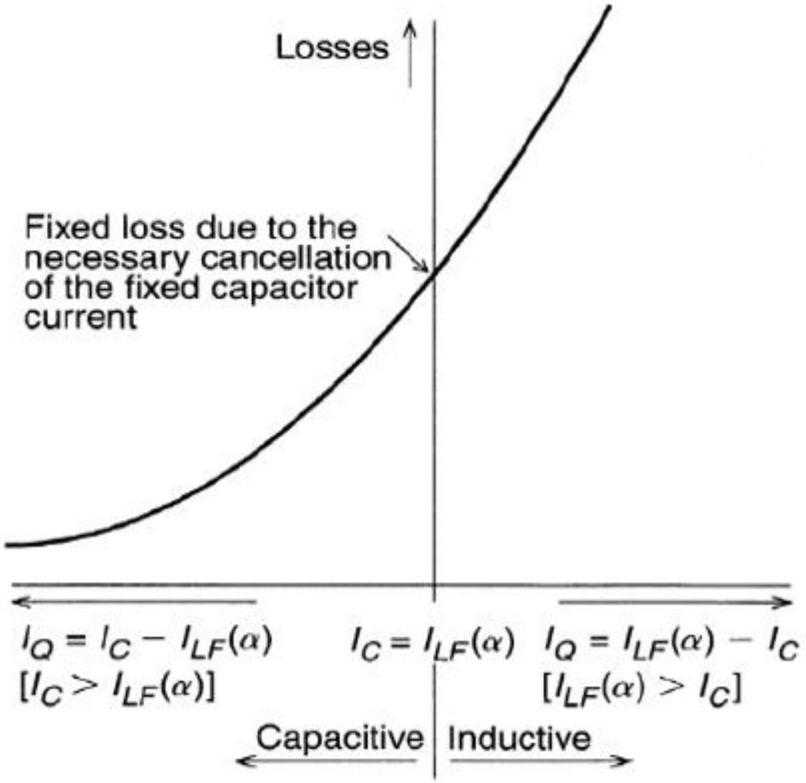

Fig. 33. Loss versus var output characteristic of the FC-TCR type static var generator

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4.SVC(TSC-TCR)

Figure 34 shows the TSC-TCR Var Generator.

The thyristor-switched capacitor, thyristor-controlled reactor (TSC-TCR) type compensator was developed for dynamic compensation with minimized standby losses and increased operating

.

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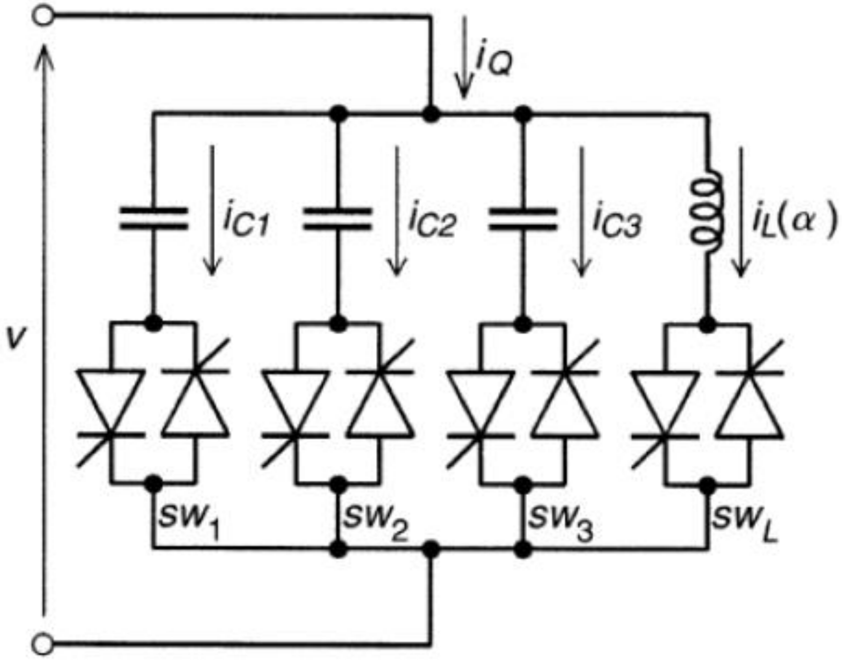

Fig. 34. TSC-TCR Var Generator

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SVC(TSC-TCR)....

- A basic single-phase TSC-TCR typically consists of n TSC branches and one TCR.
- The number of branches, n is determined by practical considerations that include the operating voltage level, maximum Var output, current rating of the thyristor valves, etc.
- The inductive range also can be expanded to any um rating by employing additional TCR or TSR ented TCR) branches.

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SVC(TSC-TCR)……

- The total capacitive output range is divided into n intervals.
- In the first interval, the output of the Var generator is controllable in the 0 to Q_{cmax}/n range, where Q_{cmax} is the total rating provided by all TSC branches.
- In this interval, one capacitor bank is switched ON and simultaneously the current in the TCR is set by the appropriate firing delay angle.
- So that the sum of the Var output of the TSC and that of the TCR equals the capacitive output required.
- In the second, third… and n^{th} intervals, the output is controllable in $_{cmax}$/n to $2Q_{cmax}$/n , $2Q_{cmax}$/n to $3Q_{cmax}$/n,……and (n-1) Q_{cmax}/n $_{max}$

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SVC(TSC-TCR)……

In all interval surplus reactive power absorbed by using the TCR. So theoretically, the TCR should have the same Var rating as the TSC. But the switching conditions at the endpoints of the intervals are not intermediate, so the Var rating of the TCR has to be somewhat larger in practice that of one TSC in order to provide enough overlap (hysteresis) between the switching in and switching out Var levels. The ve Var output is changed in a step like manner TSCs.

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SVC(TSC-TCR)……

- Approximate the Var demand with a net capacitive Var surplus and the relatively small inductive Var output of the TCR, Q_L is used to cancel the surplus capacitive vars.

- The rating of the reactor is kept relatively small (1/n times the maximum capacitive output). Figure 35 shows Var demand versus Var output characteristic he TSC-TCR type Var ato

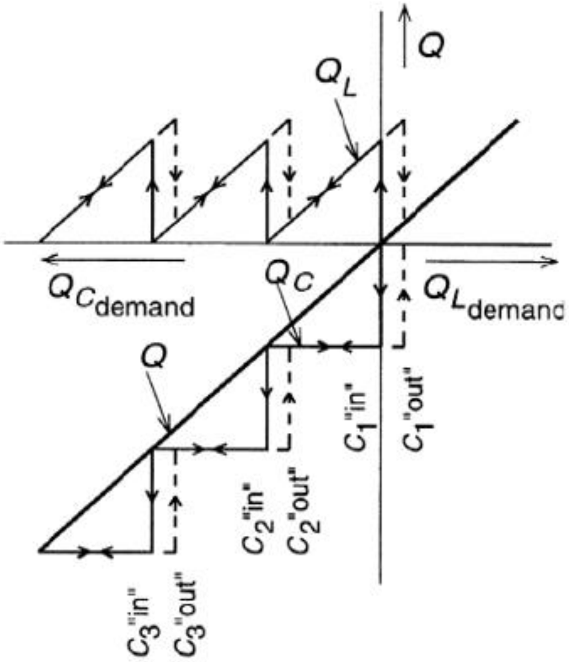

Fig.35. Var demand versus Var output characteristic of the TSC-TCR type Var generator

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SVC(TSC-TCR)......

Control scheme for the TSC-TCR type of generator have to provides three functions

1.Determines the number of TSC branches needed to be switched in to approximate the required capacitive output current and computes the amplitude of the inductive current needed to cancel the surplus capacitive current.

2. Fig. 36.Control Scheme of TSC-TCR static Var generator. Controls the switching of the TSC branches in a "transient free" manner.

the current in the TCR by firing delay angle

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SVC(TSC-TCR)......

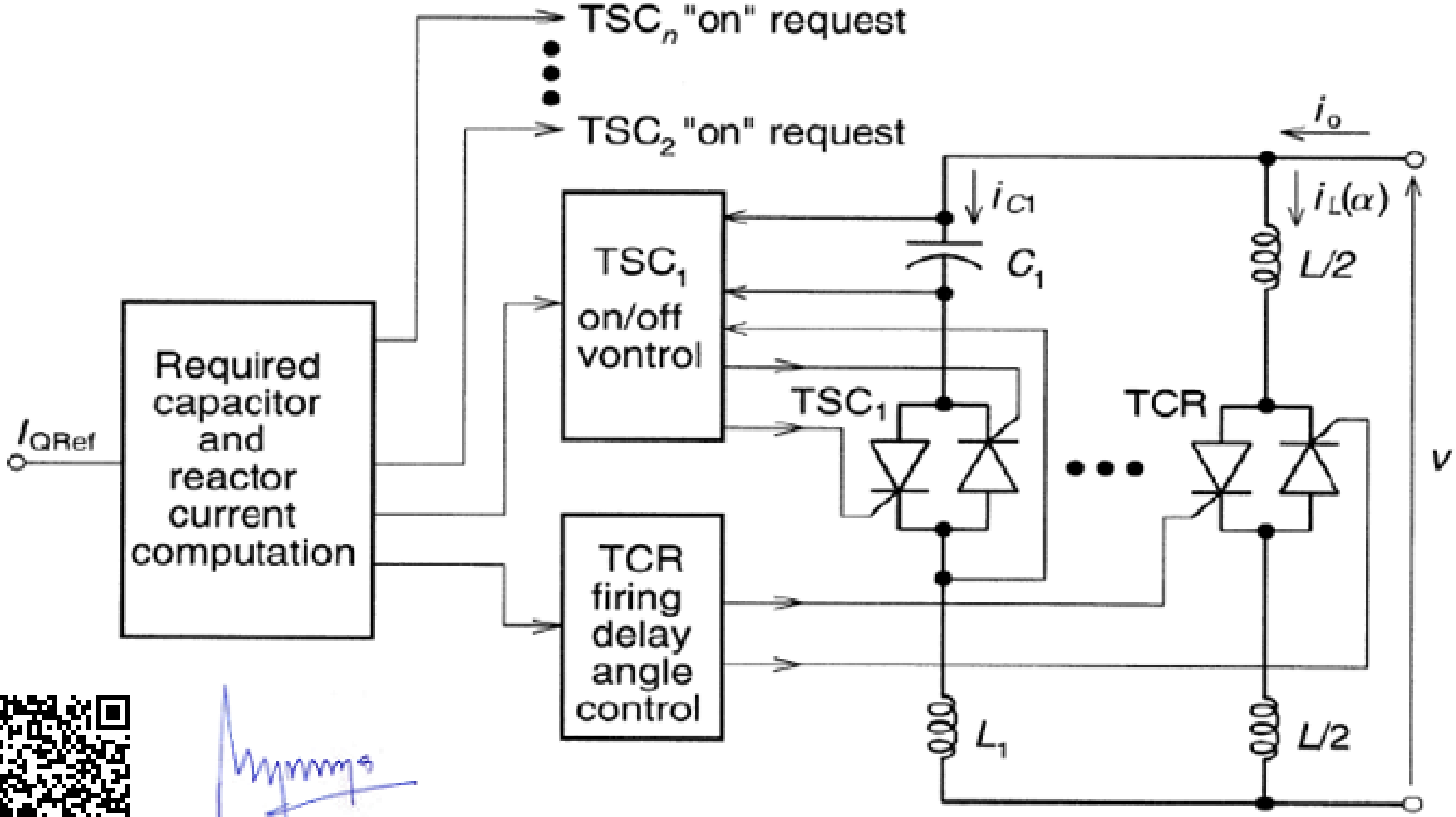

Fig. 36.Control Scheme of TSC-TCR static Var generator

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SVC(TSC-TCR)……

- **Determines the number of TSC branches needed to be switched**

In figure 36 the input current reference I_{Qref} representing the magnitude of the requested output current. Find the ratio of current reference (I_{Qref}) to current(I_c) that a TSC branch would draw at the given amplitude V of the ac voltage. The result, rounded to the next higher integer gives the number of capacitor banks needed (TSC).

- **Computes the amplitude of the inductive current needed to cancel the surplus capacitive current**

The difference in magnitude between the sum of the activated capacitor $\sum I_{cn}$ and the reference current I_{Qref} gives the amplitude $I_{LF}(\alpha)$ of amental reactor current required.

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SVC(TSC-TCR)……

Switching of the TSC branches in a "transient-free" manner

Switching of the TSC branches follows the two simple rules for "transient free" switching summarized in TSC discussion.

- That is either switch the capacitor bank, when the voltage across the thyristor valve becomes zero or when the thyristor valve voltage is at a minimum.(The first condition can be met if the capacitor residual voltage is less than the peak ac voltage and the latter condition is satisfied at those peaks of the ac voltage which has the same polarity as the residual voltage of the capacitor).
- ird function (TCR firing delay angle control) is identical to that the fixed capacitor, thyristor controlled-reactor scheme.

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SVC(TSC-TCR).....

V_{sw} is one when voltage across the thyristor is zero
V_{Pol} signal is one when the polarity of V_c and polarity of V are same
P_T (sync) is one when source voltage reaches its peak

Cause 1

TSC is on when, ON request is 1 and V_{sw} is 1.

Cause 2

TSC is on when, ON request is 1, V_{Pol} is 1

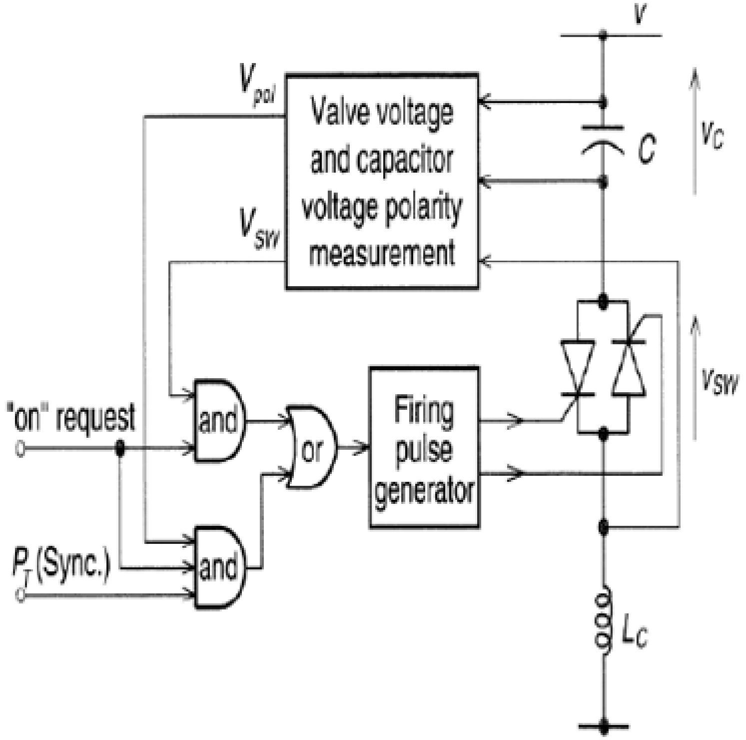

Fig.37. Control scheme for switching the TSC branches in a "transient-free" manner

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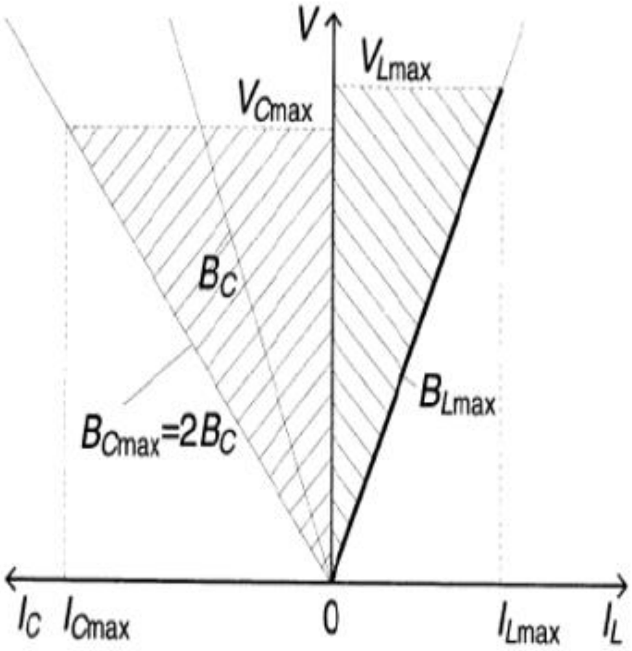
SVC(TSC-TCR)…..



V_{Lmax} = Voltage limit for TCR

V_{Cmax} = Voltage limit for capacitor

I_{Lmax} = Current limit of TCR

I_{Cmax} = Current limit of capacitor

B_{Lmax} = Maximum admittance of TCR

B_c = admittance of capacitor

3. The V-I operating area of the TSC-TCR Var
ator.

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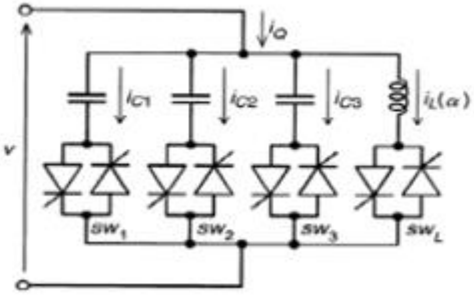
Losses versus Var output characteristic of the TSC-TCR type Var generator



- At a slightly below zero var output, all capacitor banks are switched out, the TCR current is zero or negligibly small and consequently the losses are zero or almost zero.

- As the capacitive output is increased, an increasing number of TSC banks are switched in with the TCR absorbing the surplus capacitive vars.

- Each switched-in TSC bank, the losses e by a fixed amount.

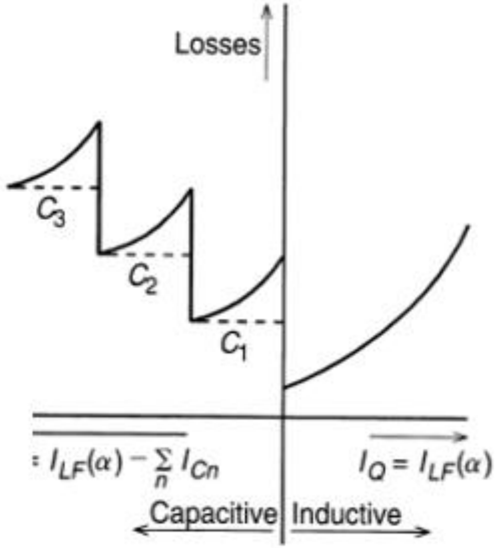


Fig.39. Loss versus var output characteristic of the TSC-TCR type static var generator.

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SVC(TSC-TCR)……

The advantages of TSC-TCR type SVC over FC-TCR type

- The reduction in the reactor size and consequently the harmonics generated.
- Greater flexibility in control
- Better performance under system fault condition.
- The power losses in the quiescent operating condition SVC output current close to zero) also tend to with TSC-TCR type SVC.

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Thank You !

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