Flexible AC Transmission Systems (FACTS)

(EE1422)

Department Elective I

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Asst. Prof.

EE Department

TIME- TABLE

Day	Time
Wednesday	3:00-400 pm
Thursday	3:00-400 pm
Friday	3:00-400 pm

Flexible AC Transmission Systems

Syllabus

Concepts of reactive power support and voltage stability, compensation at a bus and over a line. Synchronous condenser, static var compensation, static phase shifter, thyristor controlled switched capacitor, STATCONs and DVRs, Unified Power Flow Controller, Inter-line Power Flow Controller. Reactive power balance over a network and optimization.

FACTS, Detailed Syllabus

Module 1

AC transmission line and reactive power compensation: Transmission interconnection, flow of power in AC system, brief description and definitions of FACTS controllers,

analysis of uncompensated line: transmission line equations, performance of a line connected to unity power factor load, performance of a symmetrical line, passive reactive power compensation: distributed and discrete power compensation, compensation by a series capacitor connected at the mid-point of the line, shunt capacitor compensation connected at the midpoint of the line, comparison between series and shunt capacitor compensation

Module 2

Static Shunt Compensators: Objectives of shunt compensation: midpoint voltage regulation for line segmentation, end of line voltage support to prevent voltage instability, improvement of transient stability, power oscillation damping, analysis of SVC, methods of controllable VAR generation: variable impedance type static VAR generators: TSC and TCR, voltage source converter type VAR generators: Static Synchronous Compensator (STATCOM); hybrid VAR Generators: voltage source converter with TSC and TCR

Module 3

Static Series Compensators: Objectives of series compensation: voltage stability, improvement of transient stability, power oscillation damping, sub synchronous oscillation damping, variable impedance type series compensators: Thyristor-Controlled Series Capacitor (TCSC),GTO Thyristor-Controlled Series Capacitor (GCSC),voltage source converter type series compensators: Static Synchronous Series Compensator (SSSC).

Module 4

Combined Shunt and Series Compensators: Basic operating principles and characteristics: Unified Power Flow Controllers (UPFC), Interline Power Flow Controller (IPFC)

Prerequisites & Books:

1. Power Electronics
2. Electrical Power Transmission & Distribution

Text and Reference Books

- N. Hingorani. ***Understanding FACTS.*** IEEE Press
- K. R. Padiyar. ***FACTS controllers in power transmission and distribution.*** New Age
- R. Mohan Mathur, Rajiv K. Varma. ***Thyristor-based FACTS controllers for electrical transmission systems.*** IEEE and Willey-Interscience

Course Outcomes (Cos):

At the end of the course the students will be able to

1. examine the interconnection system of the transmission line with their limitations
2. analyze the effect of series and shunt passive compensators
3. performance evaluation of different static, shunt and series compensators
4. evaluation of different configurations of combined compensators

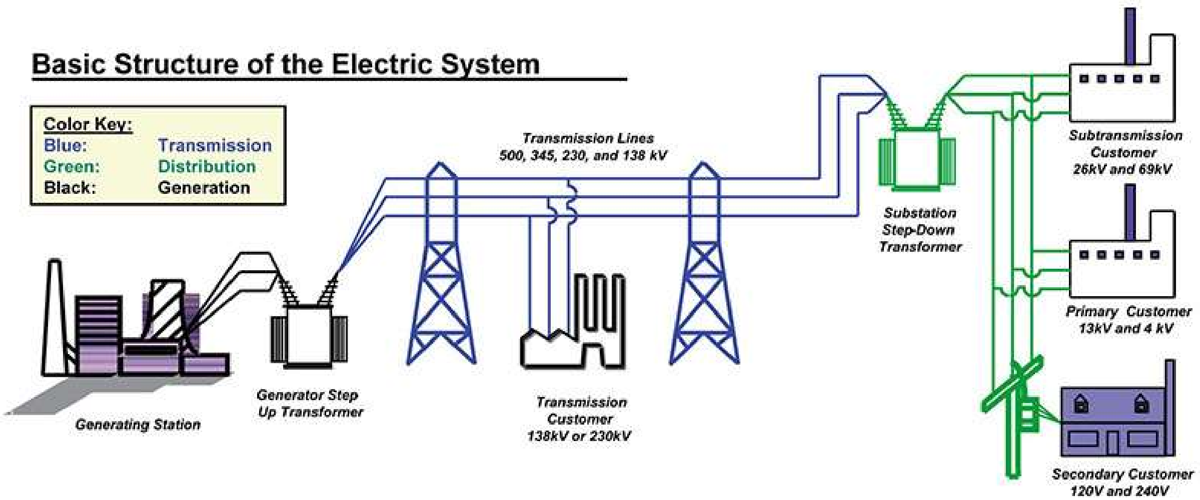
Module 1, Part 1

Transmission interconnection, flow of power in AC system, brief description and definitions of FACTS controllers,

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

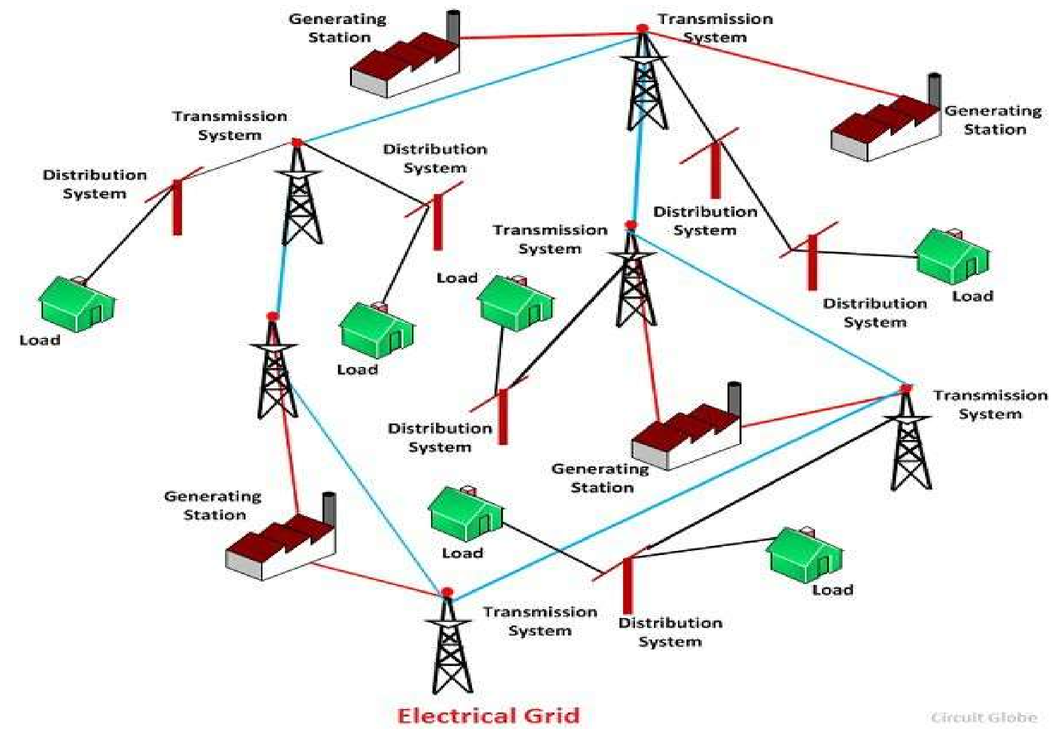


Transmission Interconnections

- 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

Transmission Interconnection in India

- State Grids- Interconnection in state owned power plants - e.g PSPCL

- State Grids Interconnected to form regional grids- ER,NR,SR,WR and NER

- National GRID

- International connections

Evolution of National Grid in INDIA

•Grid management on regional basis started in sixties.
•Initially, State grids were inter-connected to form regional grid and India was demarcated into 5 regions namely Northern, Eastern, Western, North Eastern and Southern region.

•In October 1991 North Eastern and Eastern grids were connected.
•In March 2003 WR and ER-NER were interconnected .

•August 2006 North and East grids were interconnected thereby 4 regional grids Northern, Eastern, Western and North Eastern grids are synchronously connected forming central grid operating at one frequency.

•On 31st December 2013, Southern Region was connected to Central Grid in Synchronous mode with the commissioning of 765kV Raichur-Solapur Transmission line thereby achieving **'ONE NATION'-'ONE GRID'-'ONE FREQUENCY'.**

- The Indian Power system for planning and operational purposes is divided into five regional grids.

- The integration of regional grids, and thereby establishment of National Grid, was conceptualized in early nineties.

- The integration of regional grids which began with asynchronous HVDC back-to-back inter-regional links facilitating limited exchange of regulated power was subsequently graduated to high capacity synchronous links between the regions.

- Synchronisation of all regional grids will help in optimal utilization of scarce natural resources by transfer of Power from Resource centric regions to Load centric regions.

- Further, this shall pave way for establishment of vibrant Electricity market facilitating trading of power across regions.

- **One Nation One Grid** shall synchronously connect all the regional grids and there will be one national frequency.

NR
WR
ER
NER
SR
MUZAFFARPUR
KOTA
UJJAIN
GWALIOR
VINDHYACHAL
KORBA
SIPAT
RAIPUR
ROURKELA
CHANDRAPUR
KOLHAPUR
PONDA
BELGAUM
GAZUWAKA

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**

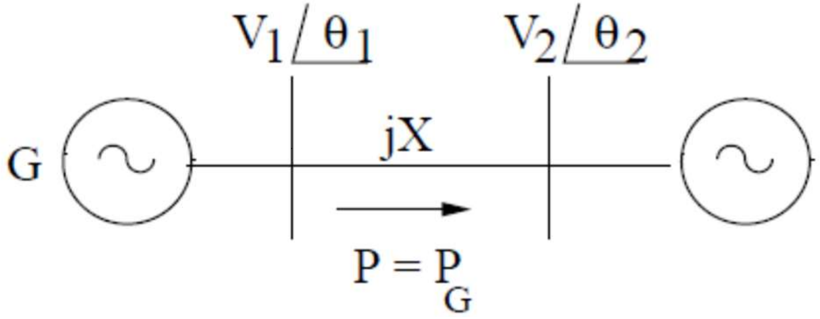
Opportunities for FACTS

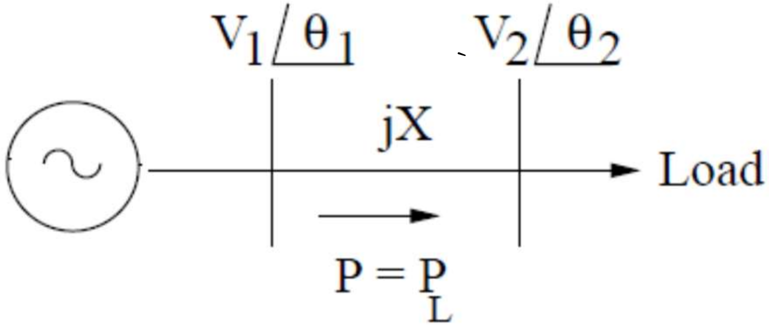
- $P = V1.V2 / X.\mathrm{Sin}\delta$
- Conventionally there is no high speed control over these parameters
- Phase angle control is rarely utilised by means of slow mechanical phase shifters
- Tap changers, reactors and capacitors are generally mechanically switched are "**slow**" methods
- There is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

Opportunities for FACTS

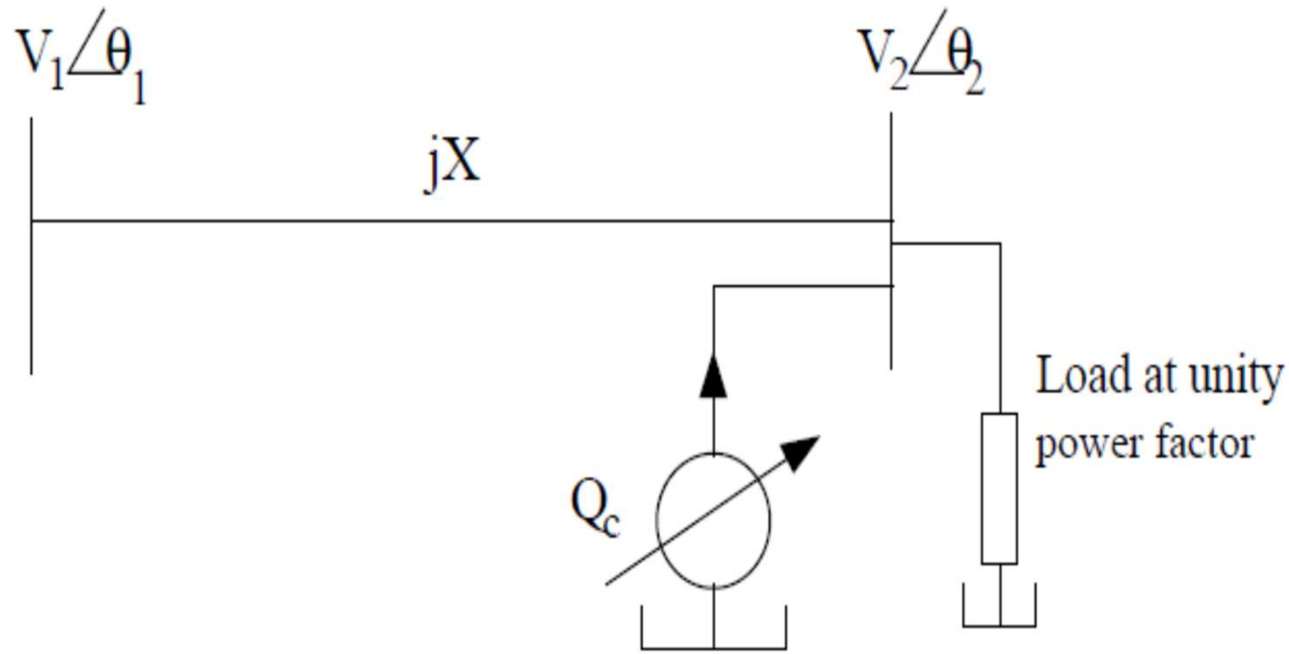
- For controlling power
- For enhancing the usable capacity of the present transmission lines

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





$$P = \frac{V_1 V_2}{X} \sin(\theta_1 - \theta_2)$$



$V_1\angle\theta_1$
$V_2\angle\theta_2$
jX
Load at unity
power factor
Q_c

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.

Power Flow control in parallel lines

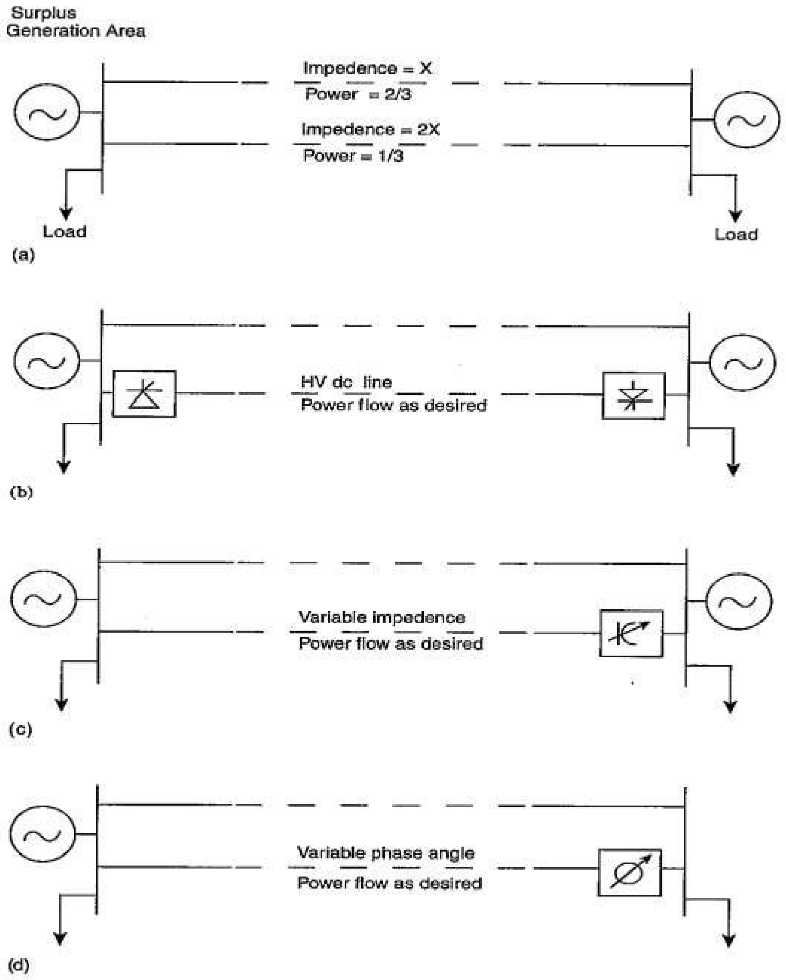
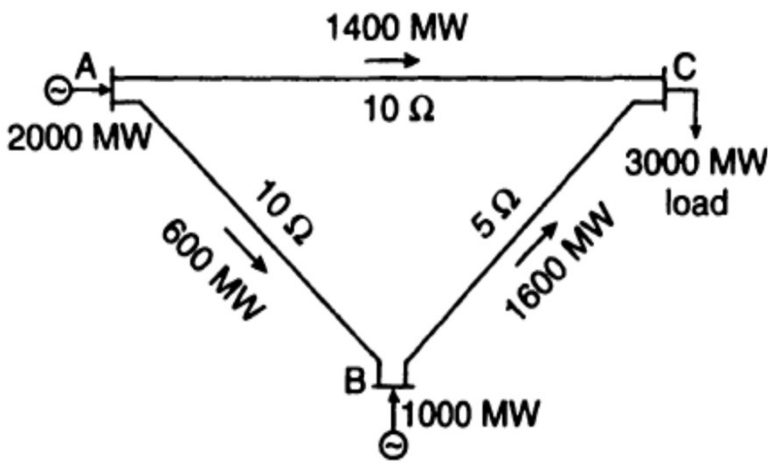


Figure 1.1 Power flow in parallel paths: (a) ac power flow with parallel paths; (b) power flow control with HVDC; (c) power flow control with variable impedance; (d) power flow control with variable phase angle.

Power Flow control in Mesh Network

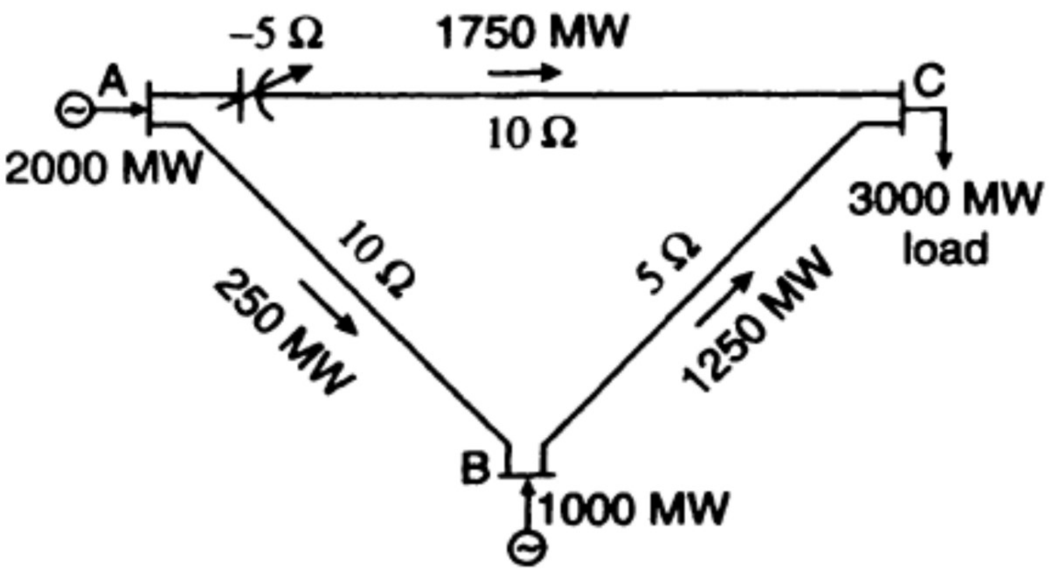


- Suppose the lines AB, BC, and AC have continuous ratings of 1000 MW, 1250 MW, and 2000 MW, respectively
  - If one of the generators is generating 2000 MW and the other 1000 MW, a total of 3000 MW would be delivered to the load center. For the impedances shown, the three lines would carry 600, 1600, and 1400 MW, respectively, as shown in Figure

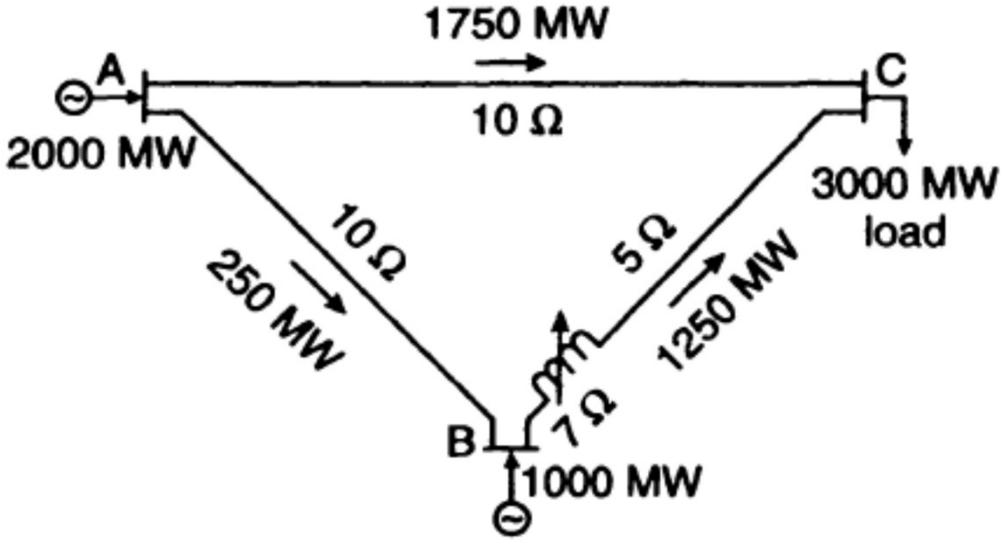
- For the impedances shown, the three lines would carry 600, 1600, and 1400 MW, respectively, as shown in Figure Such a situation would overload line BC (loaded at 1600 MW for its continuous rating of 1250 MW), and therefore generation would have to be decreased at B, and increased at A, in order to meet the load without overloading line BC.

Solution 1

If, however, a capacitor whose reactance is -5 ohms at the synchronous frequency is inserted in one line it reduces the line's impedance from 10 ohm to 5 ohm, so that power flow through the lines AB, BC, and AC will be 250, 1250, and 1750 MW, respectively.

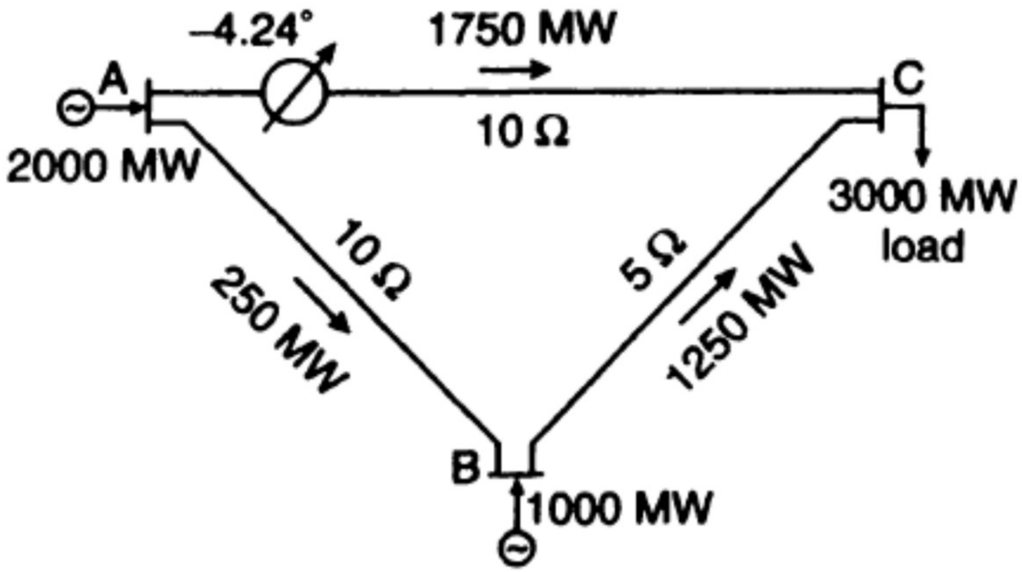


Solution 2

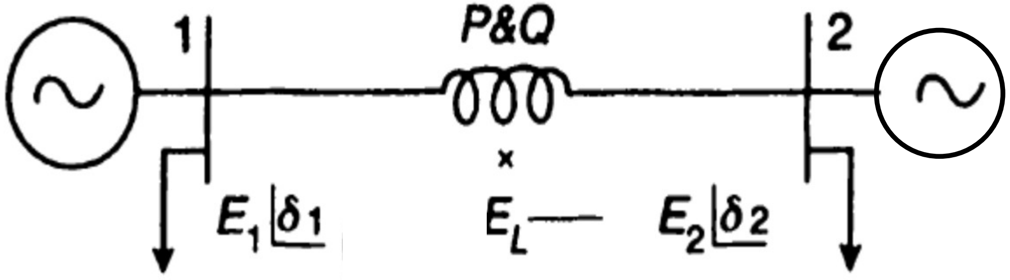


Similar results may be obtained by increasing the impedance of one of the lines in the same meshed configuration by inserting a 7 ohm reactor (inductor) in series with line AB . Again, a series inductor that is partly mechanically and partly thyristor-controlled, it could serve to adjust the steady-state power flows as well as damp unwanted oscillations.

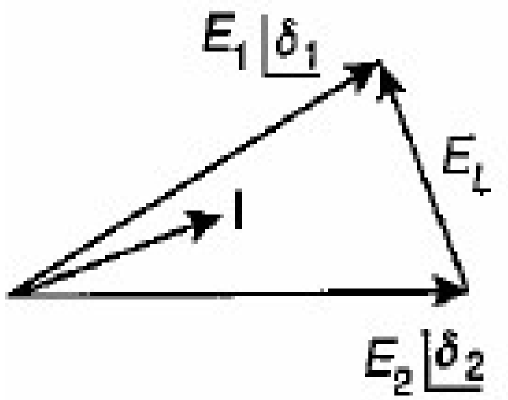
Solution 3



As another option, a thyristor-controlled phase-angle regulator could be installed instead of a series capacitor or a series reactor in any of the three lines to serve the same purpose. In Figure, the regulator is installed in the third line to reduce the total phase-angle difference along the line from 8.5 degrees to 4.26 degrees. As before, a combination of mechanical and thyristor control of the phase-angle regulator may minimize cost.



(a)



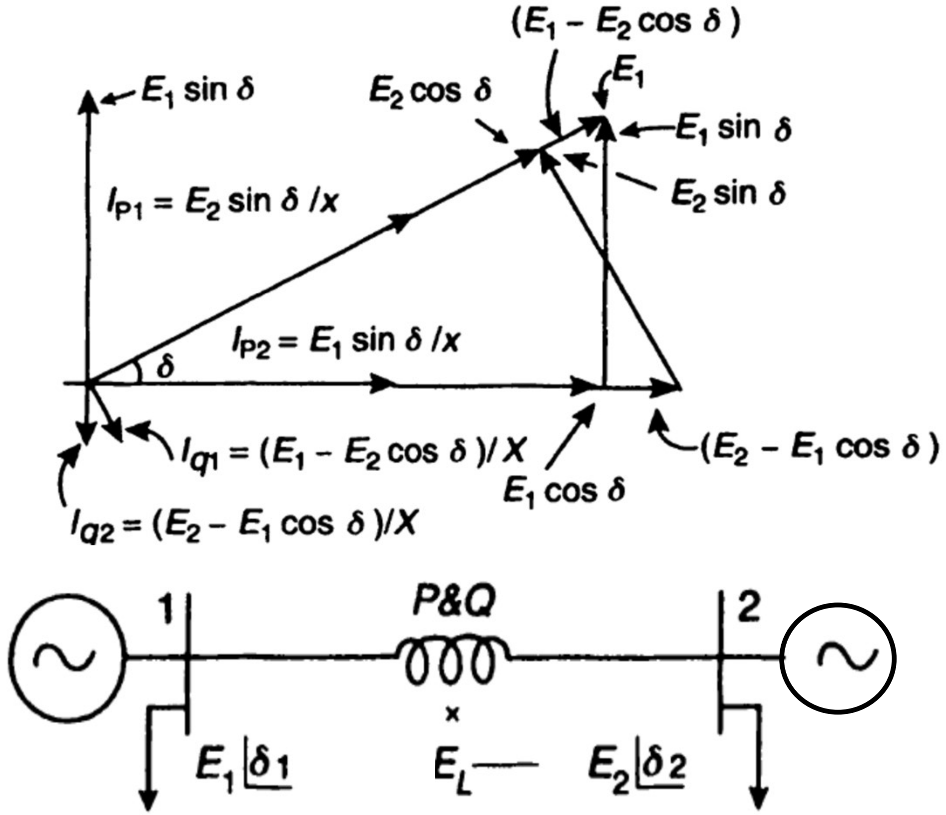
(b)

$E_L = E_1 - E_2$ 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

- If the angle between the two bus voltages is small, the current flow largely represents the active power. Increasing or decreasing the inductive impedance of a line will greatly affect the active power flow.
- Thus impedance control, which in reality provides current control, can be the most cost-effective means of controlling the power flow. With appropriate control loops, it can be used for power flow control and/or angle control for stability.



(a)

Active component of the current flow at E_1 is:

$$I_{p1} = (E_2 \sin \delta)/X$$

Reactive component of the current flow at E_1 is:

$$I_{q1} = (E_1 - E_2 \cos \delta)/X$$

Thus, active power at the E_1 end:

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

Reactive power at the E_1 end:

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

Varying X will vary P_1, Q_1 and , for a given power flow, varying of X vary the angle between the two ends.

Similarly, active component of the current flow at E_2 is:

$$I_{p2} = (E_1 \sin \delta)/X$$

Reactive component of the current flow at E_2 is:

$$I_{q2} = (E_2 - E_1 \cos \delta)/X$$

Thus, active power at the E_2 end:

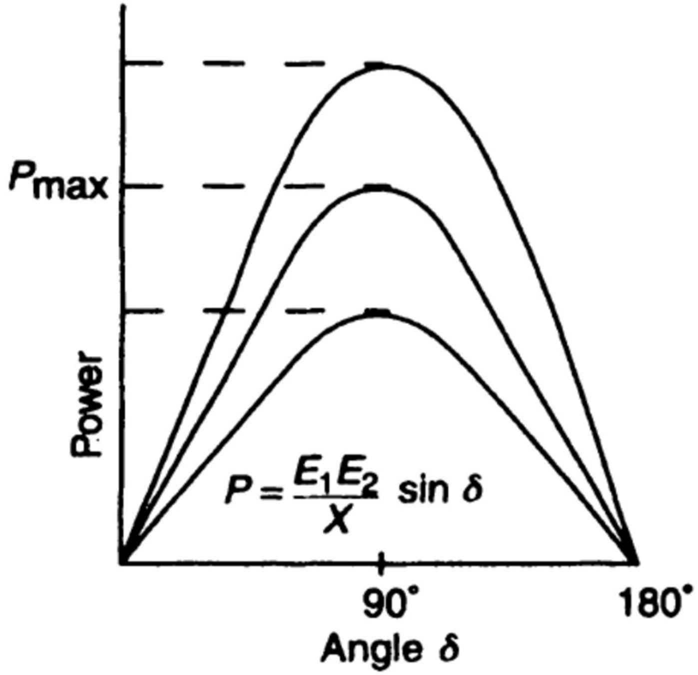
$$P_2 = E_2\,(E_1 \sin \delta)/X$$

Reactive power at the E_2 end:

$$Q_2 = E_2\,(E_2 - E_1 \cos \delta)/X$$

Naturally P_1 and P_2 are the same:

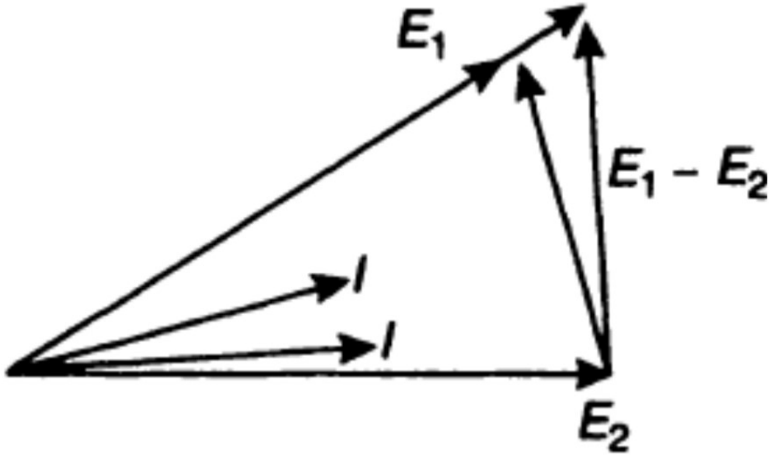
$$P = E_1\,(E_2 \sin \delta)/X$$



P_{max}
Power
$P = \frac{E_1 E_2}{X} \sin \delta$
90°
180°
Angle δ

Power flow control using Voltage injection method

Method 1

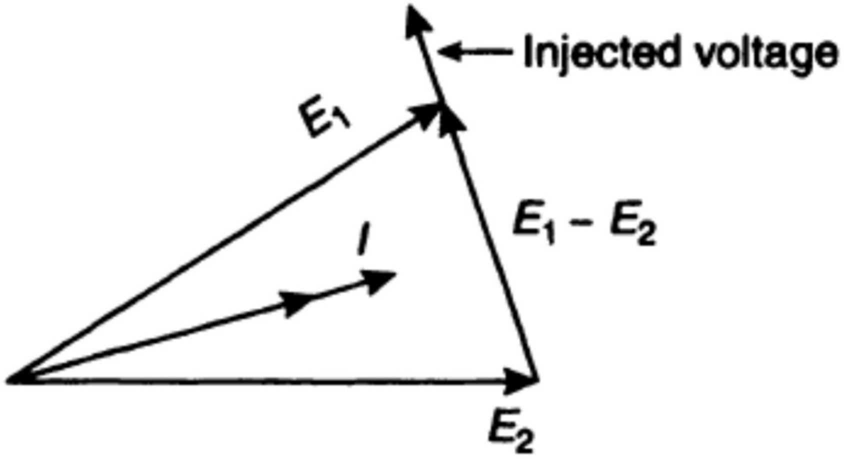


Power/current flow can be controlled by regulating the magnitude of voltage phasors E_1 or E_2.

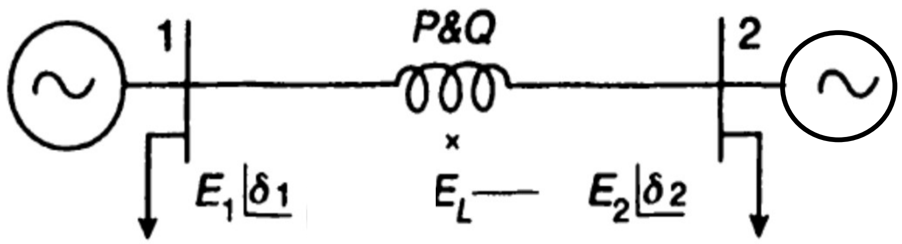
It is seen from the fig that with change in the magnitude of $E_1$the magnitude of driving voltage phasor E_1- E_2 doesn't change much, but its phase angle does.

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.

Method 2



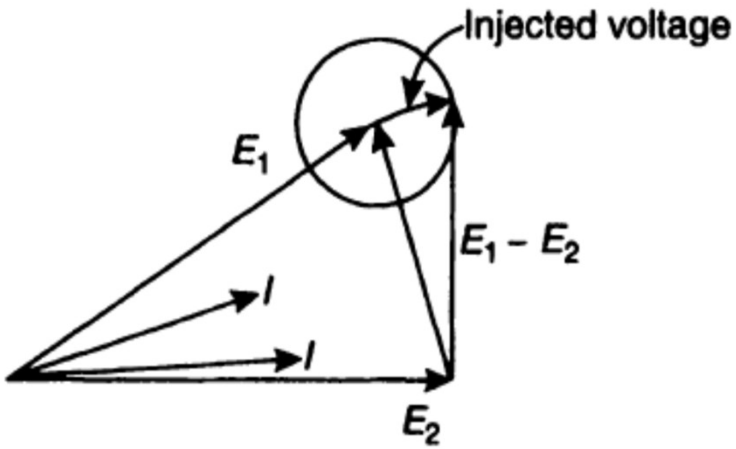
Power and current flow can also be changed by injecting voltage in series with the line.



(a)

It is seen from fig. 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

Method 3



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.

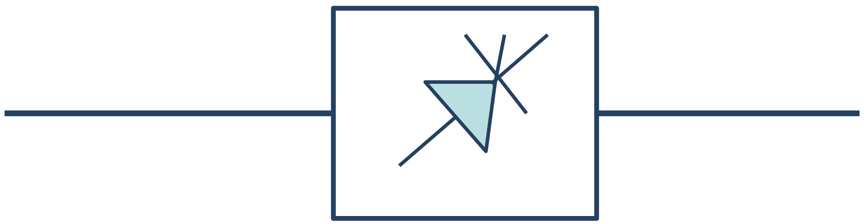
- The MVA rating of a series controller will often be a small fraction of the throughput line MVA.

- 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



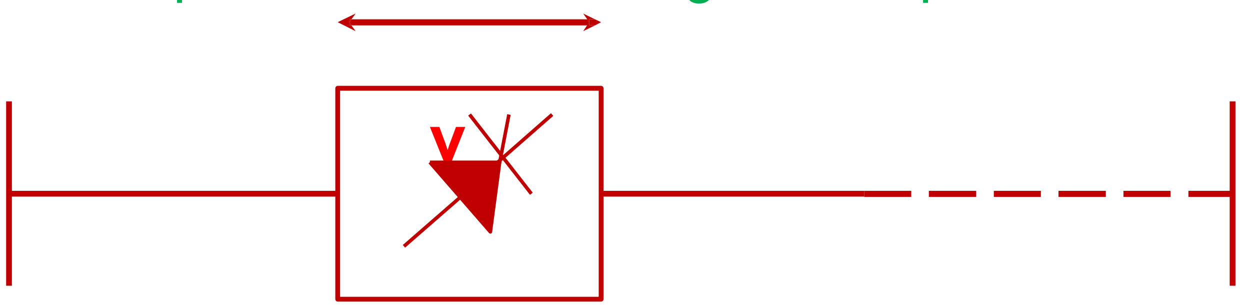
General Symbol of FACTS controller

Series controllers

- The series controller could be a

1. variable impedance such as capacitor, reactor etc. (with power electronics)
2. Power electronics based variable source (frequency, harmonics, desired need etc)

- 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.

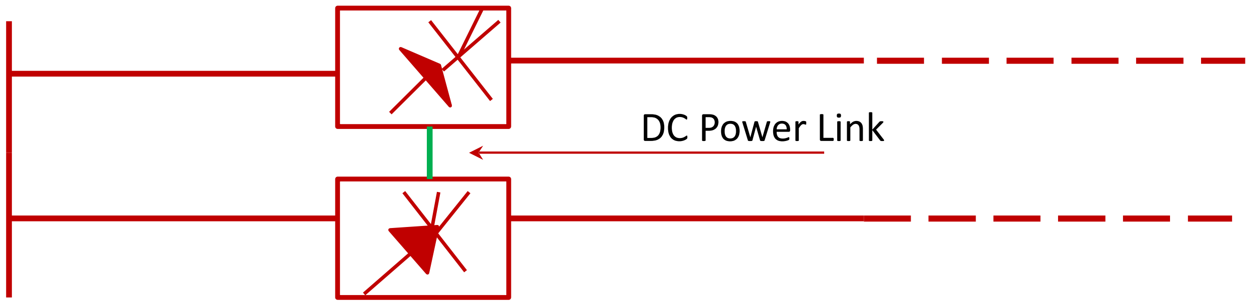
As long as the injected current is in phase quadrature with the line voltage, the shunt controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

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.

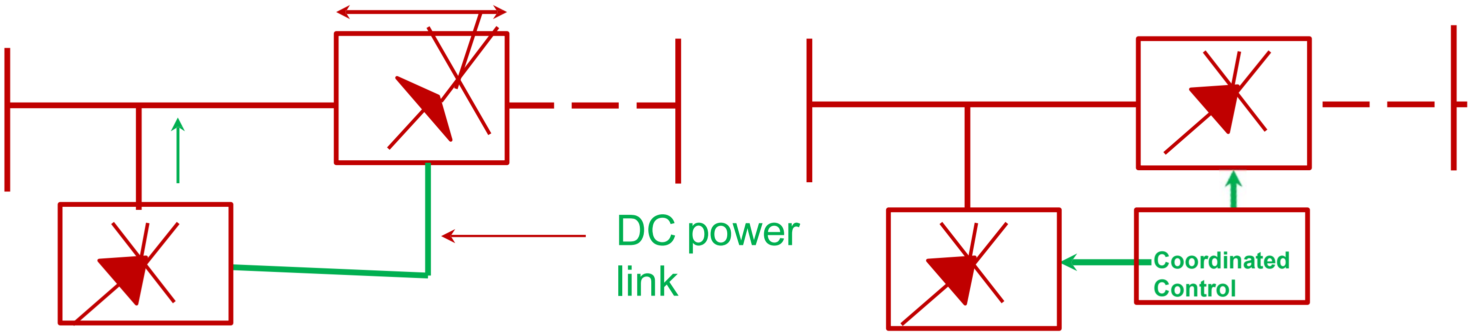


Combined Series-Shunt controllers

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 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.)

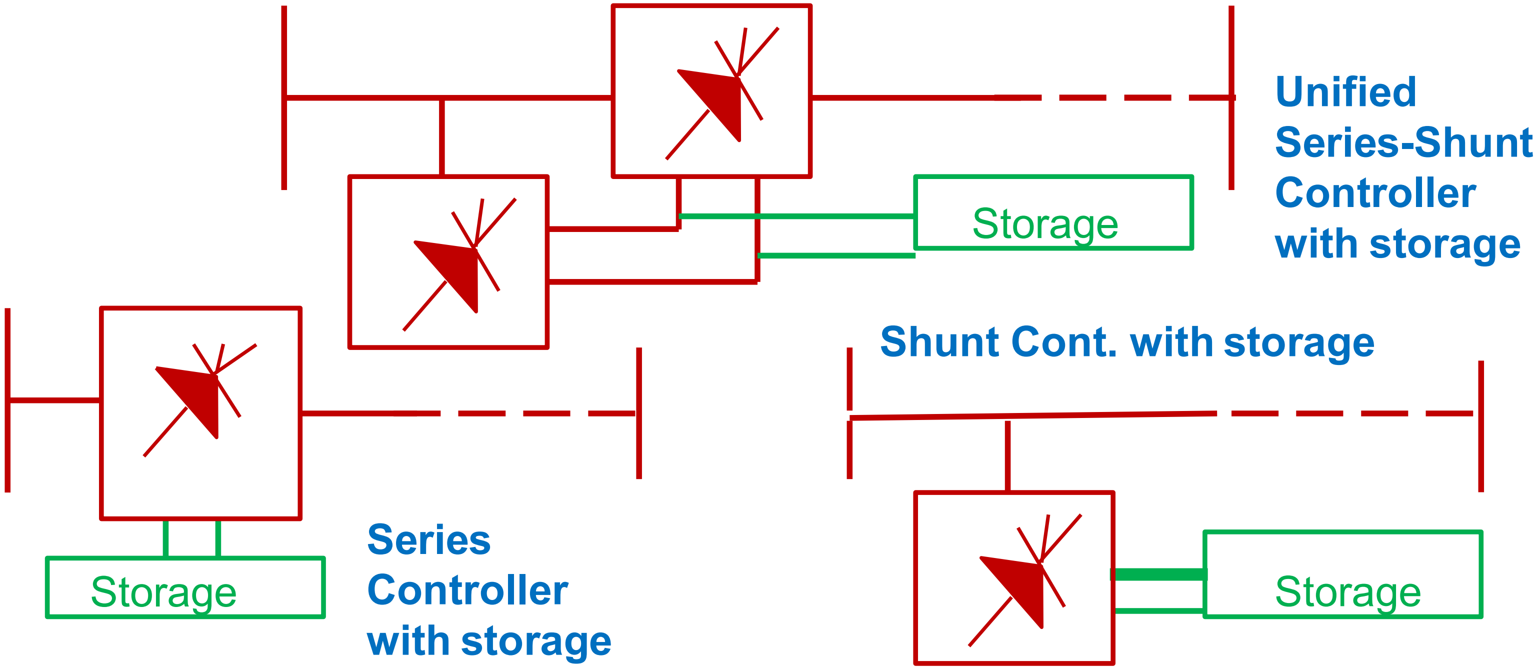
- FACTS Controllers may be based on thyristor devices with no gate turn off (only with gate turn off) or with power devices with gate turn-off capability. The controllers with gate turn-off devices are based on the dc to ac converters, which can exchange active and/or reactive power with the ac system.

- When the exchange involves reactive power only, they are provided with a minimal storage on the dc side.

- However, if the generated ac voltage or current (from the converter) is required to deviate from 90^0 w.r.t the line current or voltage, respectively, the converter dc storage can be augmented beyond the minimum required for the converter operation as a source of reactive power only.
- 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.



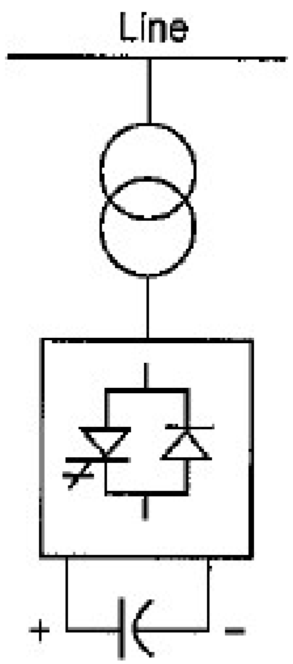
Relative Importance of different types of Controllers(cont.)

- The benefit of an added storage system(such as large capacitors, storage batteries, or superconducting magnets) to the controller is significant.

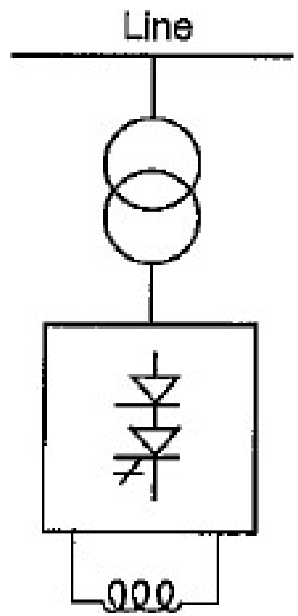
- A controller with storage is much more effective for controlling the system dynamics than corresponding controller without the storage.

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.

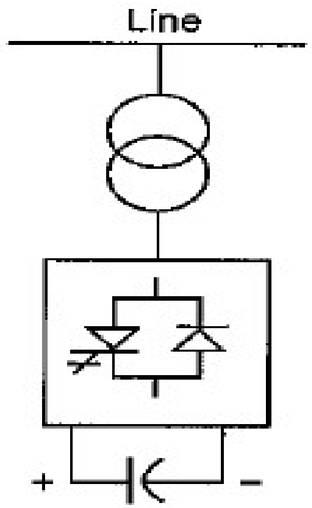


- The voltage sourced converter is represented in symbolic form by a box with a gate turn-off device paralleled by a reverse diode and a dc capacitor as a voltage source.
- The current sourced converter is represented by a box with a gate turn-off device with a diode in series and a dc reactor as its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



Shunt connected controllers (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 based on a voltage sourced or current sourced converter, however, from an overall cost point of view voltage sourced converters seem to be preferred.
- For VSC, its ac output voltage is controlled such that it is just right for the required reactive current flow for any bus voltage, dc capacitor voltage is automatically adjuste as required to serve as a voltage source for the converter.
- STATCOM can be desisgned to also act as an active filter to absorb system harmonics.

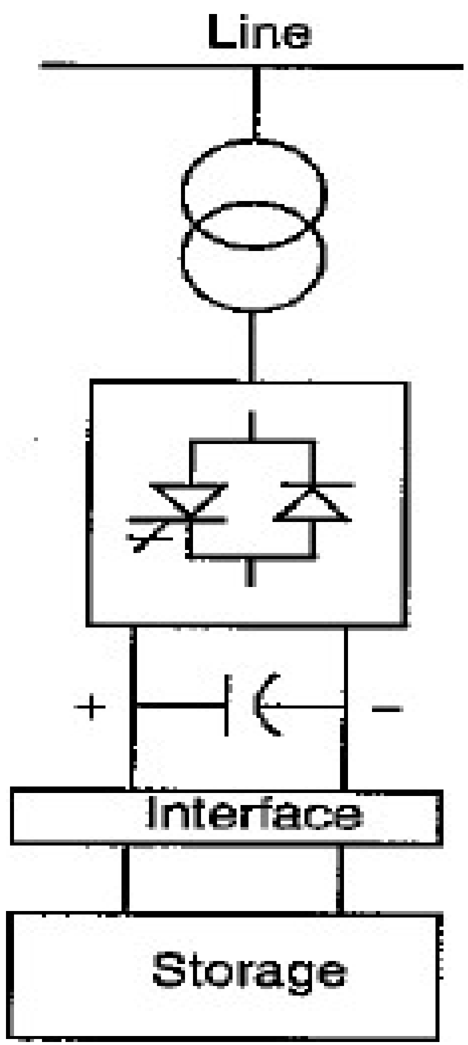


Shunt connected controllers (contd…)

- **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.

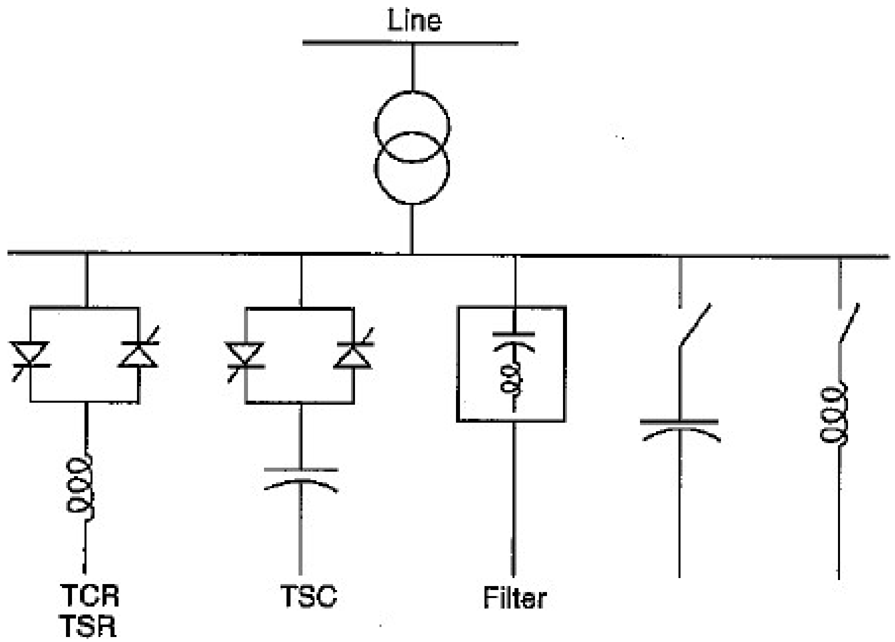
- A energy source can be a battery, flywheel, superconducting magnet, large dc storage capacitor etc.



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.

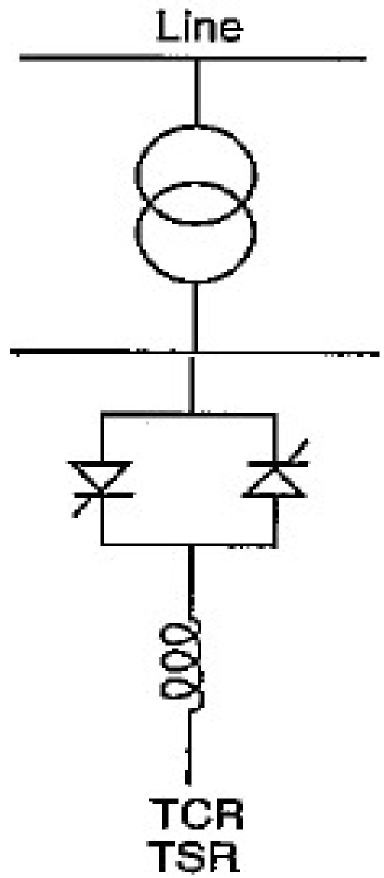
- This is a general term for a thyristor controlled or switched reactor and /or thyristor switched capacitor or combination without gate turn off capability



Shunt connected controllers

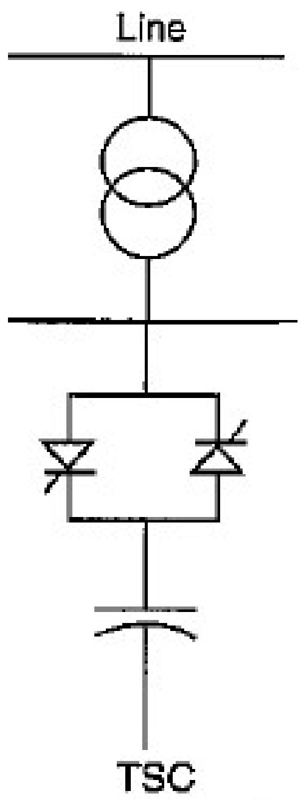
- **TCR: Thyristor Controlled Reactor :** A shunt connected thyristor controlled inductor whose effective reactance is varied in a continuous manner by partial conduction control of the thyristor valve.

- **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.

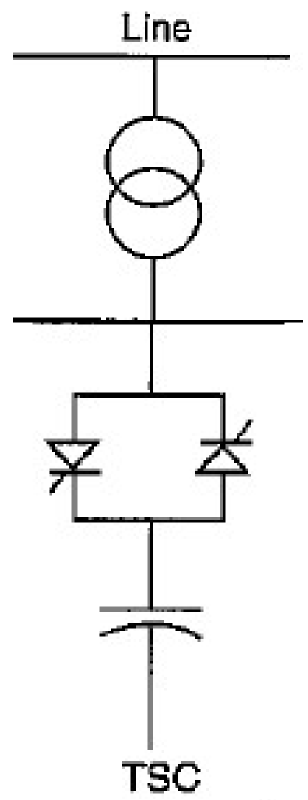


- Unlike shunt reactors, shunt capacitors cannot be switched continuously with variable firing angle control.

Shunt connected controllers (contd..)

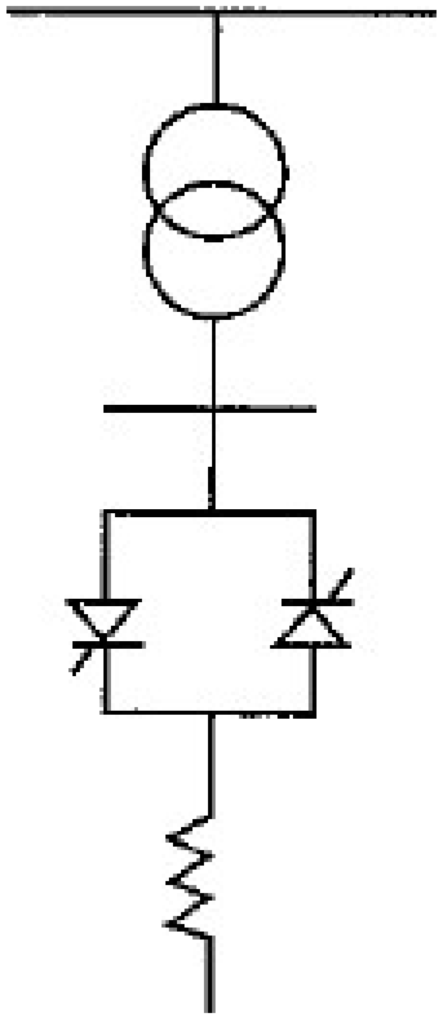
- **TSC: Thyristor Switched Capacitor :** A shunt connected thyristor switched capacitor whose effective reactance is varied in a stepwise manner by full or zero conduction operation of the thyristor valve.

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



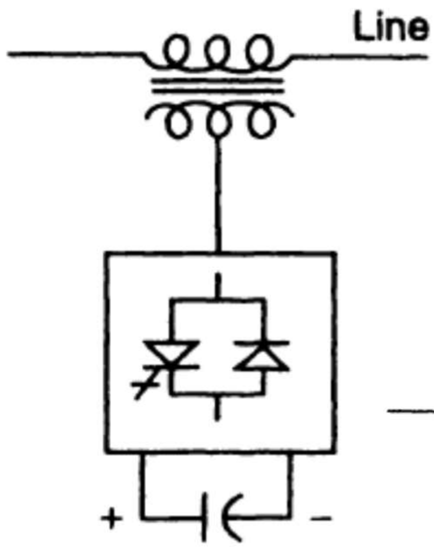
Shunt connected controllers (contd..)

- **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 .

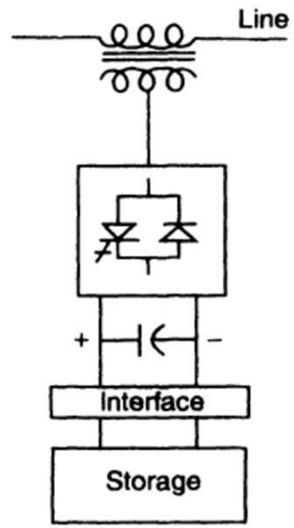


Series connected controllers (contd…)

- **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.



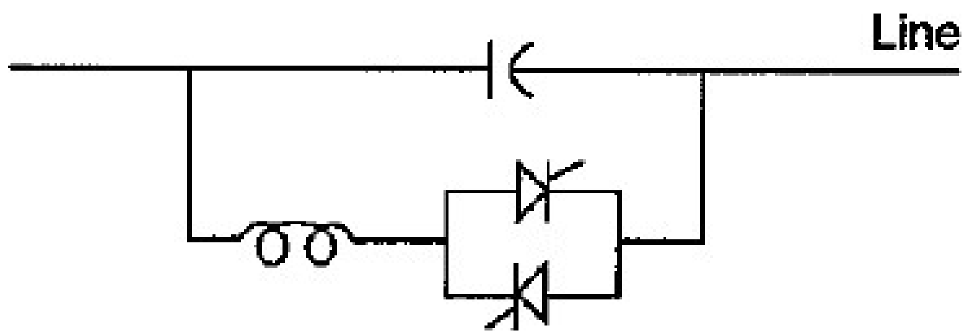
SSSC



SSSC with storage

Series connected controllers

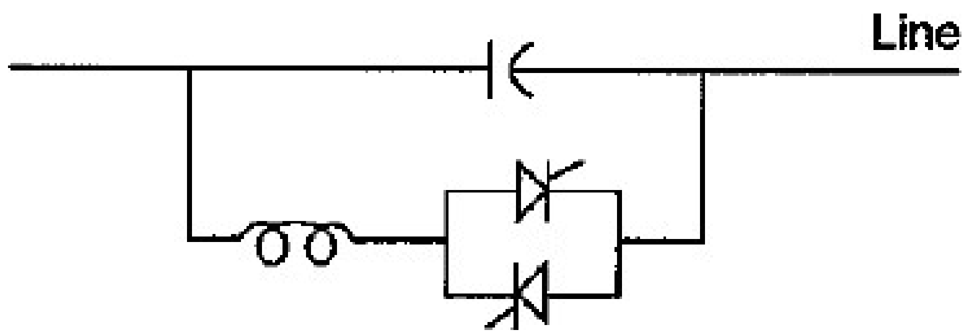
- **TCSC: Thyristor Controlled Series Capacitor:** A capacitor reactance compensator which consists of a series capacitor bank shunted by a thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance.



- **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

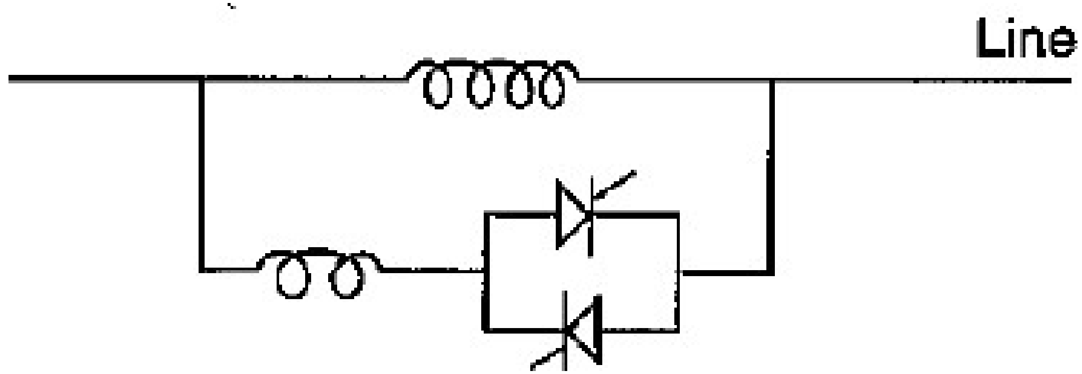
- **TCSC: Thyristor Controlled Series Capacitor:** A capacitor reactance compensator which consists of a series capacitor bank shunted by a thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance.



- **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.

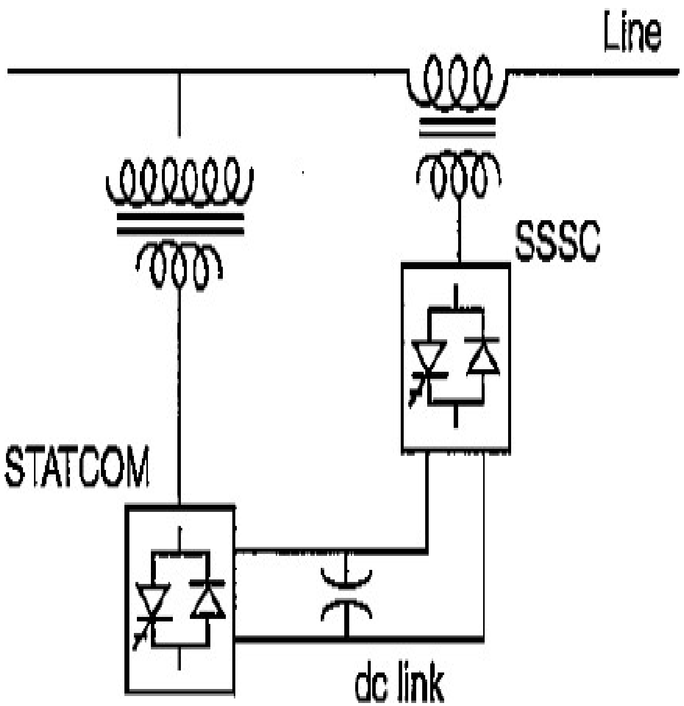


Series connected controllers (contd…)

- **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 of the SSSCs and are controlled to provide independent reactive compensation for the adjustment of real power flow in each line and maintain the desired distribution of reactive power flow among the lines.”

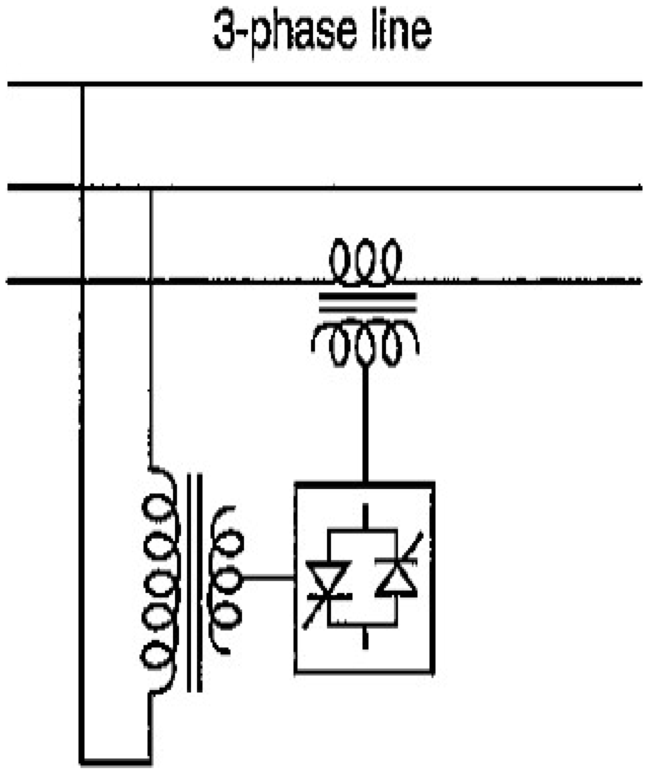
Combined shunt and series connected controllers

- **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, to allow bidirectional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source.



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).

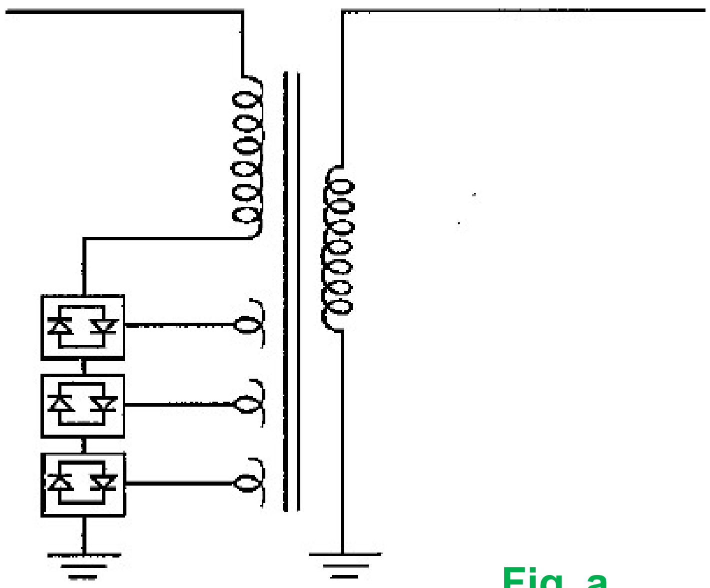


Fig. a

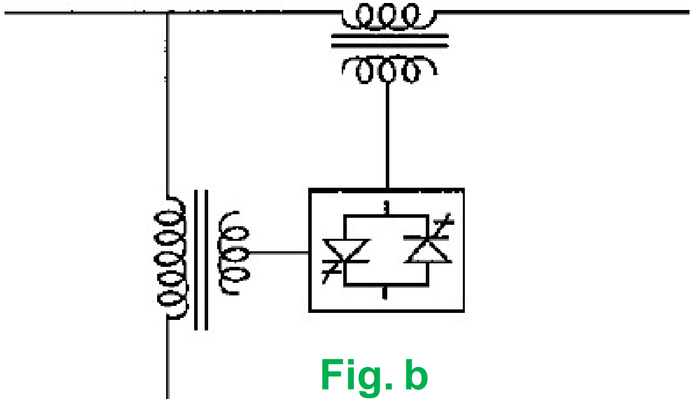


Fig. b