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ANNAMACHARYA INSTITUTE OF TECHNOLOGY AND SCIENCES TIRUPATI -517520

SUBJECT: FACTS

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BRANCH : **EEE**

FACULTY NAME : **S.JAREENA**

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Prerequisites & Books

1. Power Electronics
2. Electrical Power Transmission & Distribution
3. Power System Operation & Control

TEXT BOOK:
"***Understanding FACTS: Concepts & Technology of Flexible AC Transmission Systems***" By N.G.Hingorani & L.Gyugyi, IEEE Press, Standard Publishers Distributors, Delhi.

Reference Book:
1) Facts Controllers in Power Transmission & Distribution by K.R.Padiyan, New Age International.
2) Modelling & Simulation in Power Networks, Enrique Acha, Clandio Esquival & H.A.Perez,CA Camcho, John Wiley & Sons.

UNIT-I

CONCEPTS OF FLEXIBLE AC TRANSMISSION SYSTEMS

Transmission Interconnections

- Most of the world's electric power systems are widely interconnected
- Interconnected transmission lines- Grid
- Interconnections – Inside utilities' own territories
  - Inter utility
  - Inter regional
  - International

Transmission Interconnections

- Economic Reasons
  - -To reduce the cost of electricity
  - -To improve reliability of power supply
- Diversity of loads
- Availability of sources
- Fuel Price
- Reduction of cost of electricity

Transmission Interconnections

- If a power delivery system is made up of radial lines from individual local generators without any interconnection

- More generators are required
- Cost will be high
- Less reliable
- More reserve capacity

Transmission Interconnection in India

- State Grids- Interconnection in state owned power plants - e.g OPTCL- 400,220,132kV
- State Grids Interconnected to form regional grids- ER,NR,SR,WR and NER
- National GRID
- International connections

Opportunities for FACTS

- **FACTS** is defined by IEEE as: AC transmission systems incorporating power electronic based static controllers to enhance controllability and increase power transfer capability.

- **FACTS** controllers are designed to overcome the limitations of the present mechanically controlled ac power transmission systems by using reliable, high speed power electronic controllers.

Opportunities for FACTS

- $P = V1.V2 / X.\sin\delta$
- Conventionally there is no high speed control over these parameters.
- Phase angle control is rarely utilised by means of slow mechanical phase shifters.
- Tap changers, reactors and capacitors are generally mechanically switched are "**slow**" methods.
- There is no control for line impedance.

Opportunities for FACTS

- For controlling power
- For enhancing the usable capacity of the present transmission lines

As FACTS controllers control: Series Impedance, Shunt Impedance, Current, Voltage, Phase Angle and Damping of Oscillations

POWER FLOW IN PARALLEL PATHS

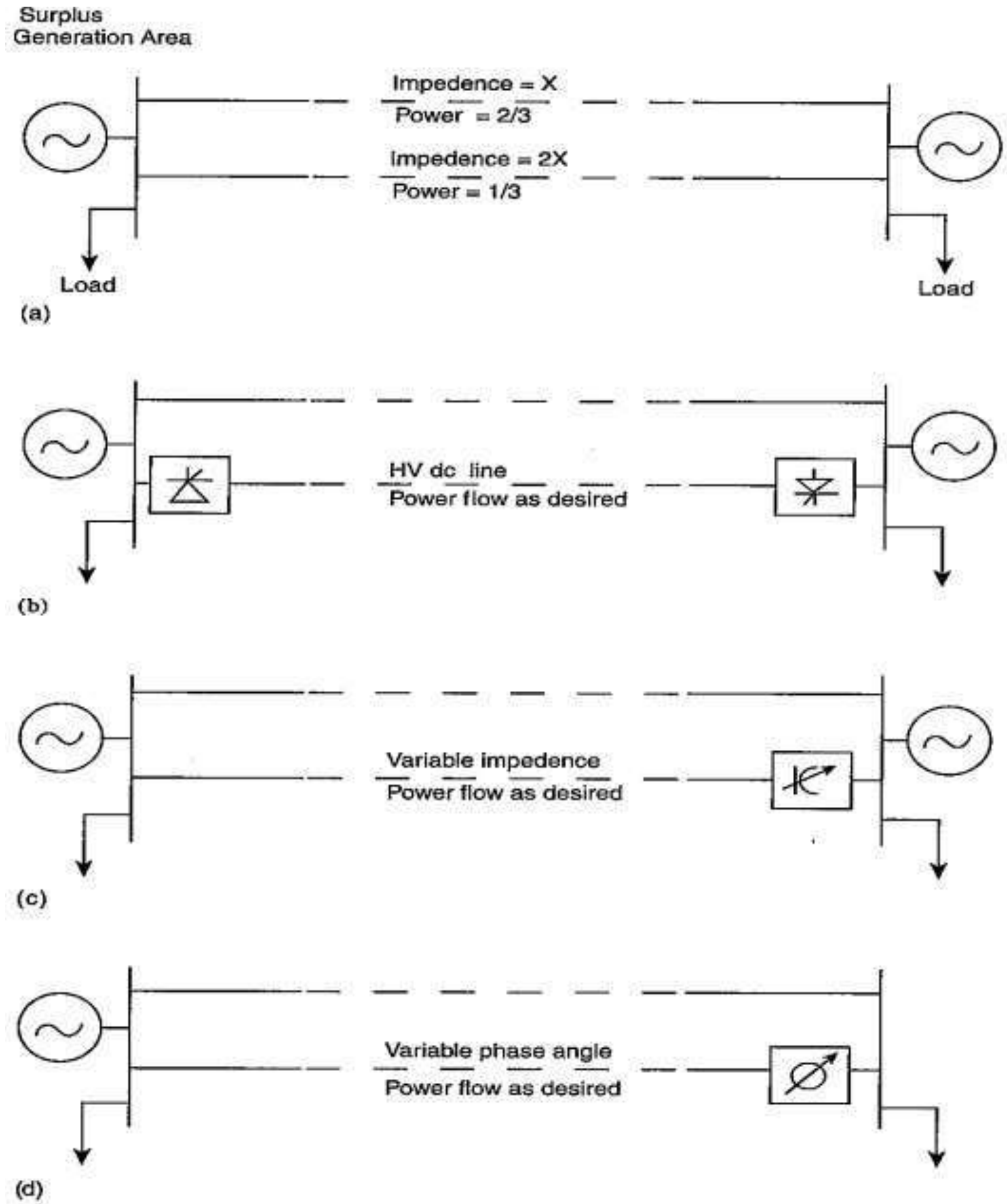


Figure 1.1 Power flow in parallel paths: (a) ac power flow with parallel paths; (b) power flow control with HVDC; (c) power flow control with variable impedance; (d) power flow control with variable phase angle.

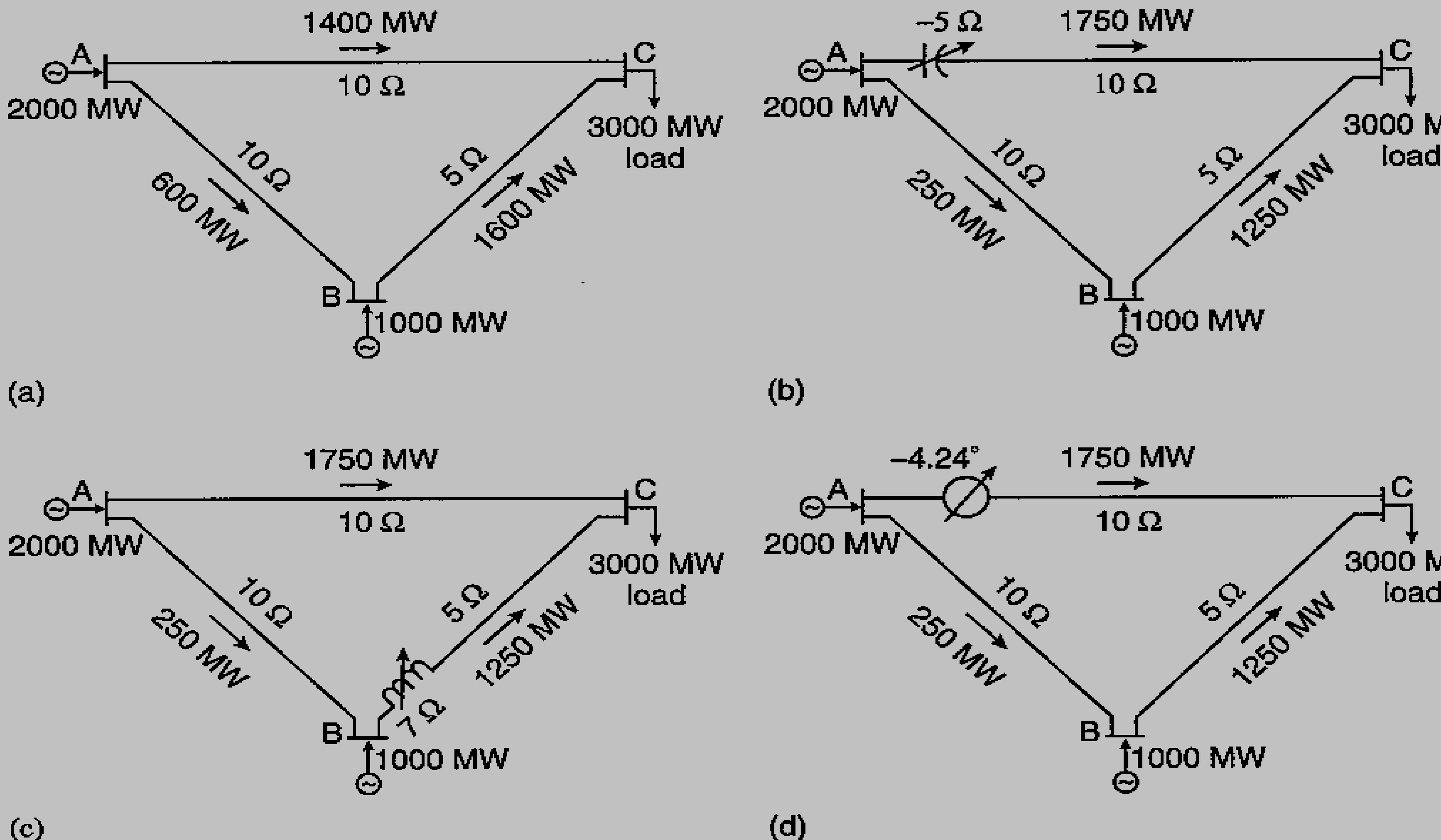


Figure 1.2 Power flow in a mesh network: (a) system diagram; (b) system diagram with Thyristor-Controlled Series Capacitor in line AC; (c) system diagram with Thyristor-Controlled Series Reactor in line BC; (d) system diagram with Thyristor-Controlled Phase Angle Regulator in line AC.

What limits the Loading Capability?

- **Thermal**

  For overhead line, thermal capability is a function of ambient temperature, wind conditions, conditions of conductor,and ground clearance. The FACTS technology can help in making an effective used of newfound line capability.

- **Dielectric**

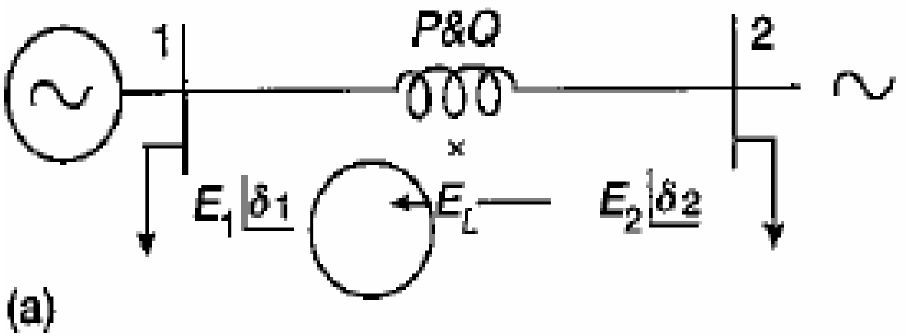
  Being designed very conservatively, most lines can increase operation voltage by 10% or even higher. FACTS technology could be used to ensure acceptable over-voltage and power flow conditions.

- **Stability**

  The stability issues that limit the transmission capability include: transient stability, dynamic stability, steady-state stability, frequency collapse. Voltage collapse, and sub-synchronous resonance.

  The FACTS technology can certainly be used to overcome any of the stability limits.

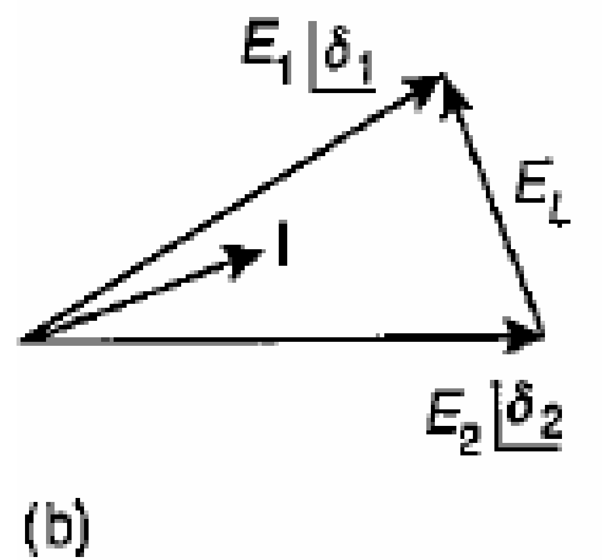
$E_L = E_1 - E_2$ and called as Driving Voltage

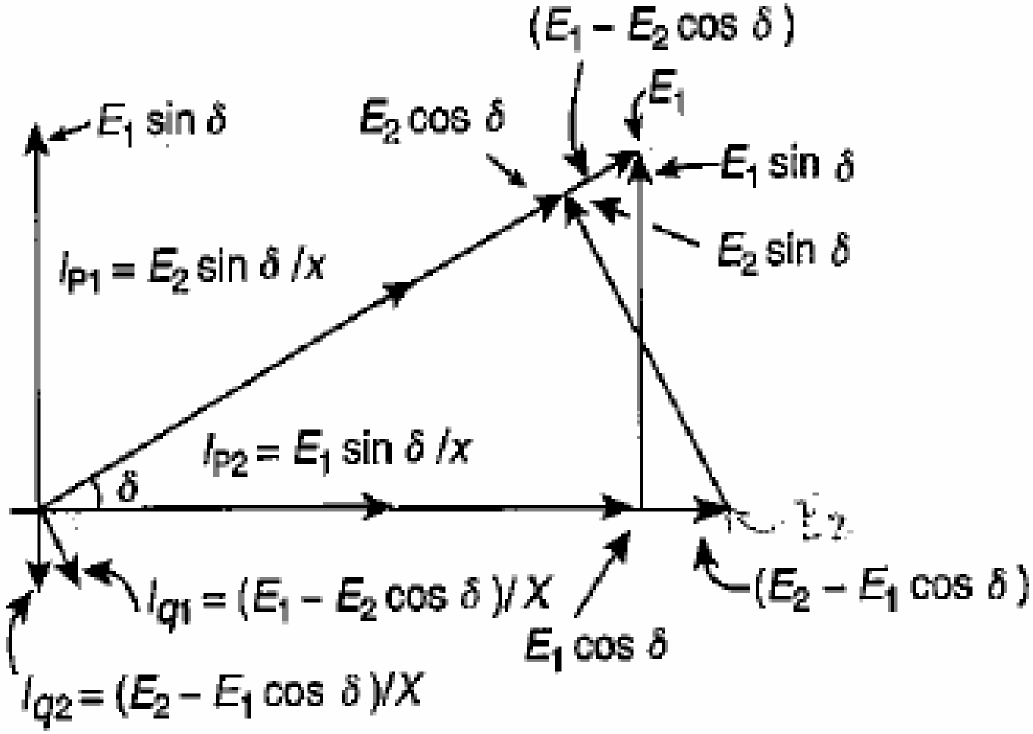


$I = E_L/X$ and lags E_L by 90^0

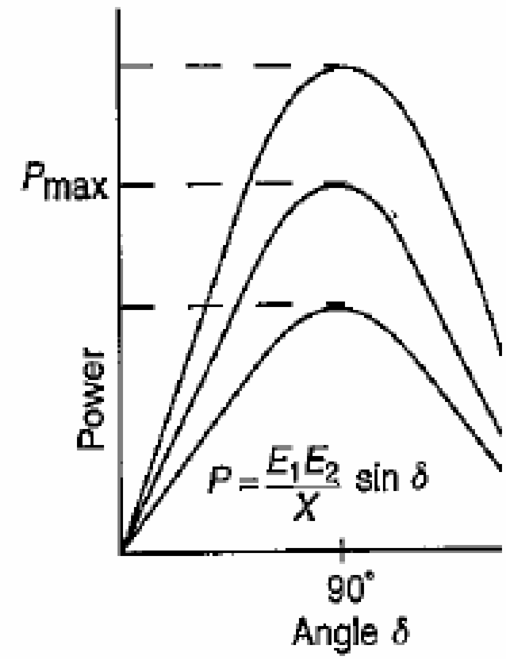
The current flow on the line can be controlled by controlling E_L or X or δ

The equipment reqd. in series with the line would not have a very high rating





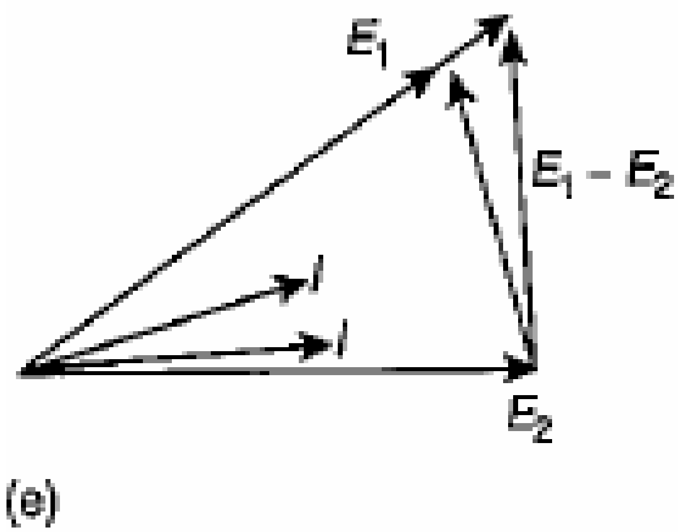
(c)



(d)

$P_1 = P_2 = P =$ active power $= E_1 E_2 \sin\delta / X$
$Q_1 =$ reactive power at 1 $= E_1(E_1 - E_2 \cos\delta)/X$
$Q_2 =$ reactive power at 2 $= E_2(E_2 - E_1 \cos\delta)/X$

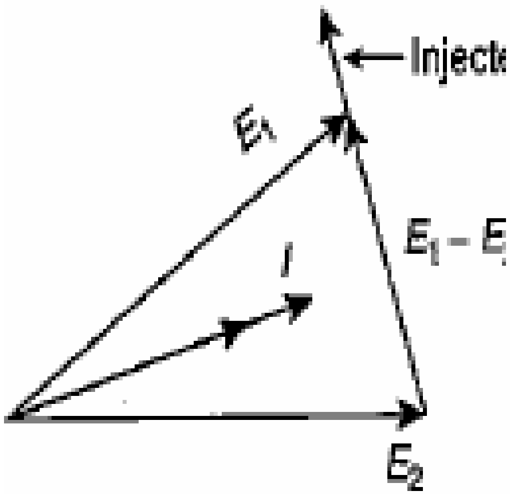
Varying X will vary P, Q_1 and Q_2. For a given power flow, varying of X vary the angle between the two ends.



Power/current flow can be controlled by regulating the magnitude of voltage phasors E_1 or E_2.

It is seen from the fig-e that with change in the magnitude of E_1 the magnitude of driving voltage phasor $E_1 - E_2$ doesn't change much, but its phase angle does.

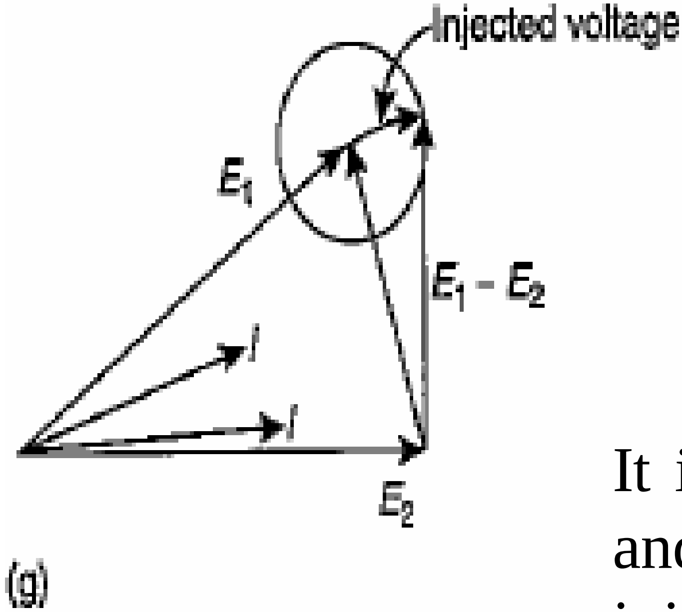
This also means that regulation of the magnitude of voltage phasor E_1 and /or E_2 has more influence over the reactive power flow than the active power flow.



(f)

Power and current flow can also be changed by injecting voltage in series with the line.

It is seen from fig.f that when the injected voltage is in phase quadrature with the current, it directly influences the magnitude of current flow and with small angle influences substantially the active power flow



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

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

Voltage injection methods form the most important portfolio of the FACTS controllers.

Relative Importance of Controllable parameters

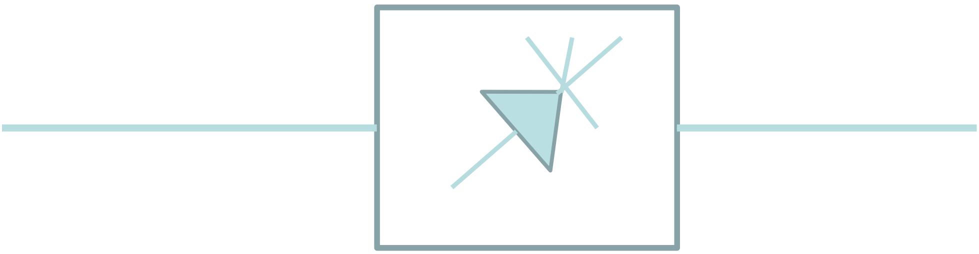
- Control of the line impedance X (e.g with a thyristor controlled series capacitor) can provide a powerful means of current control and hence the control of active power.
- Control of angle(with a phase angle regulator), which in turn controls the driving voltage, provides a powerful means of controlling the current flow and hence the active power flow when the angle is not large.
- Injecting a voltage in series with the line and perpendicular to the current flow, can increase or decrease the magnitude of current flow. Since, the current flow lags the driving voltage by 90^0, it means injection of reactive power in series(with static synchronous series compensation) can provide a powerful means of controlling the line current and hence the active power when the angle is not large.

Relative Importance of Controllable parameters(cont.)

- Injecting a voltage in series with the line and with any phase angle w.r.t the driving voltage can control the magnitude and the phase angle of line current. This means that injecting a voltage phasor with variable phase angle can provide a powerful means of precisely controlling the active and reactive power flow. This requires both active and reactive power in series.
- The MVA rating of a series controller will often be a small fraction of the throughput line MVA.
- When the angle is not large, controlling the magnitude of one or other line voltages( ) can be a very cost effective means for the control of reactive power flow through the interconnection.
- Combination of line impedance control with a series controller and voltage regulation with a shunt controller can also provide a cost effective means to control both the active and reactive power flow .

Basic types of FACTS Controllers

- Series controllers:
- Shunt controllers:
- Combined series-series controllers:
- Combined series-shunt controllers:



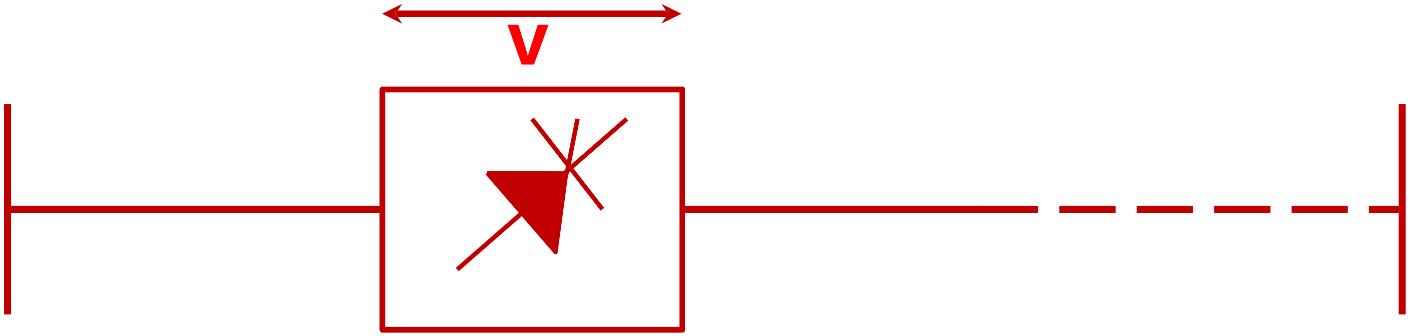
General Symbol of FACTS controller

Series controllers:

The series controller could be a variable impedance such as capacitor, reactor etc. or a variable source both are power electronics based. In principle, all series controllers inject voltage in series with the line. Even a variable impedance multiplied by the current flow through it represents an injected series voltage in the line.

As long as the voltage is in phase quadrature with the line current, the series controller only supplies or consumes variable reactive power.

Any other phase relationship will involve handling of real power as well.



Shunt controllers:

The shunt controller could be a variable impedance such as capacitor, reactor etc. or a variable source or combination of both of these. In principle, all shunt controllers inject current into the system at the point of connection. Even a variable shunt impedance connected to the line voltage causes a variable current flow and hence represents an injection of current into the line.

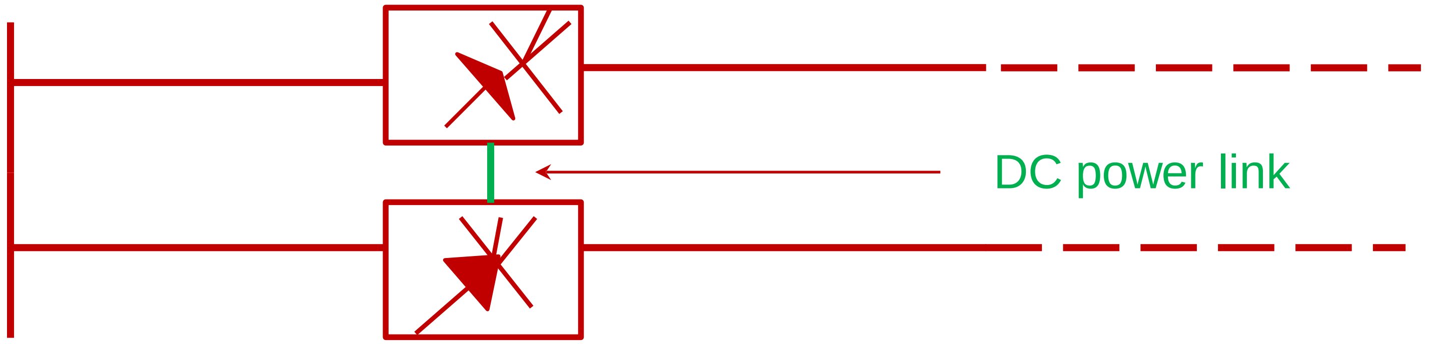
As long as the injected current is in phase quadrature with the line voltage, the shunt controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

Combined Series-Series controllers:

This controller could be a combination of separate series controllers, which are controlled in a coordinated manner in a multiline transmission system OR a unified controller in which series controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link.

The real power transfer capability of the unified series-series controller, referred to as Interline Power Flow Controller, makes it possible to balance both the real and reactive power flow in the lines.

Any other phase relationship will involve handling of real power as well.

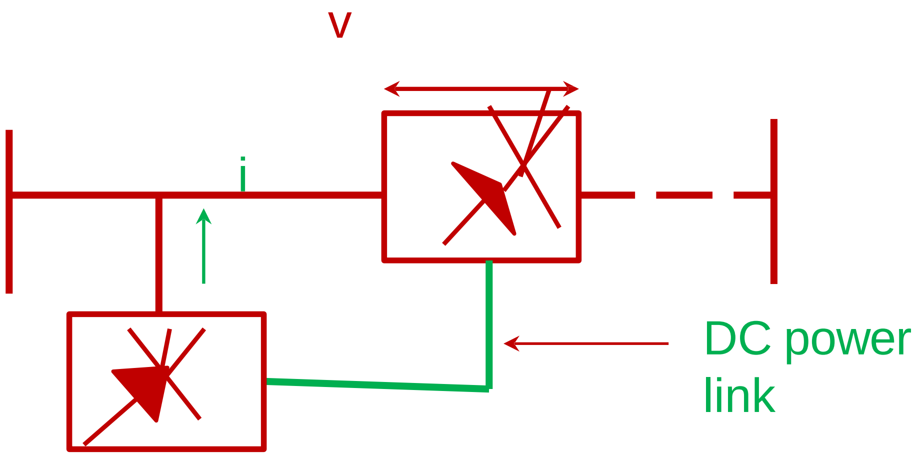


Combined Series-Shunt controllers:

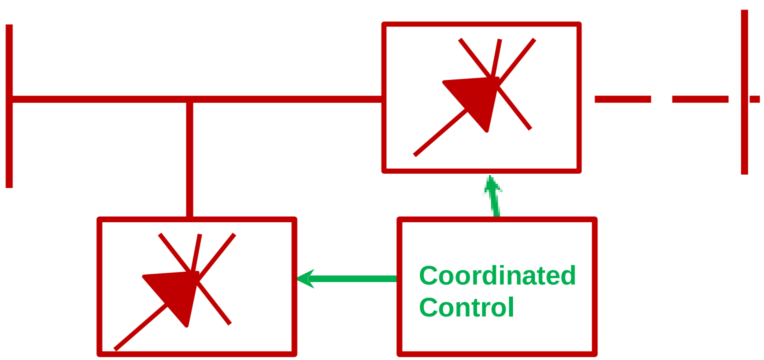
This controller could be a combination of separate shunt and series controllers, which are controlled in a coordinated manner OR a unified power flow controller series and shunt elements.

In principle, combined shunt and series controllers inject current into the system with the shunt part and voltage in series in the line with the series part.

However, when the shunt and series controllers are unified, there can be real power exchange between the series and shunt controllers via the power link.



Unified Series Shunt Controller



Coordinated Series Shunt Controller

Relative Importance of different types of Controllers

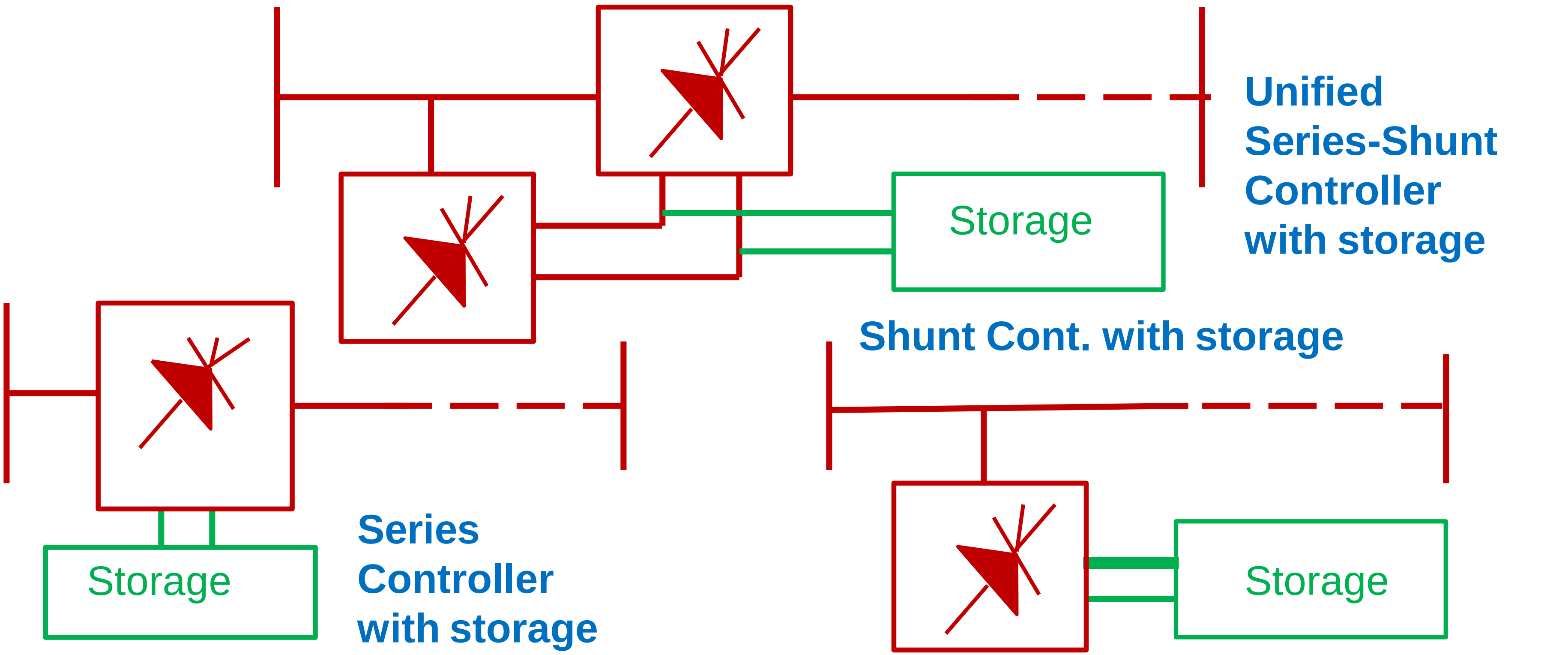
- The series connected controller impacts the driving voltage and hence the current and power flow directly. Therefore, if the purpose of application is to control the current/power flow and damp oscillations, then the series controller for a given MVA size is several times more powerful than the shunt controller.
- The shunt controller, on the other hand, is like a current source which draws from or injects currents into the line. It is therefore a good way to control voltage at and around the point of connection through injection of reactive current(leading or lagging).
- A shunt controller is much more effective in maintaining a required voltage profile at a substation bus.
- An important advantage of the shunt controller is that it serves the bus node independently of the individual lines connected to the bus

Relative Importance of different types of Controllers(cont.)

- FACTS Controllers may be based on thyristor devices with no gate turn off(only with gate turn off) or with power devices with gate turn-off capability. The controllers with gate turn-off devices are based on the dc to ac converters, which can exchange active and/or reactive power with the ac system.
- When the exchange involves reactive power only, they are provided with a minimal storage on the dc side.
- Energy storage source such as a battery, superconducting magnet or any other source of energy can be added in parallel.

Relative Importance of different types of Controllers(cont.)

- All converter based FACTS Controllers (series, shunt or combined shunt series) can generally accommodate storage ,such as capacitors, batteries and superconducting magnets, which brings an added dimension to FACTS technology.

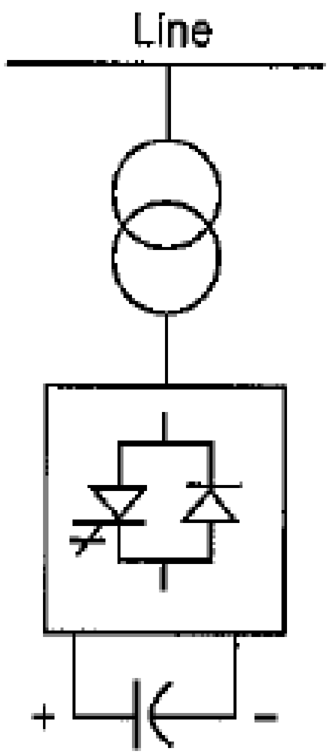


Relative Importance of different types of Controllers(cont.)

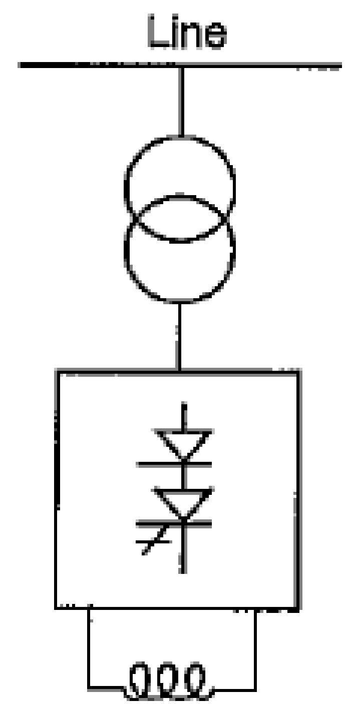
- The benefit of an added storage system(such as large capacitors, storage batteries, or superconducting magnets) to the controller is significant.
- A controller with storage is much more effective for controlling the system dynamics than corresponding controller without the storage.
- This has to do with dynamic pumping of real power in or out of the system as against only influencing the transfer of real power within the system as in the case with controllers lacking storage.

Brief Description and Definitions of FACTS Controllers

- For converter based controllers there are 2 principal types of converters with gate turn off devices: Voltage Sourced Converters and Current Sourced Converters.



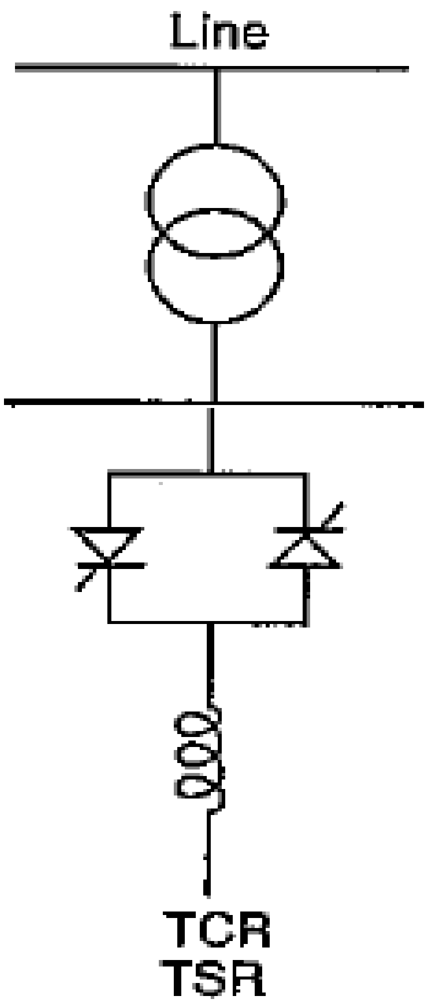
- The voltage sourced converter is represented in symbolic form by a box with a gate turn-off device paralleled by a reverse diode and a dc capacitor as a voltage source.
- The current sourced converter is represented by a box with a gate turn-off device with a diode in series and a dc reactor as its current source.



Shunt connected controllers

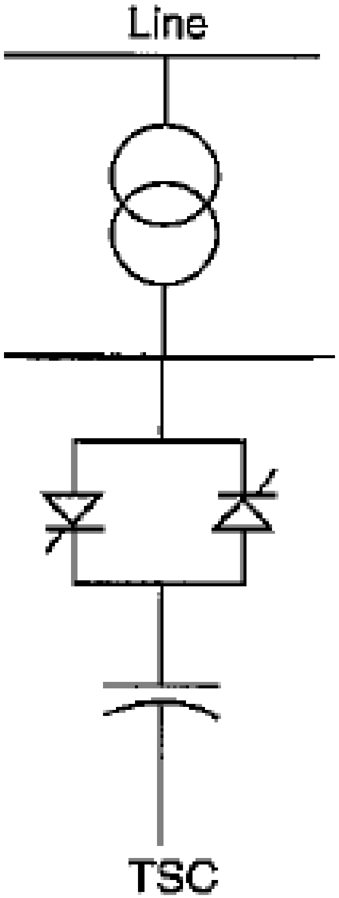
- **TCR: Thyristor Controlled Reactor :** A shunt connected thyristor controlled inductor whose effective reactance is varied in a continuous manner by partial conduction control of the thyristor valve.

- **TSR: Thyristor Switched Reactor:** A shunt connected thyristor switched inductor whose effective reactance is varied in a stepwise manner by full or zero conduction operation of the thyristr valve.



Shunt connected controllers (contd..)

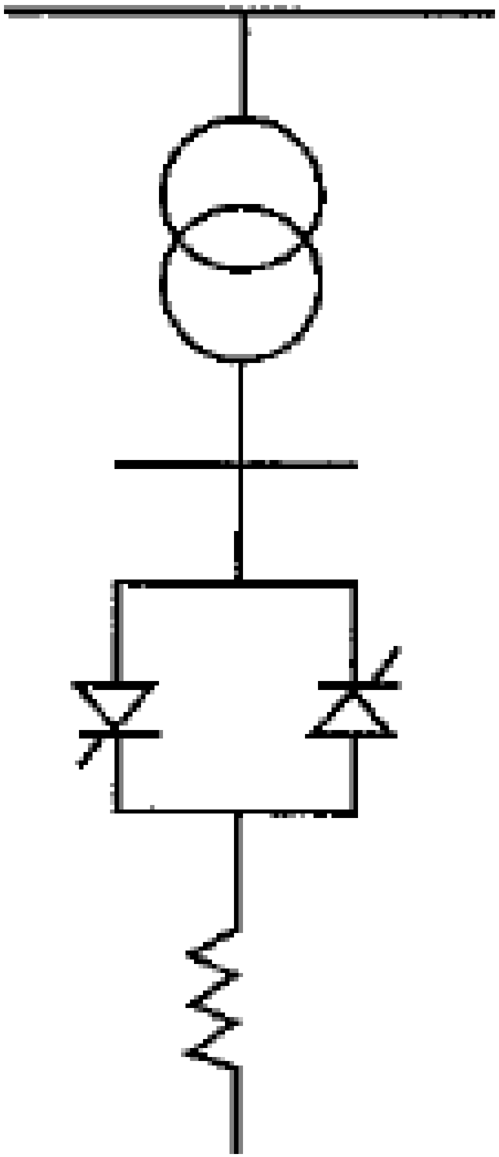
- **TSC: Thyristor Switched Capacitor :** A shunt connected thyristor switched capacitor whose effective reactance is varied in a stepwise manner by full or zero conduction operation of the thyristor valve.



- Unlike shunt reactors, shunt capacitors cannot be switched continuously with variable firing angle control.

Shunt connected controllers (contd..)

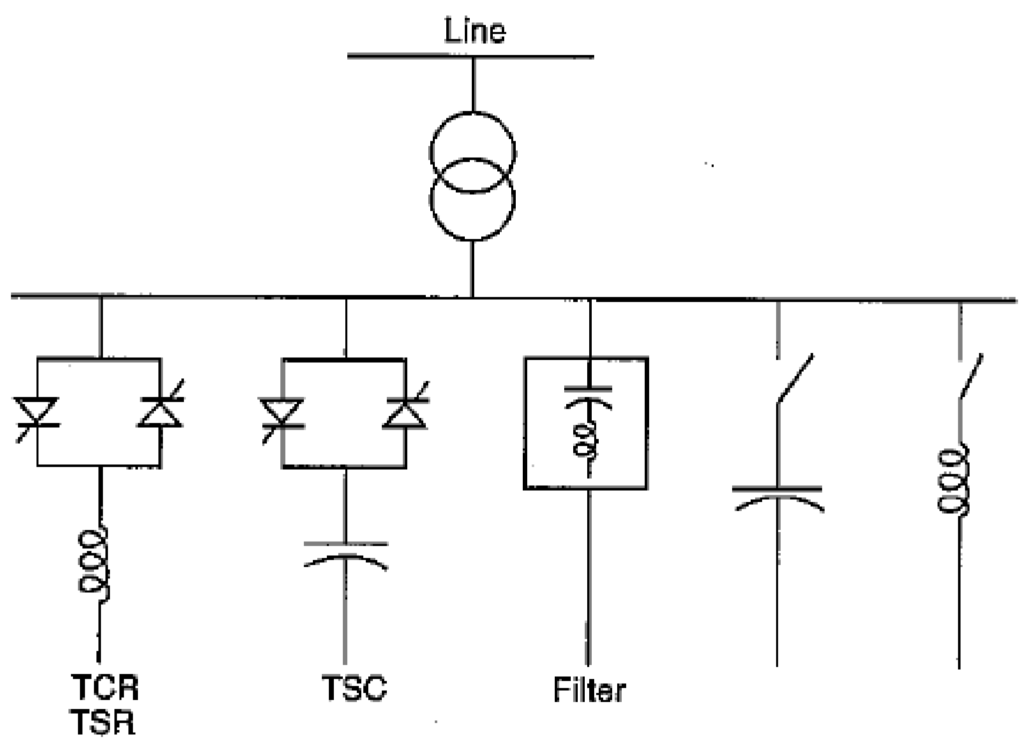
- **TCBR: Thyristor Controlled Braking Resistor :** A shunt connected thyristor controlled resistor which is controlled to aid stabilisation of a power system or to minimise power acceleration of a generating unit during a disturbance .



Shunt connected controllers (contd..)

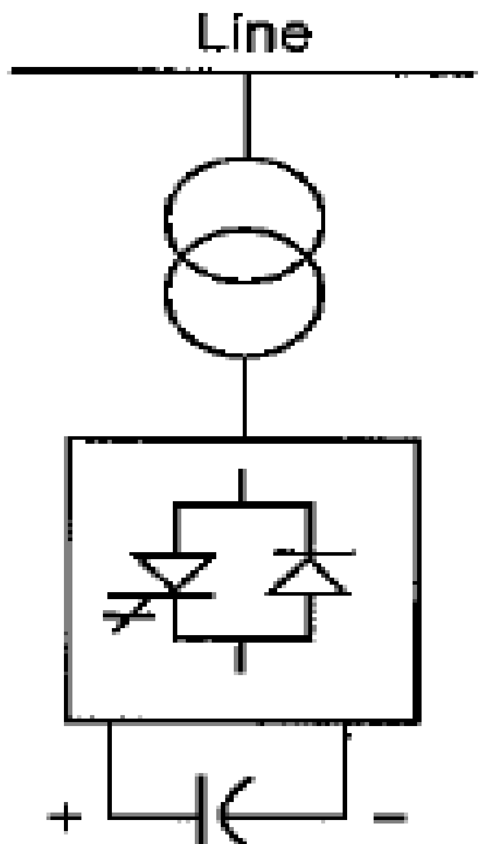
- **SVC: Static Var Compensator :** A shunt connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power sysytem- typically bus voltage.

- This is a general term for a thyristor controlled or switched reactor and /or thyristor switched capacitor or combination without gate turn off capability



Shunt connected controllers (contd…)

- STATCOM: **Static Synchronous Compensator:** A static synchronous generator operated as a shunt connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage.
- STATCOM can be … sourced or current sourced converter, … rall cost point of view voltage sourced cor … eferred.
- For VSC, its ac out … led such that it is just right for the require … v for any bus voltage, dc capacitor voltag … djuste as required to serve as a voltage s … er.
- STATCOM can be … as an active filter to absorb system harn …

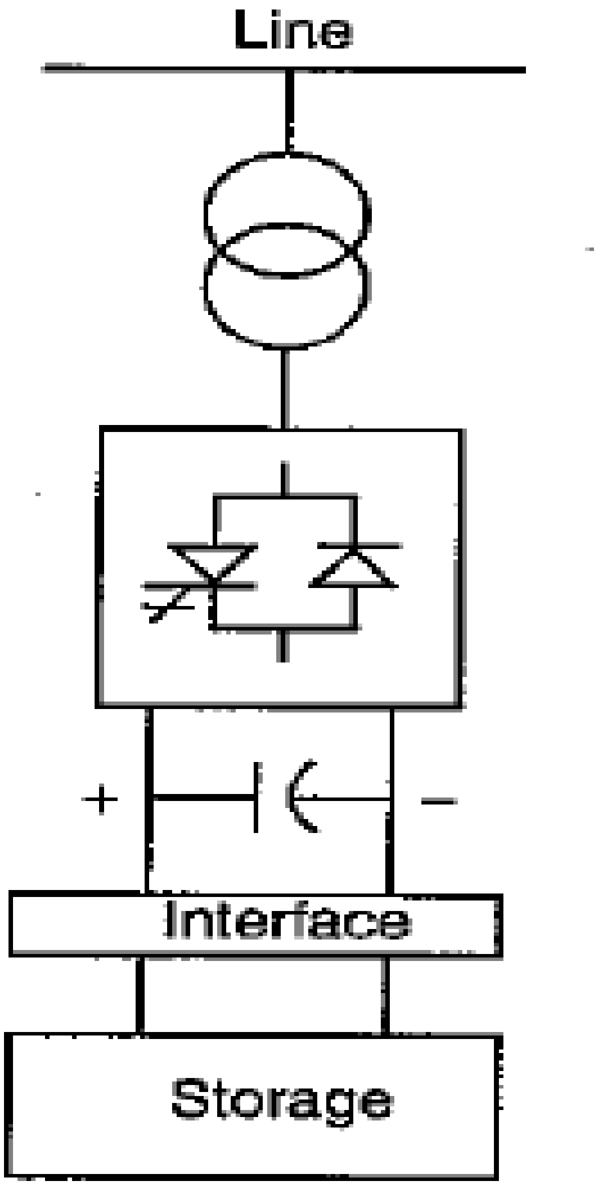


Shunt connected controllers (contd…)

- **SSG: Static Synchronous Generator:** A static self commutated switching power converter supplied from an appropriate electric energy source.

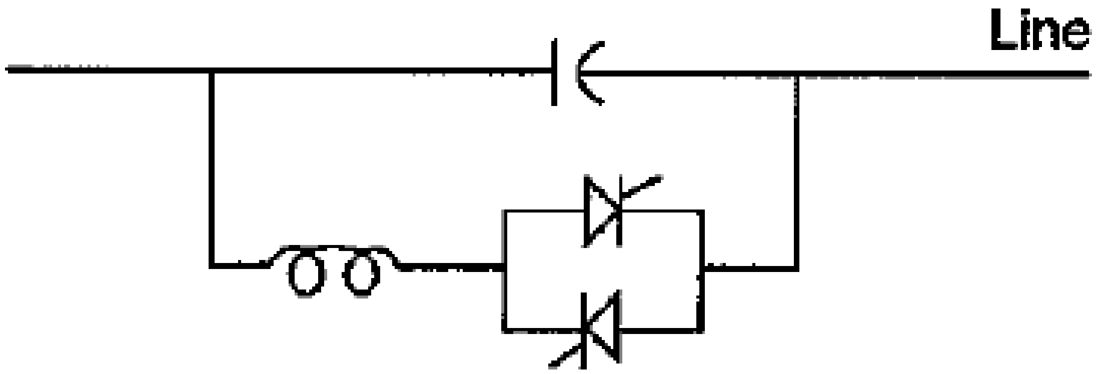
- SSG is a combination of STATCOM and any energy souce to supply or absorb power.

- A energy source can be a battery, flywheel, superconducting magnet, large dc storage capacitor etc.



Series connected controllers

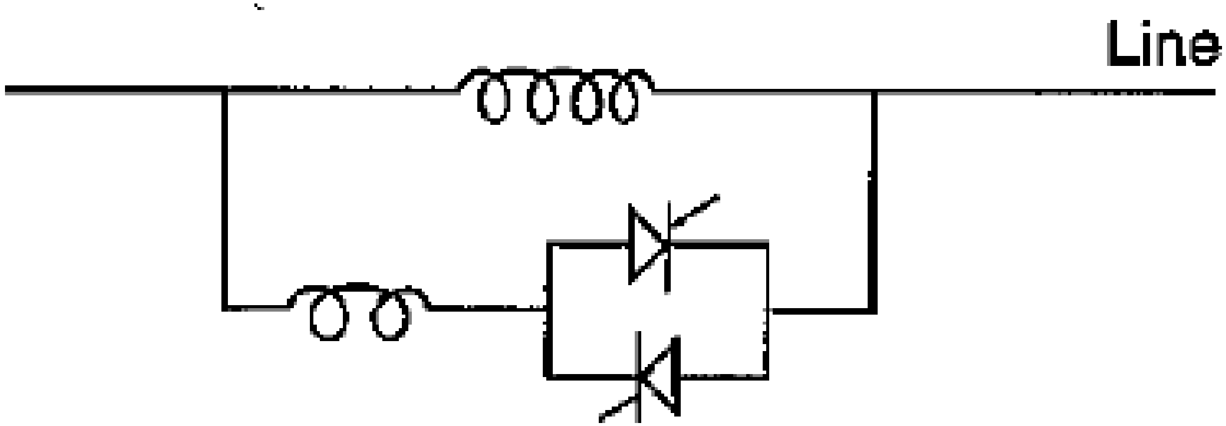
- **TCSC: Thyristor Controlled Series Capacitor:** A capacitor reactance compensator which consists of a series capacitor bank shunted by a thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance.



- **TSSC: Thyristor Switched Series Capacitor:** A capacitor reactance compensator which consists of a series capacitor bank shunted by a thyristor controlled reactor to provide a step wise control of series capacitive reactance.

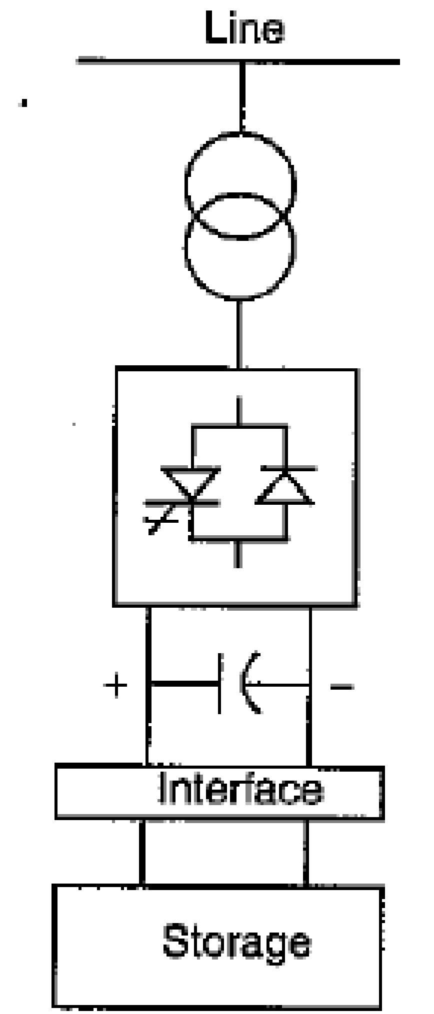
Series connected controllers (contd…)

- **TCSR: Thyristor Controlled Series Reactor:** A inductive reactance compensator which consists of a series reactor shunted by a thyristor controlled reactor in order to provide a smoothly variable series inductive reactance.



Series connected controllers (contd…)

- **SSSC: Static Series Synchronous Compensator:** A static synchronous generator operated without an external electric energy source as a series Compensator. whose output voltage is in quadrature with and controllable independently of the line current for the purpose of increasing or decreasing the overall reactive drop across the line and thereby controlling the transmitted electric power.
- The SSSC may include transiently rated energy storage or energy absorbing devices to enhance the dynamic behaviour of the power system by additional real power compensation.



C
SSSC with storage

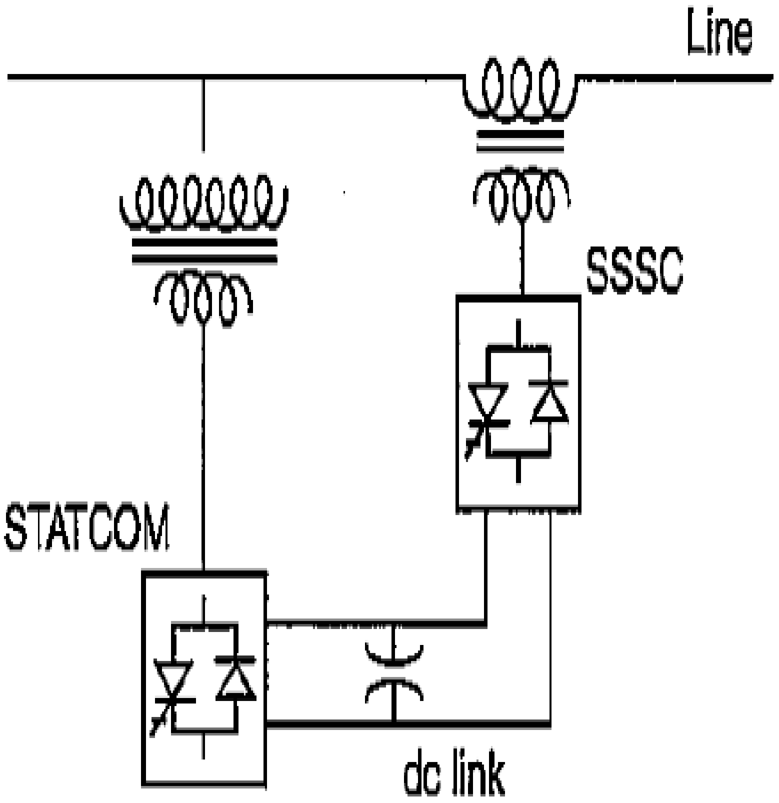
Series connected controllers (contd…)

- **IPFC: Interline Power Flow Controller:** The IPFC is a recently introduced controller.

- The possible definition is “ The combination of two or more static synchronous series compensators which are coupled via a common dc link to facilitate bi-directional current flow of real power between the ac terminals.

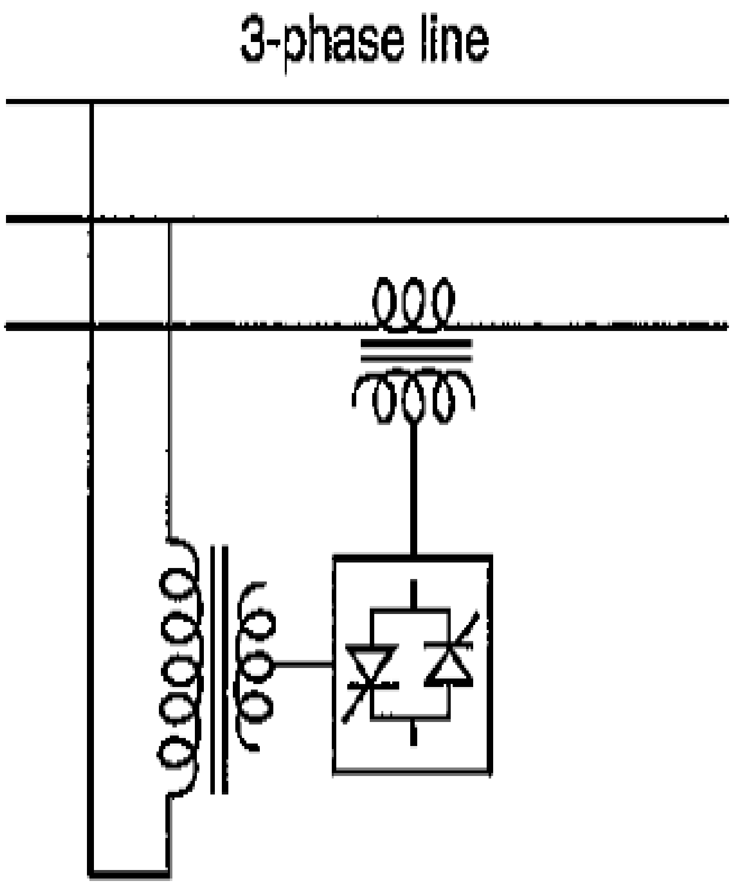
Combined shunt and series connected controllers

- **UPFC: Unified Power Flow Controller:** A combination of static synchronous compensator (STATCOM) and a static series compensator (SSSC) which are coupled via a common dc link.



Combined shunt and series connected controllers

- **TCPST: Thyristor Controlled Phase Shifting Transformer:** A Phase shifting transformer adjusted by thyristor switches to provide a rapidly variable phase angle.
- This is also known as Thyristor Controlled Phase Angle Regulator **(TCPAR)**
- Phase shifting is obtained by adding a perpendicular voltage vector in series with a phase. This vector is derived from the other two phases via shunt connected transformers.



Other controllers

- **TCVR: Thyristor Controlled Voltage Regulator:** A thyristor controlled transformer which can provide variable in phase voltage with continuous control.

- This may be a regular tranformer with a thyristor controlled tap changer(Fig. a)

- Or with a thyristor controlled ac to ac voltage converter for injection of variable ac voltage of the same phase in series with the line (Fig. b).

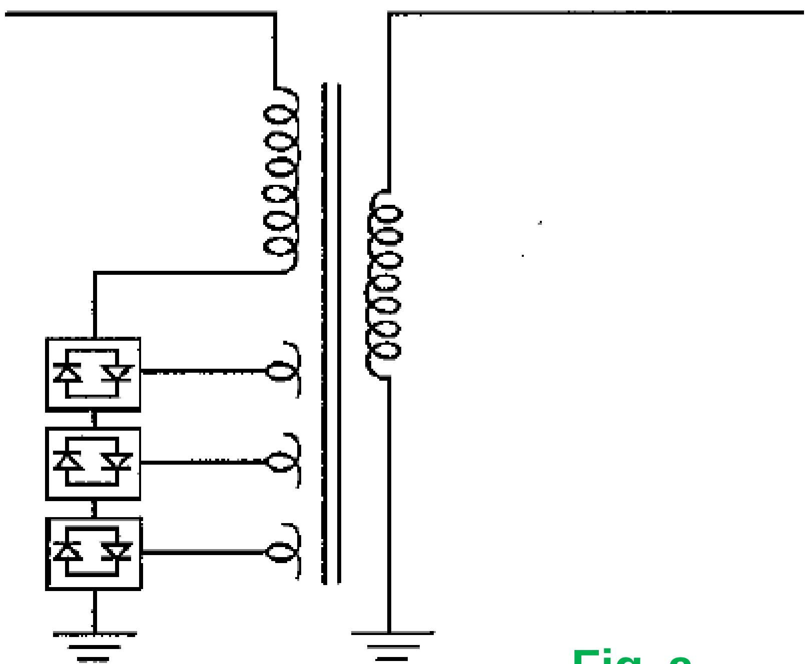


Fig. a

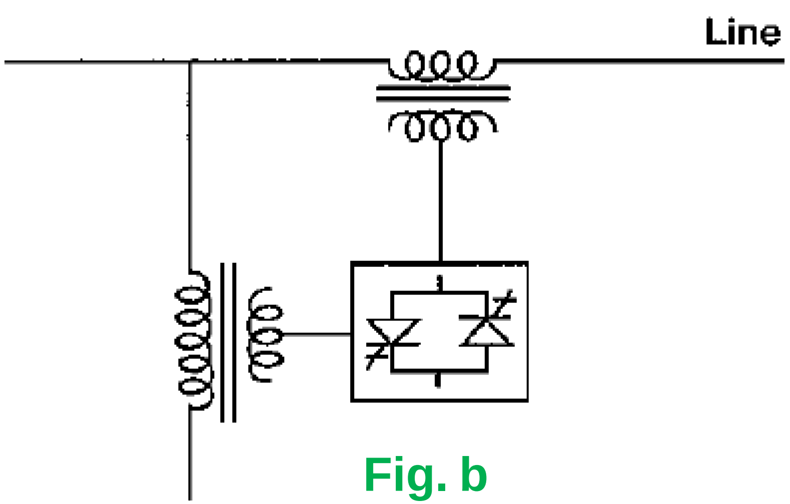


Fig. b

POSSIBLE BENEFITS OF FACTS TECHNOLOGY

- Control of Power Flow as ordered.
- Increase the loading Capability of lines to their Thermal Capabilities

POSSIBLE BENEFITS OF FACTS TECHNOLOGY(contd…)

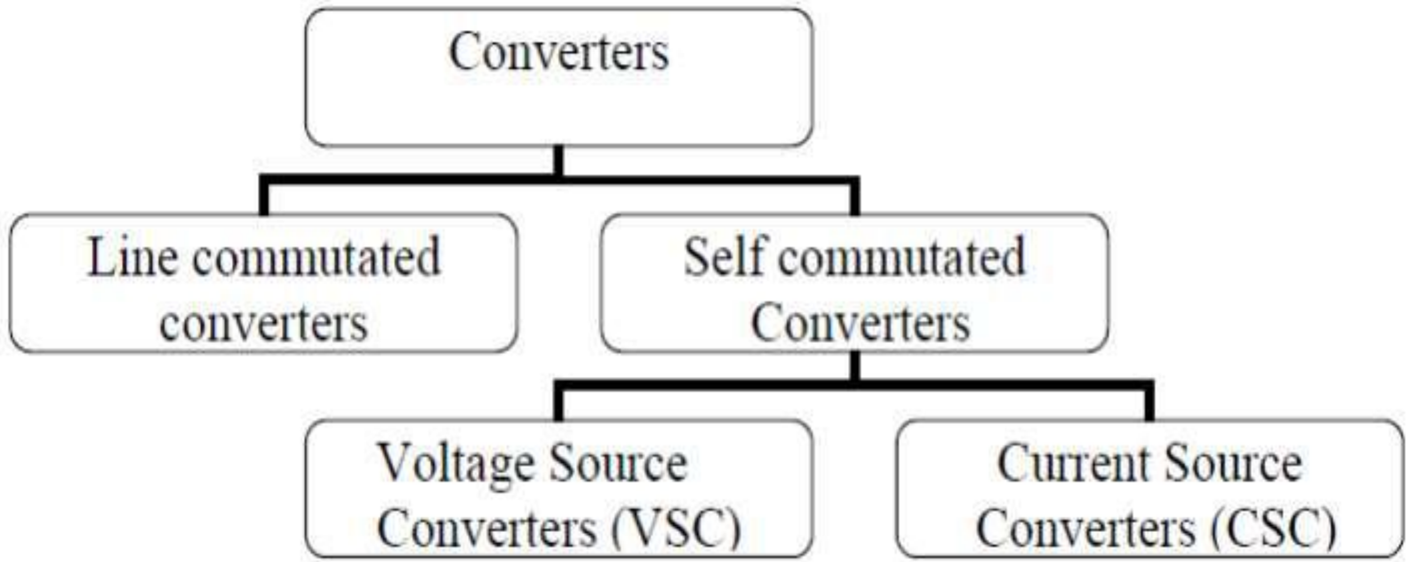
- Control of Power Flow as ordered.
- Increase the loading Capability of lines to their Thermal Capabilities

UNIT-II
VOLTAGE AND CURRENT SOURCED CONVERTERS

INTRODUCTION

- Conventional thyristor device has only the turn-on control; its turnoff depends on the current coming to zero as per circuit and system conditions.
- With some other types of semiconductor device such as the insulated-gate bipolar transistor(IGBT), both turn-on and turn-off can be controlled, they can be used to make self-commutated converters.
- In such converters, the polarity of DC voltage is usually fixed and the DC voltage, being smoothed by a large capacitance, can be considered constant. For this reason, an HVDC converter using IGBTs is usually referred to as a voltage sourced converter.

Types of Converters



Possible classification of converters

- Line commutated converters → Use switching devices such as thyristor.

  Classical HVDC system

- Self commutated converters → Use fast switching devices such as IGBT's, GTO's.

There are two basic categories of self commutating converters:

1. Current-sourced converters in which direct current always has one polarity, and the power reversal takes place through reversal of dc voltage polarity.
2. Voltage-sourced converters in which the dc voltage always has one polarity, and the power reversal takes place through reversal of de current polarity

Basic Voltage source converter

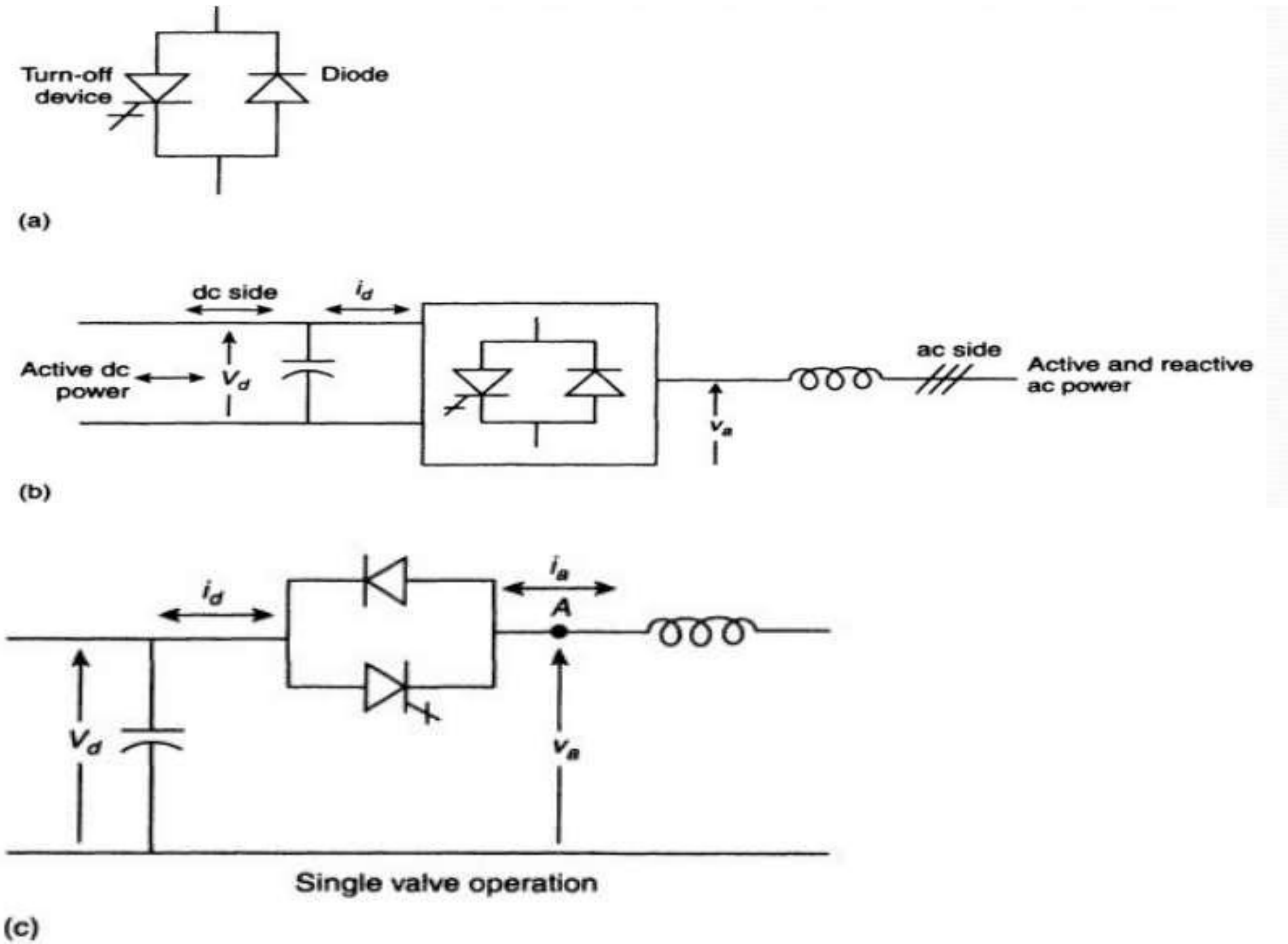
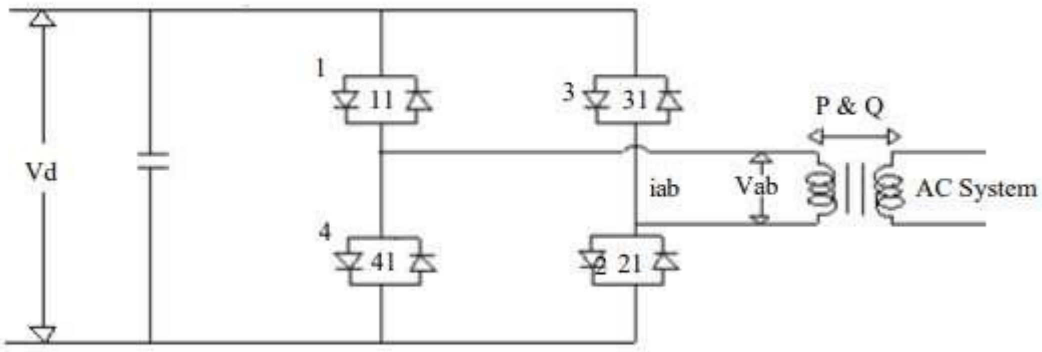
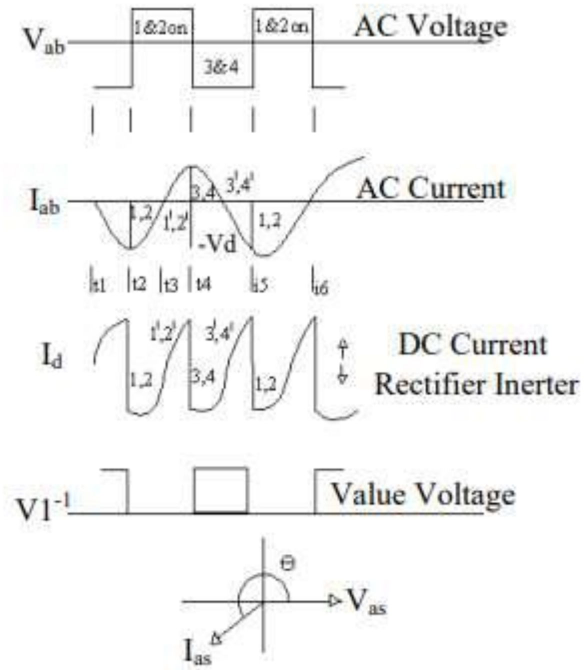


Figure Basic principles of voltage-sourced converters: (a) Valve for a voltage-sourced converter; (b) Voltage-sourced converter concept; (c) Single-valve operation.

SINGLE- PHASE FULL WAVE BRIDGE CONVERTER



(a) Single Phase Full Wave Bridge Converters



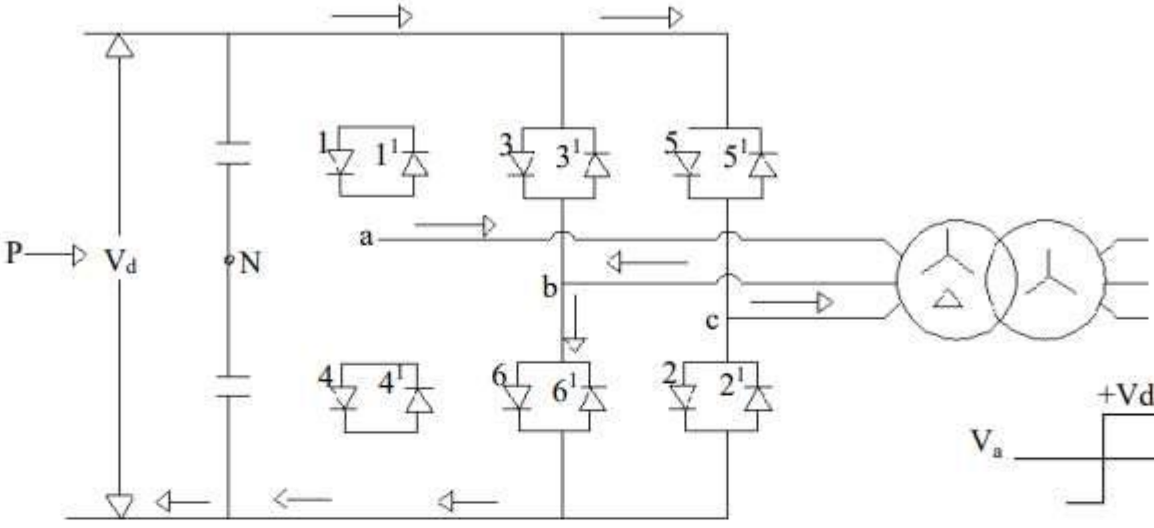
(b)

(b) Single phase full wave bridge converter

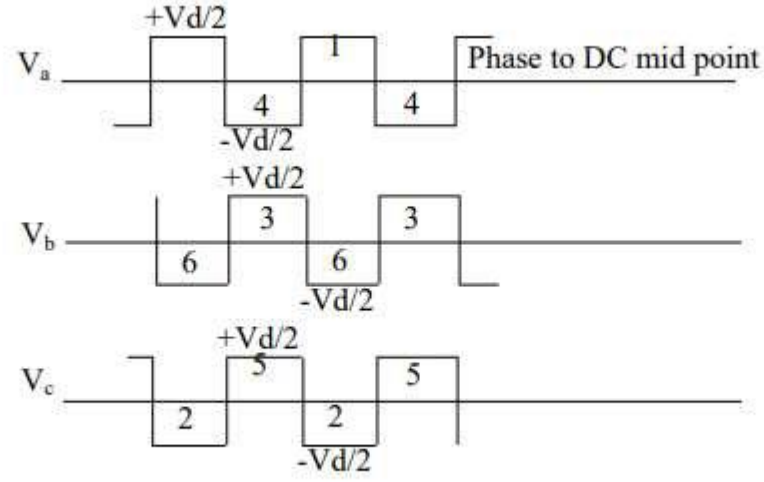
Operational mode of Single Phase Full Wave Bridge Converter

ORD	Devices	V_{ab}	I_{ab}	Conducting devices	conversion
1	1 & 2 ON 3 & 4 OFF	+ve	-ve	1 and 2	Inverter
2	1 & 2 ON 3 & 4 OFF	+ve	+ve	1' and 2'	Rectifier
3	1 & 2 OFF 3 & 4 ON	-ve	+ve	3 and 4	Inverter
4	1 & 2 OFF 3 & 4 ON	-ve	-ve	3' and 4'	Rectifier

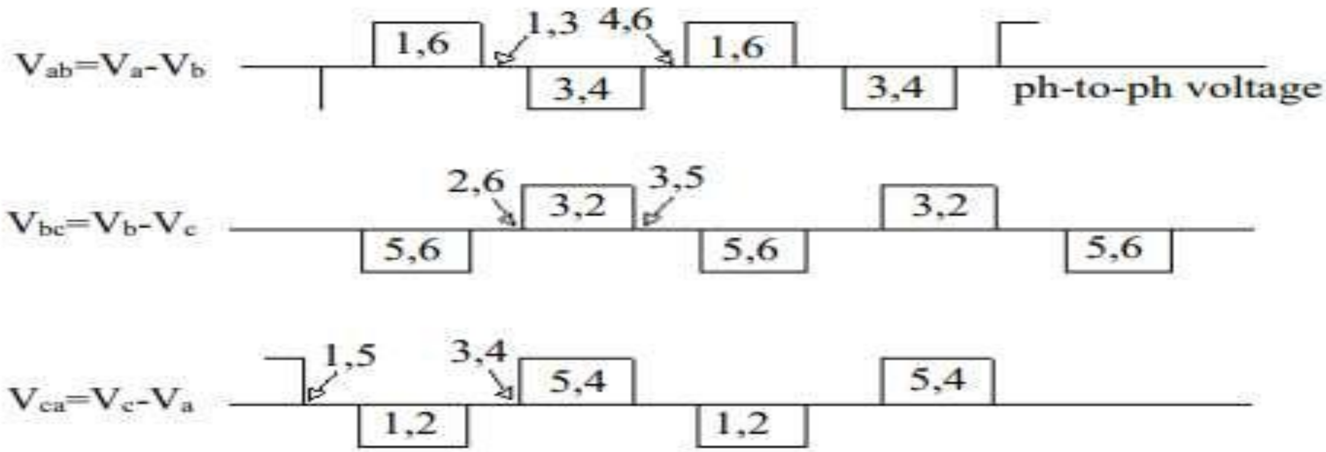
THREE PHASE FULL WAVE BRIDGE CONVERTER



(a) Three Phase Full Wave Bridge Converters



(b)



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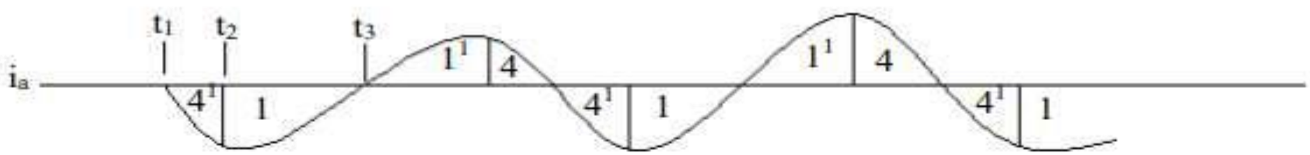
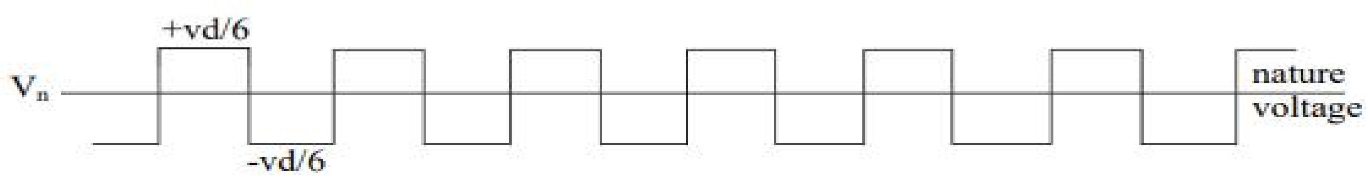
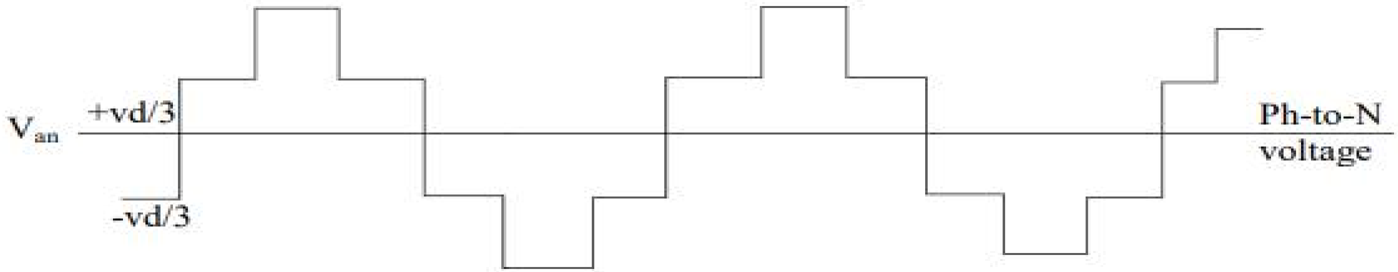


(d)



(e)

Three phase full wave bridge converter



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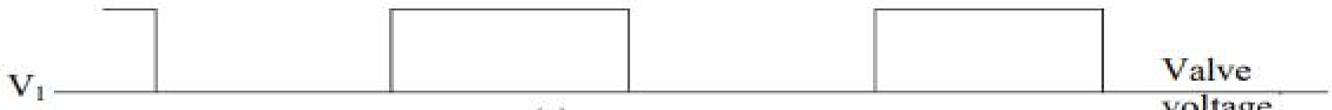
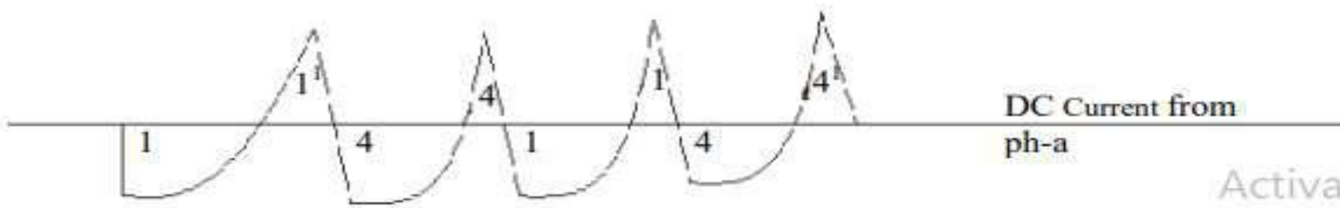
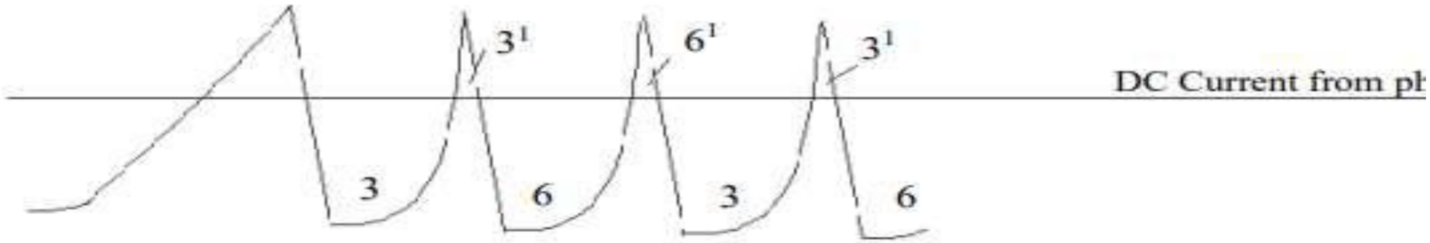


(g)

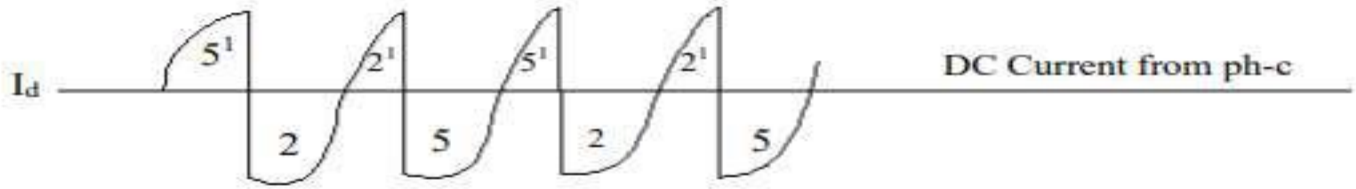


(h)

Three phase full wave bridge converter



(i)



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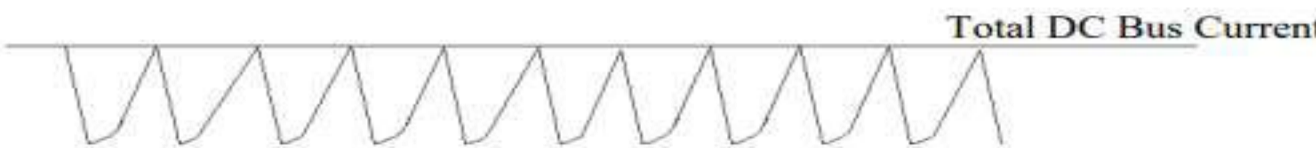
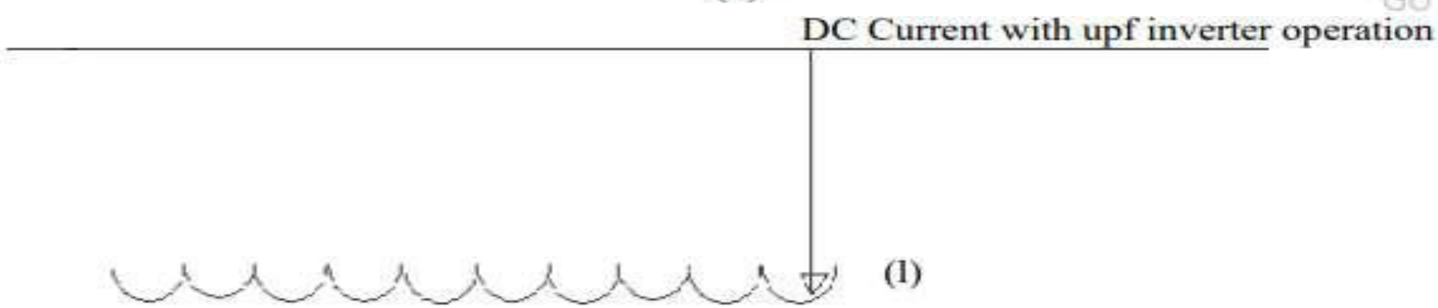


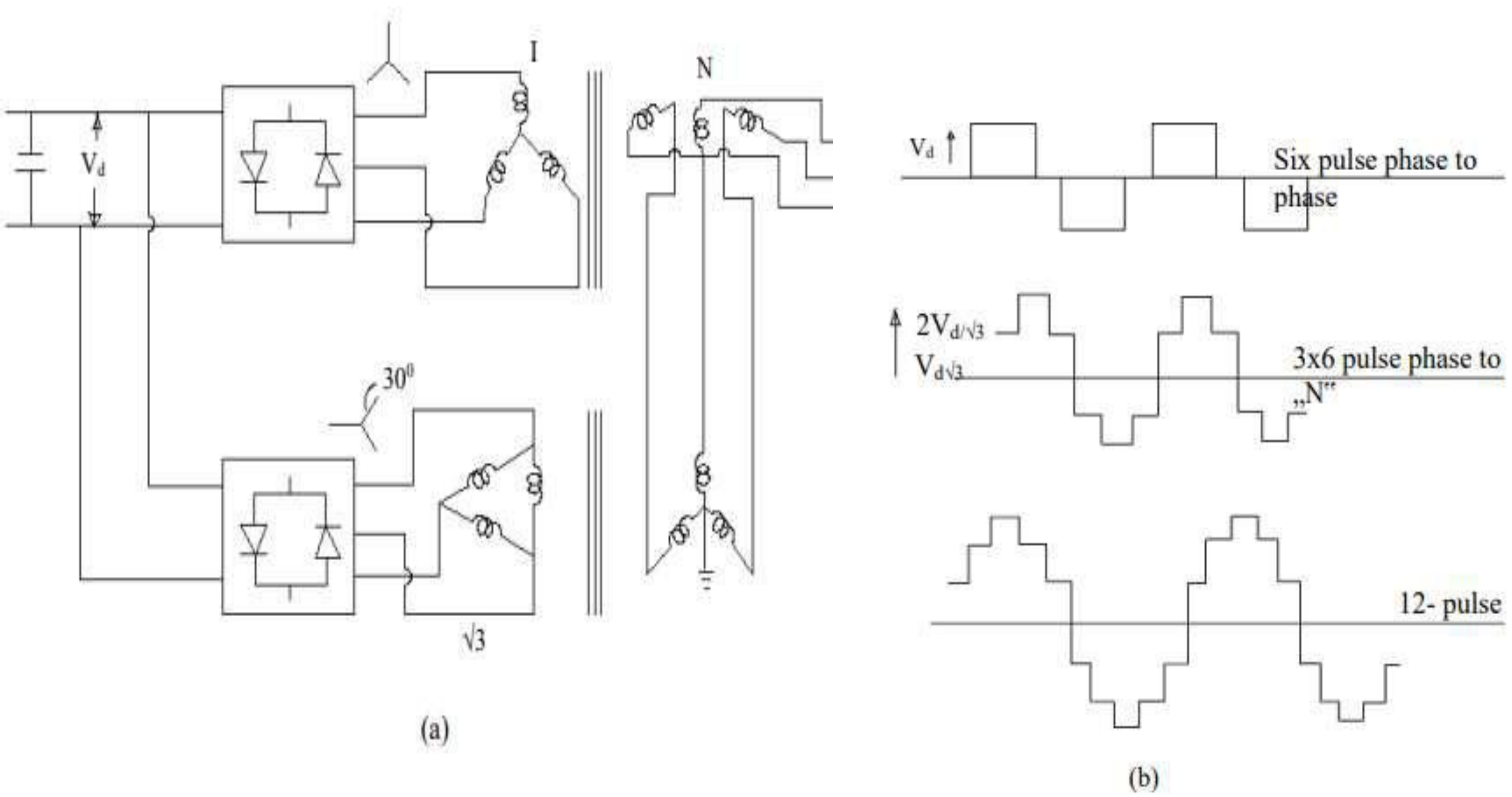
(k)



(l)

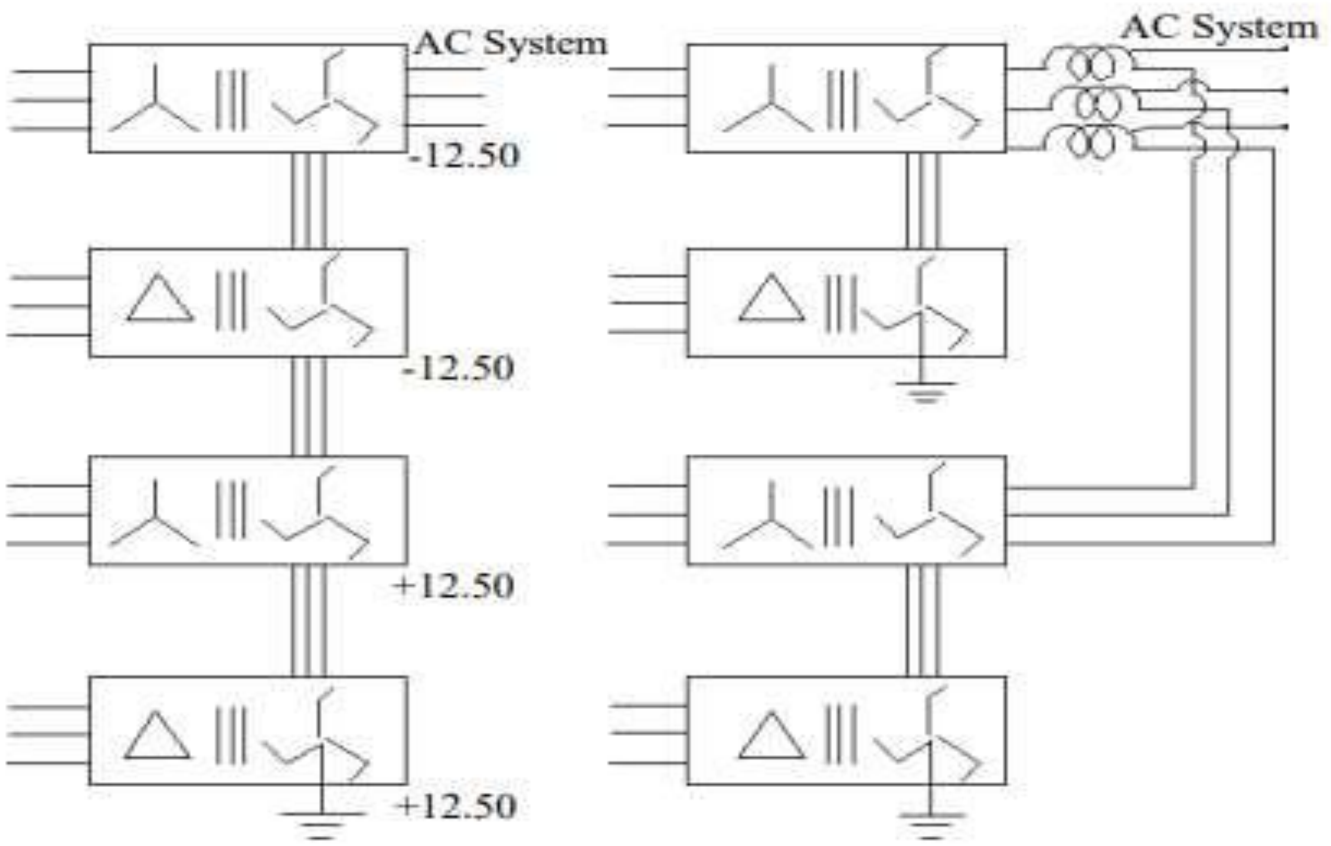
Three phase full wave bridge converter

TRANSFORMER CONNECTION FOR 12-PULSE OPERATION



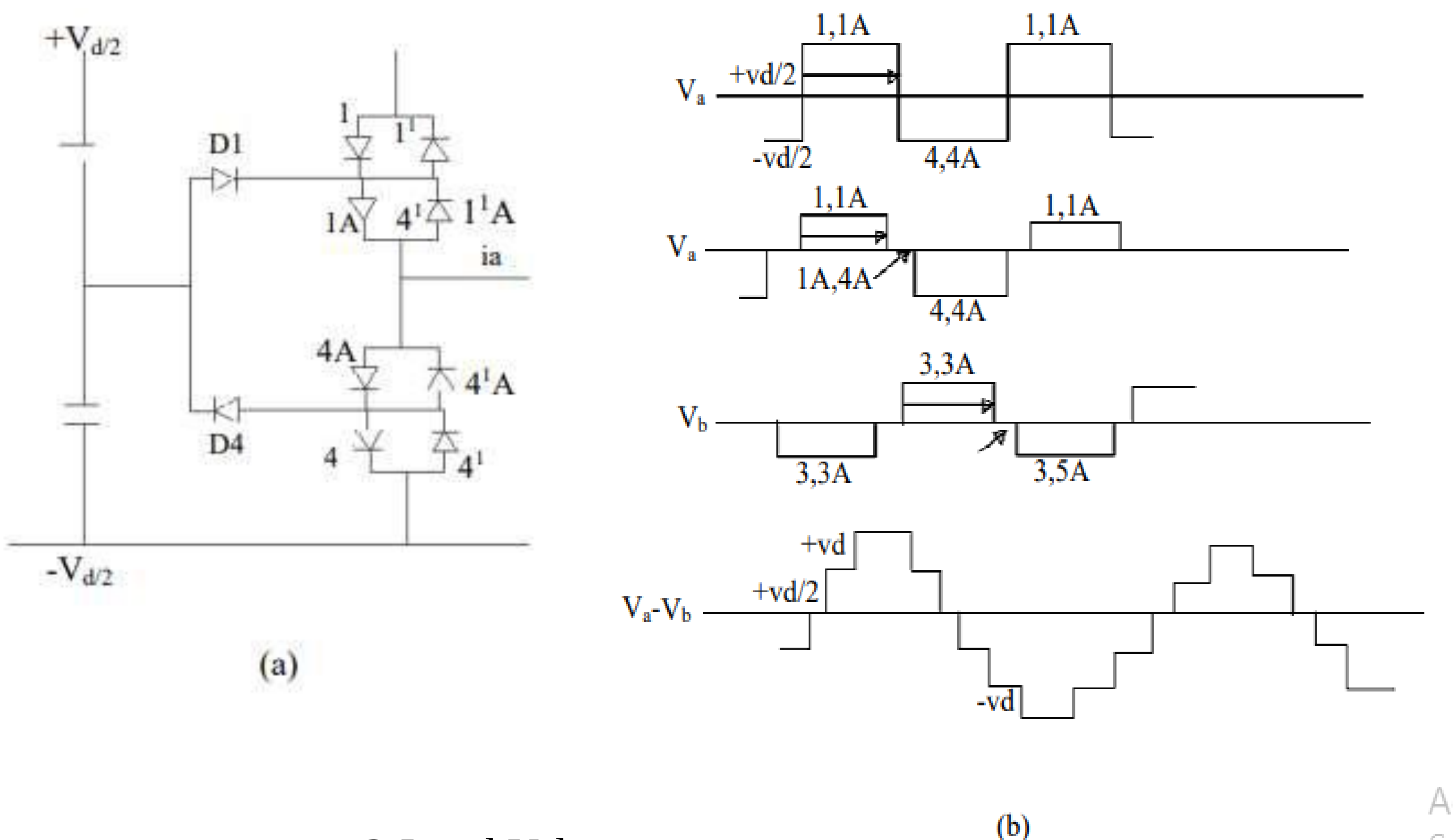
Transformer Connection for 12-Pulse Operation

TRANSFORMER CONNECTIONS FOR 24-PULSE AND 48-PULSE OPERATION



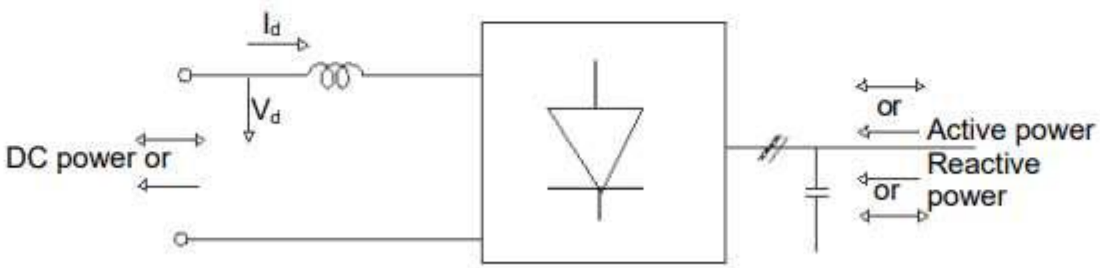
Transformer connections in series & parallel

Three level voltage source converter

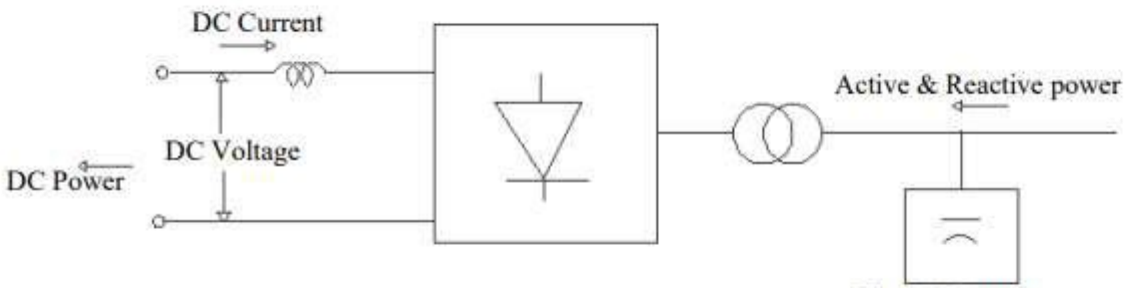


3-Level Voltage source converters

CURRENT SOURCE CONVERTERS



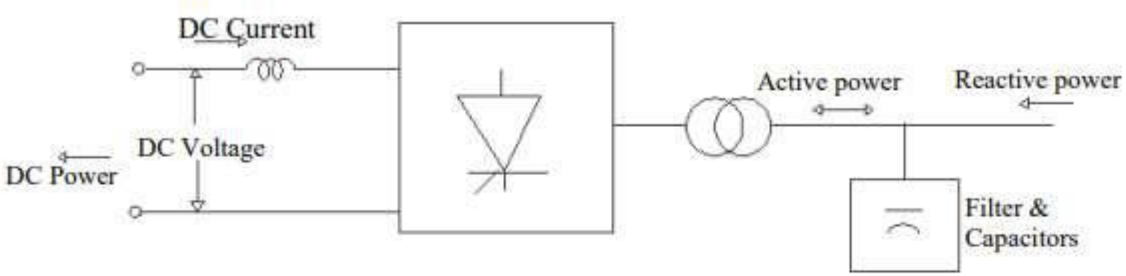
(b) Current source converter



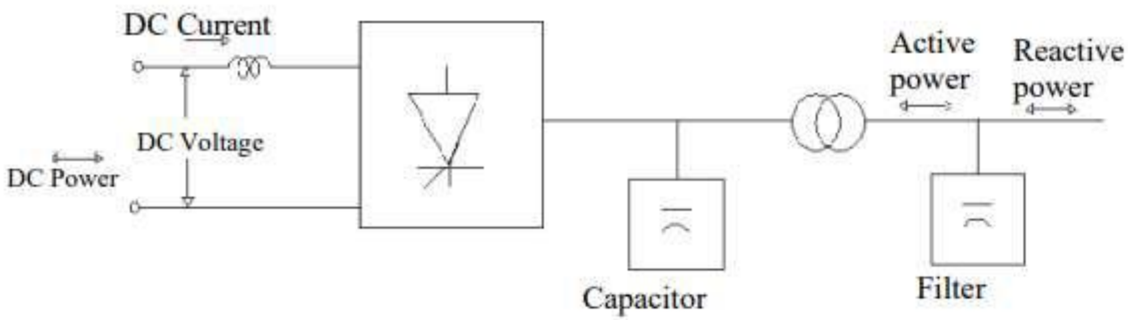
(c) Diode Rectifier

Current source converters

CURRENT SOURCE CONVERTERS



(d) Thyristor line commutated converter



(e) Self commutated converters

Current source converters

UNIT-III
STATIC SHUNT COMPENSATORS

Objectives of Shunt Compensation

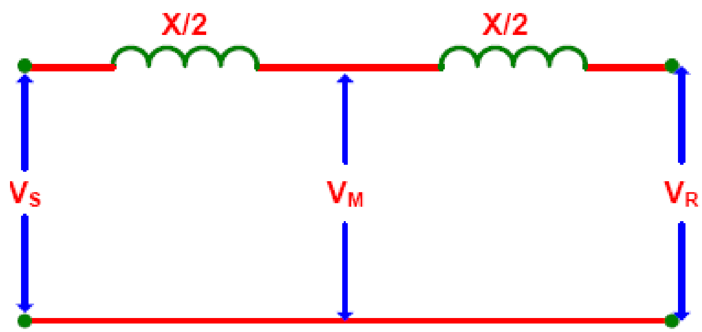
- The steady state transmittable power can be increased and the voltage profile along the line can be controlled by appropriate reactive shunt compensation.

- The shunt connected, fixed or mechanically switched inductors are applied to minimize line overvoltage under light load conditions and shunt connected fixed or mechanically switched capacitors are applied to maintain voltage levels under heavy load conditions.

Midpoint Voltage Regulation for Line Segmentation

Uncompensated Case: Let us consider a simplified model of the uncompensated system.

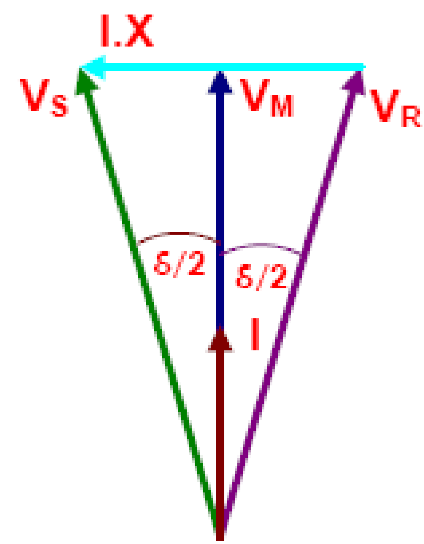
Let $|V_S|=|V_R|=V$. The voltage at the midpoint of the line is V_M which is the minimum voltage in the voltage profile.



The real power exported along the line is $P=V^2/X \sin\delta$ ------------(1)

From the phasor diagram, $\sin\delta/2=I.X / 2V$

$I=2V / X \sin\delta/2$ ------------(2)



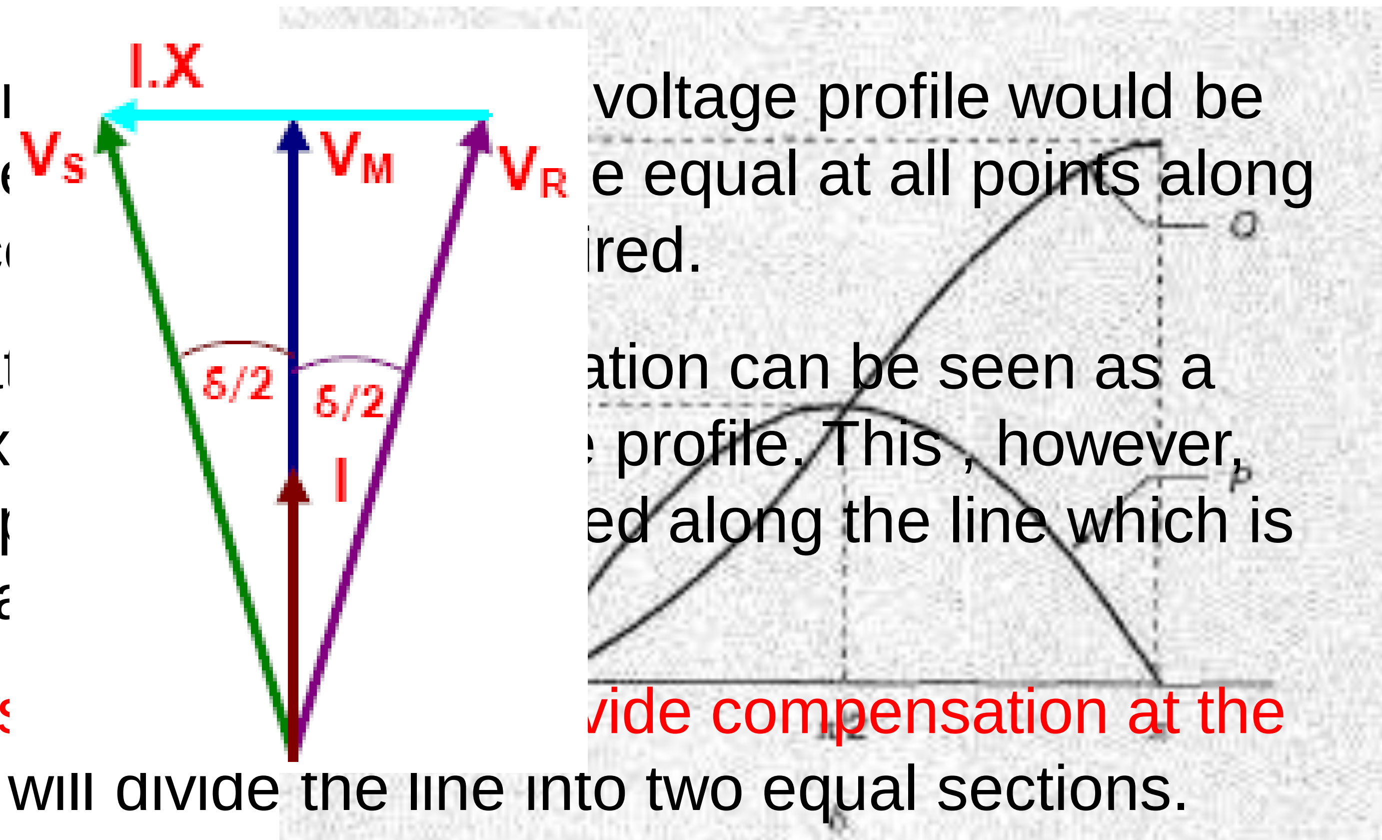
The line absorbs reactive power Q, as a function of the line current.

$Q=I^2X=4V^2/\sin^2\delta/2=2V^2/X(1-\cos\delta)$----------(3)

$P = V^2/X \, Sin\delta = P_{max} \sin\delta$------------(1)

$Q = 2V^2/X(1 - Cos\delta) = 2P_{max}(1 - Cos\delta)$-----------(3)

The voltage profile of the uncompensated transmission line is a maximum at the line ends 'V'and a minimum at the midpoint,V_M

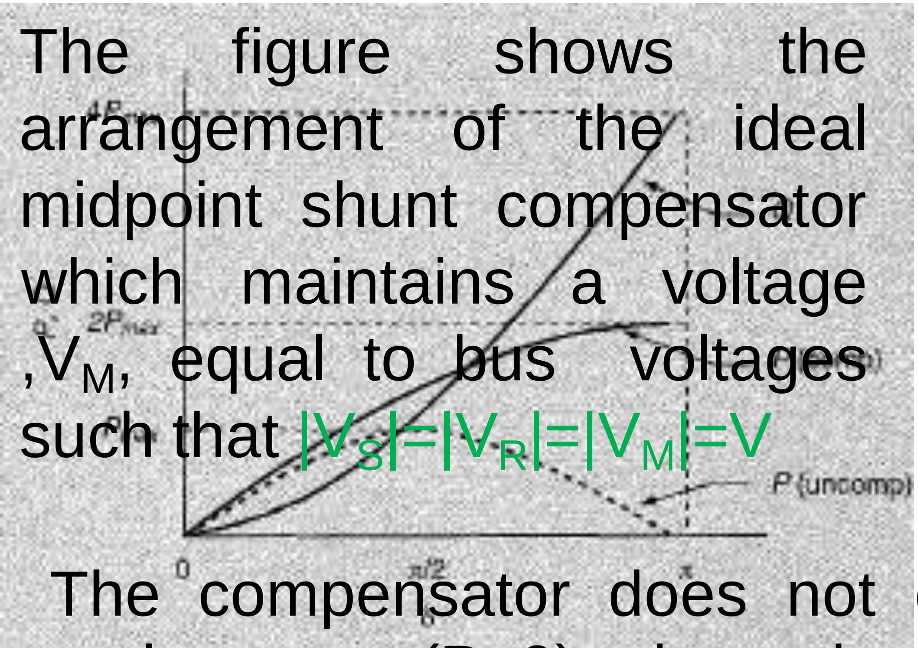


If the line is natu voltage profile would be flat i.e the voltag e equal at all points along the line and no c ired.

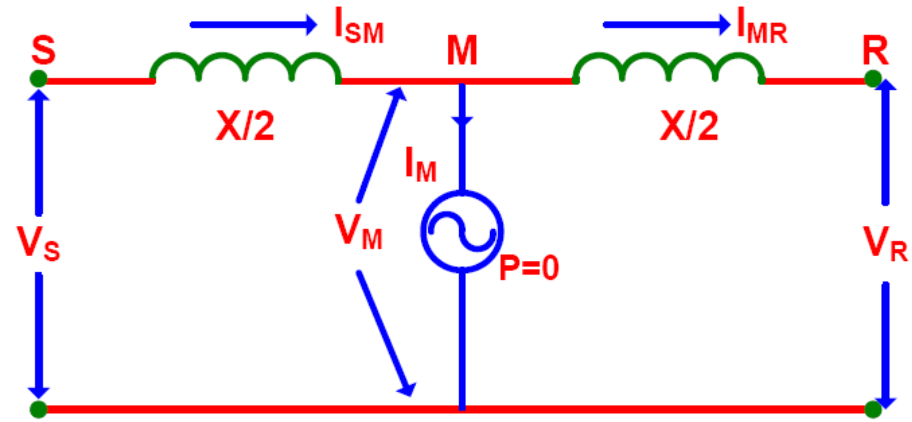
Thus the applica ation can be seen as a means of approx profile. This , however, implies that com ed along the line which is clearly impractic

So , the next bes vide compensation at the midpoint, which will divide the line into two equal sections.

Mid point compensation



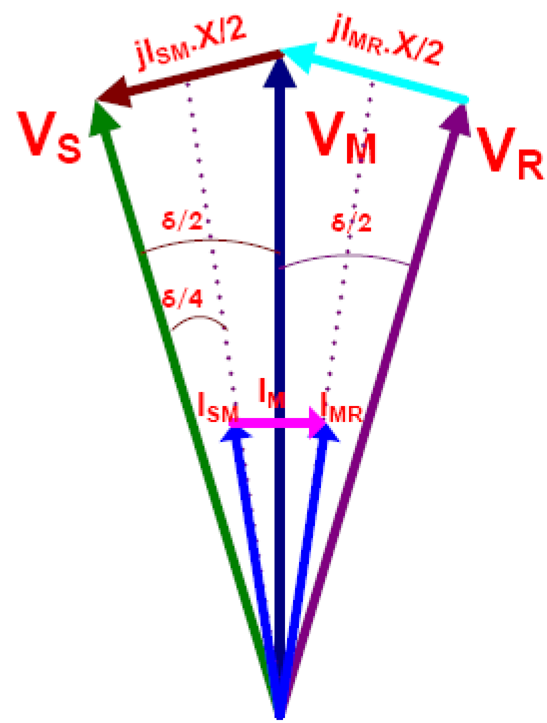
The figure shows the arrangement of the ideal midpoint shunt compensator which maintains a voltage ,V_M, equal to bus voltages such that $|V_S|=|V_R|=|V_M|=V$

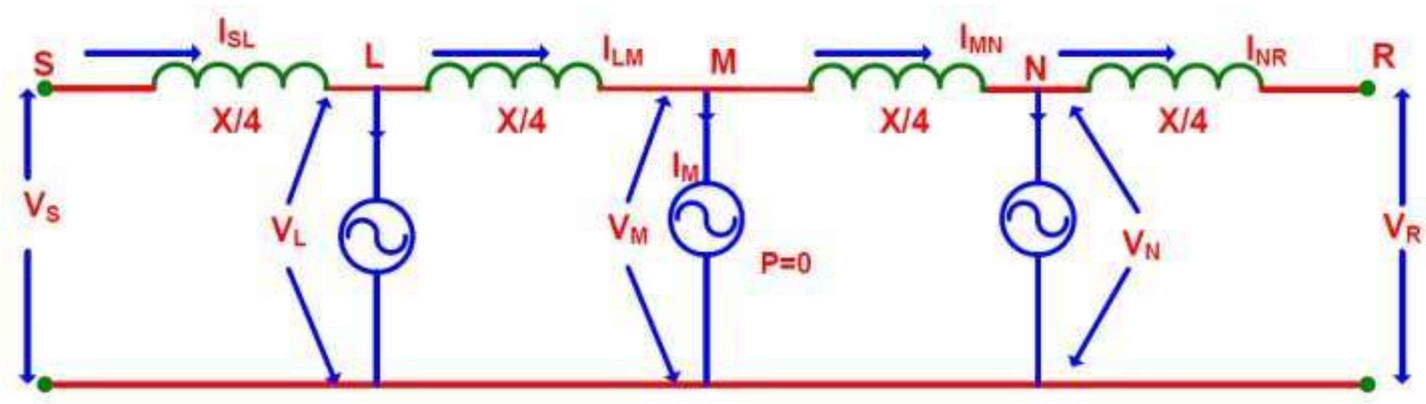


The compensator does not consume any real power (P=0) since the compensator voltage V_M, and its current I_M are in quadrature.

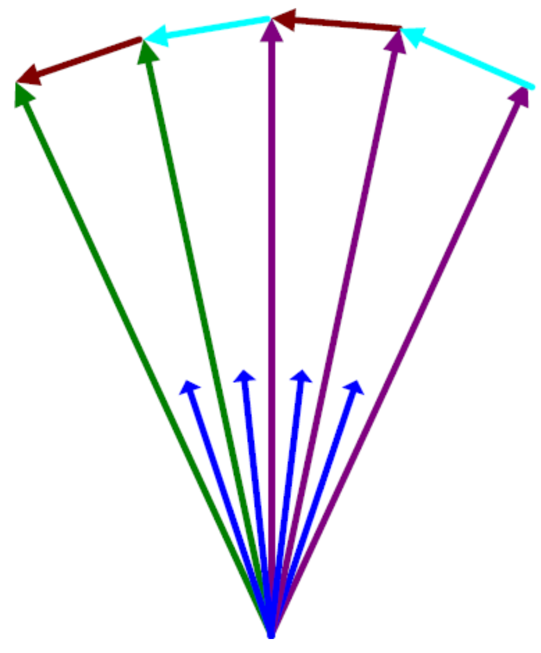
$P=2V^2/X \; Sin\delta/2=2P_{max} \; sin\delta/2$

$Q_P=4V^2/X(1-Cos\delta/2)$





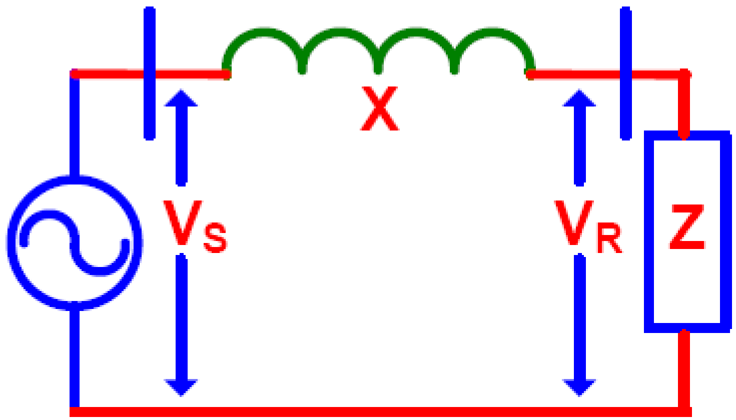
The concept of transmission line segmentation can be expanded to the use of multiple compensators, located at equal segments of the transmision line as illustrated for 4 line segments



End of Line Voltage Support to prevent Voltage Instability

The assumption of adequate reactive power control at the receiving end to maintain a constant voltage will not in general apply where the receiving end represents a load centre with little or no generation

A simple radial system with feeder line reactance X and load impedance Z is shown.

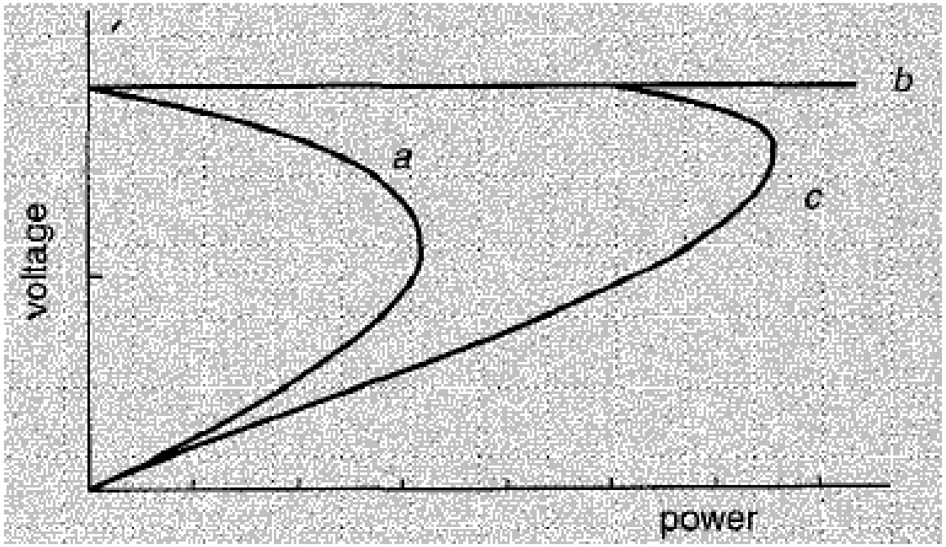


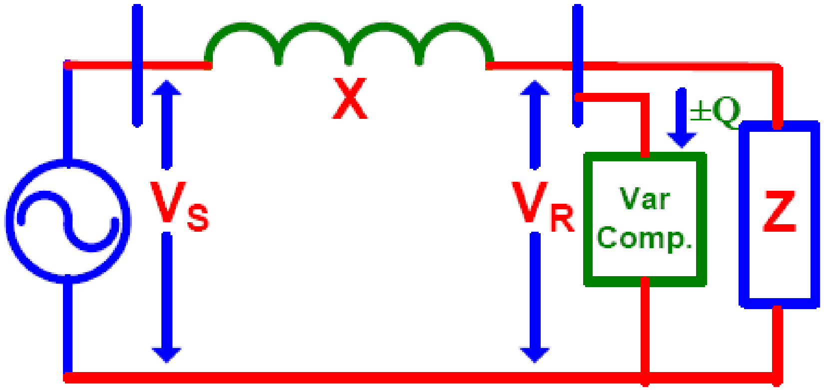
The normalised terminal voltage V_R versus power P plot at various load power factors, ranging from 0.8 lag to 0.9 lead.

The nose-point at each plot given for a specific power factor represents the voltage instability corresponding to that system condition.

End of Line Voltage Support to prevent Voltage Instability

It is evident that for a radial line, the end of the line, the end of the line, where the largest voltage variation is experienced, is the best location for the compensator.





Reactive shunt compensation is often used in practical applications to regulate the voltage at a given bus against load variations or to provide voltage support for the load .

Improvement of Transient Stability

The transient stability studies involve the determination of whether or not synchronism is maintained after the machine has been subjected to severe disturbance. This may be sudden application of load, loss of generation, loss of large load or a fault on the system.

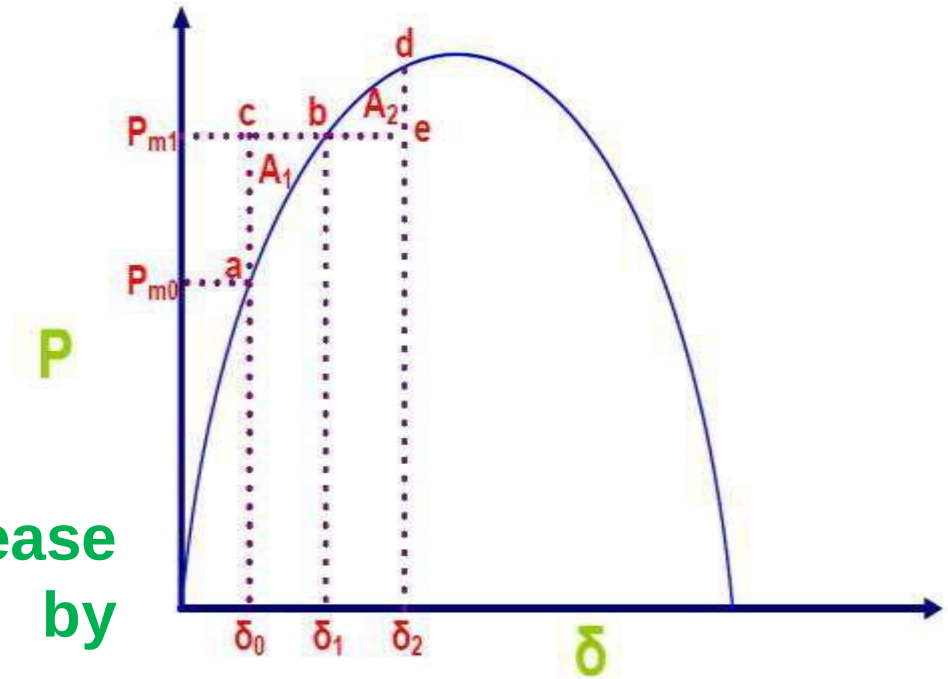
A method known as the equal area criterion can be used for a quick prediction of stability.

This method is based on the graphical interpretation of the energy stored in the rotating mass as an aid to determine if the machine maintains its stability after a disturbance.

This method is only applicable to a one machine system connected to an infinite bus or a two machine system.

Transient Stability-Equal Area Criterion

Consider the machine operating at the equilibrium point δ_0,corresponding to the mechanical power input $P_{m0}=P_{e0}$



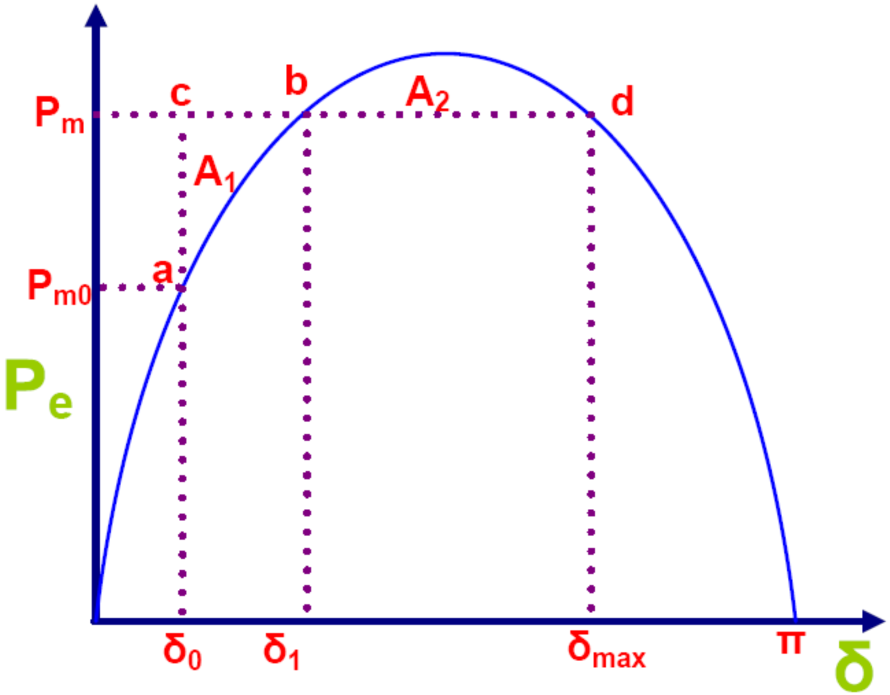
Consider a sudden step increase in input power represented by the horizontal line P_{m1} .

At $\delta = \delta_2$, the decelerating area A_2 is equal to the accelerating area A_1. This is known as Equal Area Criterion. The rotor angle would then oscillate back and forth between δ_0 and δ_2 at its natural frequency. The damping present in the machine will cause these oscillations to subside and the new steady state operating point would be at 'b'.

Transient Stability-Equal Area Criterion

With a sudden change in the power input, the stability is maintained only if area A_2(Decelerating Area) is atleast equal to A1 can be located above P_m .

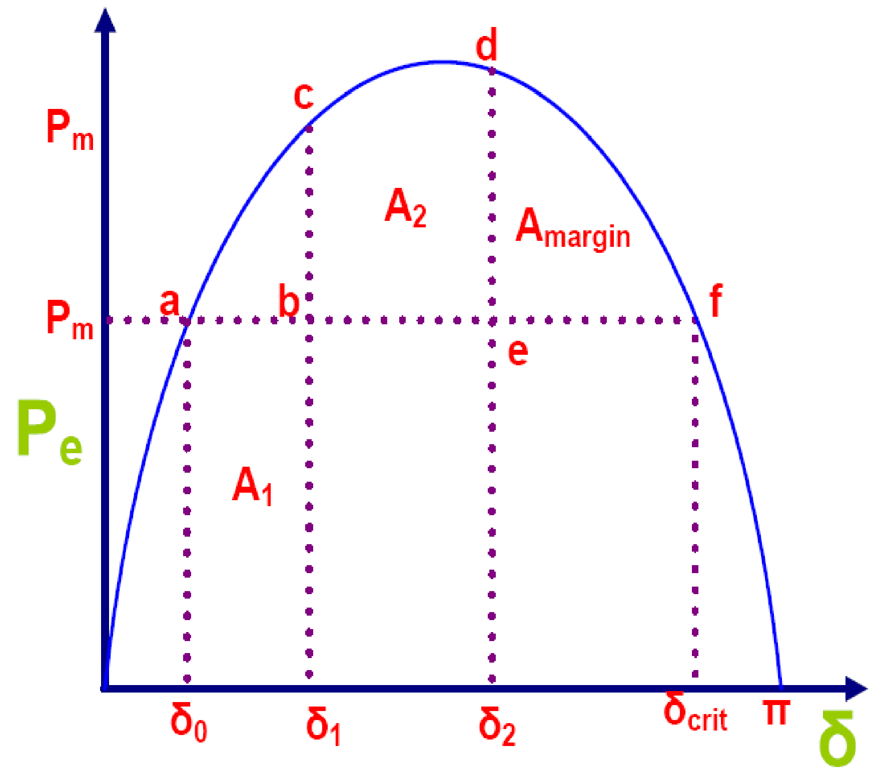
If area A_2 is less than area the accelerating momentum never be overcome.



The limit of stability occurs when $\delta_{max,}$ is at the intersection of line P_m and the power angle curve for $90^0<\delta<180^0$ Once δ_{max} is obtained, the maximum permissible power or the transient stability limit is found from $P_m= P_{max}$ Sin $\delta_{1,}$ where $\delta_{1=}$ $\pi-\delta_{max}$

Transient Stability-Equal Area Critrion

A fault occurring close to the generator will stop the flow of real power from the generator to the infinite bus bar via the line.

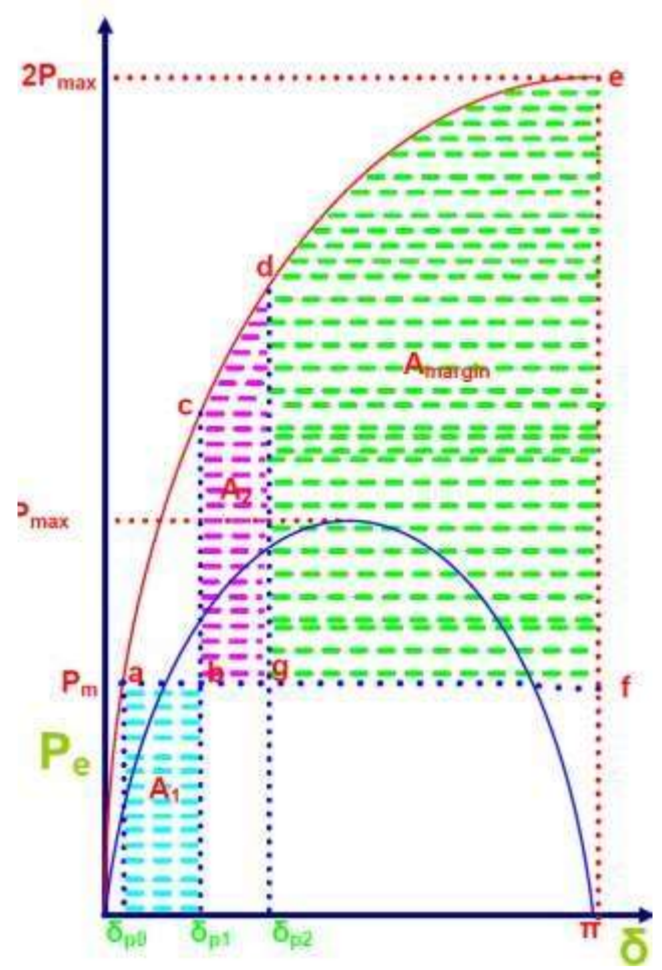


At $\delta = \delta_1$ the fault is cleared

we see that δ_2 is less than δ_{crit} and thus the extra area A_{margin}, is available. This area is referred to as the stability margin and is a measure of how close to the limit the system is being operated.

Transient Stability-Equal Area Critrion

the stability margin is increased compared to the uncompensated case.



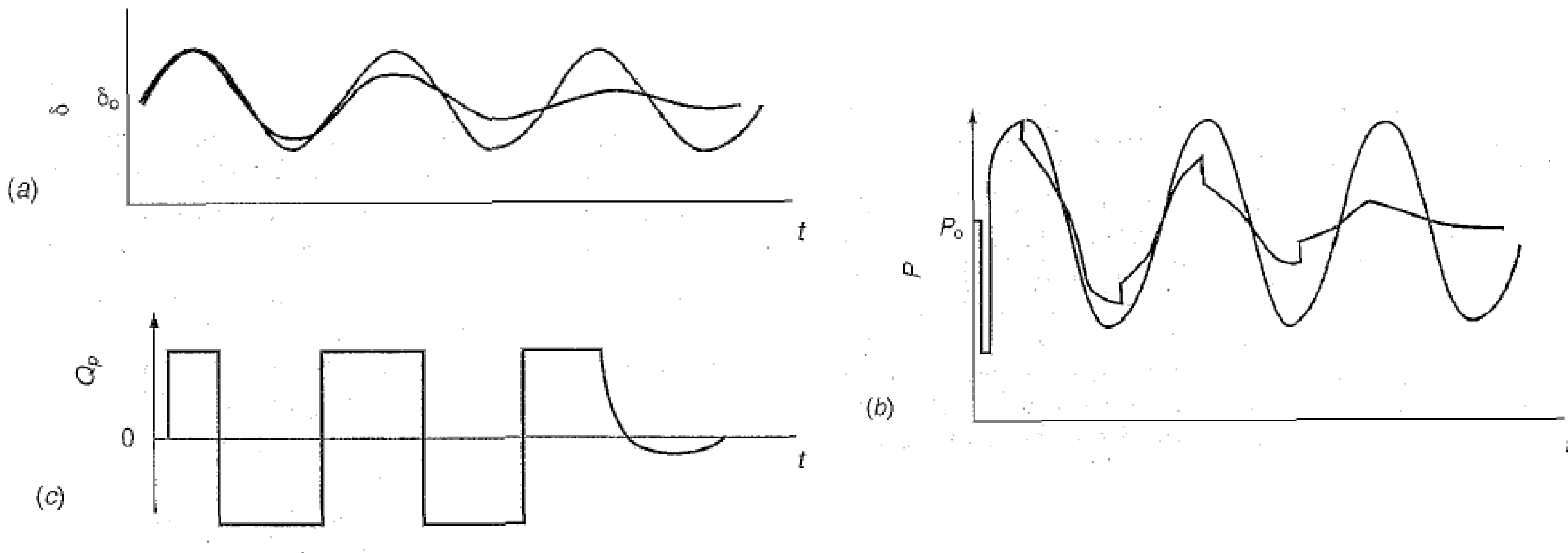
Alternatively, if the uncompensated stability margin is satisfactory, then these methods can increase the power transfer without reducing the stability margin.

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 of the electromechanical system.

Power Oscillation Damping

When the rotationally oscillating generator accelerates and angle δ increases (dδ/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 (dδ/dt<0),the electric power must be decreased to balance the insufficient mechanical input power.



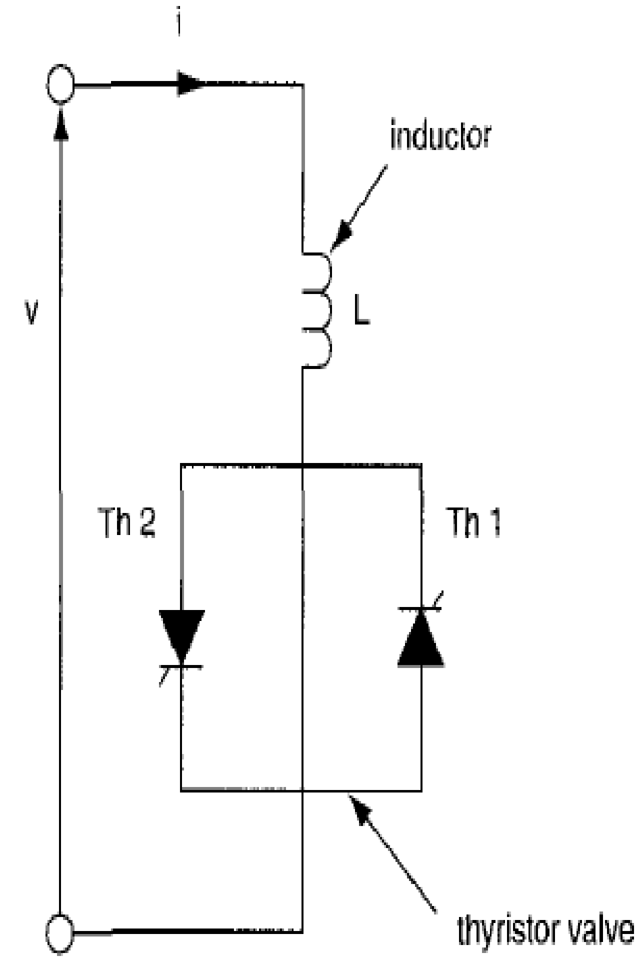
Methods of Controllable VAR generation

- Variable Impedance type Static Var generators
  - Thyristor Controlled Reactor(TCR)
  - Thyristor Switched Reactor(TSR)
  - Thyristor Switched Capacitor(TSC)

- ***STATCOM- Switching Converter type VAR generator***

Thyristor Controlled Reactor (TCR)

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. 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.

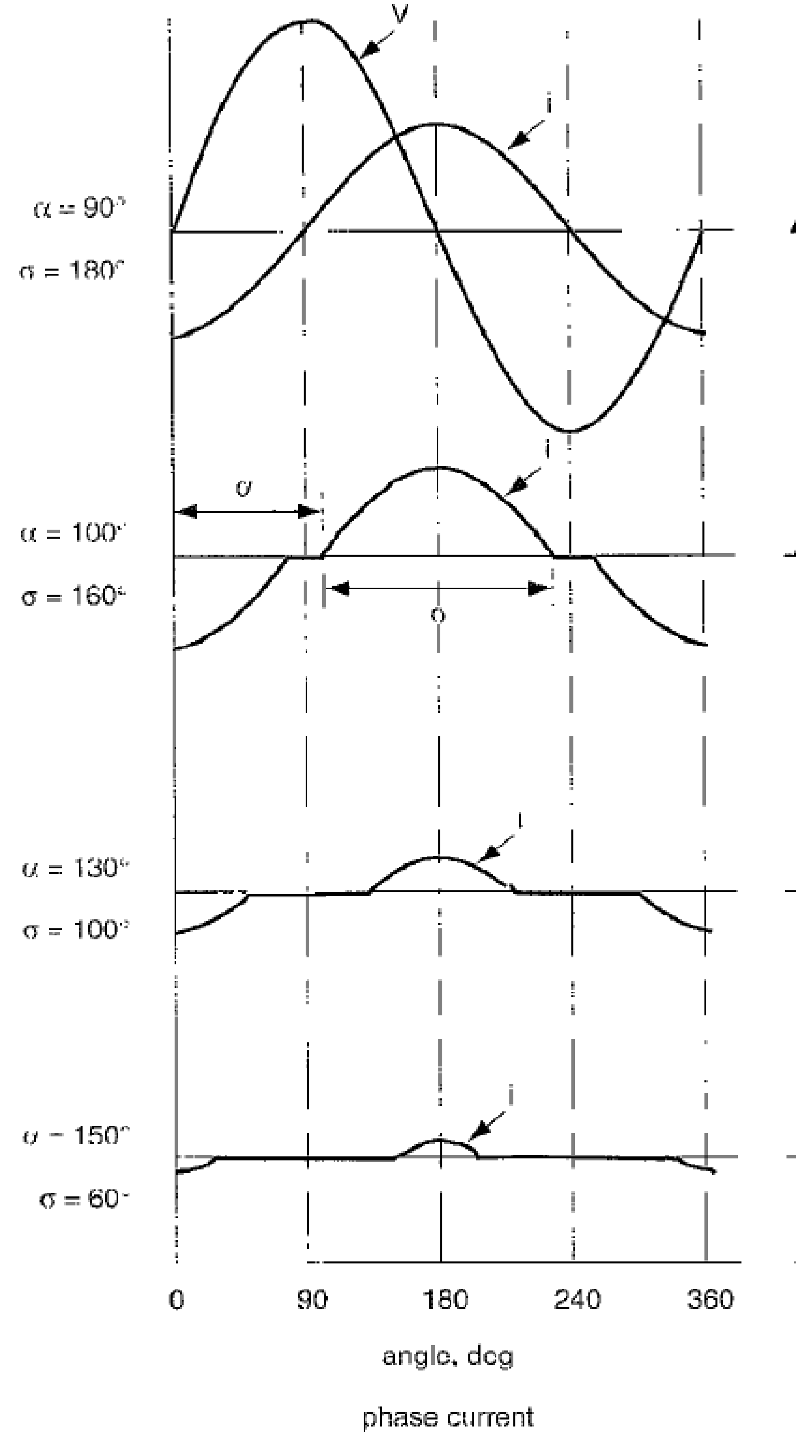


Thyristor Controlled Reactor (TCR)

If both thyristors are gated at a voltage maximum then circuit will behave as though the thyristor is short circuited and thus produce a lagging current of nearly 90^0.

The inductor current(and its stored energy) increases until the voltage reaches zero.

When voltage goes negative, the current now decreases and the stored energy is returned to the system until the current becomes zero and it no longer conducts



Thyristor Controlled Reactor (TCR)

The delay angle α varies between 90^0 (full conduction) and 180^0(no conduction).

The effect of increasing the gating delay angle is to decrease the amplitude of the current through the inductor.

Since the phase of the fundamental current component remains lagging at 90^0 to the applied voltage, we can see that changing the gating delay angle, control the effective inductance of the circuit.

The instantaneous current through the inductor I is given by.

$$i = \frac{\sqrt{2}V}{X_L}(\cos\alpha - \cos\omega t) \;\; for \;\; \alpha < \omega t < \alpha + \delta$$

$$= 0 \qquad for \;\; \alpha + \delta < \omega t < \alpha + \pi$$

The fundamental component of the current is given by.

$$I_1 = \frac{V}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right)$$

$$I_1 = \frac{V}{X_L}\frac{\delta - \sin\delta}{\pi}$$

Thyristor Controlled Reactor (TCR)

The fundamental component of the current is given by:

$$I_1 = \frac{V}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right)$$

It is clear that the TCR can control the fundamental current continuously from zero (valve open) to a maximum (valve closed) as if it was a variable admittance.

The effective reactive admittance, $B_L(\alpha)$ for the TCR can be defined as :

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

Thyristor Controlled Reactor (TCR)

The effective reactive admittance, $B_L(\alpha)$ for the TCR can be defined as :

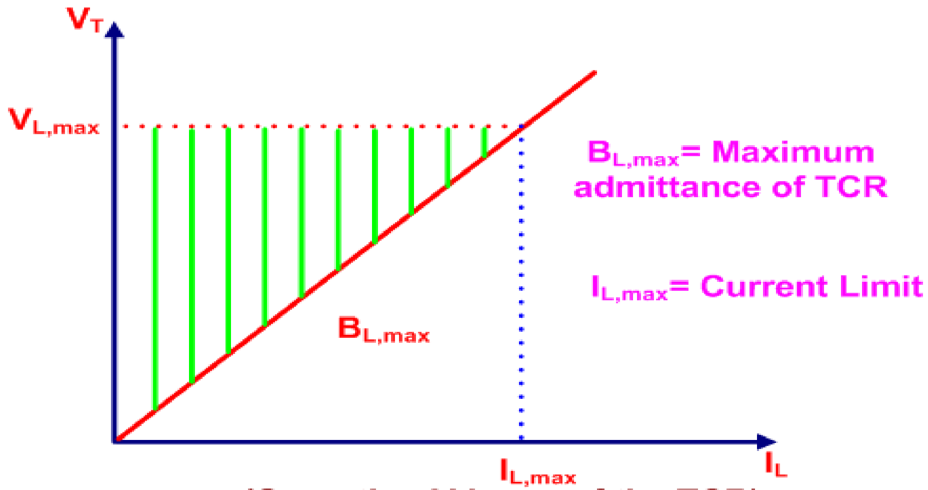
$$B_L(\alpha) = \frac{1}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right)$$

The meaning of the above equation is that at each delay angle α an effective admittance $B_L(\alpha)$ can be defined which determines the magnitude of the fundamental current $I_1(\alpha)$ in the TCR at a given applied voltage.

Thyristor Controlled Reactor (TCR)

In practice, the maximum 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

Thus 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 as shown below.

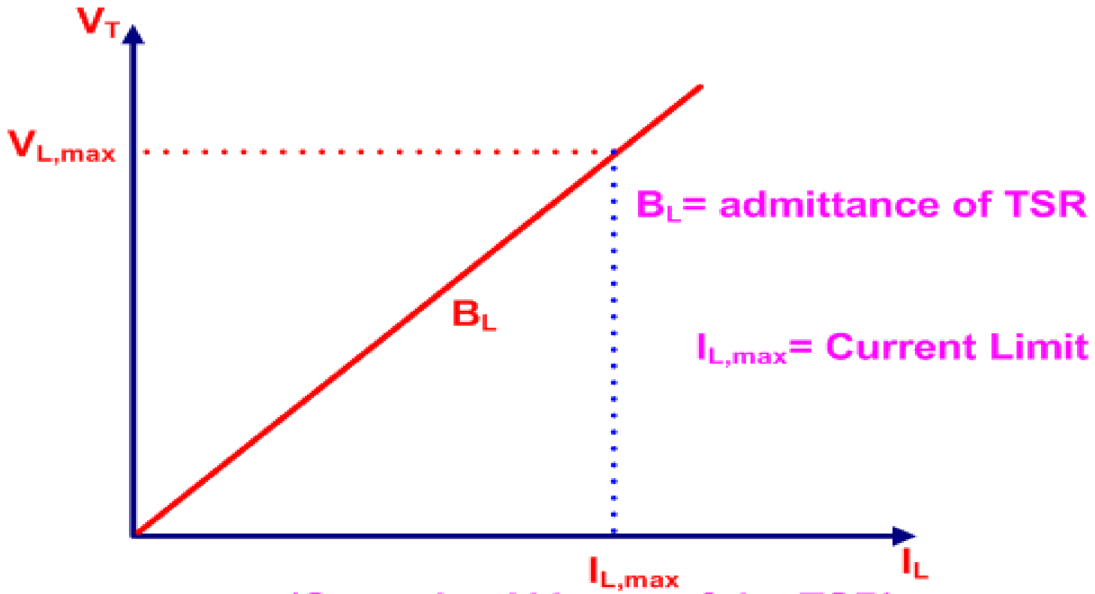


(Operating V-I area of the TCR)

Thyristor Switched Reactor (TSR)

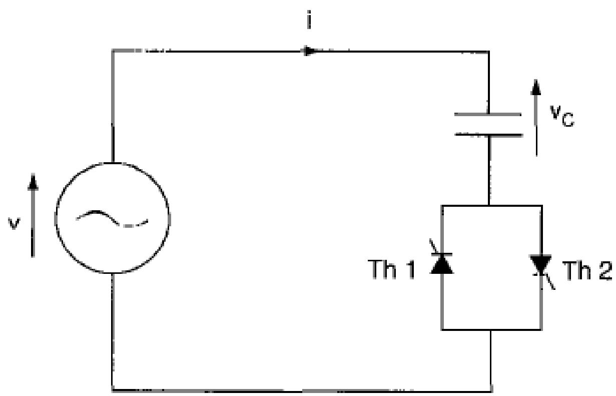
If the TCR switching is restricted to a fixed delay angle, usually α=0,then it becomes a thyristor switched reactor(TSR). The TSR provides a fixed inductive admittance.

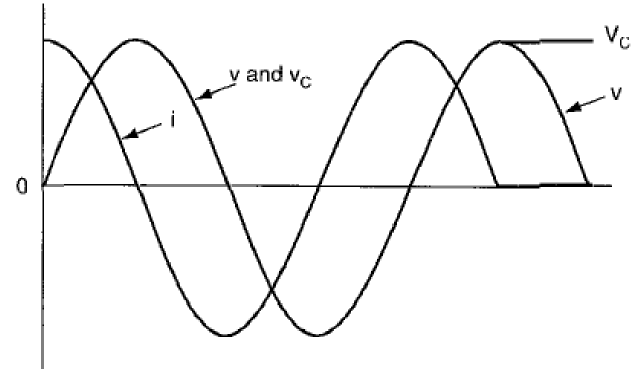
TSRs can provide a reactive admittance controllable in a step like manner. If the TSRs are operated at α=0, the resultant steady state current will be sinusoidal.



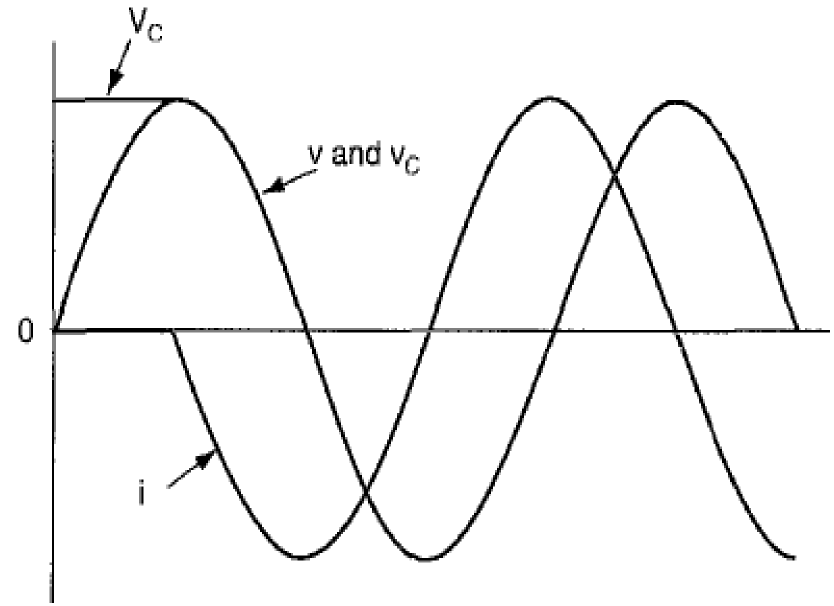
(Operating V-I area of the TSR)

Thyristor Switched Capacitor (TSC)





Ideal switching waveforms for a capacitor, the capacitor is switched off by natural commutation of the thyristor, which leaves a charge V_c on the capacitor.



In order to switch the capacitor again, the gating pulse must be applied at the supply voltage peak when the supply and capacitor voltages are equal.

Thyristor Switched Capacitor (TSC)

Let the supply voltage v is sinusoidal and given by:

$$v = V_m \sin(\omega_0 t+\alpha)\text{----------------}(1)$$

The thyristors may only be gated into conduction at a peak of the supply voltage, i.e when

$$\frac{dv}{dt} = \omega_0 V_m \cos(\omega_0 t + \alpha) = 0 - - - (2)$$

The current through the capacitor can be stated as

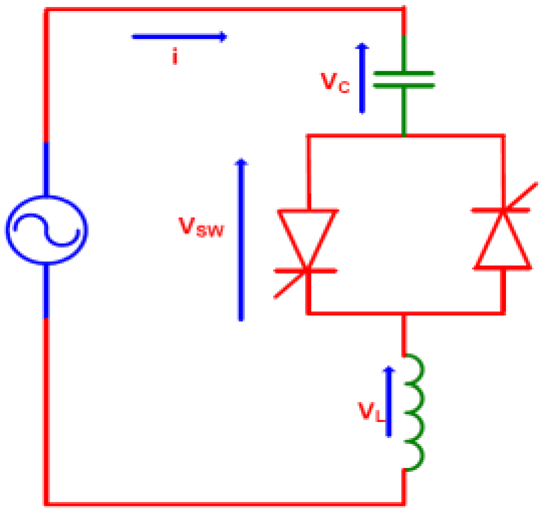
$$i = C\frac{dv}{dt} - - - - - - - (3)$$

So, gating at any instant other than the condition given in (2) will force the current to assume a discontinuous step.

Thus, to switch capacitors , it is necessary to ensure that dv/dt=0 and that the capacitor has already charged to the peak of the sytem voltage. If this conditions are not met, then a transient will result from the switching action.

Thyristor Switched Capacitor (TSC)

A single phase thyristor switched capacitor(TSC) is shown below which contains some series inductance to prevent high di/dt which may cause the thyristors to conduct in the absence of a gating pulse.



$$V(s) = (Ls + \frac{1}{Cs}).I(s) - \frac{V_{CO}}{s}$$

$$i(t) = \mathrm{I_m}\cos(\omega_0 t + \alpha) - \mathrm{nB_c}(V_{co} - \frac{n^2}{n^2-1}V_m \sin\alpha)\sin\omega_n t - \mathrm{I_m}\cos\alpha.\cos\omega_n t \quad --(4)$$

$$where\ \mathrm{I_m} = V_m.B_c, B_c = \omega_0 C, \omega_n = \frac{1}{\sqrt{LC}}\ \text{and n}=\sqrt{\frac{\mathrm{X_c}}{\mathrm{X_L}}}$$

Thyristor Switched Capacitor (TSC)

In order to attain transient free switching of the circuit, it is necessary to make the last two terms on the right hand side of eq.(4) equal to zero.

This can be achieved by simultaneously satisfying the following two conditions.

$$\cos\alpha = 0 \; and \; \mathrm{V_{CO}} = \pm V_m \frac{n^2}{n^2-1} \quad --(5)$$

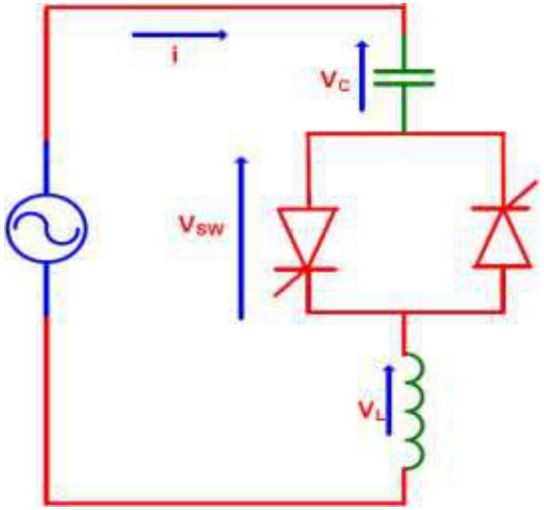
The first condition implies that the capacitors are gated at supply voltage peak.

The second condition implies that the capacitors must be charged to a voltage higher than the supply voltage prior to gating.

Thyristor Switched Capacitor (TSC)

Under steady state conditions,when the thyristor valve is closed and the TSC branch is connected to a sinusoidal voltage source, $v=V_m \sin\omega t$, the current in the branch is given by.

$$i(t) = V_m \frac{n^2}{n^2-1}\omega C.\cos\omega t \quad --(6)$$



The amplitude of the voltage across the capacitor is

$$V_C = V_m \frac{n^2}{n^2-1} \quad --(7)$$

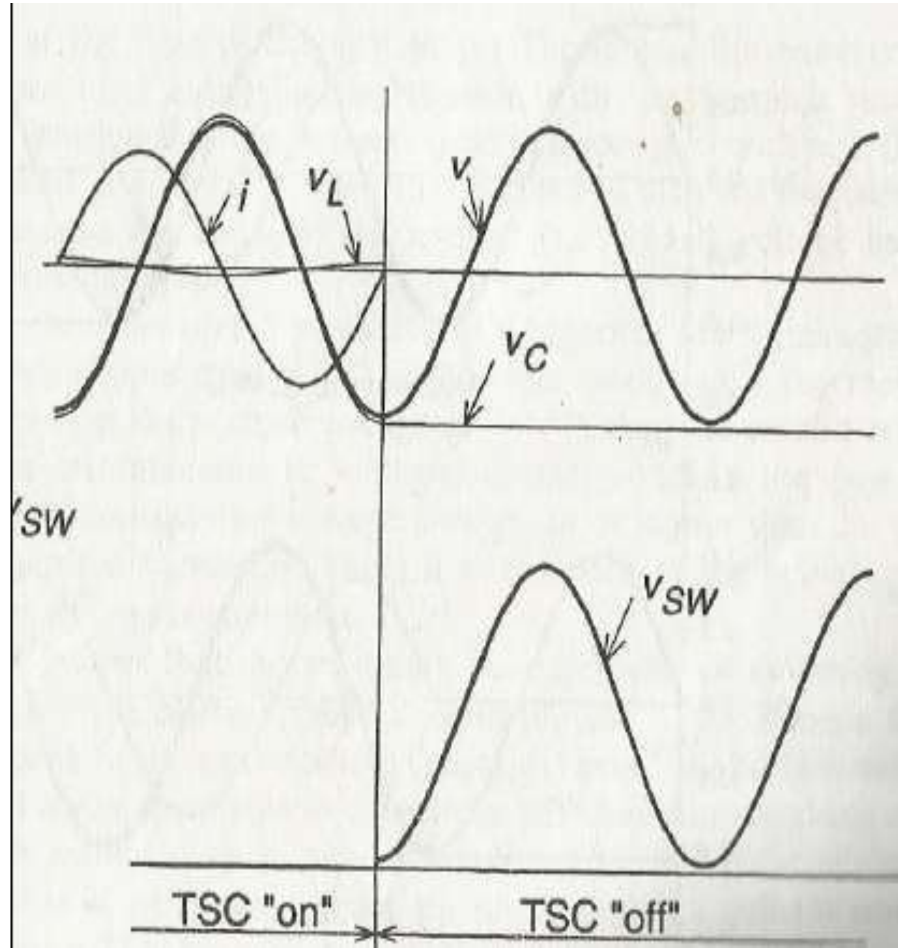
$$n=\sqrt{\frac{X_C}{X_L}}$$

Thyristor Switched Capacitor (TSC)

The TSC branch can be disconnected “switched out” at any current zero by prior removal of the gate drive to the thyristor valve.

At current zero crossing, the capacitor voltage is at its peak value,

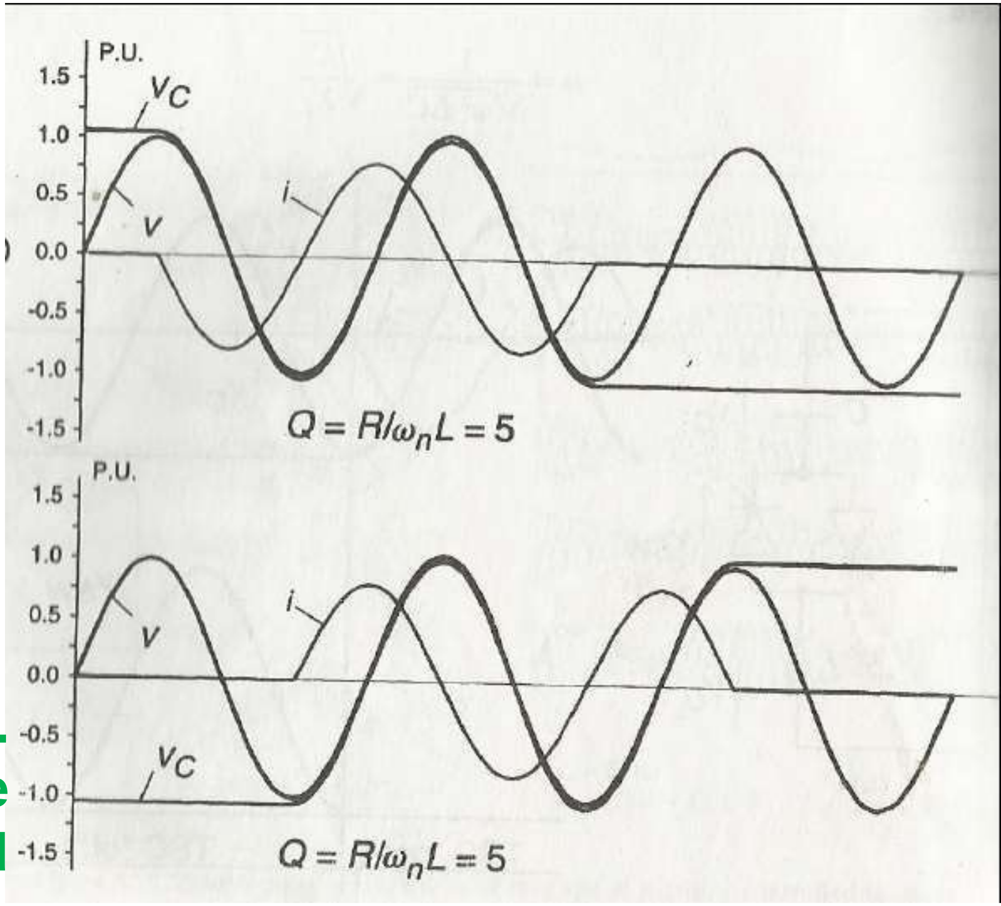
$$V_{C,\,i\,=\,0} = V_m \frac{n^2}{n^2 - 1}$$



The disconnected capacitor stays charged to this voltage and consequently, the voltage across the non conducting thyristor value varies between zero and peak to peak value of the applied ac voltage.

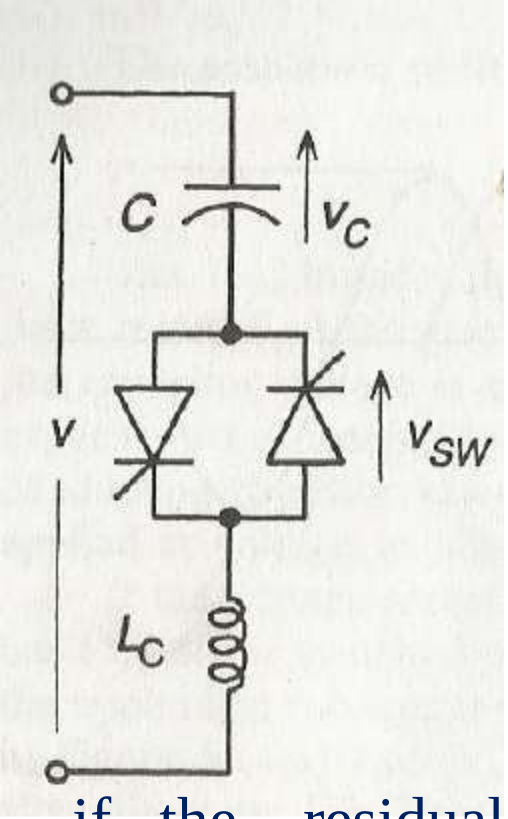
Thyristor Switched Capacitor (TSC)

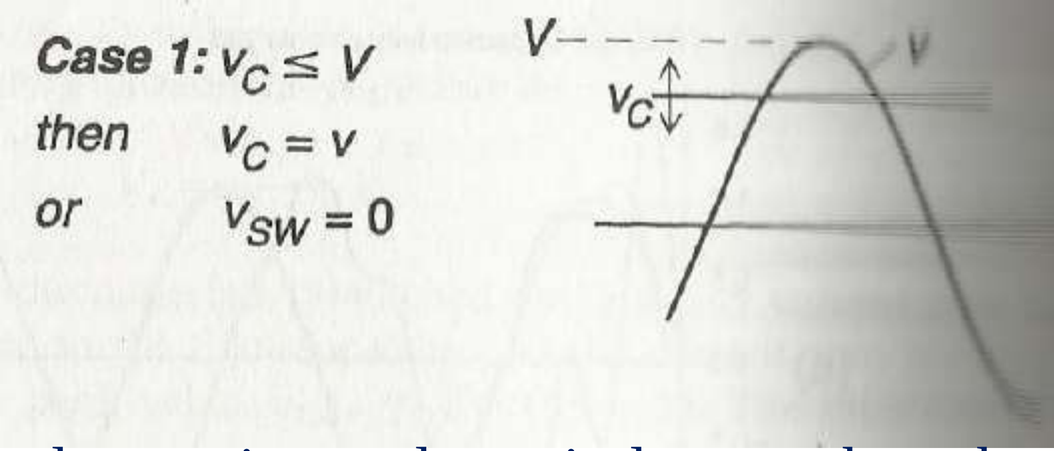
If the voltage across the disconnected capacitor remained unchanged, the TSC bank could be switched in again at the appropriate peak of the applied a.c voltage without any transient.



But normally, the capacitor bank is discharged after disconnection. Thus the reconnection of the capacitor may have to be executed at some residual voltage between zero and $V.n^2/n^2-1$.

This can possible with minimum transient disturbance if the thyristor valve is turned on at those instants at which capacitor residual voltage and the applied a.c voltage are equal, i.e when the voltage across the thyristor valve is zero.

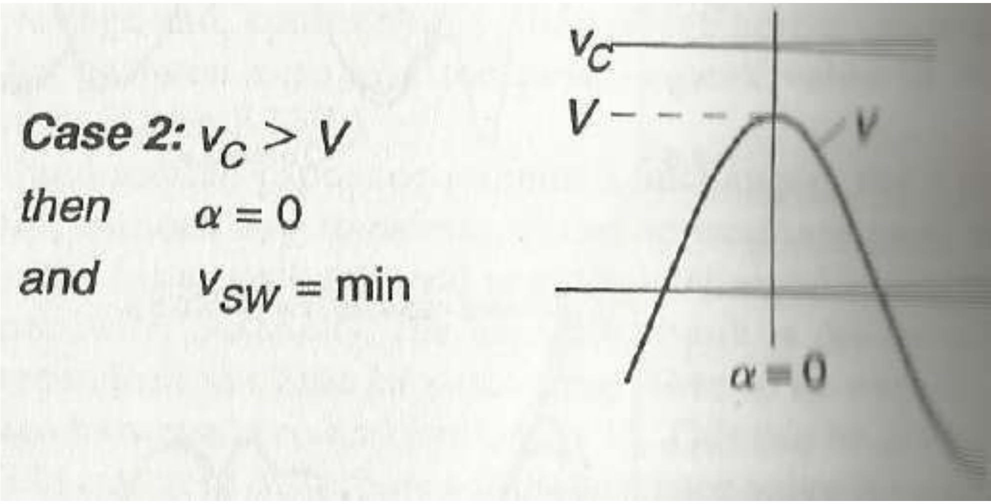




if the residual capacitor voltage is lower than the peak a.c voltage(V_C<V_m), then the correct instant of switching is when instantaneous a.c voltage becomes equal to the capacitor voltage.

capacitor

if the residual voltage is equal to higher than the peak a.c voltage, then the correct instant of switching is at the peak of the a.c voltage at which thyristor valve voltage is minimum.



Thyristor Switched Capacitor (TSC)

- It is clear that 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 condition for minimum transient are satisfied i.e when the voltage across the thyristor valve is zero or minimum.

- A TSC branch can provide only a step like change in the reactive current it draws(maximum or zero).

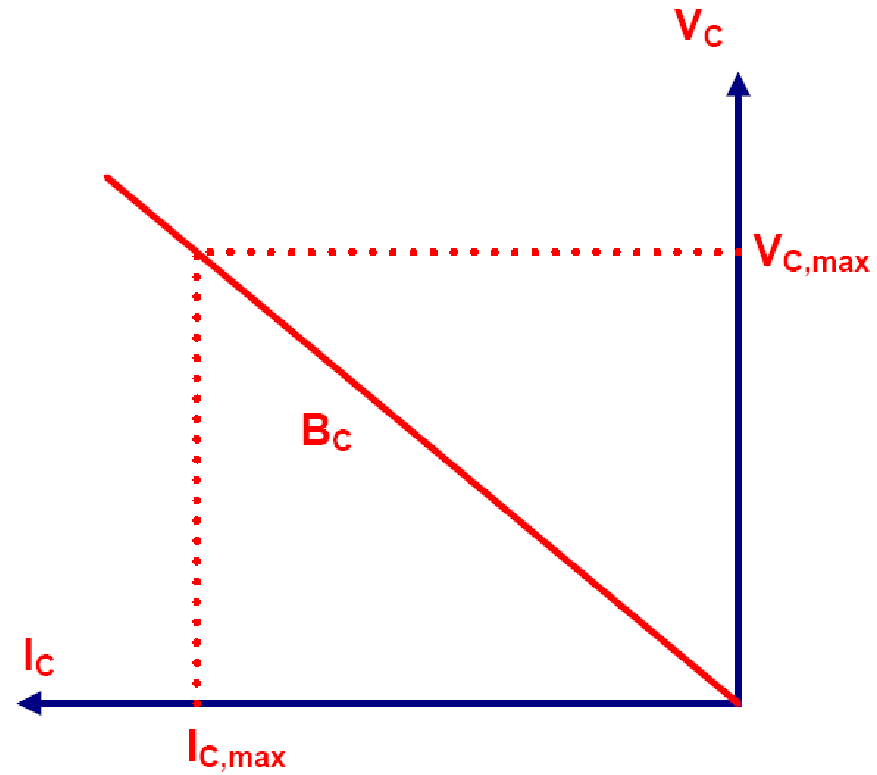
- TSC branch represents a single capacitive admittance which is either connected to or disconnected from the a.c system.

Thyristor Switched Capacitor (TSC)

The current in the TSC branch varies linearly with the applied voltage across according to the admittance of the capacitor as shown below by V-I plot.

The maximum applicable voltage and corresponding current are limited by the rating of the TSC components(capacitor and thyristor valve).

To approximate continuous current variation several TSC branches in parallel (which would increase in a step like manner the capacitive admittance) may be employed.



Static Var Compensators(SVC)

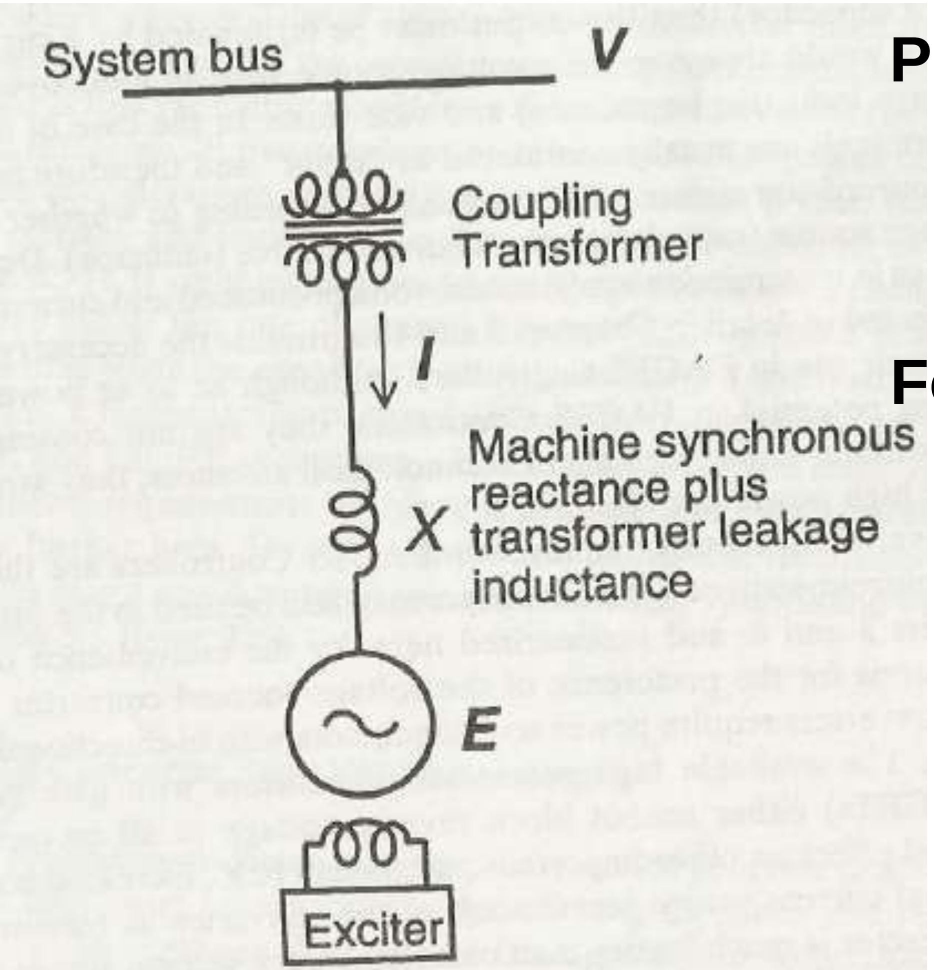
- Static Var Compensator is considered as the first generation FACTS controller. It is a variable impedance device where the current through a reactor is controlled using back to back connected thyristor valves.
- A SVC has no inertia compared to synchronous condensors and can be extremely fast in response. (2-3 cycles)

- There are two types of SVC:

1. Fixed Capacitor –Thyristor Controlled Reactor(FC-TCR)
2. Thyristor Switched Capacitor-Thyristor Controlled Reactor(TSC-TCR)

STATCOM

Basic Operating Principles



- Principle of reactive power generation by a VSC is akin to the conventional rotating synchronous machine.
- For purely reactive power flow, the three phase induced emfs e_a, e_b and e_c of the synchronous rotating machine are in phase with the system voltages v_a, v_b and v_c. The reactive current I drawn by the synchronous compensator is determined by the magnitude of the system voltage V, internal voltage E and X.

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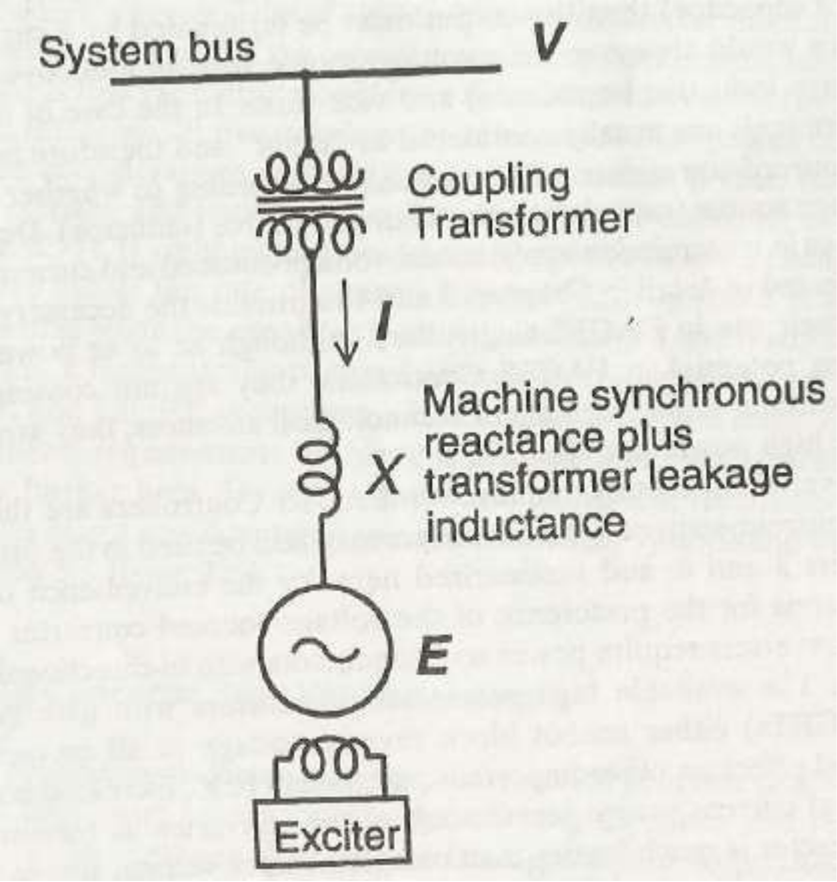

$$I = \frac{V - E}{X}$$

The corresponding reactive power Q exchanged is

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

By controlling the excitation of the machine, and hence the amplitude E of its internal voltage relative to the amplitude V of the system voltage, the reactive power can be controlled. Increasing E above V (operating overexcited) results in a leading current, i.e the machine becomes a capacitor.

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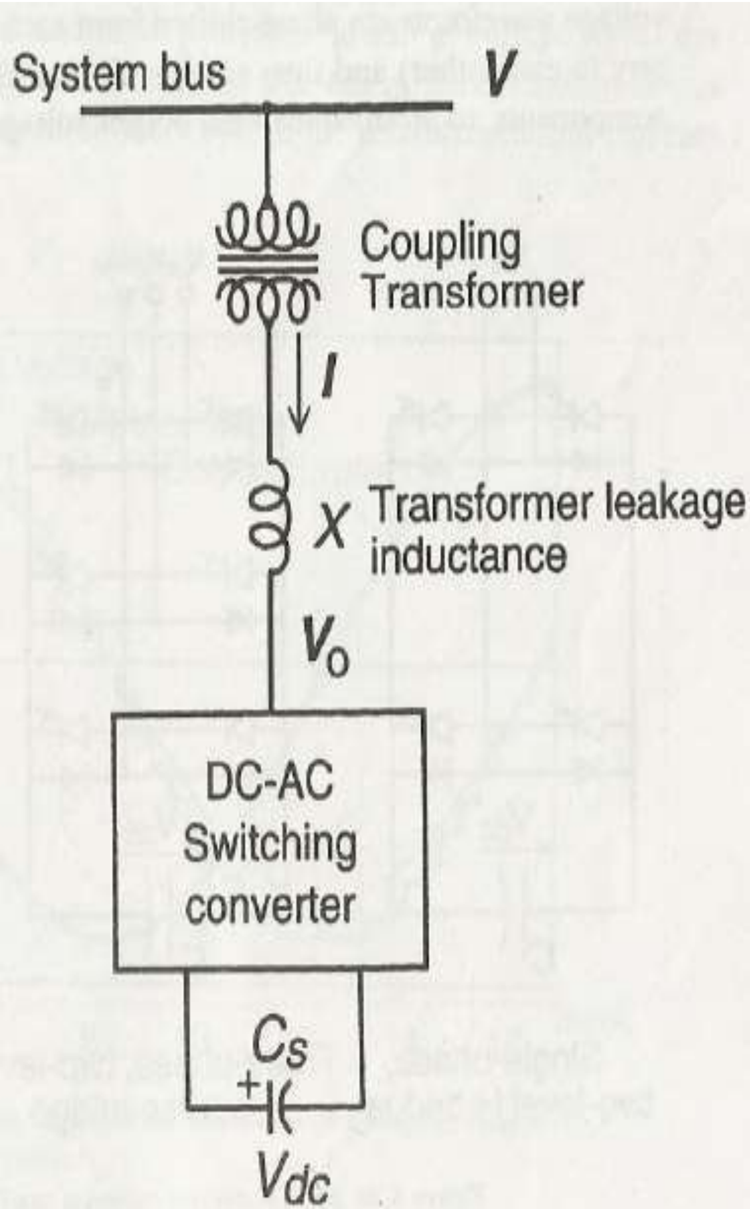

From a dc input voltage source, provided by the charged capacitor CS, the converter produces a set of controllable three phase output voltages is in phase with and coupled to corresponding ac system by the leakage reactance X.

By varying the amplitude of the output voltages produced, the reactive power exchange between the converter and the ac system can be controlled in a manner similar to that of the rotating synchronous machine.

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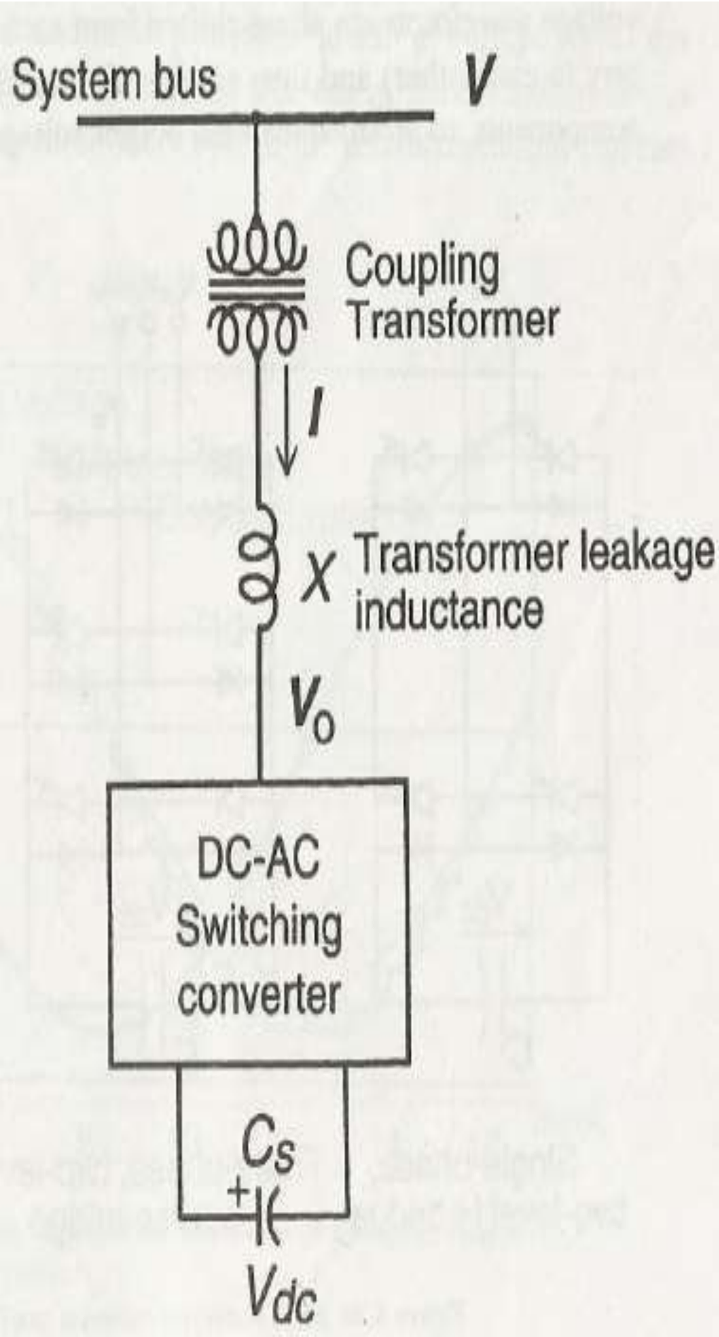


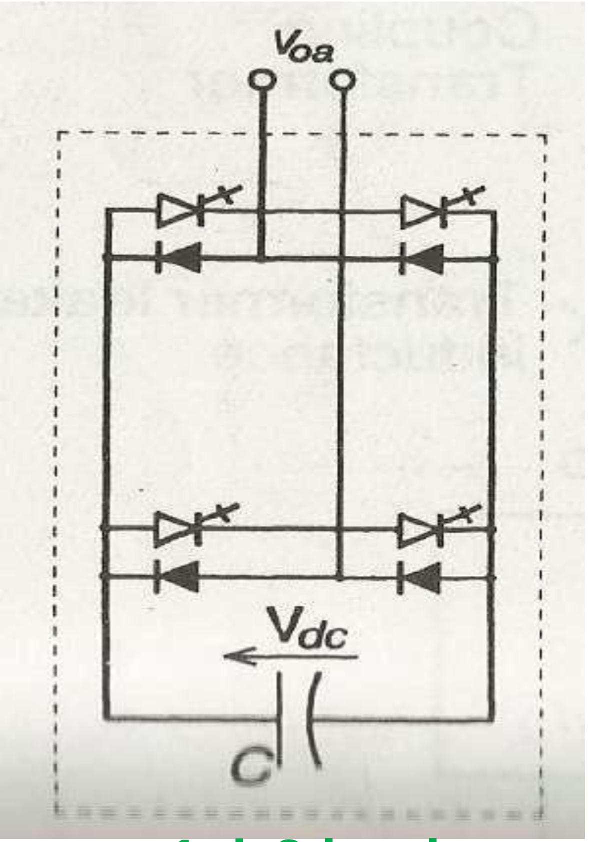
If the amplitude of the output voltage is increased above the system voltage, then current flows through the tie reactance from the converter to the ac system and the converter generates capacitive reactive power.

If the amplitude of the output voltage is decreased below the system voltage, then current flows from the ac system to the converter. The converter absorbs inductive reactive power.

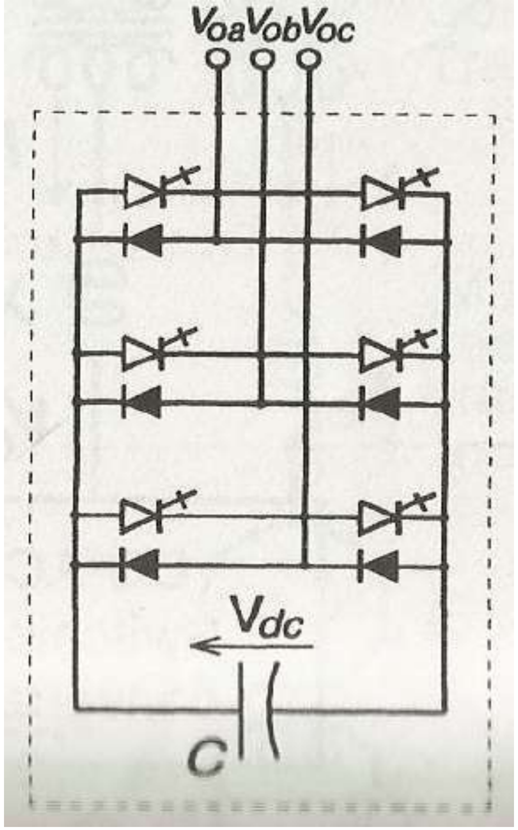
If the amplitude of the output voltage is equal to the ac system voltage, the reactive power exchange is zero.

The 3-phase output voltage is generated by a voltage sourced dc to ac converter operated from an energy storage capacitor.

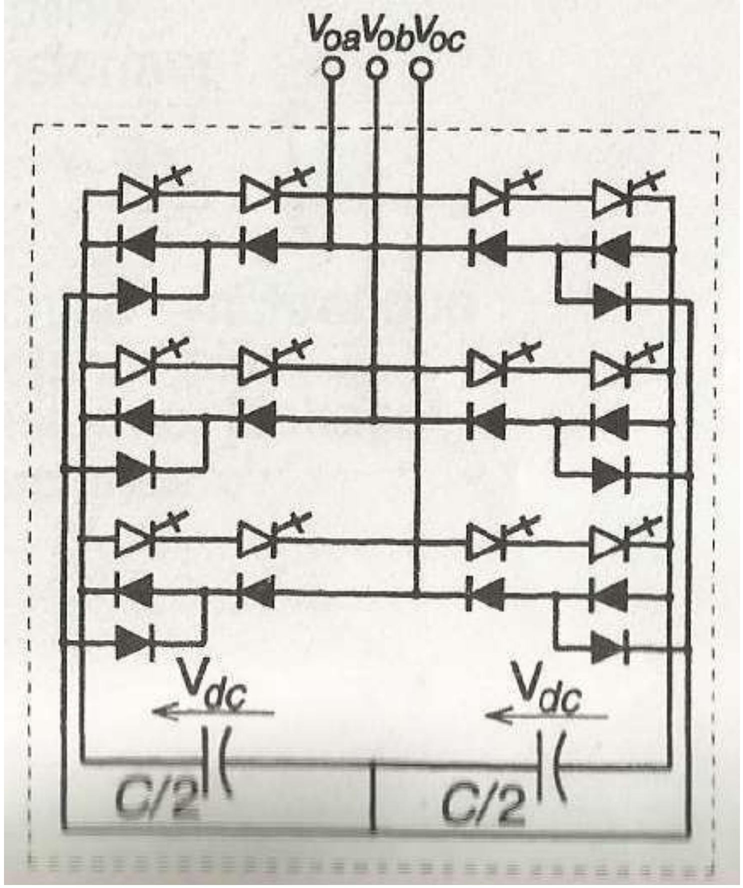
All of the practical converters employed in actual transmission lines are composed of a number of elementary converters, i.e single phase H-bridges or 3-phase 2-level 6-pulse bridges or 3-phase 3-level 12-pulse bridges.



1-Φ 2-level H-bridge



3-Φ 2-level 6-pulse bridge



3-Φ 3-level 12-pulse bridge

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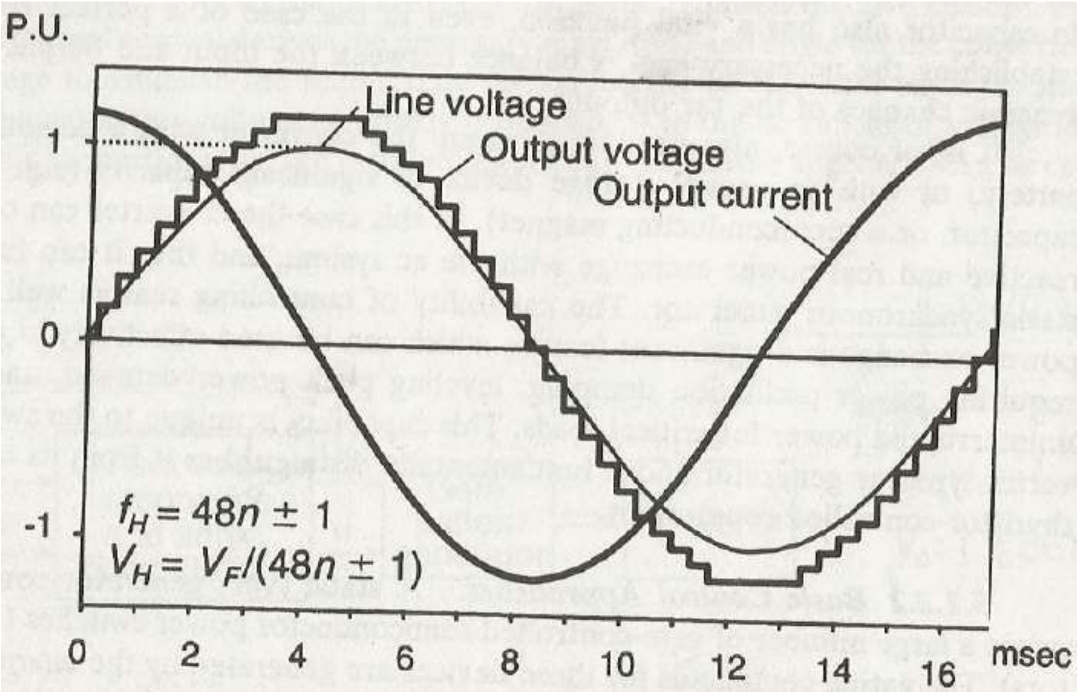
- Each elementary converter produces a square or quasi square or a pulse width modulated output waveform.
- These component voltage waveforms are phase-shifted from each other and then combined usually with the use of appropriate magnetic components, to produce the final output voltage of the total converter.
- With sufficient design, this final output voltage can be made to approximate a sine wave closely.



COMPARISON BETWEEN STATCOM & SVC

S.No.	STATCOM	SVC
1	Acts as a voltage source behind a reactance	Acts as a variable susceptance
2	Insensitive to transmission system harmonic resonance	Sensitive to transmission system harmonic resonance
3	Has a larger dynamic range .	Has a smaller dynamic voltage
4	Lower generation of harmonics .	Higher generation of harmonics
5	Faster response and better performance during transients	Somewhat slower response
6	Both inductive and capacitive regions of operation is possible	Mostly capacitive region of operation
7	Can maintain a stable voltage even with a very weak a.c. system	Has difficulty operating with a very weak a.c. system

UNIT-IV

STATIC SERIES COMPENSATORS

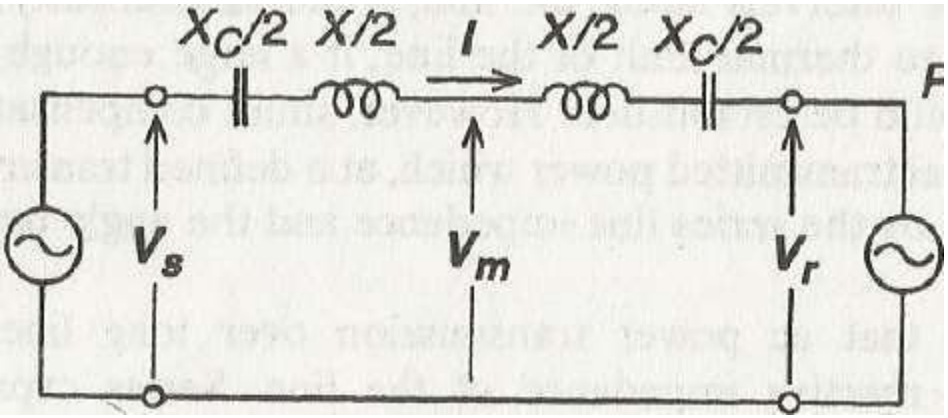
Objectives of Series Compensation

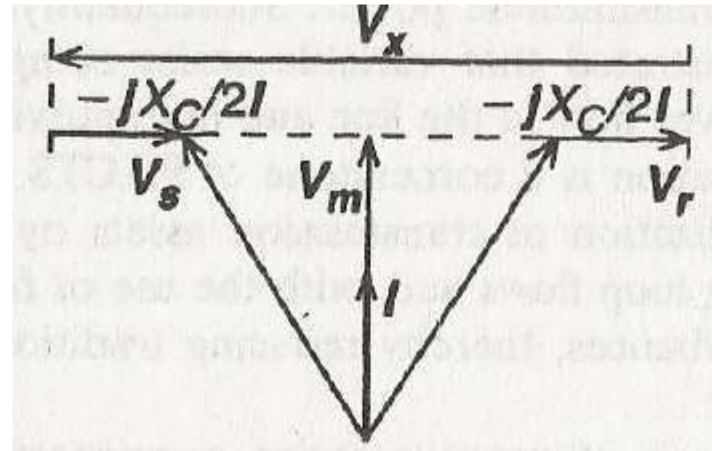
- The ac power transmission over long lines was primarily limited by the series reactive impedance of the line. Series capacitive compensation cancel a portion of the reactive line impedance and thereby increase the transmittable power.
- Variable series compensation is highly effective in both controlling power flow in the line and improving stability. FACTS technology based variable controllable series line compensation can be applied to achieve full utilization of transmission assets by controlling the power flow in the lines, preventing loop flows and with the use of fast controls, minimizing the effect of system disturbances, thereby reducing traditional stability margin requirements.
- It helps damping power oscillations and sub synchronous oscillations and improve voltage stability .

Concept of Series Capacitive Compensation

- The basic idea behind series capacitive compensation is to decrease the overall effective series transmission impedance from the sending end to the receiving end i.e, X in the $P=(V^2/X)\sin\delta$ relationship characterizing the power transmission over a single line.

Concept of Series Capacitive Compensation





For the same end voltages the magnitude of the total voltage across the series line inductance, V_X=2V_X/2 is increased by the magnitude of the opposite voltage, V_C, developed across the series capacitor.

The effective transmission impedance Xeff with the series capacitive compensation is given by: $\mathbf{X_{eff}=X-X_C}$ and $\mathbf{X_{eff}=(1-k)X}$, where 'k' is the degree of series compensation ,so k=$\mathbf{X_C}$/X and 0≤k<1

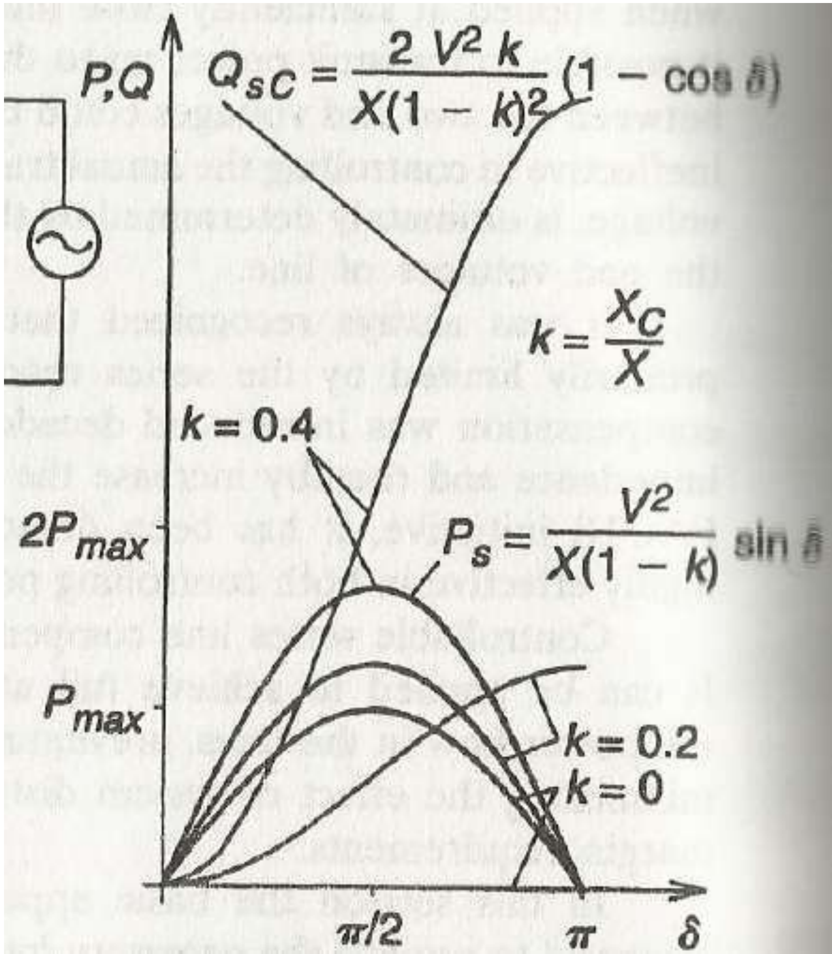
Concept of Series Capacitive Compensation

Assuming $V_s = V_r = V$, the real power transferred is given by : $P = V^2/X\ .\ .\sin\delta = V^2/X(1-k)\ .\ \sin\delta$

The reactive power supplied by the series capacitor can be expressed as :

$$Q_C = I^2 X_C = \frac{2V^2}{X} \cdot \frac{k}{(1-k)^2}(1-\cos\delta)$$

The transmittable power rapidly increased by with the degree of series compensation 'k'. Similarly, the reactive power supplied by the series capacitor also increases sharply with 'k' and varies with angle δ



Concept of Series Capacitive Compensation

- The impedance of the series compensating capacitor cancels a portion of the actual line reactance and thereby the effective transmission impedance is reduced as if the line was physically shortened.

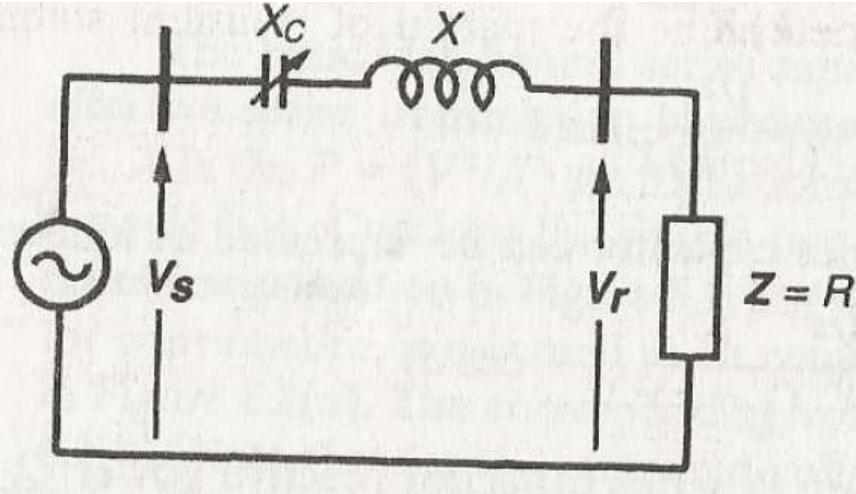
- Alternatively, in order to increase the current in the given series impedance of the actual physical line(thereby the corresponding transmitted power), the voltage across this impedance must be increased, which is accomplished by a series connected capacitor.

- An alternating compensating circuit element can be an ac voltage source in series with line. So, the switching power converter STATCOM can be applied as a voltage source in series with the line and can act as a series capacitive compensator.

Voltage Stability

Assuming $V_s = V_r = V$, the real power transferred is given by : $P = V^2/X \,.\, .\sin\delta = V^2/X(1-k) \,.\, \sin\delta$

The reactive power supplied by t
expressed as :



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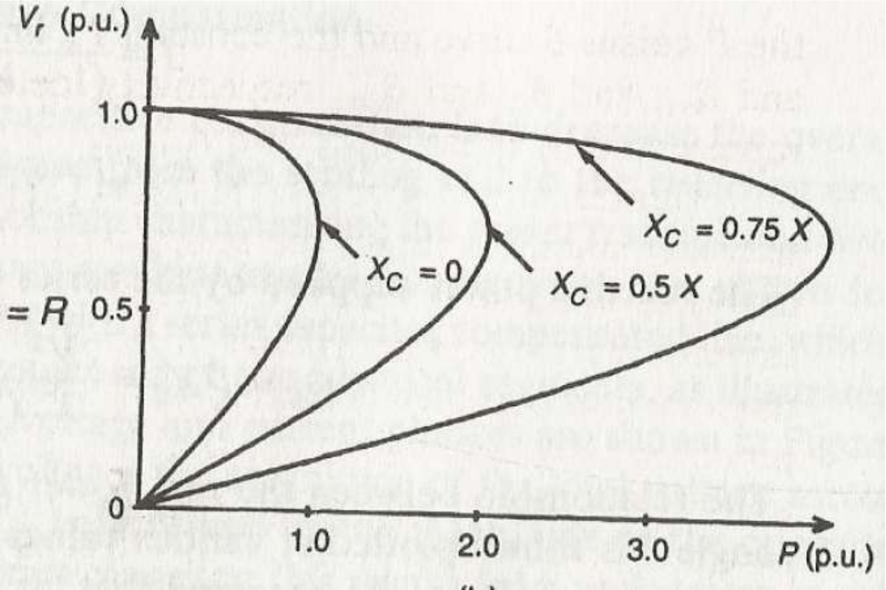


Subsynchronous Oscillation Damping

- Sustained oscillation below the fundamental system frequency can be caused by series capacitive compensation.

- In series compensated transmission lines which are fed by thermal generation, particularly in cases of high degrees of compensation, the series resonance frequency may coincide with some poorly damped torsional vibration frequency of the turbo generator shaft. Hence it could induce increased mechanical stresses in the shafts. This phenomenon is known as Sub Synchronous Resonance(SSR).

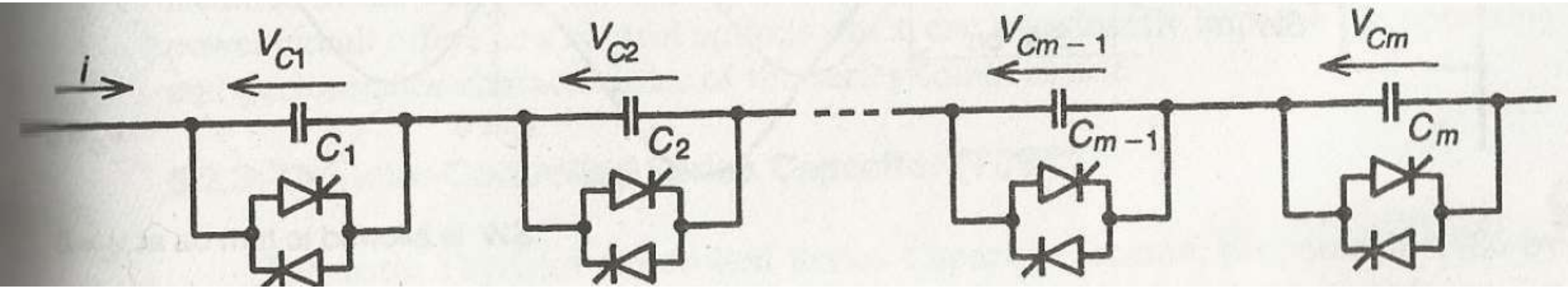
- By the use of TCSC, the series capacitor(s) act inductive in the range sub synchronous frequency band thus almost making the SSR impossible to occur.

Variable Impedance Type Series Compensators

- Thyristor Switched Series Capacitor(TSSC)
- Thyristor Controlled Series Capacitor(TCSC)
- GTO Thyristor Controlled Series Capacitor

Thyristor Switched Series Capacitor(TSSC)

- The basic circuit arrangement of a TSSC is shown

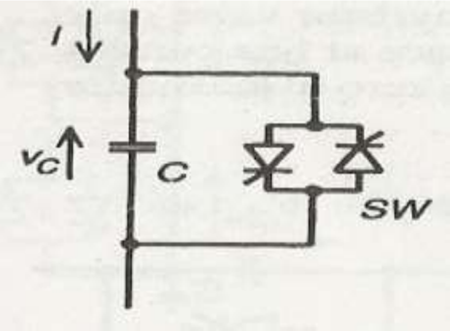


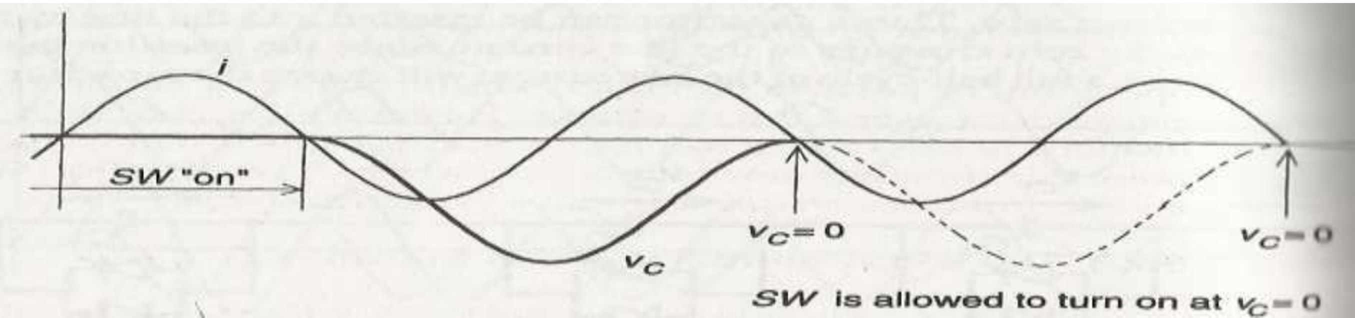
Operating Principle:

- 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 bypassed by turning on the corresponding thyristor valve.

Thyristor Switched Series Capacitor(TSSC)

- The thyristor valve commutates “naturally”, i.e it turns off when the current crosses zero. Thus a capacitor can be inserted into the line by the thyristor valve only at the zero crossings of the line current.
- Since the insertion takes place at line current zero, a full half cycle of the line current will charge the capacitor from zero to maximum and the successive opposite polarity half cycle of the line current will discharge it from this maximum to zero.
- The capacitor insertion at line current zero due to the switching limitation of the thyristor valve, results in a dc offset voltage. In order to minimize the initial surge current in the valve and the corresponding circuit transient, the thyristor valve should be turned on for bypass only when the capacitor voltage is zero.





Thyristor Switched Series Capacitor(TSSC)

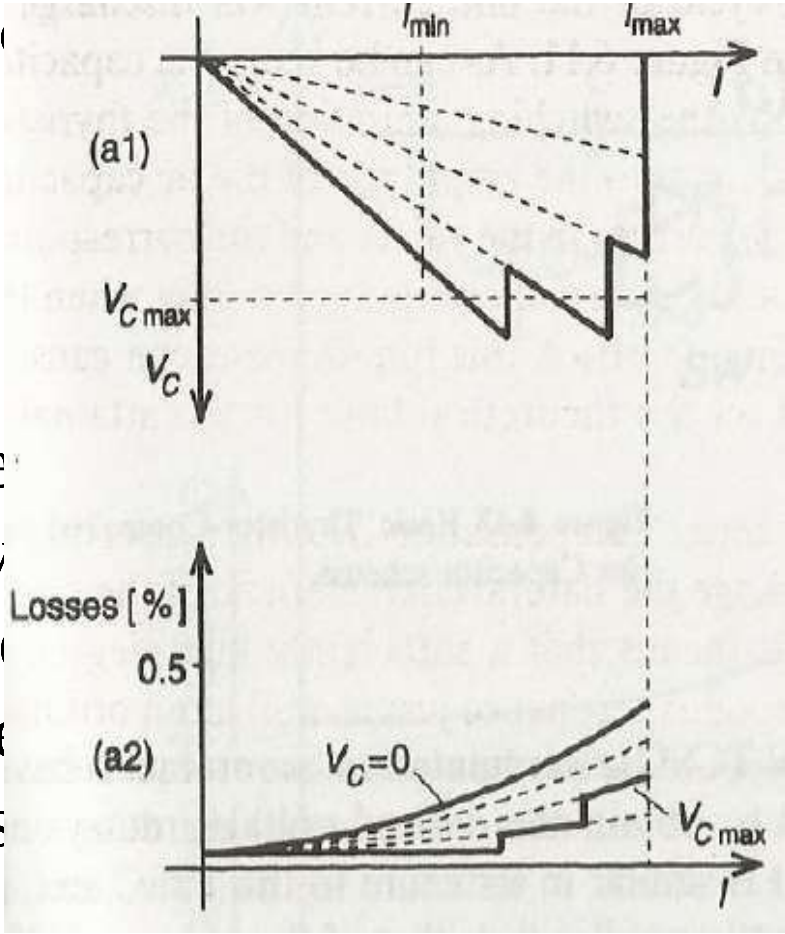
- The TSSC can control the degree of series compensation by either inserting or bypassing series capacitors but it cannot change the natural characteristics of the classical series capacitor compensated line.
- A sufficiently high degree of TSSC compensation could cause sub synchronous resonance.
- The TSSC switching could be modulated to counter act sub synchronous oscillations, but likely to be not effective due to relatively long switching delays.
- Therefore, pure TSSC scheme would not be used in critical applications where a high degree of compensation is required and the danger of SSR is present.
- The TSSC could be applied for power flow control and for damping power oscillation where the required speed of response is moderate.

Thyristor Switched Series Capacitor(TSSC)

The basic V-I characteristic of the TSSC with 4 series connected compensator modules operated to control the compensating voltage is shown:

The reactance of the capacit capacitor banks is chosen such that $V_{cmax}=4X_C.I_{min}$, in the face of decreasing line current over a

- defined interval $I_{min}<=I<=I_{max}$.
- As the current Imin is increase capacitor banks are progressiv related thyristor valves to r capacitive reactance in a ste therby maintain the compens increasing line current.



Thyristor Switched Series Capacitor(TSSC)

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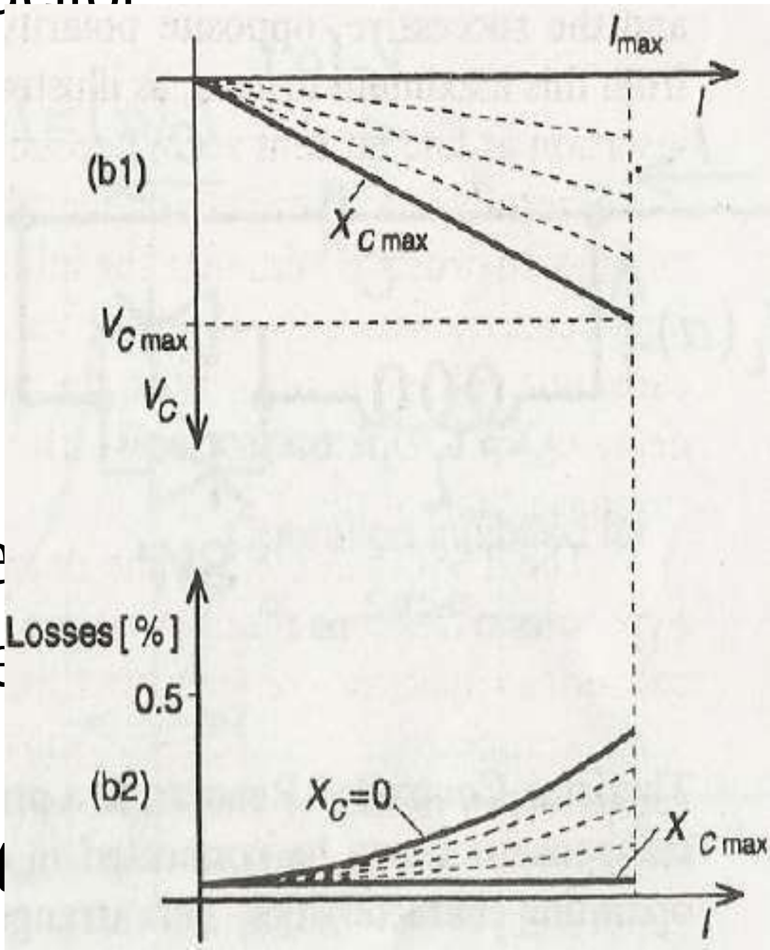
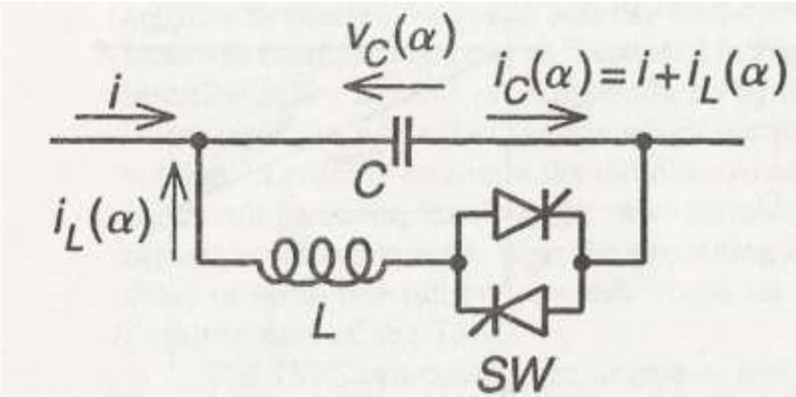


- defined interval $I_{min}<=I<=I_{max}$.
- As the current Imin is increas the capacitor banks are progre by the related thyristor valve overall capacitive reactance manner and therby maintain t voltage with increasing line current.

Thyristor Controlled Series Capacitor(TCSC)

The basic TCSC scheme was proposd in 1986 by Vithayathil with others as a method of "rapid adjustment of network impedance":



It consists of the series compensating capacitor shunted by a Thyristor Controlled Reactor.

In a practical TCSC implementation, several such basic compensators may be connected in series to obtain the desired voltage rating and operating characteristics.

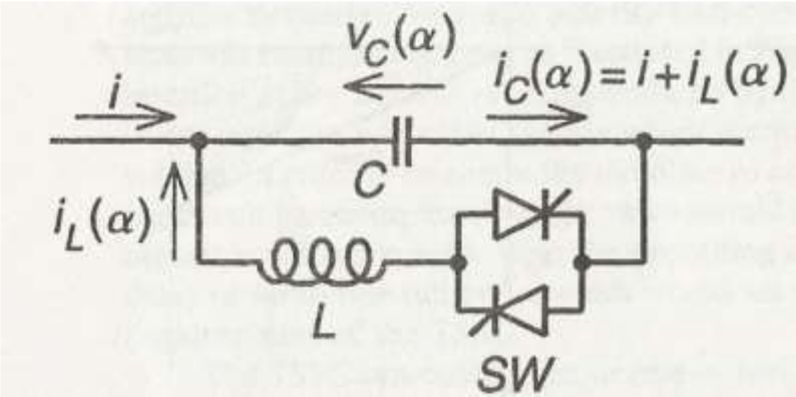
If X_L is sufficiently smaller than that of the capacitor X_C, it can be operated in an on/off manner like the TSSC.

The basic idea behind the TCSC scheme is to provide a continuously variable capacitor by means of partially cancelling the effective compensating capacitance by the TCR.

Thyristor Controlled Series Capacitor(TCSC)

The TCR at the fundamental system frequency is a continuously variable reactive impedance, controllable by delay angle α

Thus the steady state impedance of the TCSC is that of a parallel LC circuit, consisting of a fixed capacitive impedance , X_C, and a variable inductive impedance, $X_L(\alpha)$.



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

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

X_L=Ωl and α is the delay angle measured from the crest of the capacitor voltage or equivalently the zero crossing of the line current.

Thyristor Controlled Series Capacitor(TCSC)

The TCSC thus presents a tunable parallel LC circuit to the line current.

As the impedance of the controlled reactor, $X_L(\alpha)$ is varied from its maximum (infinity) towards its minimum (ωL) ,the TCSC increases its minimum capacitive impedance, $X_{TCSC,min}=X_C=1/\omega C$ (and thereby the degree of series capacitive compensation) until parallel resonance at $X_c=X_L(\alpha)$ is established and $X_{TCSC,max}$ theoritically becomes infinite.

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

Deceasing X_L further, the impedance of the TCSC, $X_{TCSC}(\alpha)$ becomes inductive , reaching its minimum value of $X_L . X_C/(X_L-X_C)$ at $\alpha=0$, where the capacitor is in effect bypassed by the TCR.

Thyristor Controlled Series Capacitor(TCSC)

With the usual TCSC arrangement in which the impedance of the TCR reactor, X_L, is smaller than that of the capacitor, X_C, the TCSC has two operating ranges around its internal circuit resonance: one is the $\alpha_{Clim} \leq \alpha \leq \pi/2$ range where $X_{TCSC}(\alpha)$ is capacitive, and the other is the $0 \leq \alpha \leq \alpha_{Llim}$ range, where $X_{TCSC}(\alpha)$ is inductive as shown below.

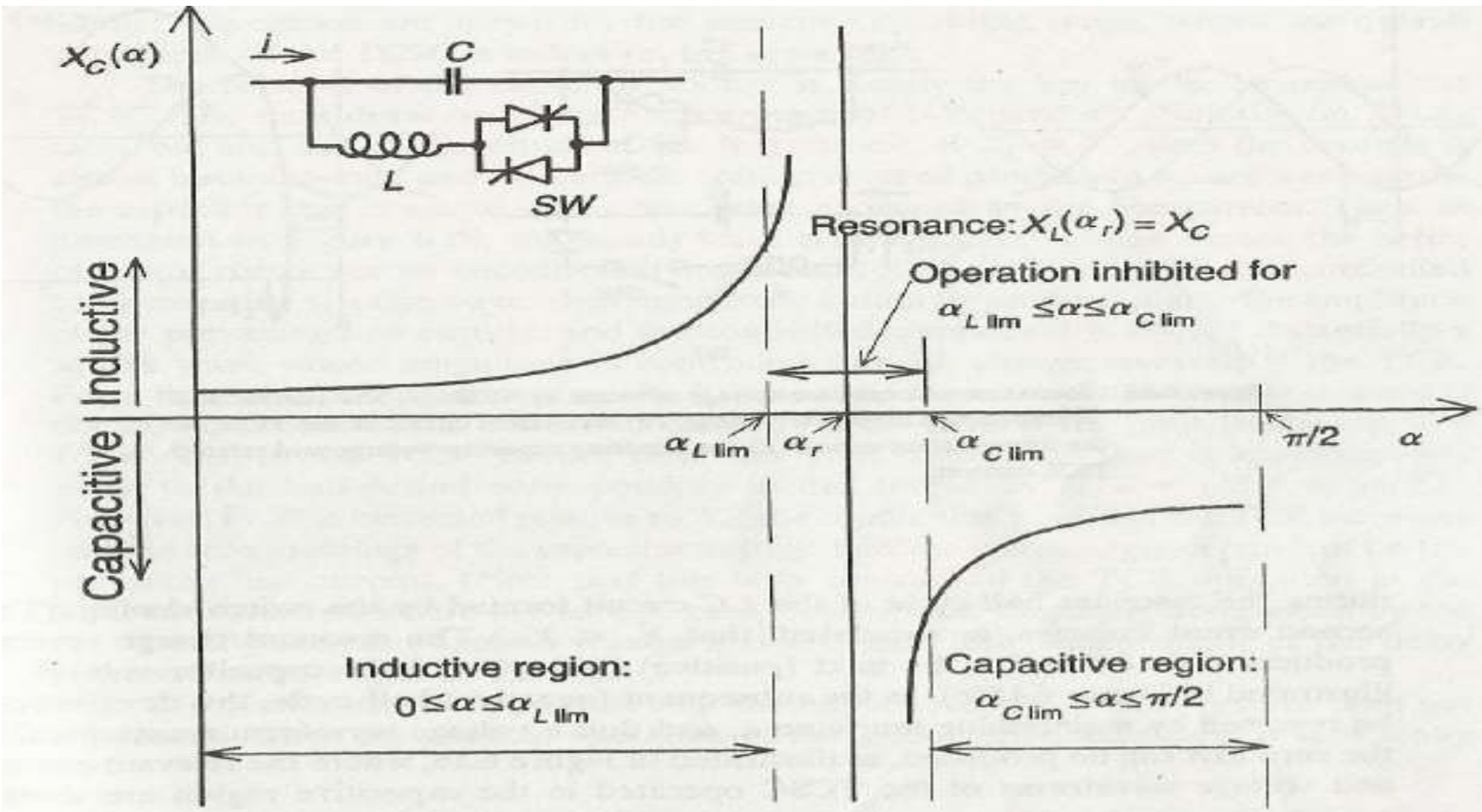
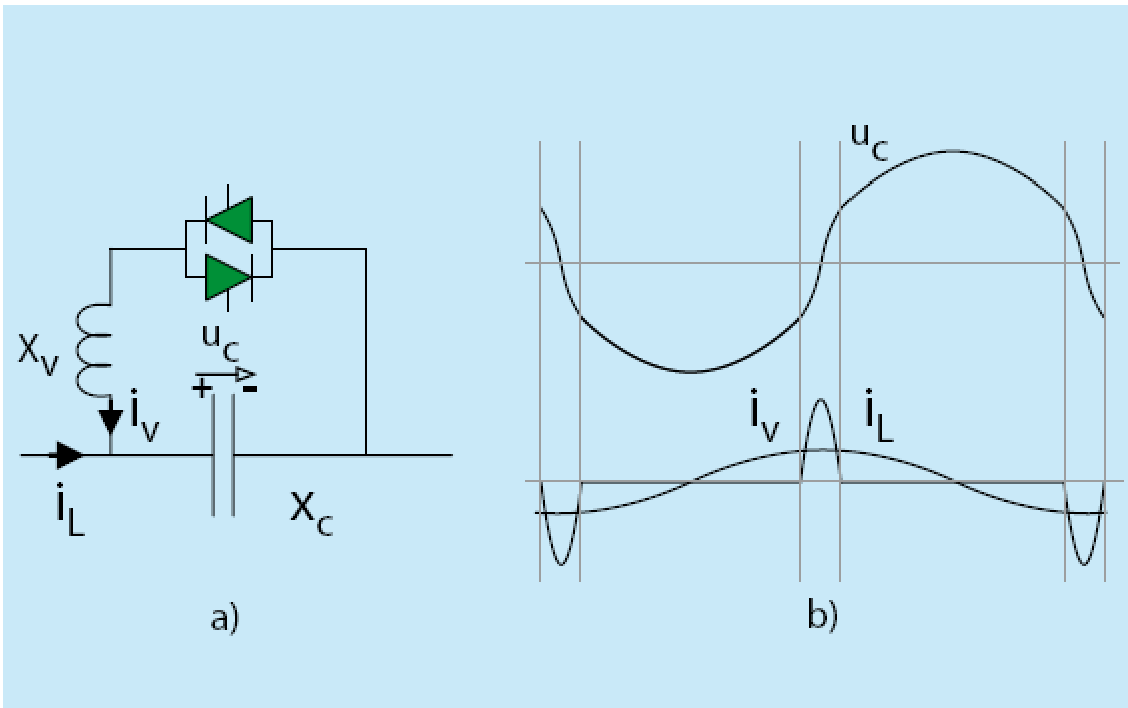


Figure 6.14 The impedance vs. delay angle α characteristic of the TCSC.

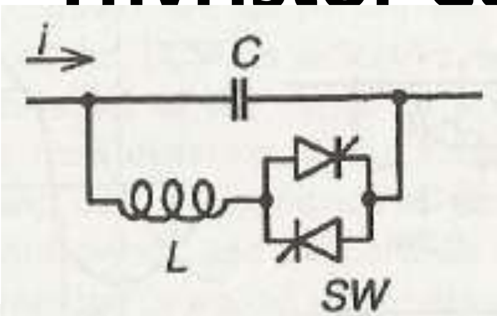
Thyristor Controlled Series Capacitor(TCSC)

In a TCSC arrangement, the whole capacitor bank or a section of it, is provided with a parallel thyristor controlled inductor which circulates current pulses that add in phase with the line current so as to boost the capacitive voltage beyond the level that would be obtained by the line current alone.

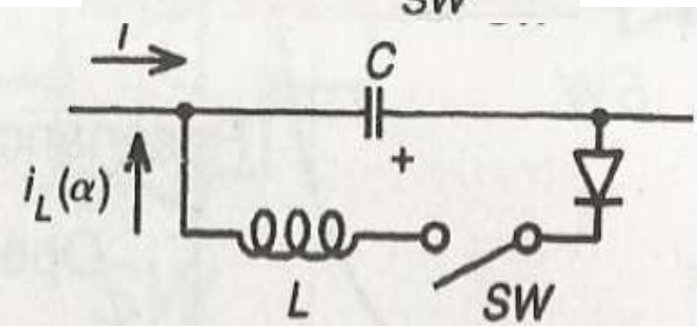
Each thyristor is triggered once per cycle and has a conduction interval that is shorter than half a cycle of the main supply frequency.

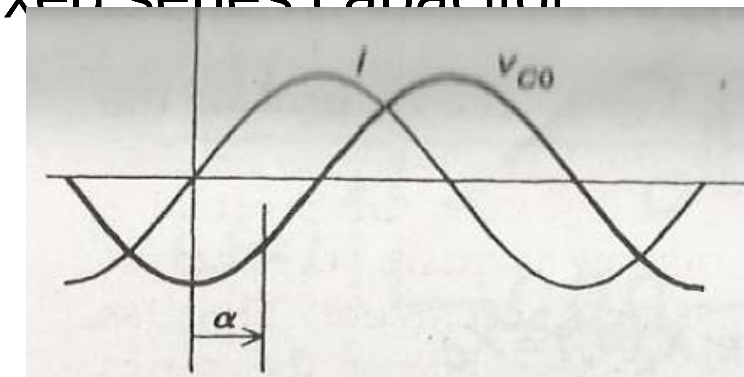


Thyristor Controlled Series Capacitor(TCSC)



Assume that the ‘sw’ is initially open and the prevailing line current ‘i‘ produces voltage v_{co} across the fixed series capacitor.





Suppose the TCR is to be turned on at αmeasured from the negative peak of the capacitor voltage.

At this instant of turn-on, the capacitor voltage is negative, the line current is positive and thus the charging the capacitor in the positive direction.

During this first half cycle (and all similar subsequent half cycles) of TCR operation, the thyristor valve can be viewed as an ideal switch, closing at α, in series with a diode of appropriate polarity to stop conduction as the current crosses zero.

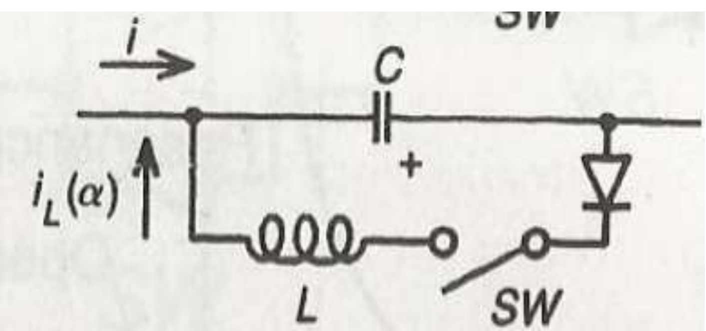
Thyristor Controlled Series Capacitor(TCSC)

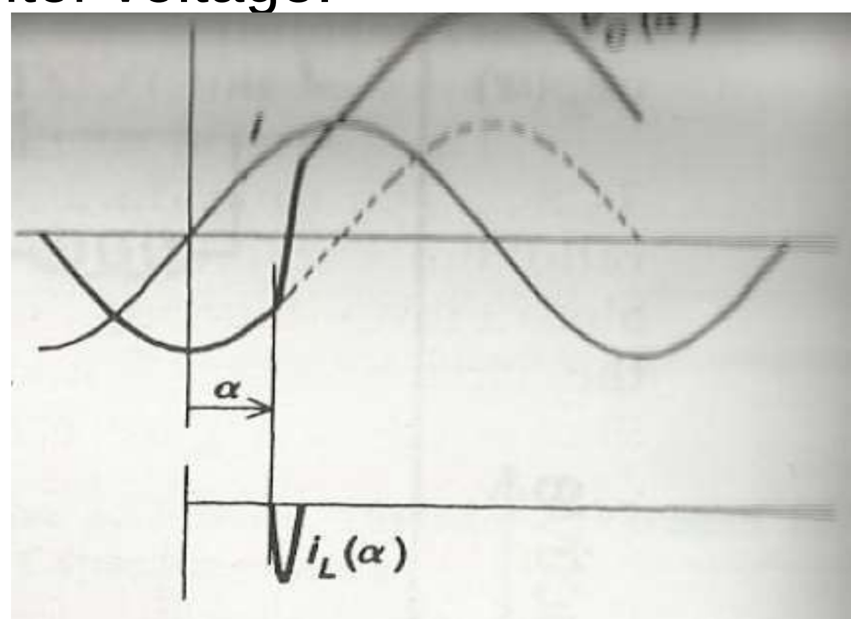
At the instant of closing the switch sw, two independent events will take place:

One is that the line current, being a constant current source, continues to (dis)charge the capacitor.

The other is that the charge of the capacitor will be reversed during the resonant half cycle of the LC circuit formed by the switch closing.

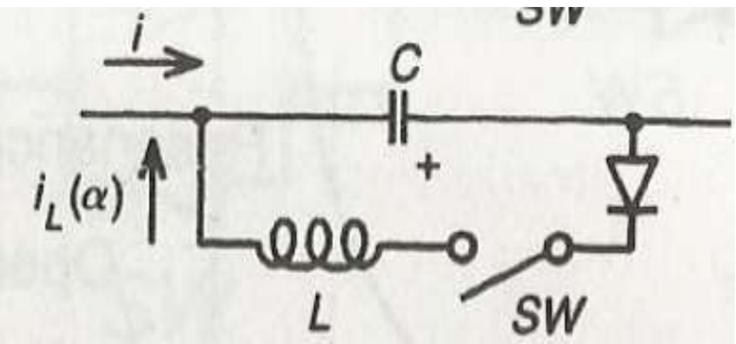
The resonant charge reversal produces a dc offset for the next(positive) half cycle of the capacitor voltage.

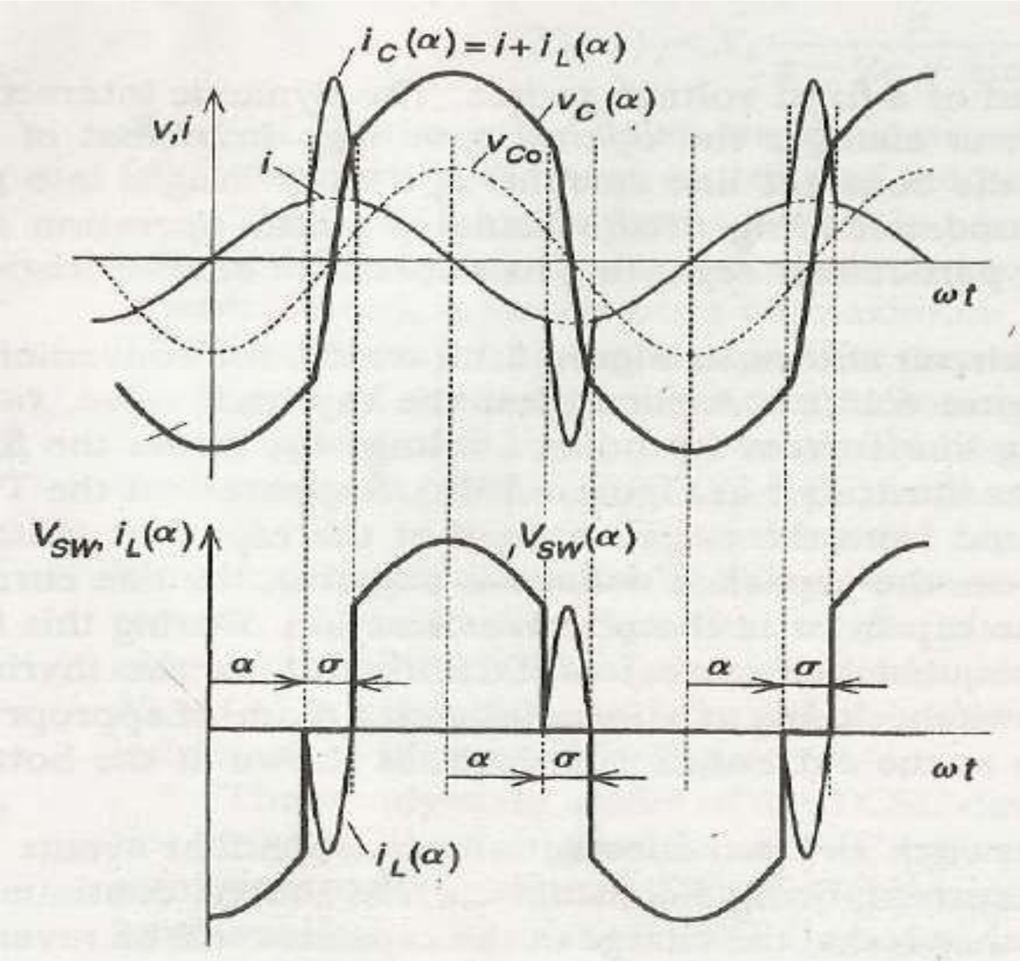




Thyristor Controlled Series Capacitor(TCSC)

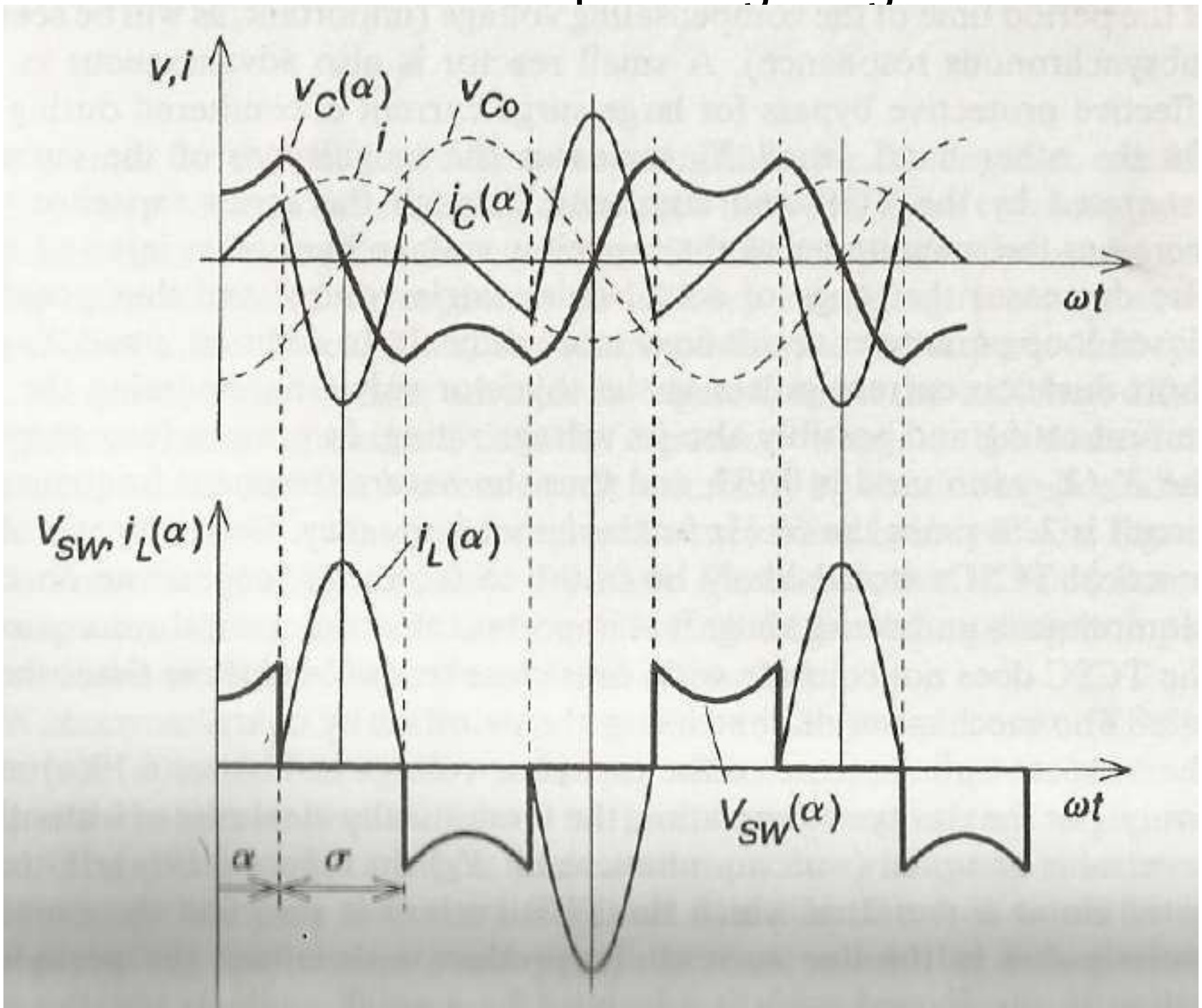
In the subsequent (negative) half-cycle , this dc offset can be reversed by maintaining the same 'α' and thus a voltage waveform symmetrical to the zero axis can be produced, where the relevant current and voltage waveforms of the TCSC operated in the capacitive region are shown.





Thyristor Controlled Series Capacitor(TCSC)

The relevant current and voltage waveforms of the TCSC operated in the inductive operating range are shown



Thyristor Controlled Series Capacitor(TCSC)

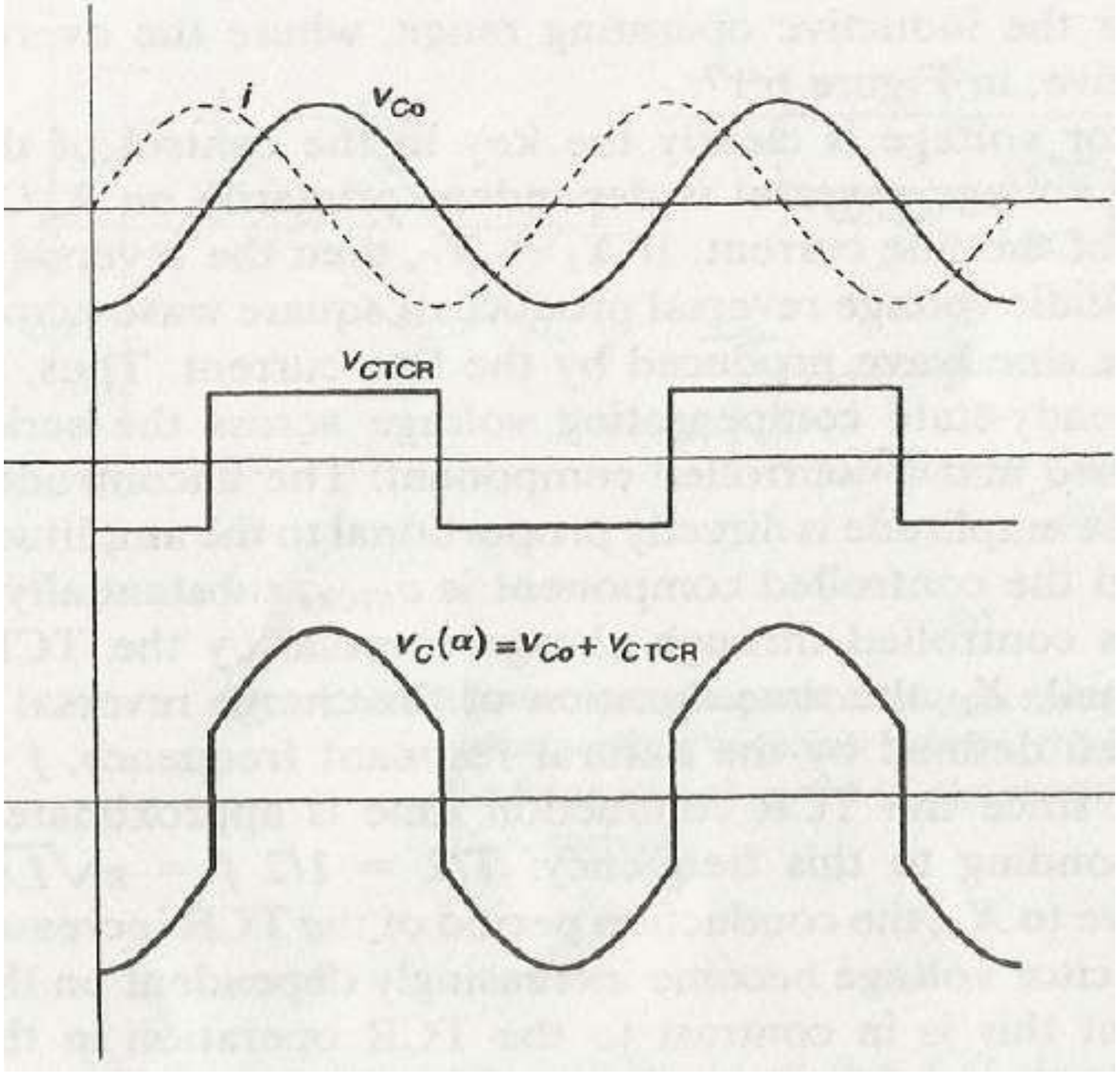
The reversal of the capacitor voltage is clearly the key to the control of the TCSC.

The time duration of the voltage reversal is dependent primarily on X_L/X_C ratio, but also on the magnitude of the line current.

If $X_L << X_C$, then the reversal is almost instantaneous, and the periodic voltage reversal produces a square wave across the capacitor that is added to the sine wave produced by the line current.

Thus, the steady state compensating voltage across the capacitor comprises an uncontrolled and a controlled component: the uncontrolled component is v_{Co}, a sine wave whose amplitude is directly proportional to the amplitude of the prevailing line current and the controlled component is v_{CTCR}, a square wave whose magnitude is controlled through charge reversal by the TCR.

Thyristor Controlled Series Capacitor(TCSC)



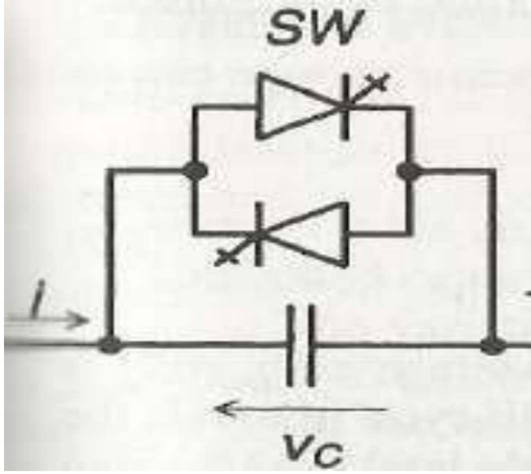
Thyristor Controlled Series Capacitor(TCSC)

For a finite, but still relatively small X_L, the time duration of charge reversal is not instantaneous but is quite well defined by the natural resonant frequency, $f=1/2\pi\sqrt{LC}$, of the TCSC circuit, since the TCR conduction time is approximately equal to the half period of this frequency.

However, as X_L is increased relative to X_C, the conduction period of the TCR increases and the zero crossings of the capacitor voltage become increasingly dependent on the prevailing line current.

GTO Thyristor Controlled Series Capacitor(GCSC)

An elementary GCSC, proposed in 1992 by Karady with others is shown:



It consists of a fixed capacitor in parallel with a GTO Thyristor.

The objective of the GCSC scheme is to control across the capacitor at a given line current i.

When the GTO valve ,sw, is closed, the voltage across the capacitor is zero, and when the valve is open, it is maximum.

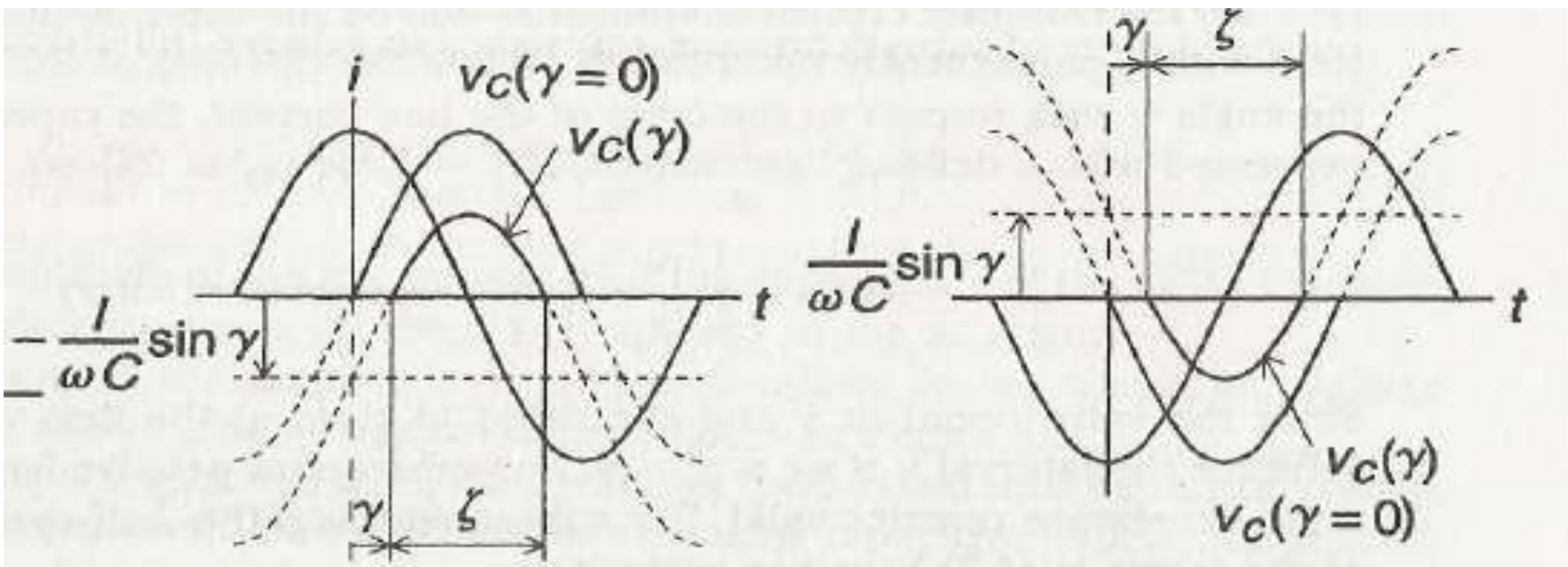
For controlling the capacitor voltage, the closing and opening of the valve is carried out in each half cycle in synchronism with the ac system frequency.

GTO Thyristor Controlled Series Capacitor(GCSC)

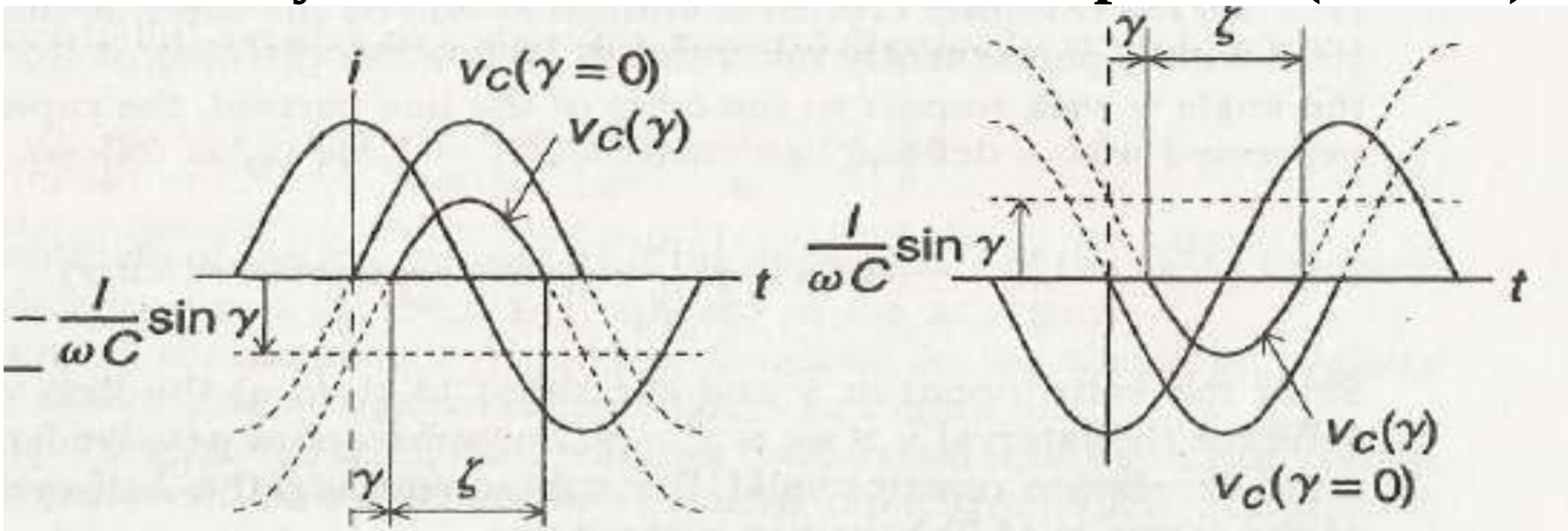
The GTO valve is stipulated to close automatically (through appropriate control action) whenever the capacitor voltage crosses zero.

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

The line current 'i' and the capacitor voltage $v_c(\gamma)$ are shown at $\gamma=0$(valve open) and at an arbitrary angle γ for a positive and negative half cycle.



GTO Thyristor Controlled Series Capacitor(GCSC)

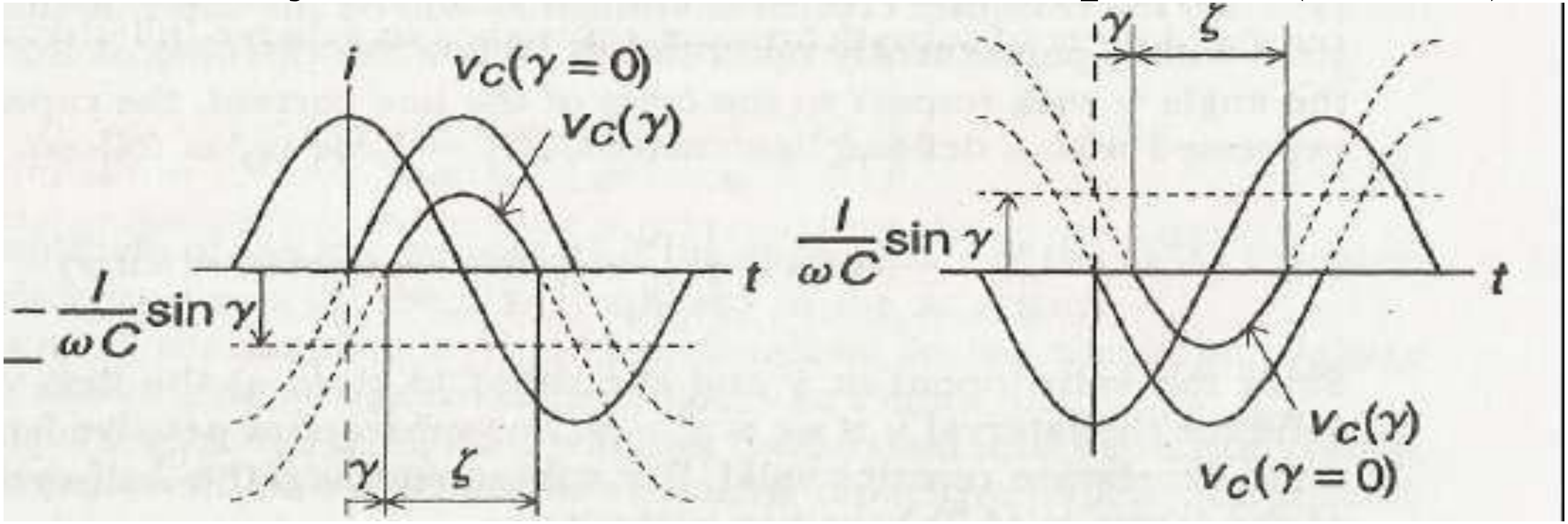


When the valve sw is opened at the crest of the line current(ɤ=0), the resultant capacitor voltage v_c is same as that obtained in steady state with a permanently open switch .

When the opening of the valve is delayed by the angle ɤw.r.t the crest of the line current, the $v_c(t)$ can be expressed with a line current, i(t)=I cosωt as .

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

GTO Thyristor Controlled Series Capacitor(GCSC)



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

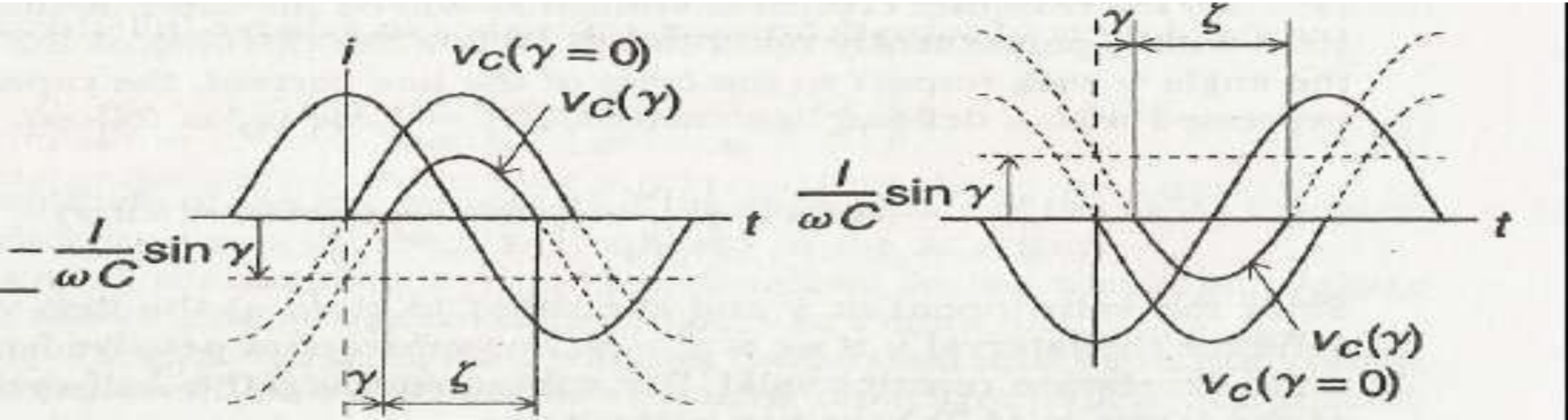
Since the valve opens at ɤ and stipulated to close at the first voltage zero the above equation valid for the interval ɤ≤ωt≤π- ɤ. For subsequent positive half cycle intervals the same expression remains valid. For subsequent negative half cycles intervals, the sign of the terms in the above equation becomes opposite.

GTO Thyristor Controlled Series Capacitor(GCSC)

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

The term (I/ωC) sin ɣis simply a ɣdependent constant by which the sinusoidal voltage obtained at ɣ=0 is offset, shifted down for positive and up for negative voltage half cycles.

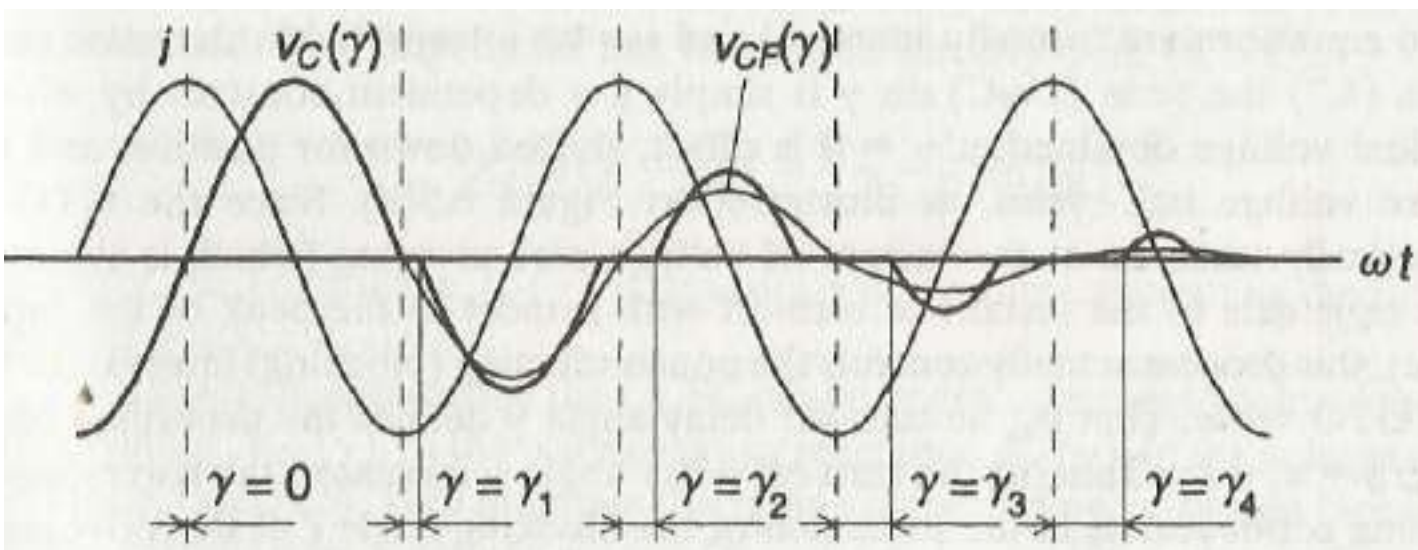
Since the GTO valve automatically turns on at the instant of voltage zero crossing(which is symmetrical on the time axis to the instant of turn off w.r.t the peak of the capacitor voltage), this process actually controls the nonconducting(blocking) interval of the GTO valve.



GTO Thyristor Controlled Series Capacitor(GCSC)

The magnitude of the capacitor voltage can be varied continuously by this method of turn-off delay angle control from maximum (γ=0) to zero (γ=π/2) as shown below where the capacitor voltage $v_c(\gamma)$ together with its fundamental component $v_{CF}(\gamma)$ are shown at various turn off delay angles γ.

The adjustment of the capacitor voltage ,similar to the adjustment of the TCR current, is discrete and can take place only once in each half cycle.



GTO Thyristor Controlled Series Capacitor(GCSC)

The wave shape obtained for the current of the TCR is identical to that for voltage of GTO thyristor-controlled series capacitor and confirms the duality between the GCSC and TCR.

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

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

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

The TCR is controlled by a turn on delay w.r.t the crest of the applied voltage, which defines the conduction interval of the valve. The GCSC is controlled by a turn off delay w.r.t the peak of the line current, which defines the blocking interval of the valve.

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

GTO Thyristor Controlled Series Capacitor(GCSC)

The duality established between TCR and GCSC enables us to write the equation for GCSC, the amplitude $V_{CF}(\gamma)$ of the fundamental capacitor voltage $v_{CF}(\gamma)$ can be expressed as :

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

Where I is the amplitude of the line current, C is the capacitance of the GTO thyristor controlled capacitor, and ω is the angular frequency of the ac system.

An effective capacitive impedance X_C for a given value of angle γ for the GCSC,

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

GTO Thyristor Controlled Series Capacitor(GCSC)

In a practical application the GCSC can be operated either to control the compensating voltage $V_{CF}(\gamma)$ or the compensating reactance $X_C(\gamma)$.

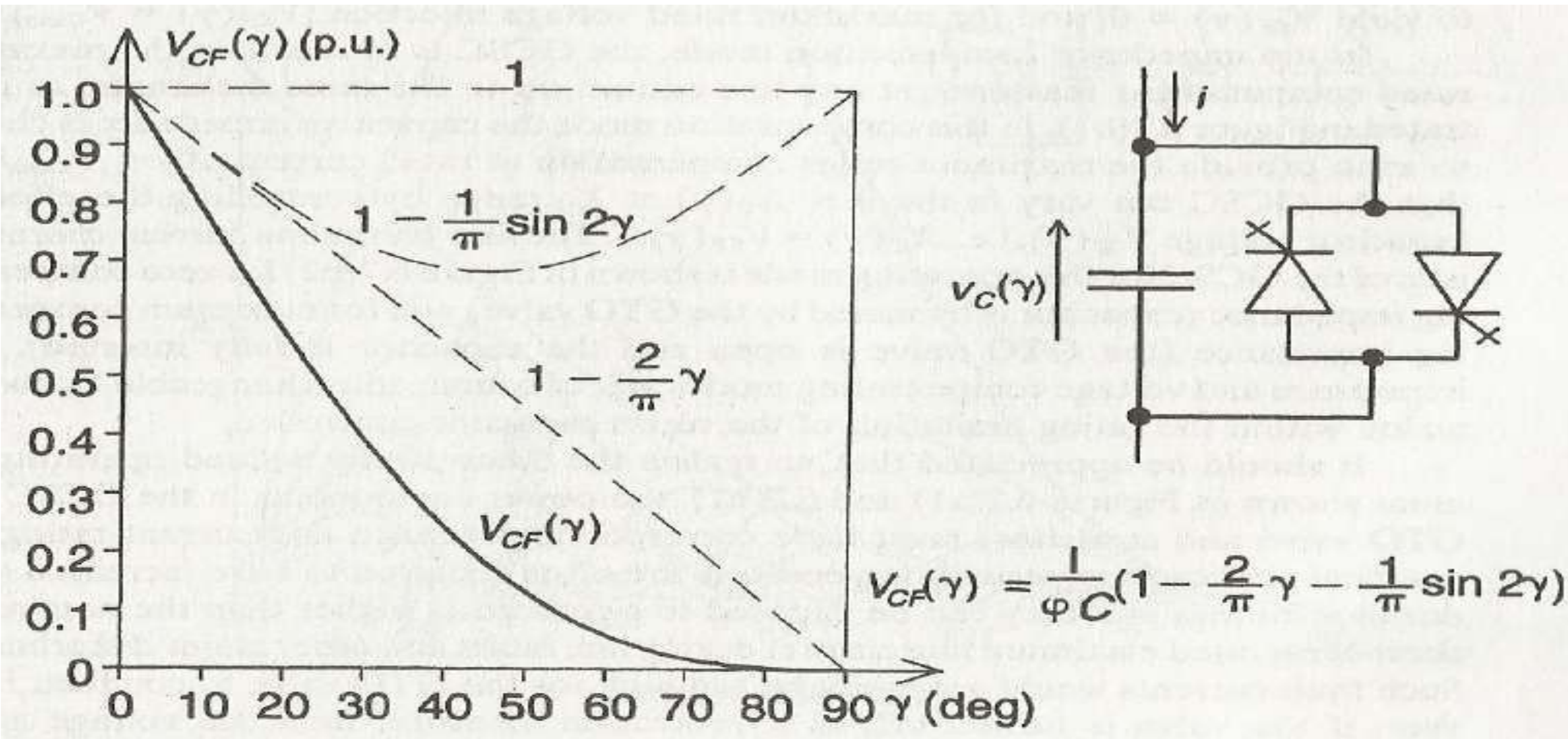
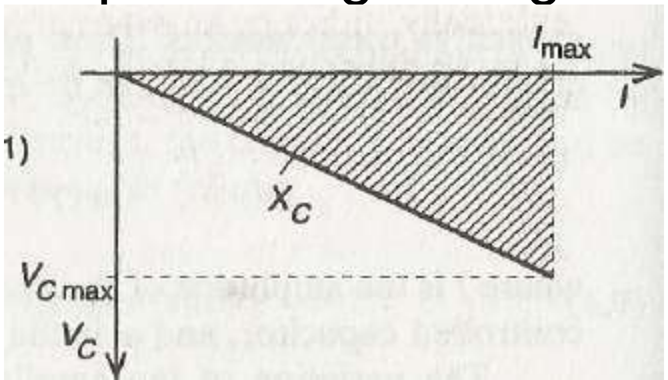


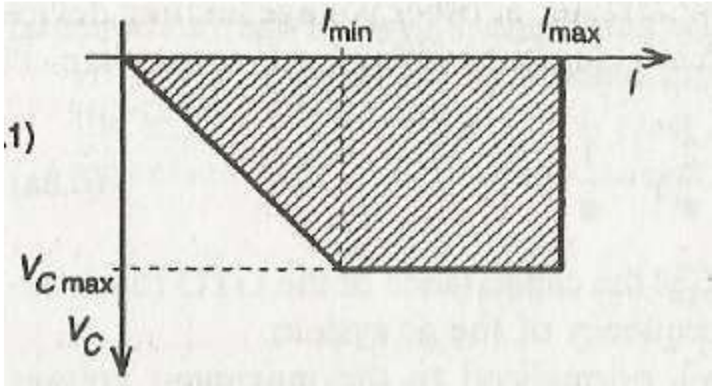
Figure 6.6 Fundamental component of the series capacitor voltage vs. the turn-off delay angle γ.

GTO Thyristor Controlled Series Capacitor(GCSC) In a practical application the GCSC can be operated either to control the compensating voltage $V_{CF}(\gamma)$ or the compensating reactance $X_C(\gamma)$.

In the voltage compensating mode, the GCSC is to maintain the rated compensating voltage in face of decreasing line current over a demand interval $I_{min} \leq I \leq I_{max}$.

In this compensation mode the capacitive reactance X_C is selected so as to produce the rated compensating voltage with $I=I_{min}$ i.e $V_{Cmax}=X_C I_{min}$ .As the current I_{min} is increased toward I_{max}, the turn off delay angle γ is increased to reduce the duration of capacitor injection and thereby maintain the compensating voltage with increasing line current

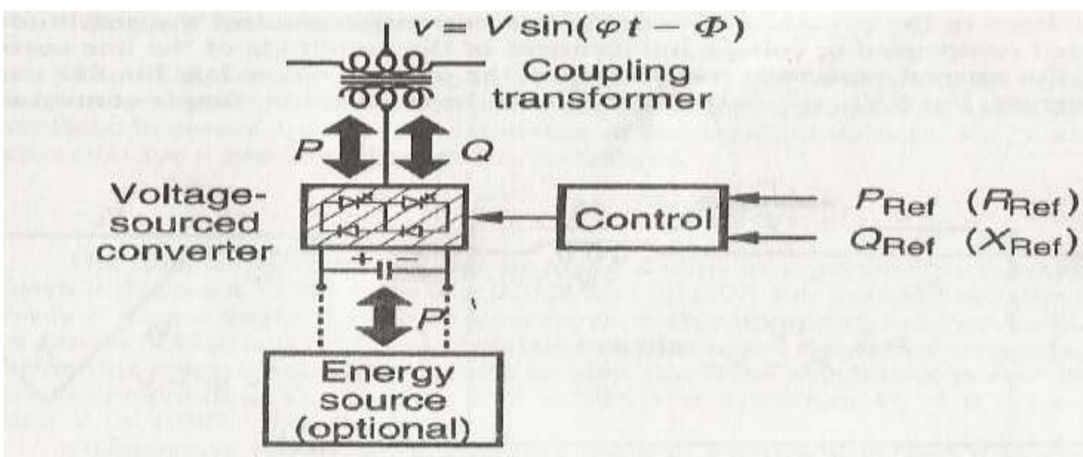




Switching Converter type Series Compensators

A voltage sourced converter with its internal control can be considered a synchronous voltage source(SVS) analogous to an ideal electromagnetic generator: it can produce a set of 3 alternating substantially sinusoidal voltages at the desired fundamental frequency with controllable amplitude and phase angle, generate or absorb, reactive power; and exchange real power with the ac system when its dc terminals are connected to a suitable electric dc energy source or storage.

References Q_{Ref} and P_{Ref} define the amplitude V and phase angle Ψ of the generated output voltage necessary to exchange the desired reactive and active power at the ac output.

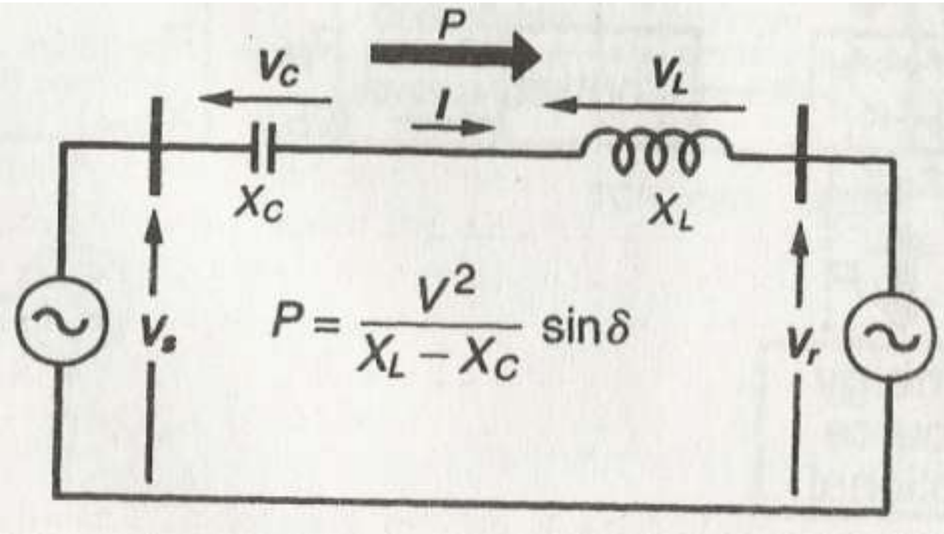


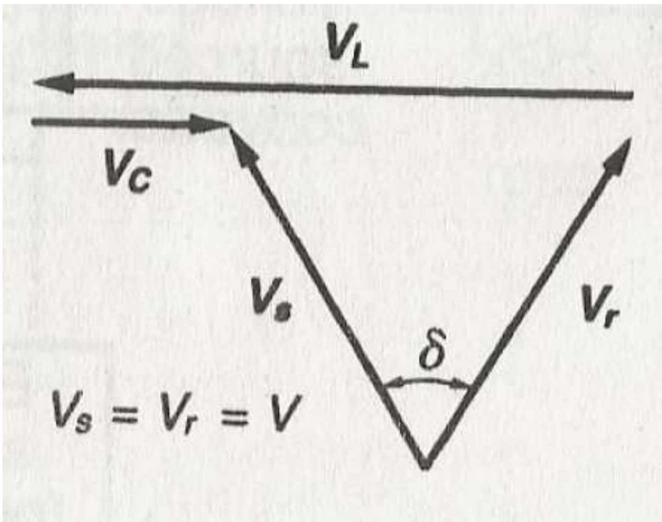
Static Synchronous Series Compensator(SSSC)

Voltage sourced converter based series compensator, called SSSC, was proposed by Gyugi in 1989.

The phasor diagram clearly shows that at a given line current the voltage across the series capacitor forces the opposite polarity voltage across the series line reactance to increase by the magnitude of the capacitor voltage.

Thus , the series capacitive compensation works by increasing the voltage across the impedance of the given physical line, which in turn increases the corresponding line current and transmitted power.



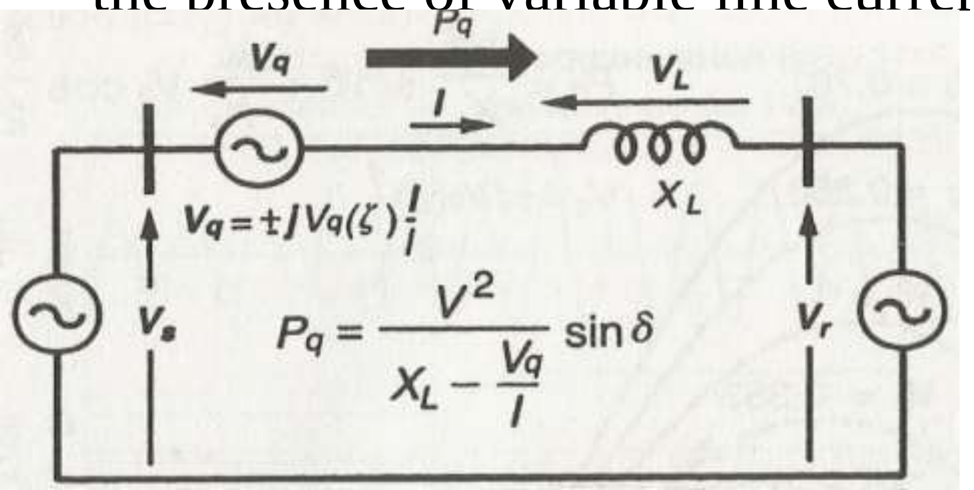


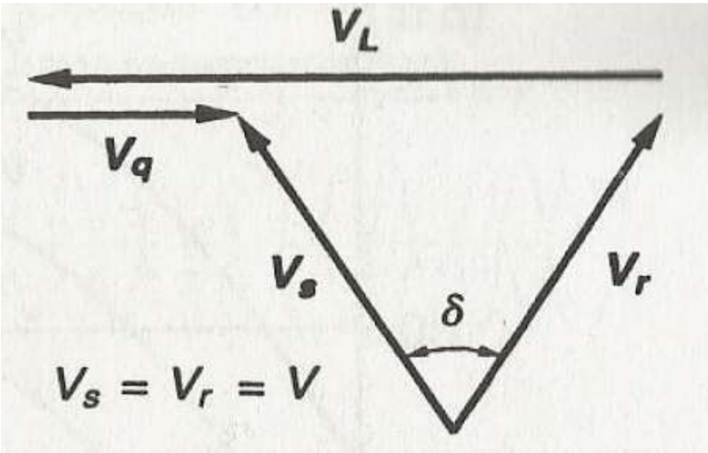
Static Synchronous Series Compensator(SSSC)

In SSSC the series compensation is provided by a synchronous ac voltage source, as shown, whose output precisely matches the voltage of the series capacitor i.e $V_q=V_C=-jX_CI=-jkXI$, where V_q is the injected compensating voltage,I is the line current, X_C is the reactance of the series capacitor, X is the line reactance, $k=X_C/X$ is the degree of series compensation.

Thus by making the output voltage of the synchronous voltage source a function of the line current, the same compensation as provided by the series capacitor is accomplished.

The SVS is able to maintain a constant compensating voltage in the presence of variable line current.



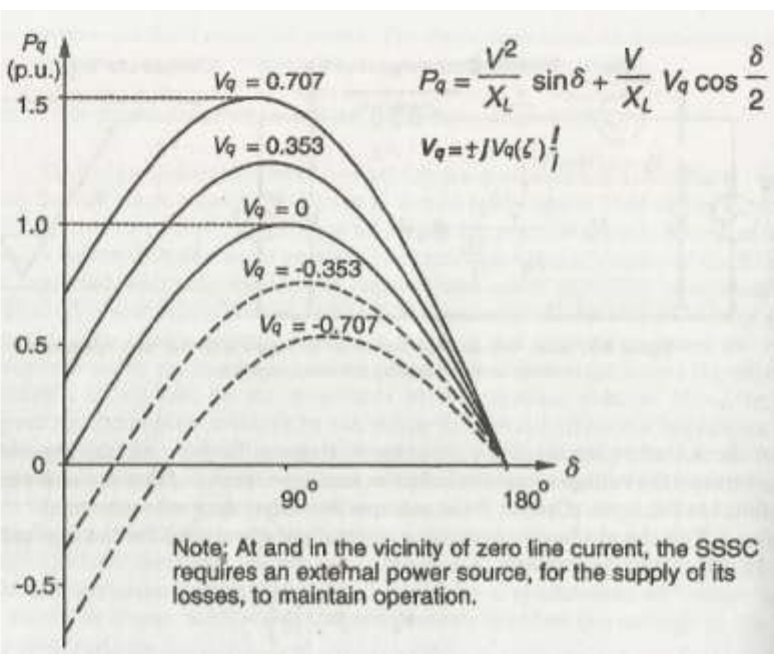


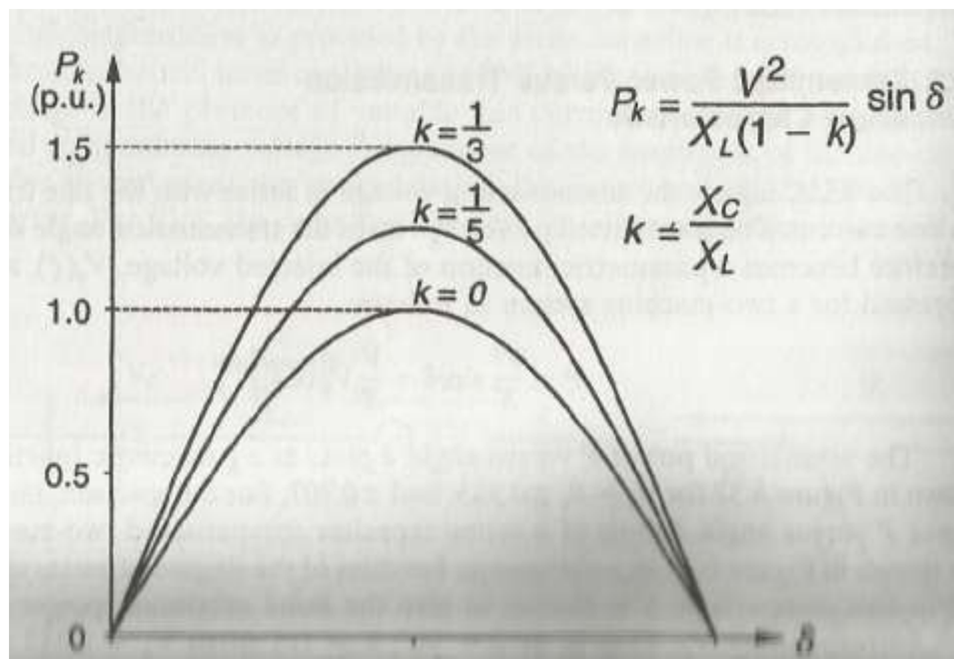
Static Synchronous Series Compensator(SSSC)

The SSSC injects the compensating voltage in series with the line irrespective of the line current. The transmitted power P_q versus the transmission angle δ relationship therefore becomes a parametric function of the injected voltage.

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

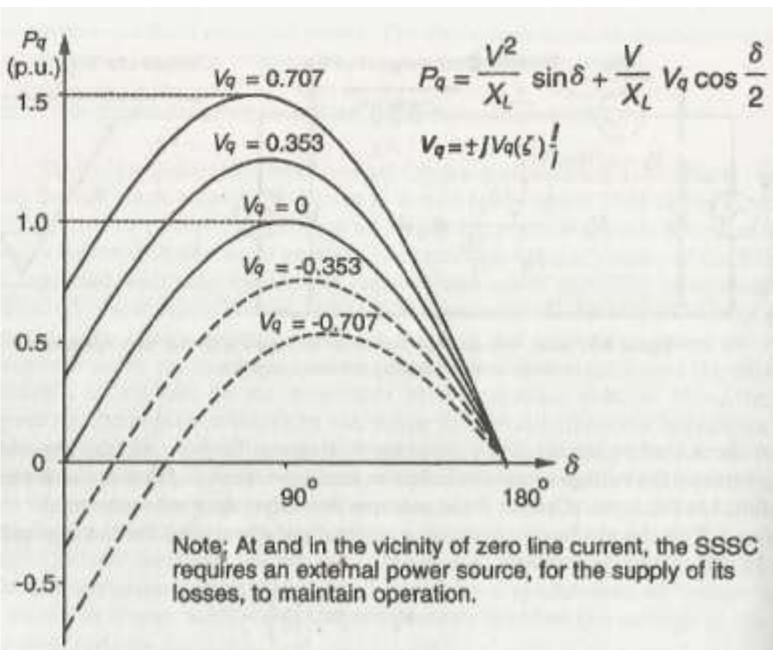
The normalized power P versus angle δ plots as a parametric function of V_q are shown for Vq=0,±0.353 and ± 0.707.

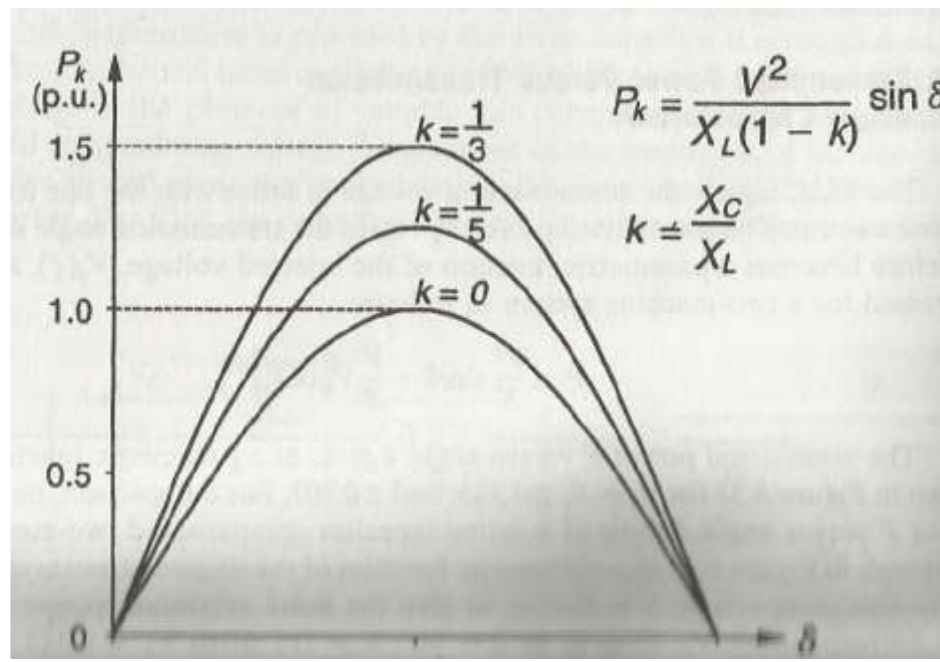




Static Synchronous Series Compensator(SSSC)

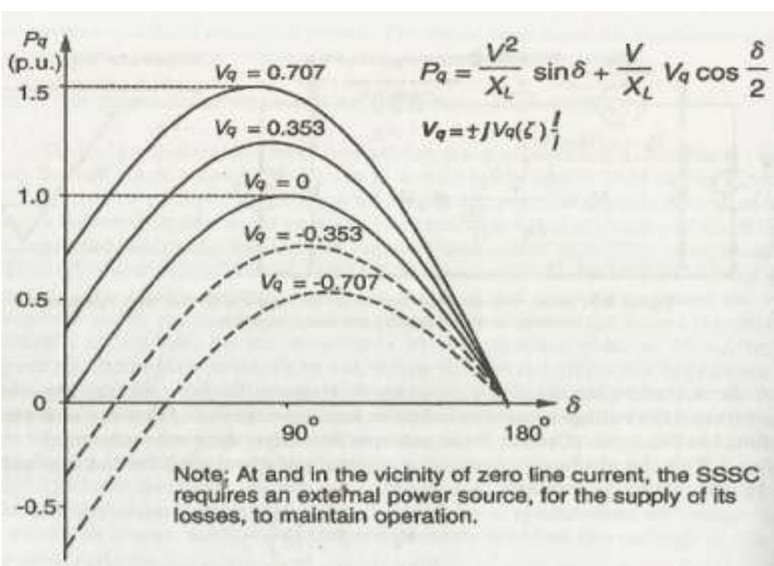
Comparison of the corresponding plots clearly shows that the series capacitor increases the transmitted power by a fixed % of that transmitted by the uncompensated line at at a given δ, SSSC can increase it by a fixed fraction of the maximum power transmittable by the uncompensated line , independent of δ, in the important operating range of 0≤δ≤π/2

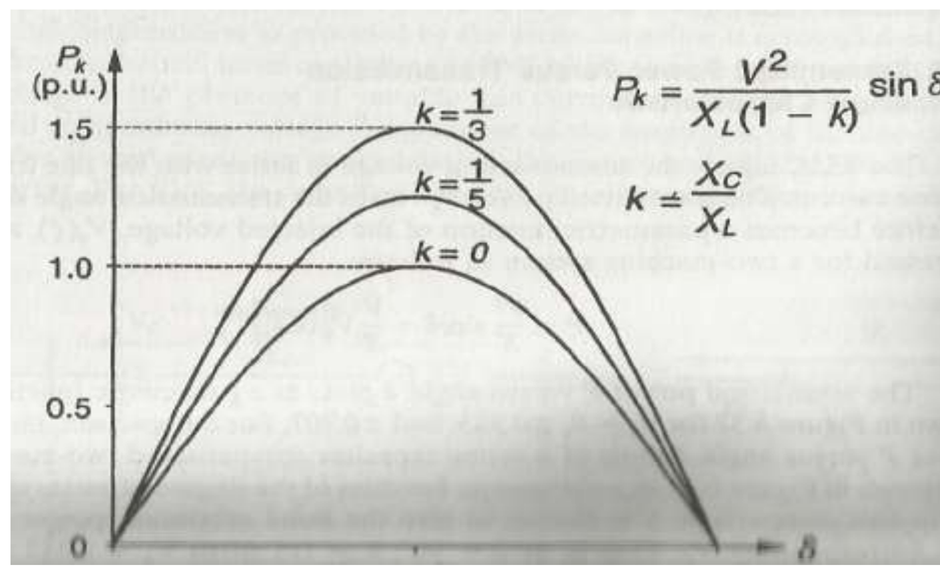




Static Synchronous Series Compensator(SSSC)

SSSC inherently has twice as wide controlled compensation range as the VA rating of the converter. This means that the SSSC can decrease, as well increase the power flow to the same degree ,simply by reversing the polarity of the injected ac voltage. The reversed (180^0 phase shifted)voltage adds directly to the reactive voltage drop of the line as if the reactive line impedance was increased. Furthermore, if this (reverse polarity) injected voltage is made larger than the voltage impressed across the uncompensated line , then the power flow will reverse.





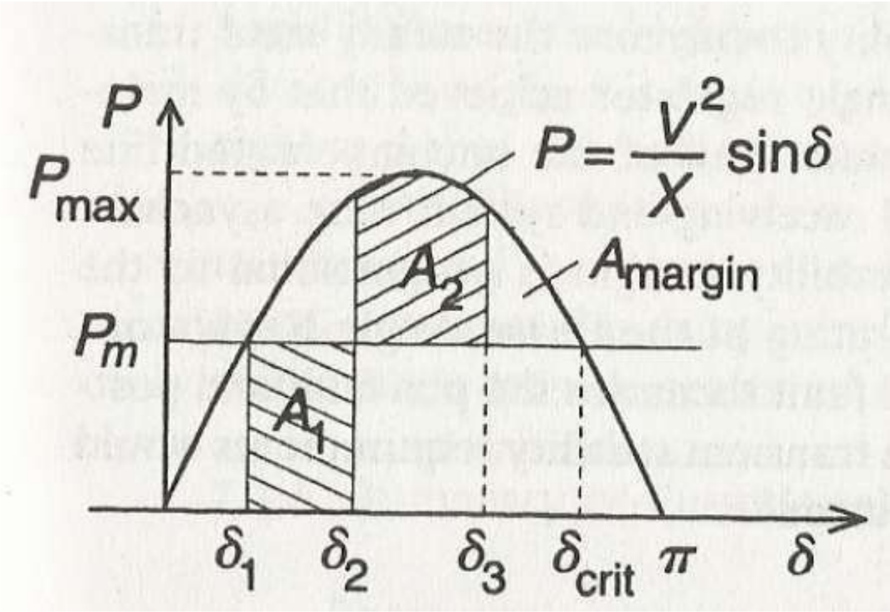
Static Synchronous Series Compensator(SSSC)

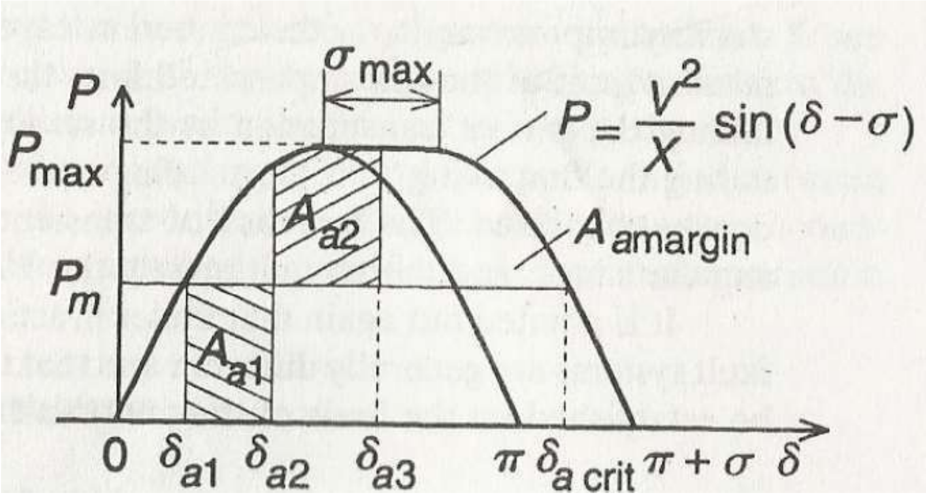
Apart from the bi-directional compensation capability, the basic operating characteristic of the SSSC suggests a significant difference between the SSSC and the series capacitor.

The SSSC can not be tuned with any finite line inductance to have a classical series resonance at the fundamental frequency because the voltage across the line reactance would in all practical cases be greater than and inherently limited by the compensating voltage of SSSC.

Improvement of Trasient Stability with PAR

with the circuit loop resulting in the





UNIT-V
POWER FLOW CONTROLLERS

Unified Power Flow Controller(UPFC)

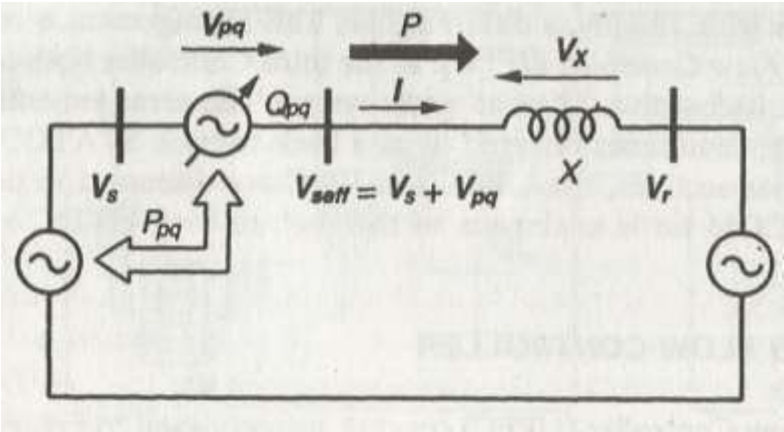
The UPFC concept scheme was proposed by Gyugyi in 1991. Devised for the "real-time control and dynamic compensation of ac transmission systems and providing multifunctional flexibility.

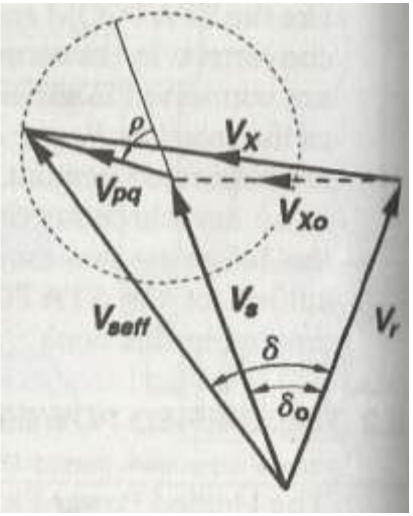
UPFC is able to control, simultaneously or selectively all the parameters affecting power flow in the transmission line i.e voltage, impedance and phase angle and this unique capability is signified by the adjective " unified " in its name.

The UPFC is a generalized synchronous voltage source (SVS) , represented at the fundamental(power system) frequency by voltage phasor V_{pq} with controllable magnitude $|V_{pq}|$ $(0 \leq |V_{pq}| \leq V_{pqmax})$ and angle $\rho (0 \leq \rho \leq 2\pi)$, in series with the transmission line for the usual two machine system.

Unified Power Flow Controller(UPFC)

Thus the SVS exchanges both reactive and real power with the transmission system. Since an SVS is able to generate only the reactive power exchanged, the real power must be supplied to it, or absorbed from it , by a suitable power supply or sink. In the UPFC arrangement the real power exchanged is provided by one of the end buses(sending end bus).





Unified Power Flow Controller(UPFC)

The UPFC consists of 2 VSCs. These back to back converters, labeled “Converter-1” and “Converter-2” in the figure are operated from a common dc link provided by a storage capacitor.

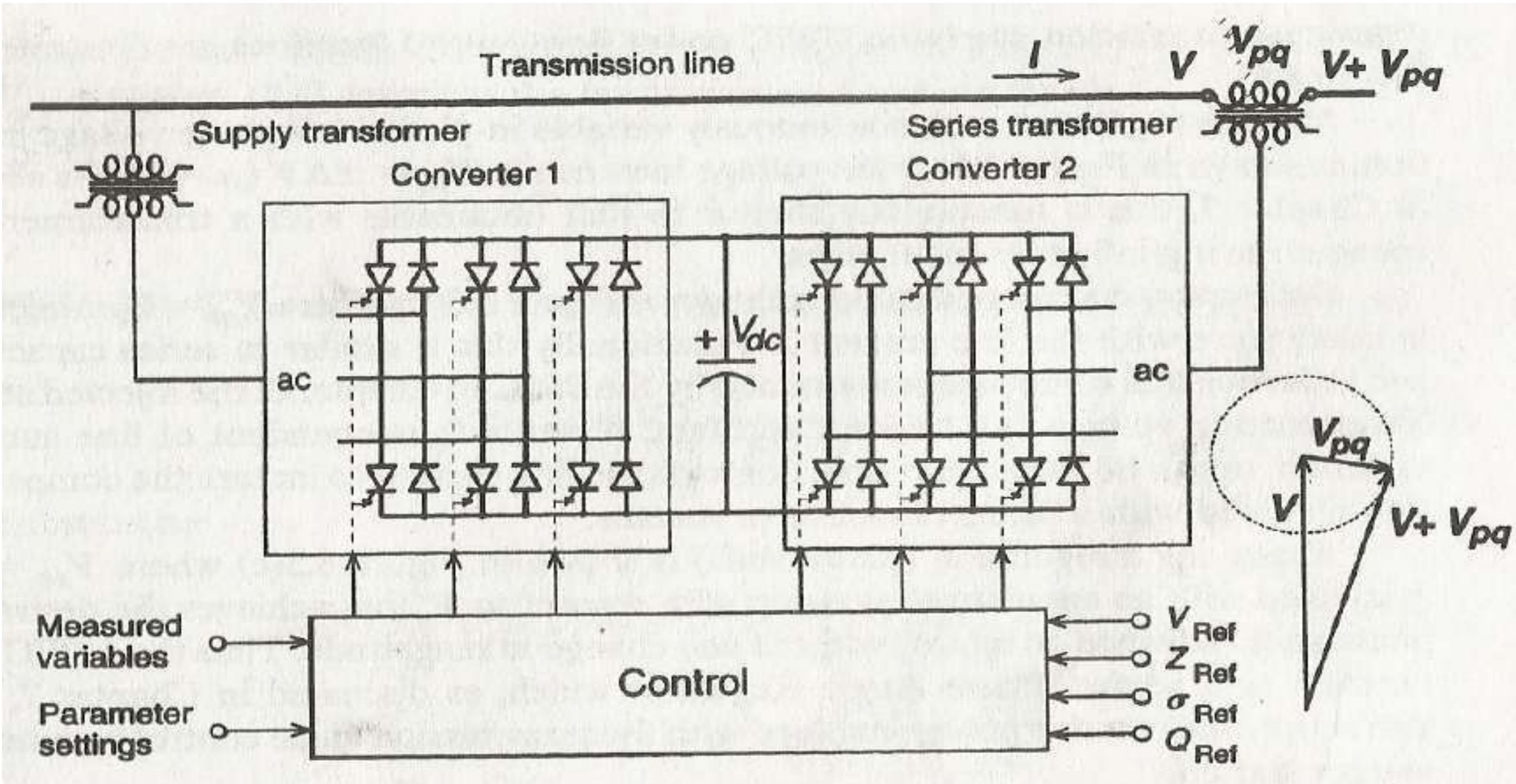


Figure 8.4 Implementation of the UPFC by two back-to-back voltage-sourced converters.

Unified Power Flow Controller(UPFC)

This arrangement functions as an ideal ac-to-ac power converter in which the real power can freely flow in either direction between the ac terminals of the two converters, and each converter can independently generate(or absorb) reactive power at its own ac output terminals.

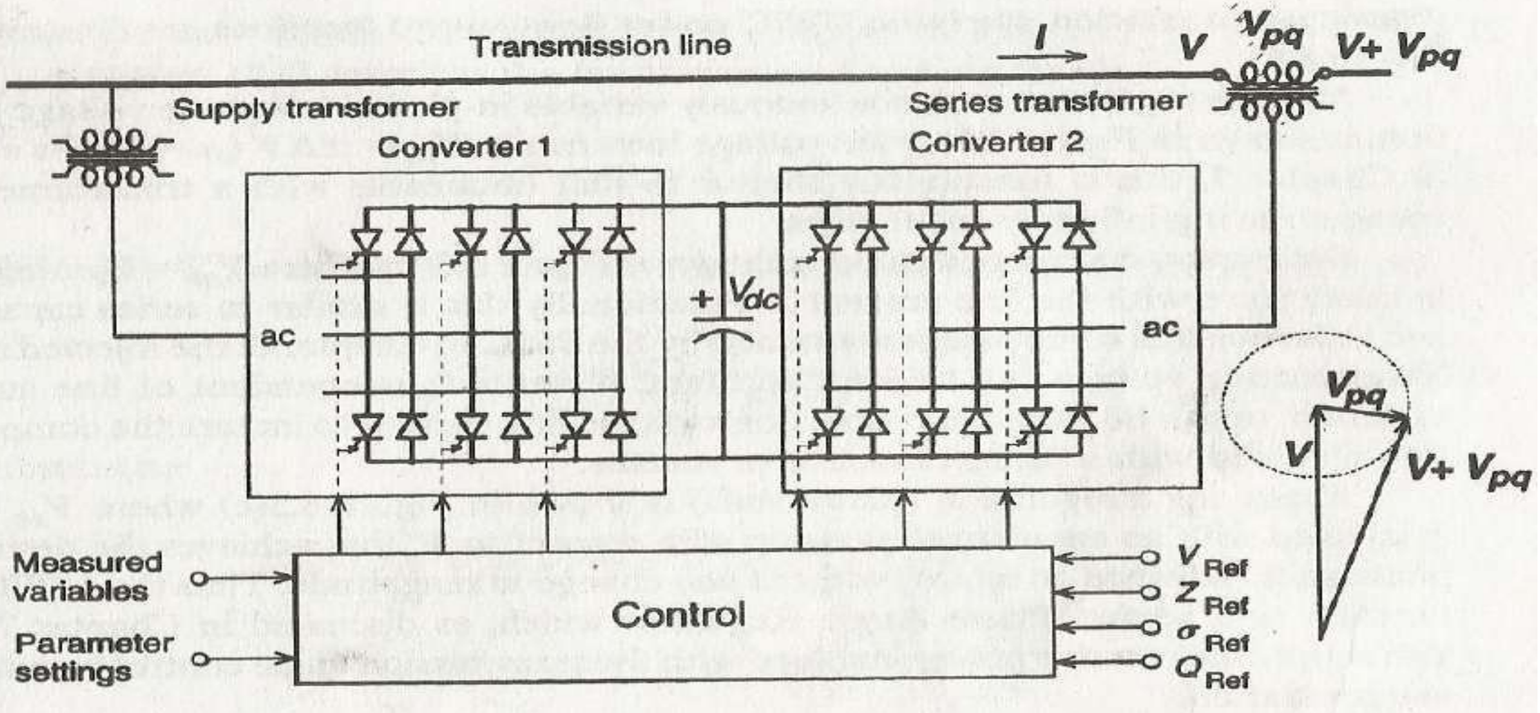


Figure 8.4 Implementation of the UPFC by two back-to-back voltage-sourced converters.

Unified Power Flow Controller(UPFC)

Converter-2 provides the main function of the UPFC by injecting a voltage V_{pq} with controllable magnitude $|V_{pq}|$ and phase angle ρ in series with the line via an insertion transformer. This injected voltage acts essentially as a synchronous ac voltage source.

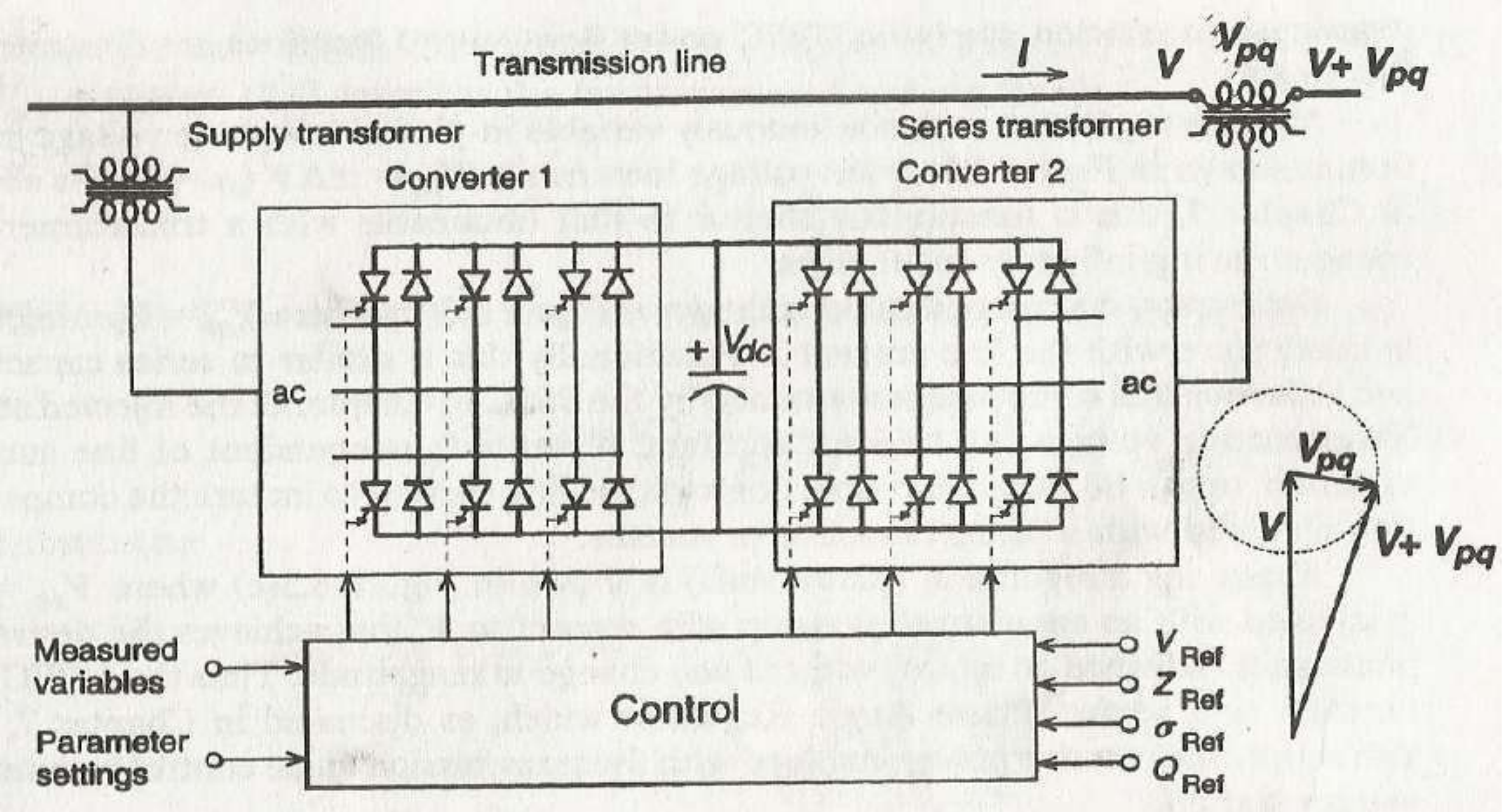


Figure 8.4 Implementation of the UPFC by two back-to-back voltage-sourced converters.

Unified Power Flow Controller(UPFC)

The transmission line current flows through this VSC resulting in reactive and real power exchange between it and the ac system. The reactive power exchanged at the ac terminal (at the terminal of the series insertion transformer) is generated internally by the converter. The real power exchanged at the ac terminal is converted into dc power which appears at the dc link as a positive or negative real power demand..

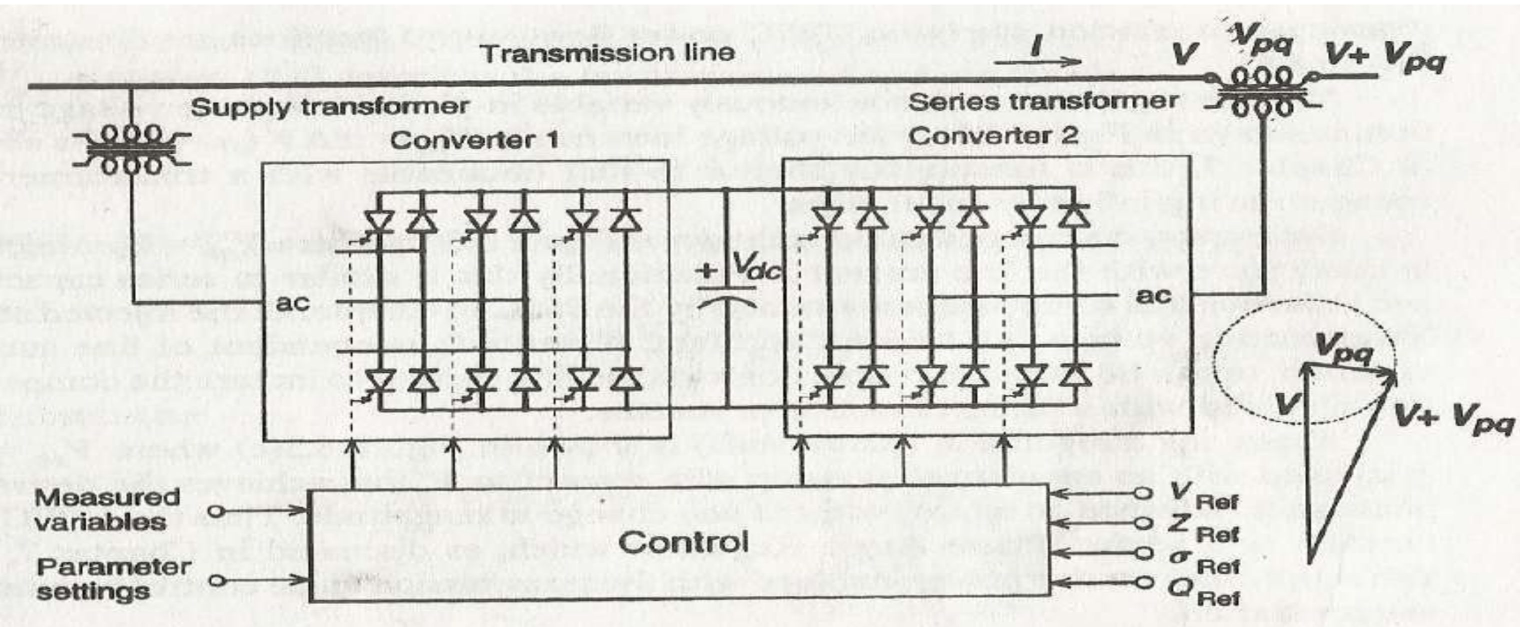


Figure 8.4 Implementation of the UPFC by two back-to-back voltage-sourced converters.

Unified Power Flow Controller(UPFC)

The basic function of Converter 1 is to supply or absorb the real power demanded by Converter 2 at the common dc link to support the real power exchange resulting from the series voltage injection. This dc link power demand of Converter 2 is converted back to ac by Converter 1 and coupled to the transmission line bus via a shunt connected transformer.

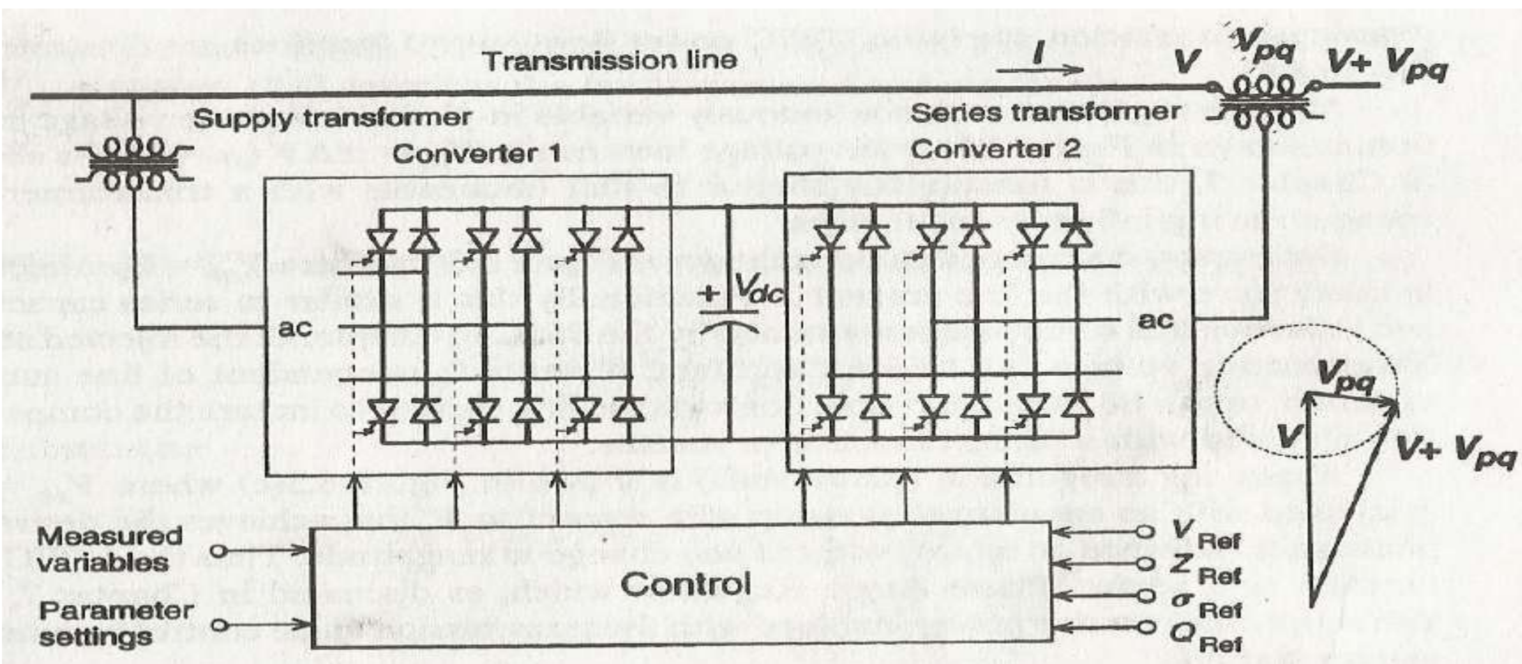


Figure 8.4 Implementation of the UPFC by two back-to-back voltage-sourced converters.

Unified Power Flow Controller(UPFC)

In addition to the real power need of the Converter 2, Converter 1 can also generate or absorb controllable reactive power, if it is desired and thereby, provide independent shunt reactive compensation for the line.

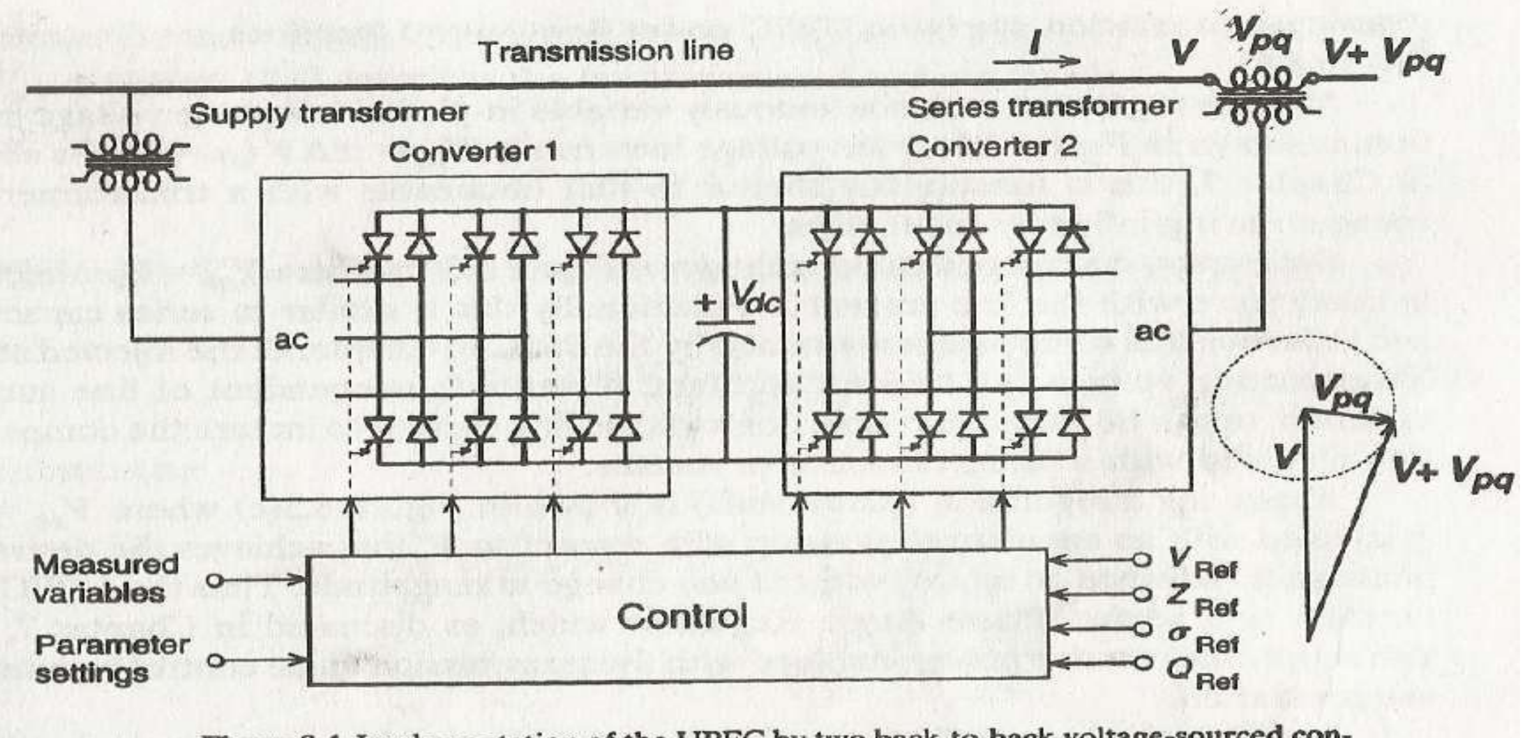


Figure 8.4 Implementation of the UPFC by two back-to-back voltage-sourced converters.

Unified Power Flow Controller(UPFC)

There is a closed direct path for the real power negotiated by the action of series voltage injection through Converters-1 and 2 back to the line and the corresponding reactive power exchanged is supplied or absorbed locally by Converter 2 and therefore does not have to be transmitted by the line.

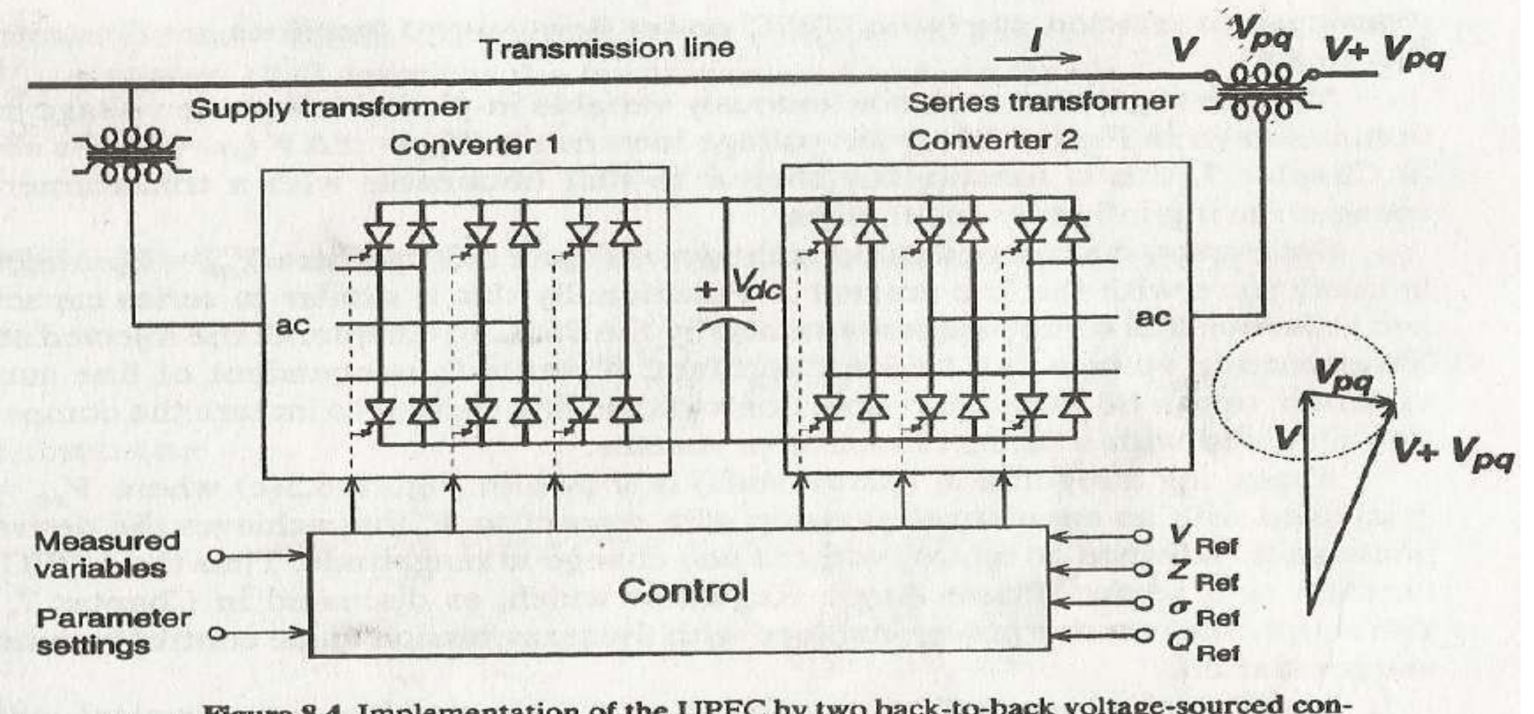


Figure 8.4 Implementation of the UPFC by two back-to-back voltage-sourced converters.

Unified Power Flow Controller(UPFC)

Thus, Converter-1 can be operated at a unity power factor or be controlled to have a reactive power exchange with the line independent of the reactive power exchanged by Converter 2.

Obviously, there can be no reactive power flow through the UPFC dc link.

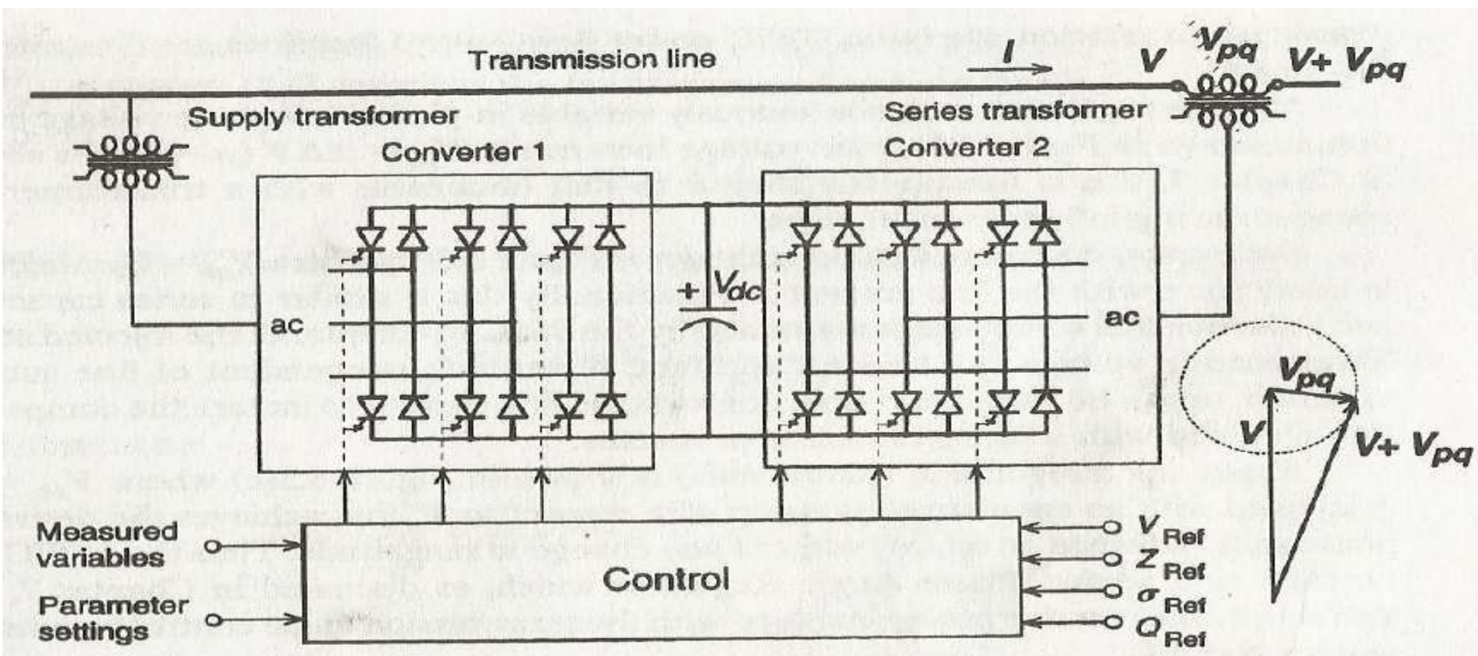
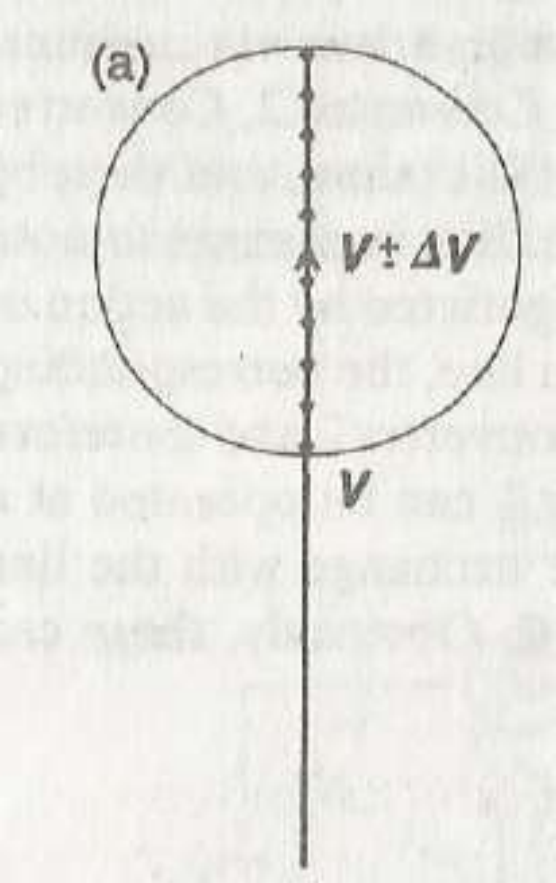


Figure 8.4 Implementation of the UPFC by two back-to-back voltage-sourced converters.

Unified Power Flow Controller(UPFC)

UPFC can perform all traditional control such as reactive shunt compensation, series compensation and phase angle regulation by injecting voltage V_{pq} with controllable magnitude $|V_{pq}|$ and phase angle ρto the sending end terminal voltage V_s.

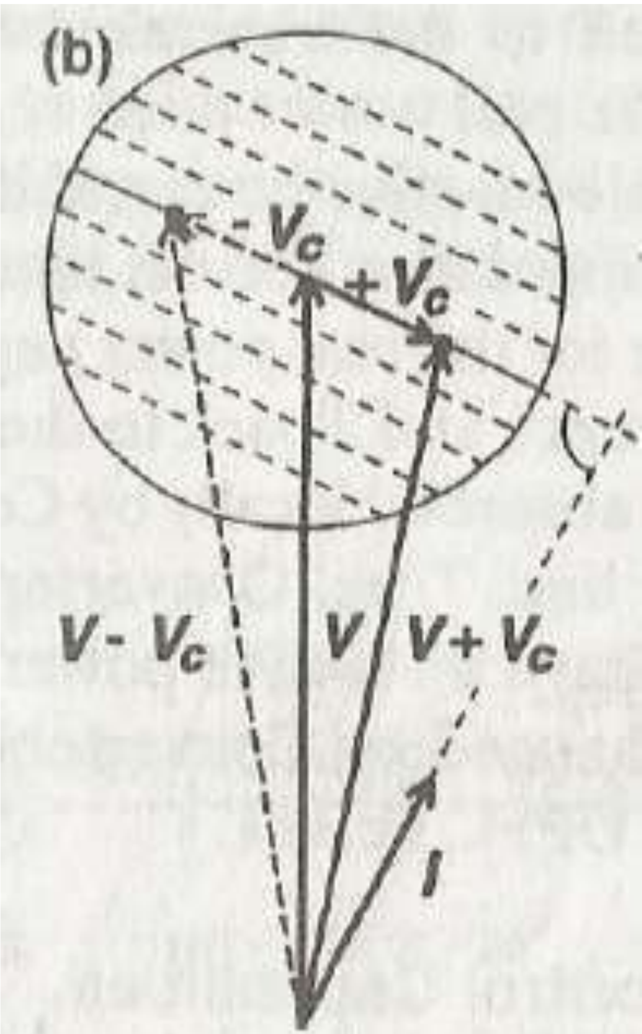


Voltage regulation with continuously variable in-phase /anti phase voltage injection for voltage increments $V_{pq} = \pm\Delta V(\sigma=0)$.

This is functionally similar to that obtainable with a transformer tap changer having infinitely small steps.

Unified Power Flow Controller(UPFC)

Series reactive compensation is shown in Fig. (b) where $V_{pq} = V_q$ is injected in quadrature with the line current I.

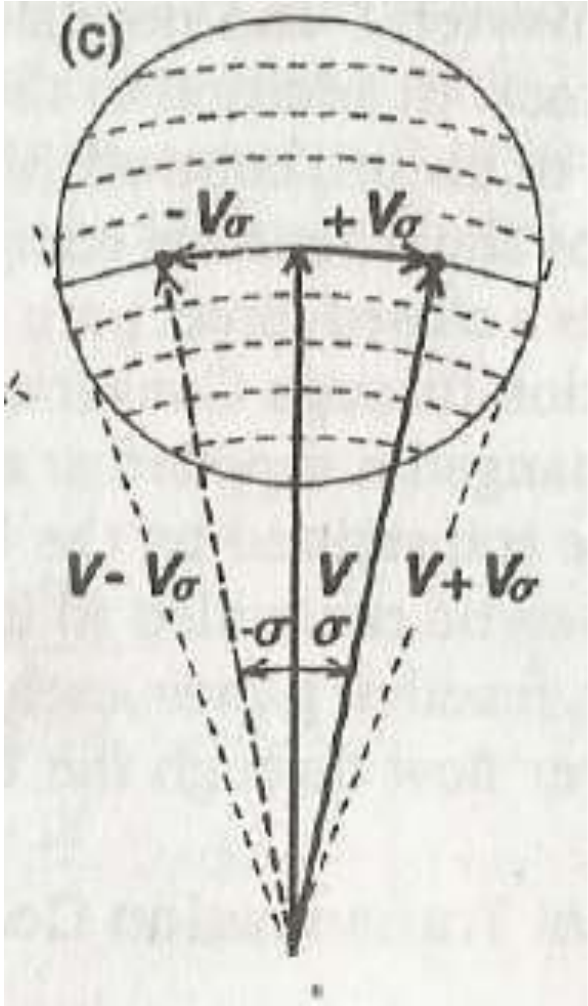


Functionally, this is similar to series capacitive and inductive line compensation attained by the SSSC.

The injected series compensating voltage can be kept constant , if desired , independent of line current variation, or can be varied in proportion with the line current to imitate the compensation obtained with a series capacitor or reactor.

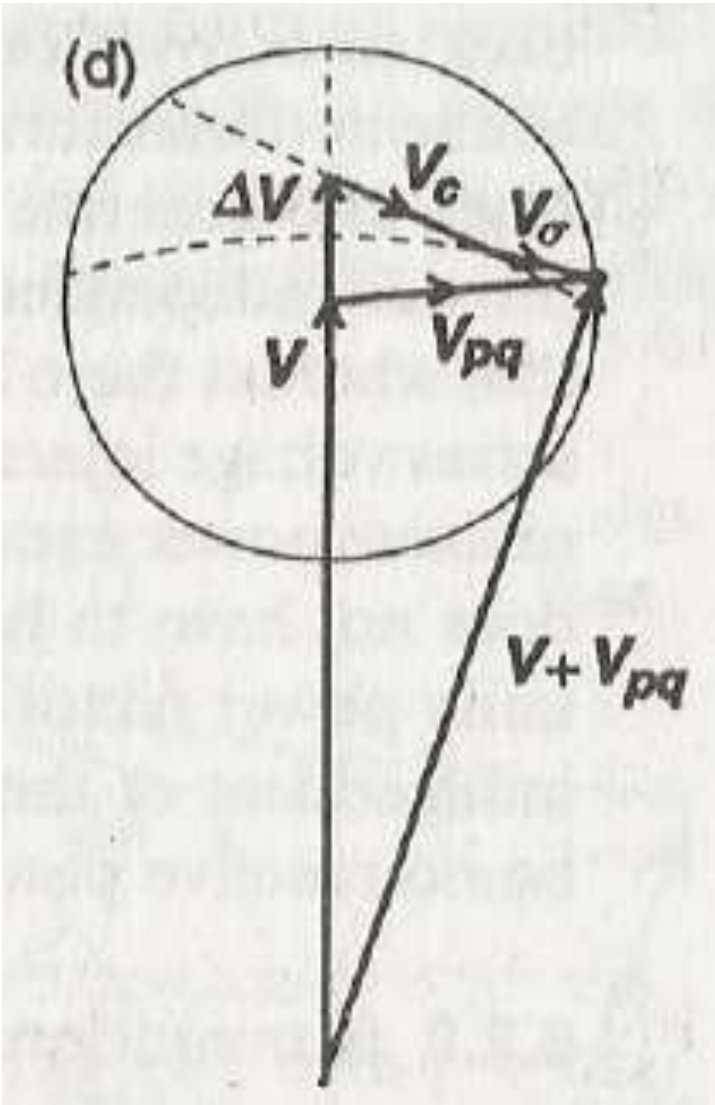
Unified Power Flow Controller(UPFC)

Phase angle regulation (phase shift) is shown in Fig. (c) where $V_{pq} = V_{\sigma}$ is injected with an angular relationship w.r.t V_s that achieves the desired σ phase shft (advance or retard) witout any change in magnitude.



Thus UPFC can function as a perfect Phase Angle Regulator which can also supply the reactive power involved with the transmission angle control by internal var generation.

Unified Power Flow Controller(UPFC)



Multifunction power flow control, executed by simultaneous terminal voltage regulation , series capacitive line compensation, and phase shifting is shown in Fig. (d) where $V_{pq} = \Delta V + V_q + V_\sigma$ is injected with an angular relationship w.r.t V_s that achieves the desired σ phase shift (advance or retard) without any change in magnitude.

Unified Power Flow Controller(UPFC)

The transmitted power P and reactive power $-jQ_r$, supplied by the receiving end , can be expressed as :

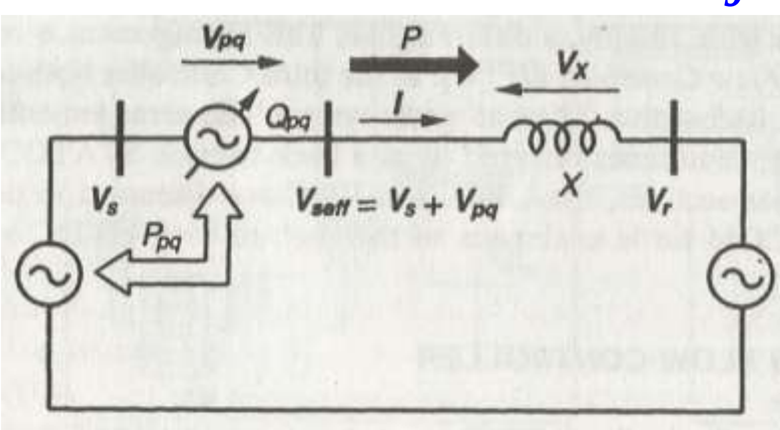
$$P - jQ_r = V_r \left(\frac{V_s + V_{pq} - V_r}{jX} \right)^* \qquad (1)$$

With V_{pq}=0, the expression represents an un-compensated case:

$$P - jQ_r = V_r \left(\frac{V_s - V_r}{jX} \right)^* \qquad (2)$$

With V_{pq}≠0, the total real and reactive power can be written as:

$$P - jQ_r = V_r \left(\frac{V_s - V^r}{jX} \right)^* + \frac{V_r . V_{pq^*}}{-jX} \qquad (3)$$



Unified Power Flow Controller(UPFC)

Substituting :

$$V_s = V.e^{j\delta/2} = V\left(\cos\frac{\delta}{2} + j\sin\frac{\delta}{2}\right) \qquad (4)$$

$$V_r = V.e^{-j\delta/2} = V\left(\cos\frac{\delta}{2} - j\sin\frac{\delta}{2}\right) \qquad (5)$$

$$V_{pq} = V_{pq}.e^{j(\delta/2+\rho)} = V_{pq}\left\{\cos\left(\frac{\delta}{2}+\rho\right) + j\sin\left(\frac{\delta}{2}+\rho\right)\right\} \qquad (6)$$

The following expressions are obtained for P and Q_r:

$$) = P_0(\delta) + P_{pq}(\rho) = \frac{V^2}{X}\sin\delta - \frac{V.V_{pq}}{X}\cos\left(\frac{\delta}{2}+\rho\right) \qquad (7)$$

$$Q_r(\delta,\rho) = Q_{0r}(\delta) + Q_{pq}(\rho) = \frac{V^2}{X}(1-\cos\delta) - \frac{V.V_{pq}}{X}\sin\left(\frac{\delta}{2}+\rho\right) \qquad (8)$$

$$P_0(\delta) = \frac{V^2}{X}\sin\delta \qquad (9)$$

$$Q_{0r}(\delta) = -\frac{V^2}{X}(1-\cos\delta) \qquad (10)$$

These are real and reactive power for the uncompensated line.

Unified Power Flow Controller(UPFC)

Since angle ρ is freely variable between 0 and 2π at any given transmission angle $\delta(0\leq\delta\leq\pi)$, it follows that $P_{pq}(\rho)$ and $Q_{pq}(\rho)$ are controllable between $-V.V_{pq}/X$ and $+V.V_{pq}/X$ independent of angle δ. Therefore, the transmittable real power P is controllable between :

$$P_0(\delta) - \frac{V.V_{pq\max}}{X} \leq P_0(\delta) \leq P_0(\delta) + \frac{V.V_{pq\max}}{X} \qquad (11)$$

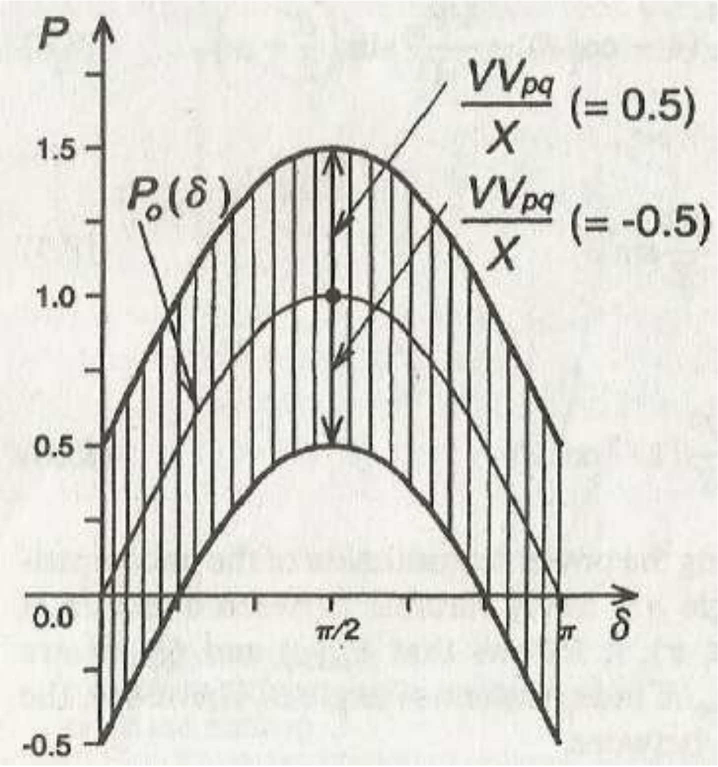
And the reactive power Q_r is controllable between :

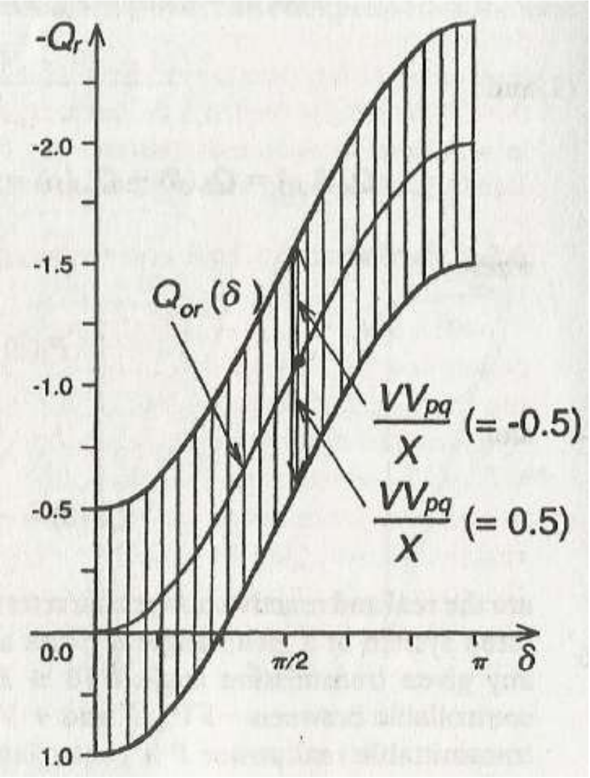
$$Q_{0r}(\delta) - \frac{V.V_{pq\max}}{X} \leq Q_{0r}(\delta) \leq Q_{0r}(\delta) + \frac{V.V_{pq\max}}{X} \qquad (12)$$

Unified Power Flow Controller(UPFC)

The wide range of control of transmitted power is independent of the transmission angle δ

This indicates not only superior capability of the UPFC in power flow applications, but it also suggests powerful capacity for transient stability improvement and power oscillation damping.





Interline Power Flow Controller(IPFC)

The IPFC concept scheme was proposed by Gyugyi with Sen and Schauder in 1998 addresses the problem of compensating a number of transmission lines at a given substation.

Conventionally, series capacitive compensation (TCSC or SSSC) is employed to increase the transmittable real power over a given line and also to balance the loading of a normally encountered multiline transmission system.

However, independent of their means of implementation , series reactive reactors are unable to control the reactive power flow in, and thus the proper load balancing of, the lines.

This problem becomes particularly evident where the ratio of reactive to resistive line impedance(X/R) is relatively low. Series reactive compensation reduces only the effective reactance and decreases the X/R ratio and increases the reactive power flow and losses in the line.

Interline Power Flow Controller(IPFC)

The IPFC scheme, together with independently controllable reactive series compensation of each individual line , provides a capability to directly transfer real power between the compensated lines.

This capability makes it possible to: equalize both real and reactive power flow between the lines ,reduce the burden of overloaded lines by real power transfer; compensate against resistive line voltage drops and corresponding reactive power demand and increase the effectiveness of the overall compensating system for dynamic disturbances.

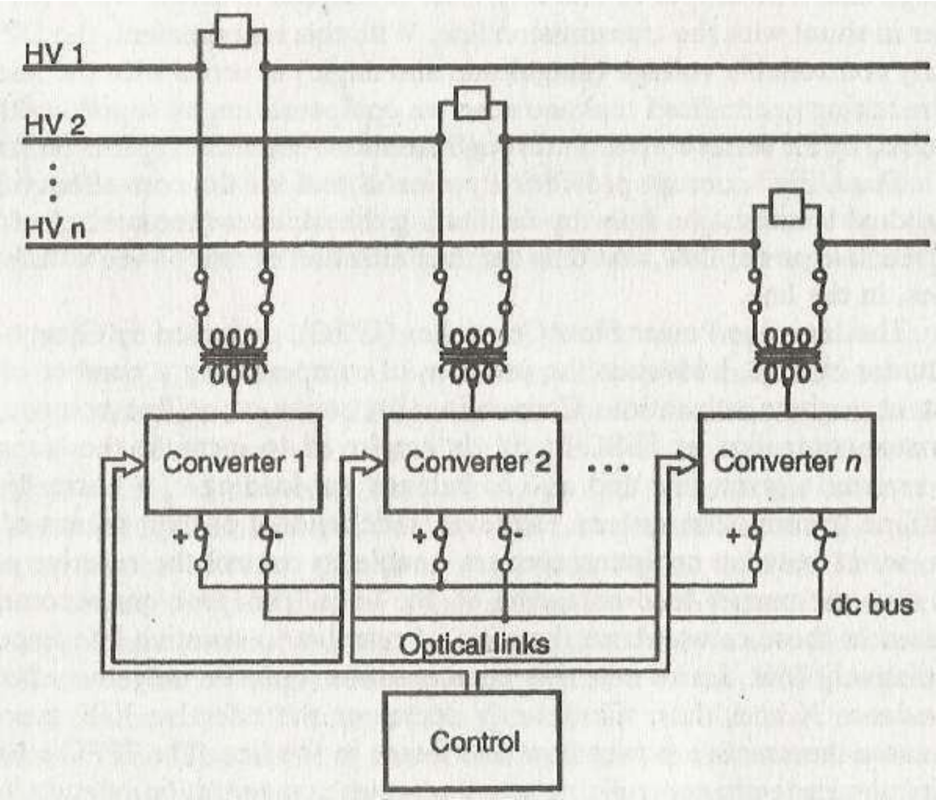
The IPFC can thus potentially provide a highly effective scheme for power transmission management at a multiline substation.

Interline Power Flow Controller(IPFC)

Basic Operating Principles:

In its general form the Interline Power Flow Controller employs a number of dc to ac converters each providing series compensation for different line. In other words, the IPFC comprises a number of SSSCs.

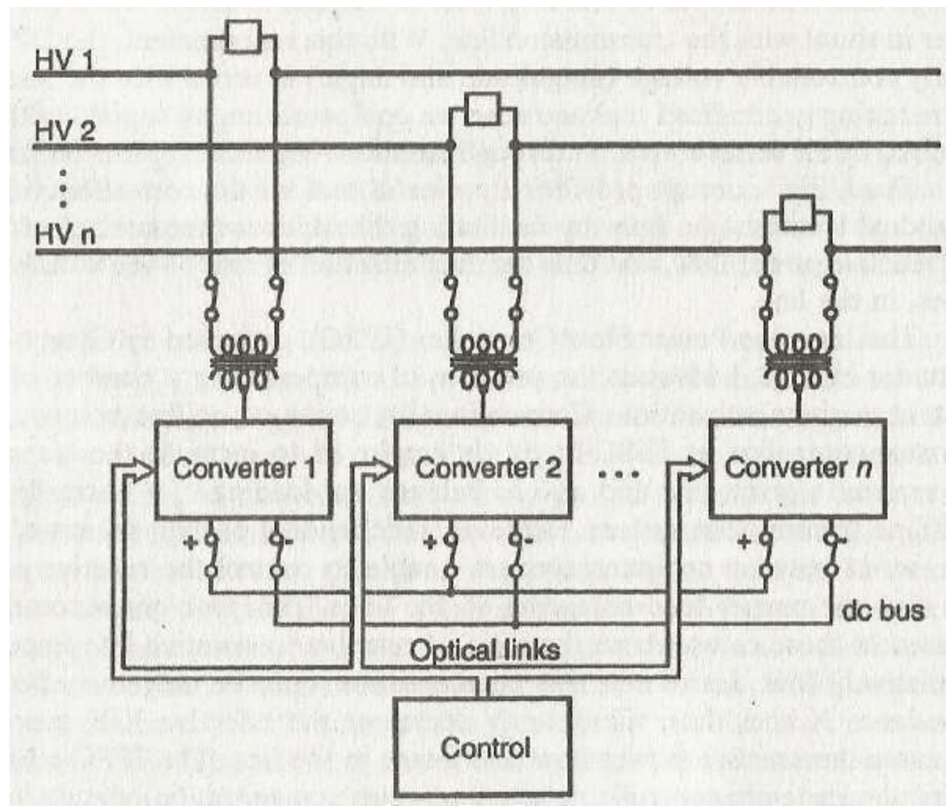
Within the general concept of IPFC, these converters are linked together at their dc terminals.



Interline Power Flow Controller(IPFC)

Basic Operating Principles:

With this scheme, in addition to providing series reactive compensation, any converter can be controlled to supply real power to the common dc link from its own transmission line. Thus an overall surplus power can be made available from the under utilized lines which then can be used by other lines for real power compensation.



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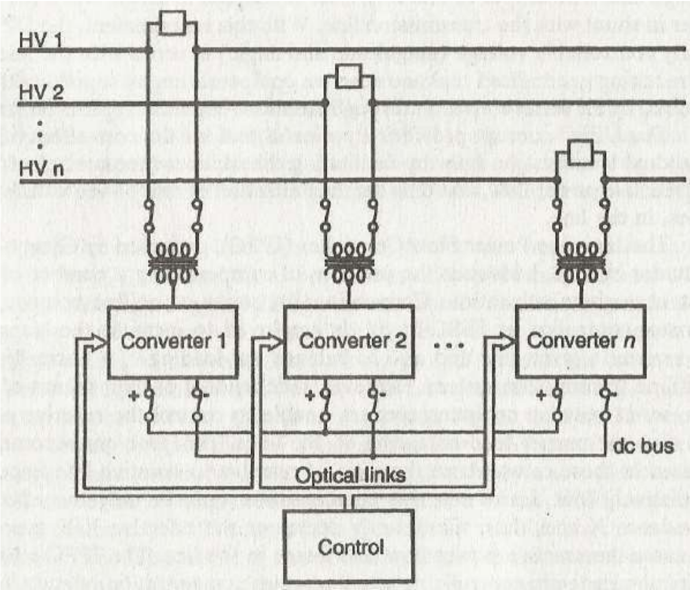
Interline Power Flow Controller(IPFC)

Basic Operating Principles:

In this way ,some of the converters, compensating overloaded lines or lines with a heavy burden of reactive power flow, can be equipped with full two dimensional, reactive and real power control capability, similar to UPFC.

This arrangement requires rigorous maintenance of the overall power balance at the common dc terminal by appropriate control action, using the general principle that the unde rloaded lines are to provide help, in the form of appropriate real power transfer, for the overloaded lines.

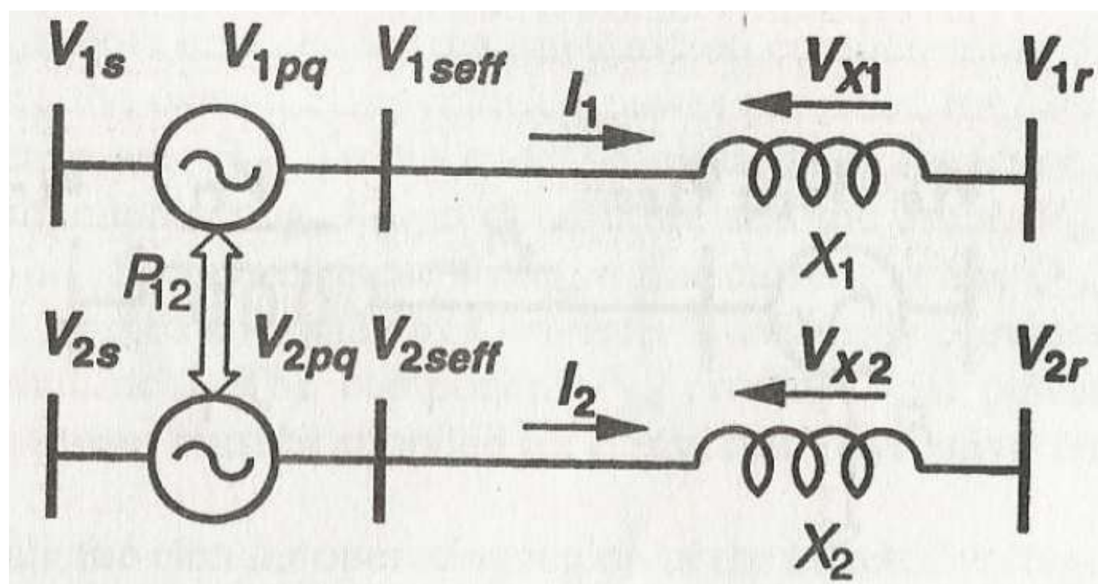


Interline Power Flow Controller(IPFC)

Basic Operating Principles:

Consider an elementary IPFC scheme consisting of two back to back dc-to-dc converters, each compensating a transmission line by series voltage injection.

The 2 SVSs with phasors V_{1pq} and V_{2pq}, in series with transmission lines 1 and 2, represent the two back to back dc to ac converters. The common dc is represented by a bidirectional link for real power exchange between the two voltage sources.



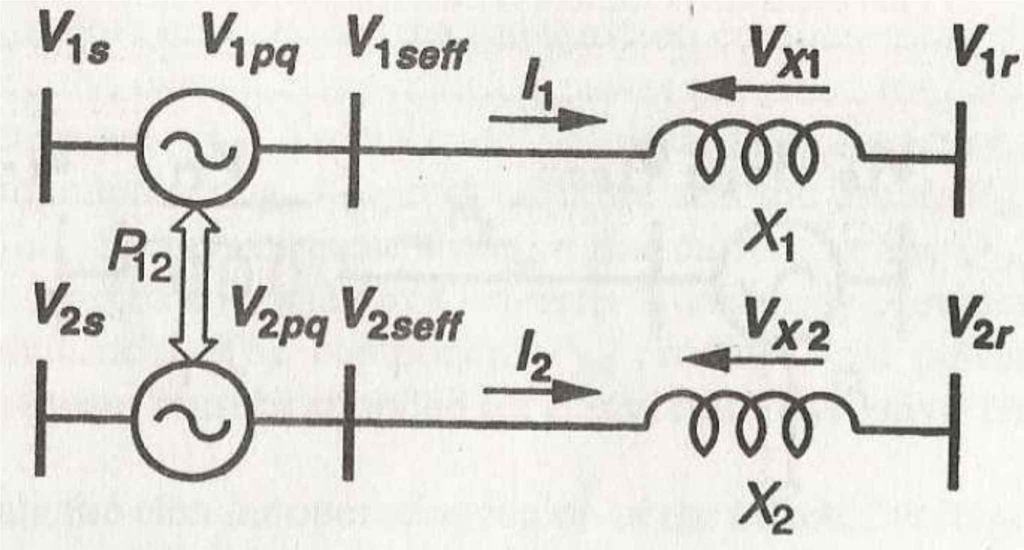
Interline Power Flow Controller(IPFC)

Basic Operating Principles:

Transmission line 1 ,represented by reactance X_1, has a sending end bus with voltage phasor V_{1s} and a receiving end bus with voltage phasor V_{1r}.

Transmission line 2 ,represented by reactance X_2, has a sending end bus with voltage phasor V_{2s} and a receiving end bus with voltage phasor V_{2r}.

For clarity, all the sending end and receiving end voltages are assumed to be constant $|V_{1s}|= |V_{2s}|= |V_{1r}|= |V_{2r}|= 1.0$ pu and with fixed angles $\delta_1=\delta_2=30^0$.



UPFC, unified power flow controller (combined shunt and series connected controllers)

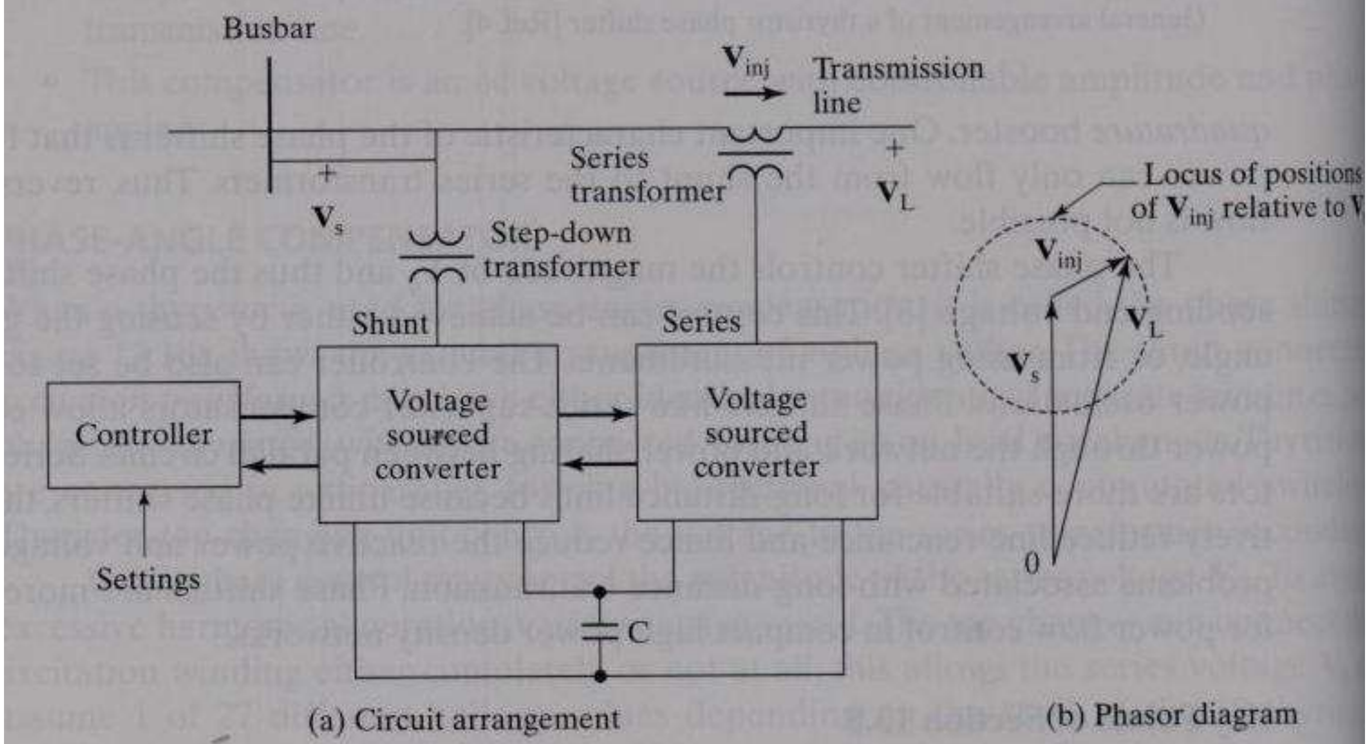


FIGURE 13.19

Unified power flow controller [Ref. 4].

1. The UPFC consists of an a series STATCOM and a shunt SATACOM with a common DC link.
2. Power control is achieved by adding series voltage Vinj to Vs, thus giving the line voltage VL.
3. With two converters, the UPFC can supply active power in addition to reactive power.

Reference

1. L. Gyugyi, N.G. Hingorani, **"Understanding FACTS,"** IEEE Press, 1st Edition, December 1999.

2. M.H. Rashid, "Power Electronics," Prentice Hall, 3rd Edition, 2004.