POWERPOINT PRESENTAION

FACTS

ELECTRICAL AND ELECTRONICS DEPARTMENT

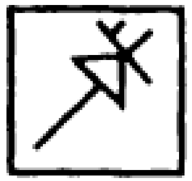
UNIT-1

FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEMS

INTRODUCTION

Flexible AC Transmission System (FACTS):

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



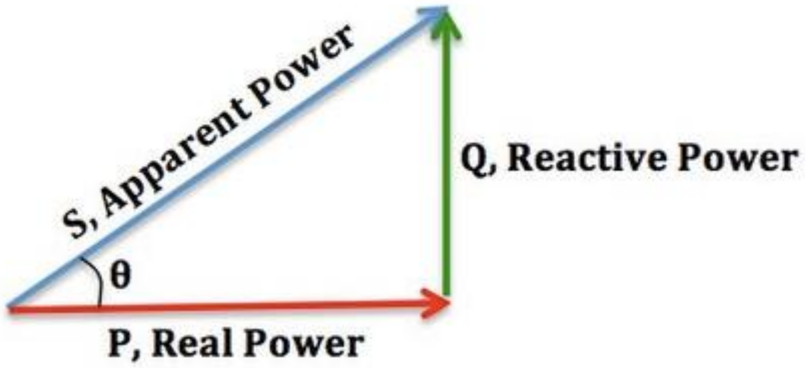
General symbol of FACTS controller

FACTS Controller:

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

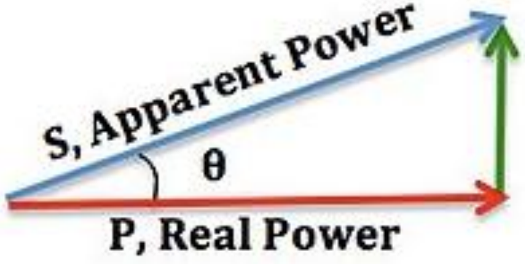
Power Factor

The power factor is the ratio of Active Power component (kW) & Apparent power component(kVA) of any A.C. system.



A Lagging Power Factor signifies that the load is inductive, more current is drawn, the load will "consume" reactive power. Here reactive component Q is positive

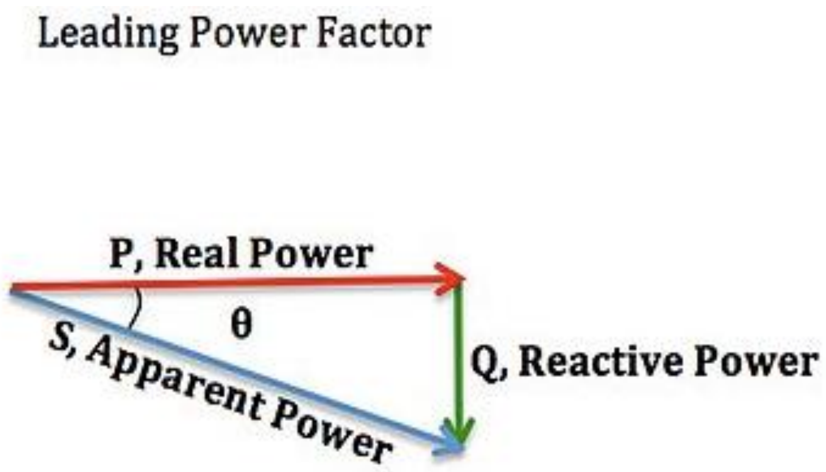
Lagging Power Factor



Power Factor

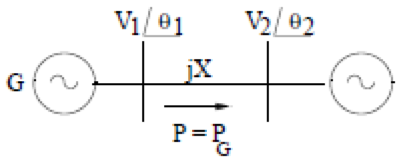
The power factor is the ratio of active power component (kW) &apparent power component(kVA) of any A.C. system.

A leading power factor signifies that the load is capacitive, as the load will "supplies" reactive power. Here reactive component Q is negative.



Real Power (PR) flow between two buses is obtained by

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



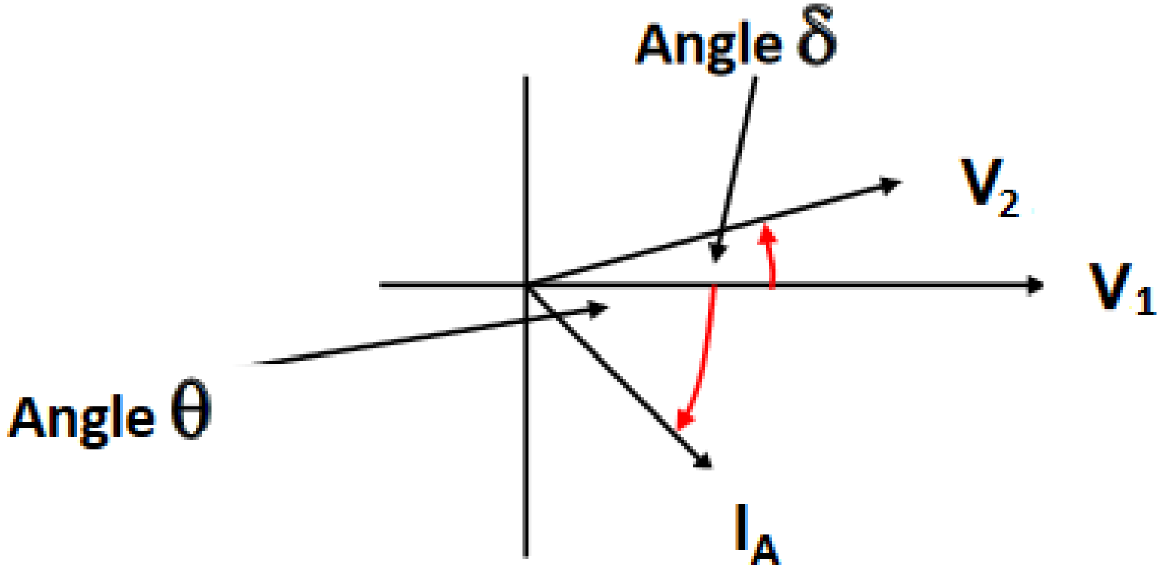
(a) A line transmitting power from a generating station

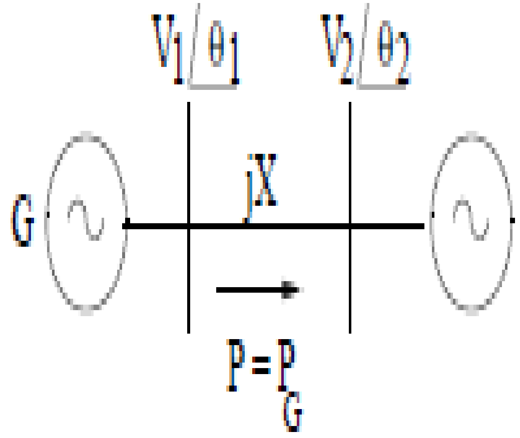
Where,P = Real power in MW

V1 = Sending-end voltage

V2= Receiving-end voltage

X = Line impedance between buses





(a) A line transmitting power from a generating station

Basic types of FACTS Controllers

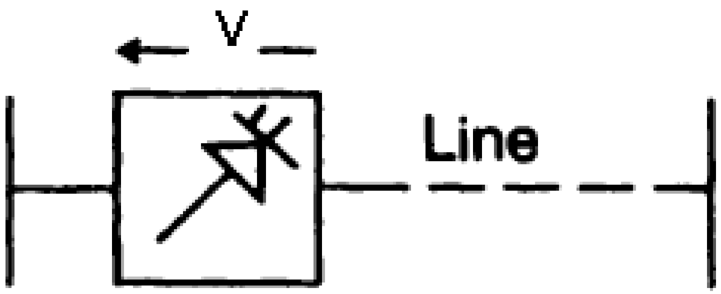
Based on the connection, generally FACTS controller can be classified as follows:

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

Basic types of FACTS Controllers

Series controllers:

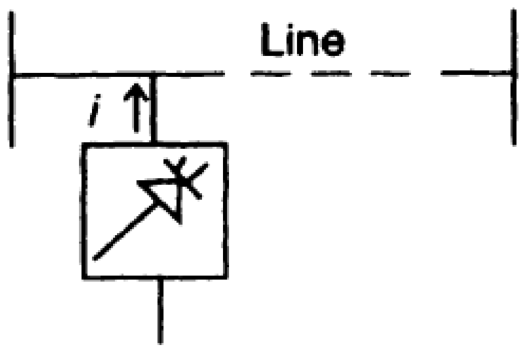
The series controller could be a variable impedance or a variable source, both are power electronics based devices to serve the desired needs. In principle, all series controllers inject voltage in series with the line.



General symbol of Series controller

Shunt controllers:

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

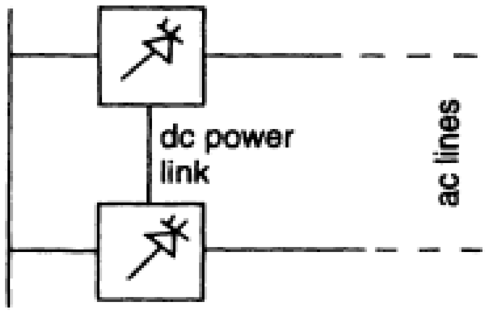


General symbol of Shunt controller

Basic types of FACTS Controllers

Combined series-series controllers:

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

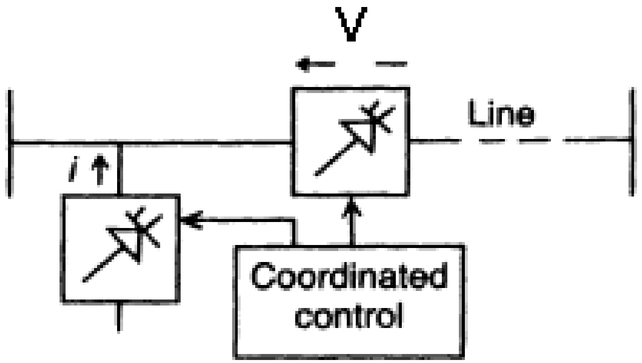


Symbol of Series- Series controller

Basic types of FACTS Controllers

Combined series-shunt controllers:

- The combination could be separated series and shunt controllers or a unified power flow controller. In principle, combined shunt and series Controllers inject current into the system with the shunt part of the Controller and voltage in series in the line with the series part of the Controller.



Symbol of Series- Shunt controller

Shunt Connected Controllers:

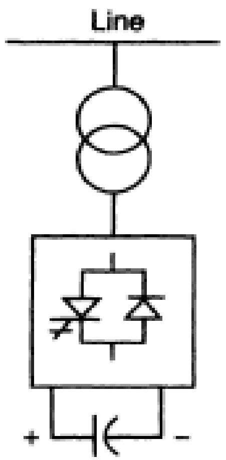
Types of shunt connected controllers available in the market

- *Static Synchronous Generator (SSG)*
- ***Static Synchronous Compensator (STATCOM)***
- Battery *Energy* Storage *System (BESS)*
- *Superconducting Magnetic Energy* Storage (SMES)
- ***Static Var Compensator (SVC)***
- *Thyristor Controlled Reactor (TCR)*
- *Thyrlstor Swltched Reactor (TSR)*
- *Thyristor Switched Capacitor (TSC)*
- *Static Var Generator or Absorber (SVG)*

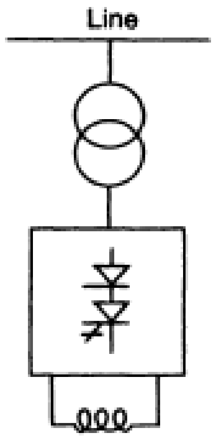
Shunt Connected Controllers:

Static Synchronous Compensator (STATCOM):

- 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 based on voltage-sourced converters



STATCOM based on current-sourced converters

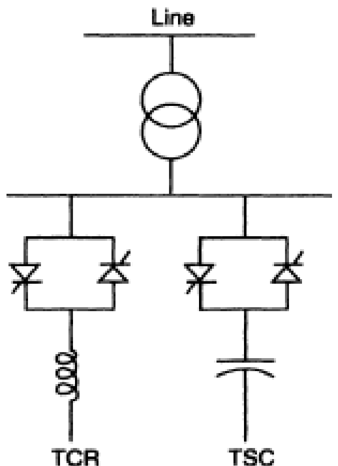
- **In cost point of view, the voltage-sourced converters seem to be preferred, and will be the basis for presentations of most converter-based FACTS Controllers.**

Shunt Connected Controllers:

Static Var Compensator (SVC):

- 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 system (typically bus voltage).

- ✓The thyristor-controlled reactor (TCR) or thyristor-switched reactor (TSR) for absorbing reactive power and thyristor-switched capacitor (TCS) for supplying the reactive power.
- ✓ SVC is considered by some as a lower cost alternative to STATCOM.



Series connected controllers:

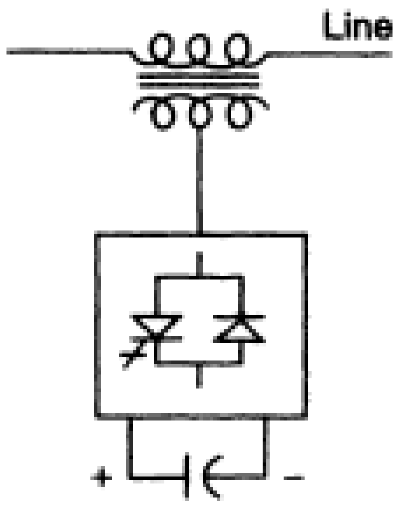
Types of series connected controllers available in the market

- **Static Synchronous Series Compensator (SSSC)**
- Interline Power Flow Controller (IPFC)
- **Thyristor Controlled Series Capacitor (TCSC)**
- Thyristor-Switched Series Capacitor (TSSC)
- Thyristor-Controlled Series Reactor (TCSR)
- Thyristor-Switched Series Reactor (TSSR)

Series connected controllers:

Static Synchronous Series Compensator (SSSC):

- In a Static Synchronous Series Compensator, output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line

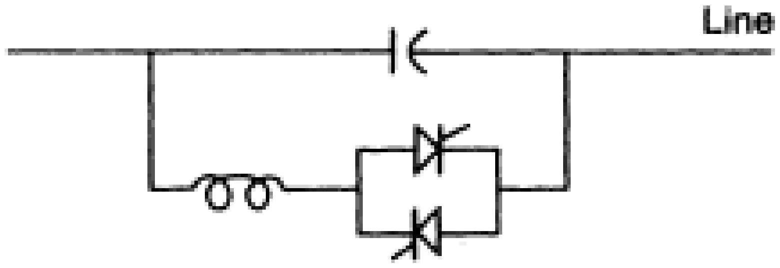


- It is like a STATCOM, except that the output ac voltage is in series with the line.

Series connected controllers:

Thyristor Controlled Series Capacitor (TCSC):

A capacitive 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.



- ✓ It is an alternative to SSSC.

- ✓ The TCSC may be a single, large unit, or may consist of several equal or different-sized smaller capacitors in order to achieve a superior performance.

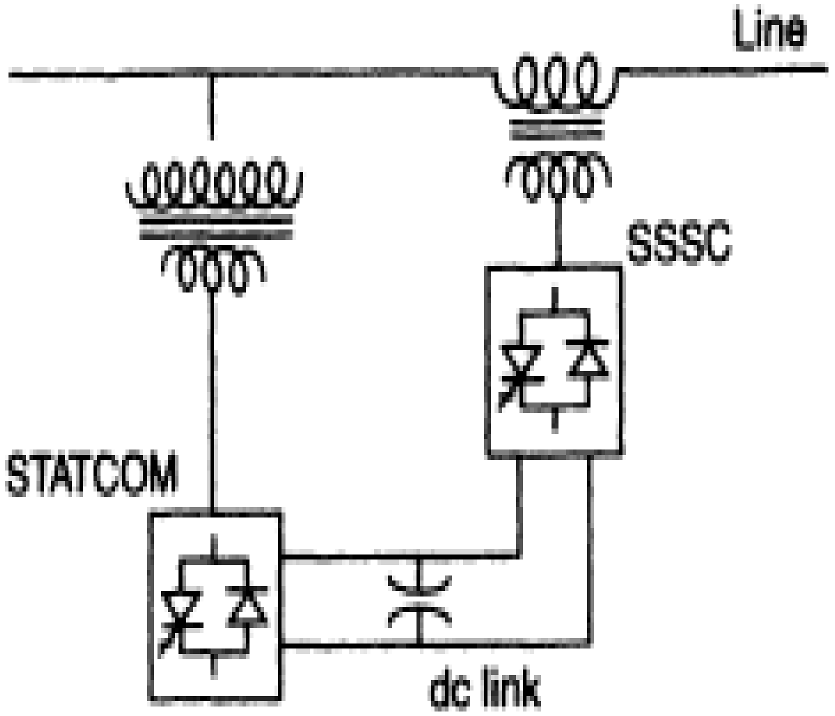
Combined shunt-series connected controllers

Types of shunt series connected controllers available in the market

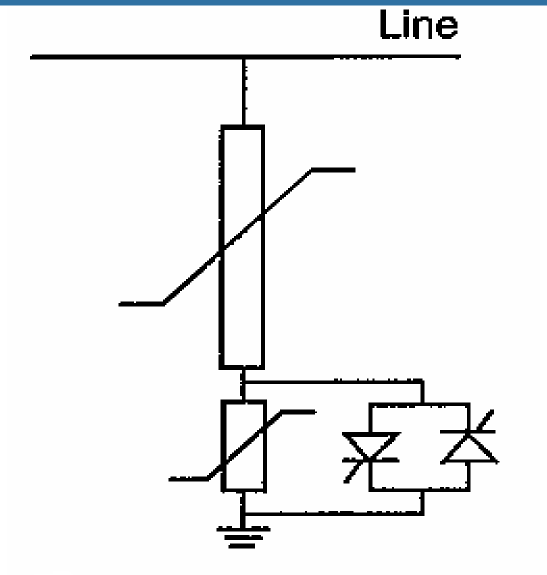
- **Unified Power Flow Controller (UPFC)**
- Thyristor-Controlled Phase Shifting Transformer (TCPST)
- Interphase Power Controller (IPC):

Unified Power Flow Controller (UPFC):

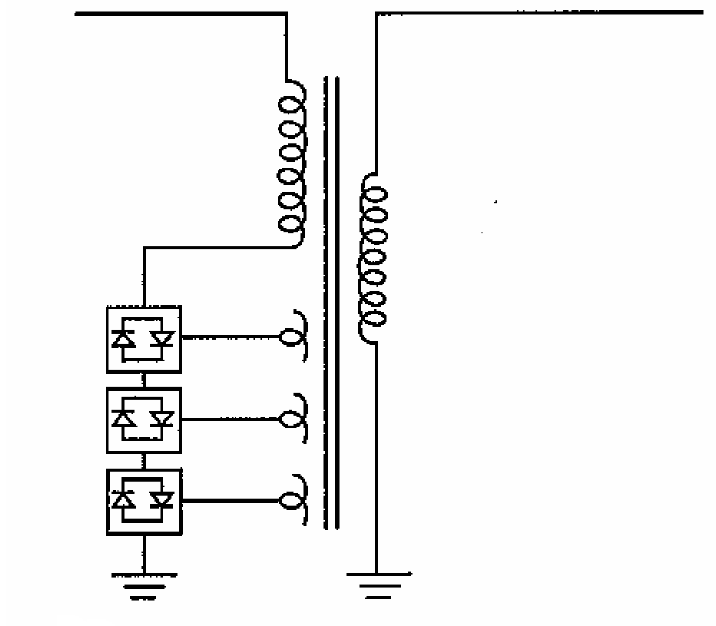
- A combination of static synchronous compensator (STATCOM) and a static series compensator (SSSC) which are coupled via a common dc link, to allow bidirectional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source.



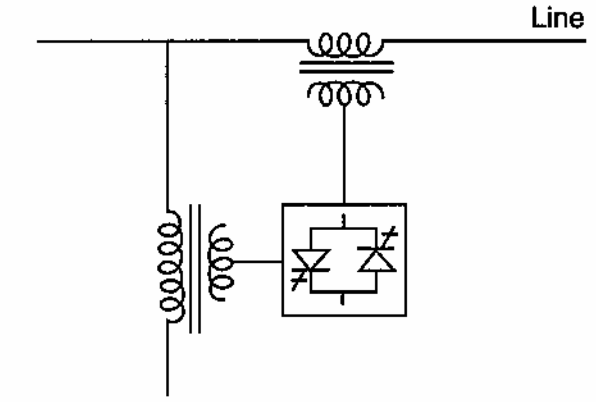
Other controllers:



Thyristor-Controlled Voltage Limiter (TCVL)



Thyristor-Controlled Voltage Regulator (TCVR) based on tap changing;



Thyristor-Controlled Voltage Regulator (TCVR) based on voltage injection

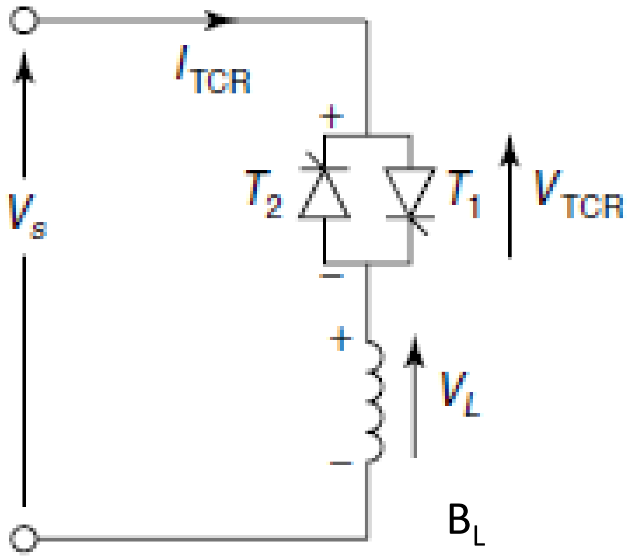
Benefits from FACTS Technology:

- Control of power flow as ordered.
- Increase the loading capability of lines to their thermal capabilities, including short term and seasonal.
- Increase the system security through raising the transient stability limit, limiting short-circuit currents and overloads, managing cascading blackouts and damping electromechanical oscillations of power systems and machines.
- Provide secure tie line connections to neighboring utilities and regions thereby decreasing overall generation reserve requirements on both sides.
- Provide greater flexibility in siting new generation.
- Reduce reactive power flows, thus allowing the lines to carry more active power.

UNIT-2
STATIC VAR COMPENSATOR (SVC)

Static VAR Compensator (SVC) :

Thyristor control reactor (TCR)



- The controllable range of the TCR firing angle, alpha, extends from 90 degree to 180 degree.
- A firing angle of 90 degree results in full thyristor conduction with a continuous sinusoidal current flow in the TCR.
- The current reduces to zero for a firing angle of 180 degree.
- Thyristor firing at angles below 90 degree introduces dc components in the current, disturbing the symmetrical operation of the two anti parallel valve branches.

Static VAR Compensator (SVC) :

Let the source voltage be expressed as

$$v_s(t) = V \sin \omega t$$

Where,

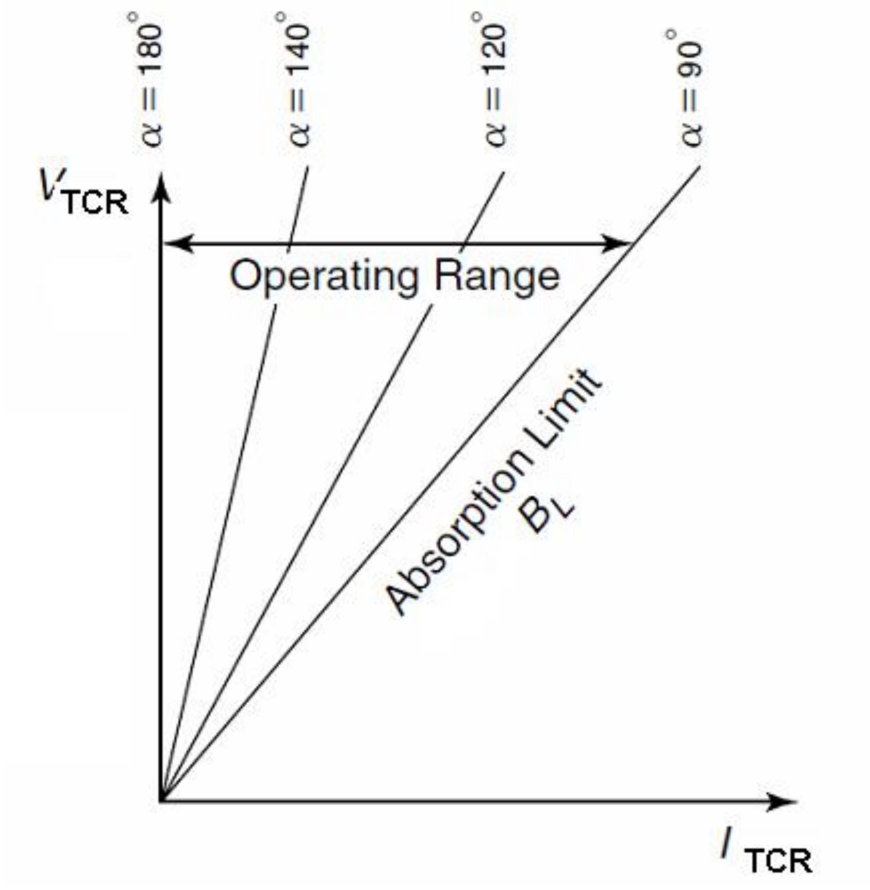
V=*P*eak value of the applied voltage

ω=Angular frequency of supply voltage.

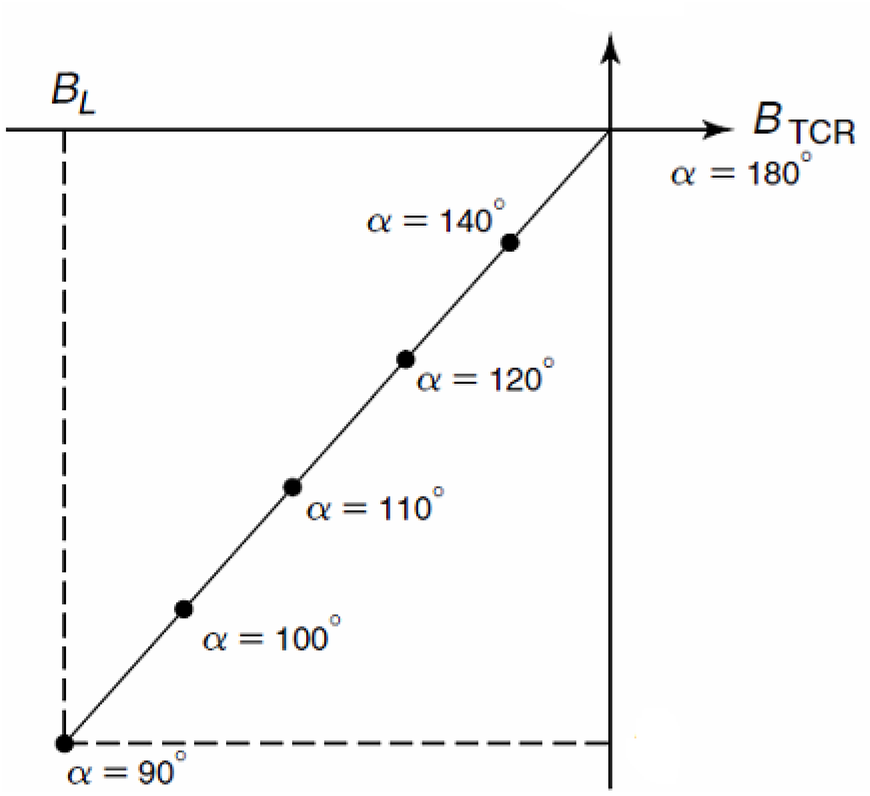
The TCR current is then given by the following differential equation:

$$i(t) = -\frac{V}{\omega L}(\cos \alpha - \cos \omega t)$$

TCR operating Characteristic:

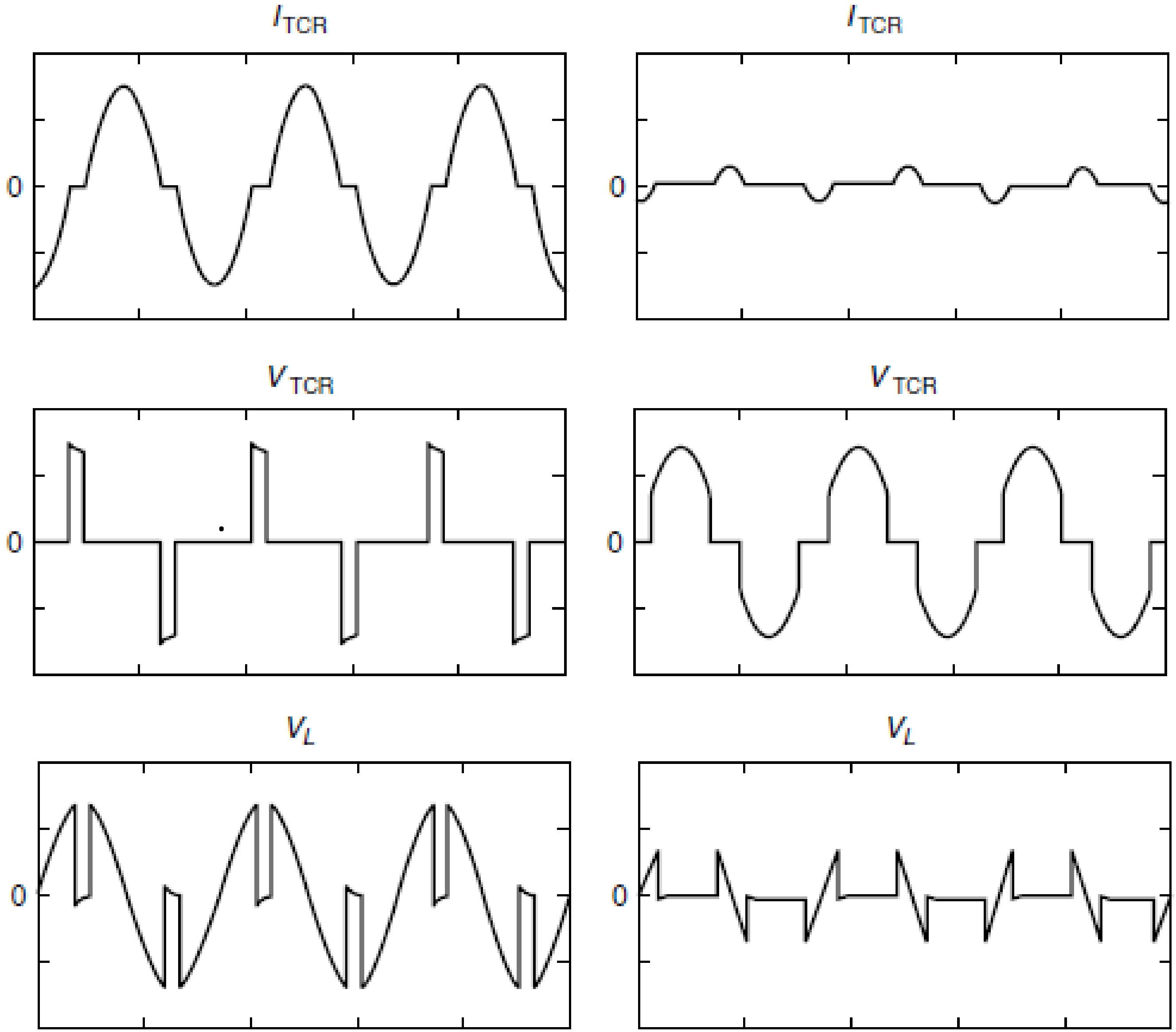


TCR V-I Characteristic



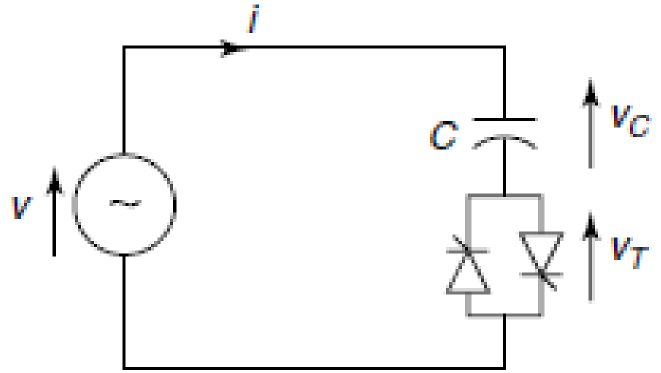
TCR susceptance characteristic.

Current and voltages for different α in a TCR :



Thyristor Switched Capacitors:

❖ The capacitor voltage *is not equal* to the supply voltage when the thyristors are fired. Immediately after closing the switch, a current of infinite magnitude flows and charges the capacitor to the supply voltage in an infinitely short time.



❖ The capacitor voltage *is equal* to the supply voltage when the thyristors are fired. The analysis shows that the current will jump immediately to the value of the steady-state current. The steady state condition is reached in an infinitely short time.

Static VAR Compensator (shunt connected controller):

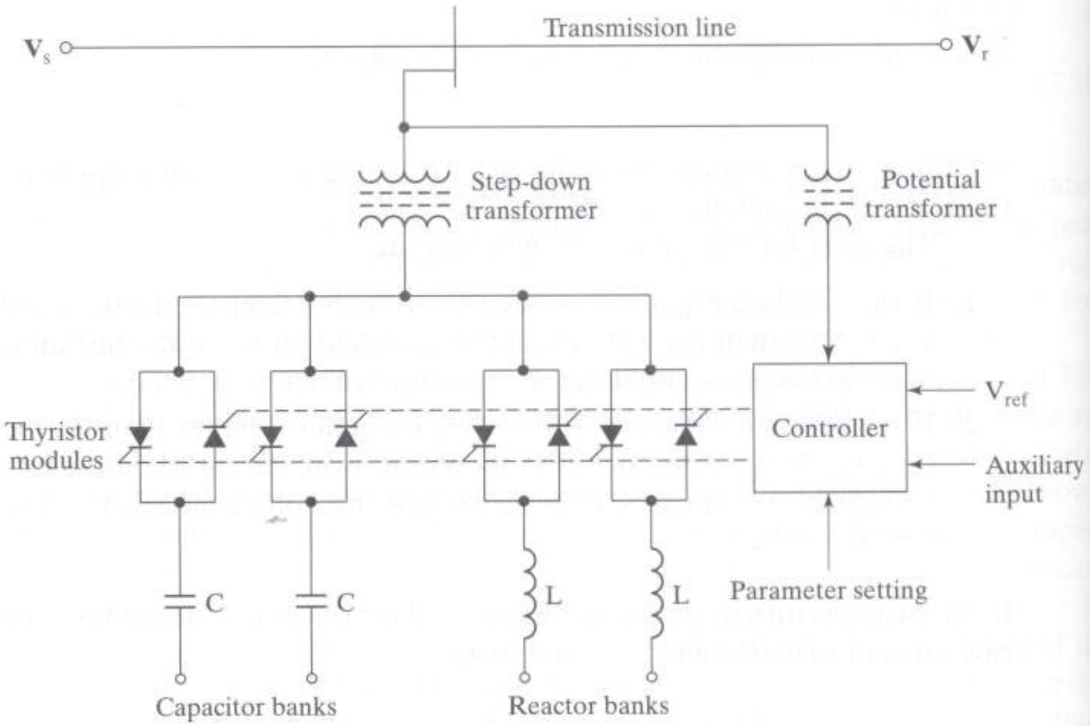


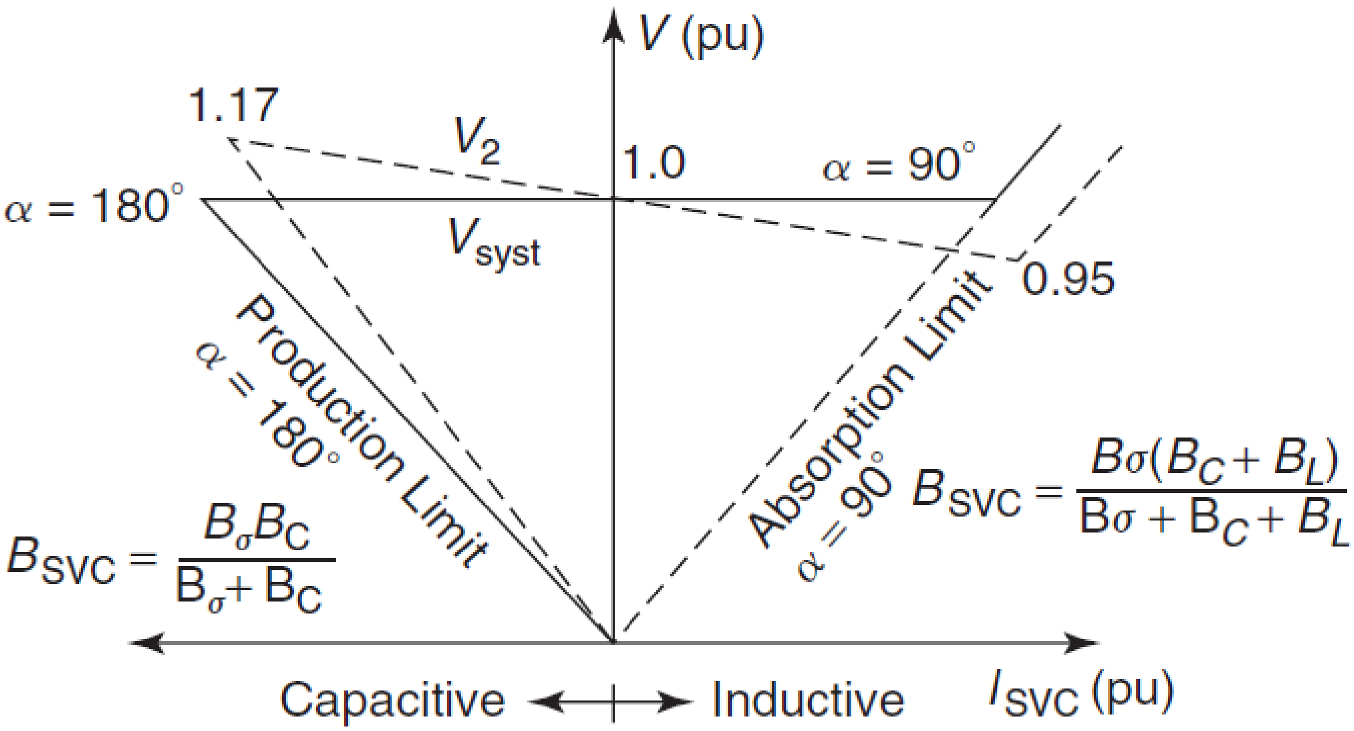
FIGURE 13.6

General arrangement of static VAR compensator [Ref. 4].

Note:

The control strategy usually aims to maintain the transmission line voltage at a fixed level.

Static VAR Compensator (shunt connected controller):



SVC V-I Characteristic

UNIT-3
THYRISTOR AND GTO THYRISTOR CONTROLLED SERIES CAPACITORS (TCSC and GCSC)

TCSC Controller:

Basic Module

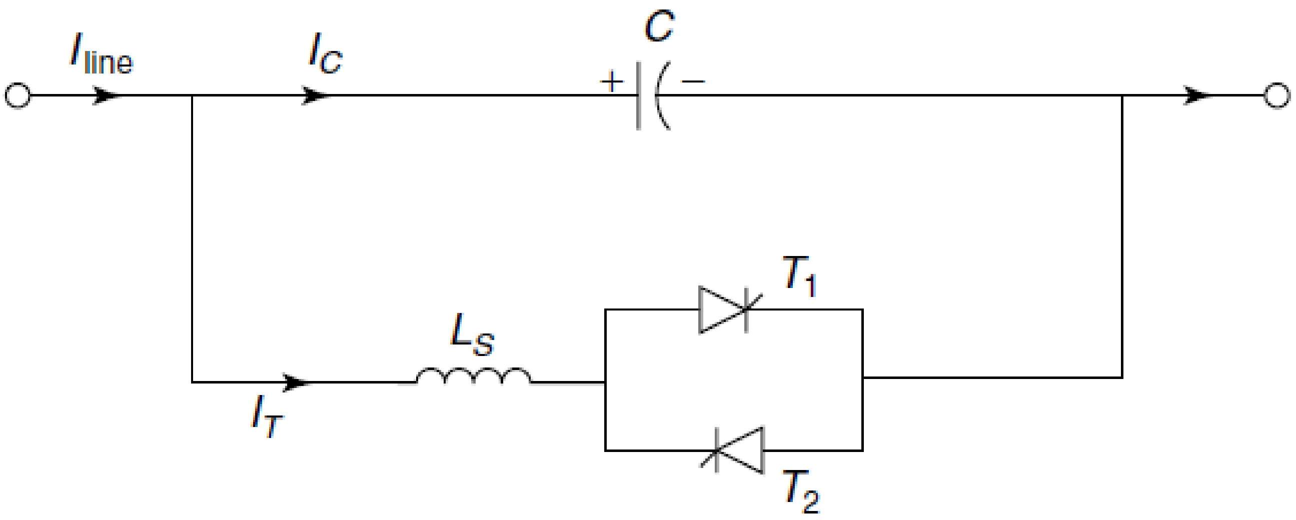


Fig. A Basic Module

- It provides smooth variable series capacitive reactance
- The cost of series capacitor is lower

Practical Module:

CB-Circuit Breaker

G-Spark gap

MOV-Multi oxide

varistor

UHSC-Ultra high speed

contact

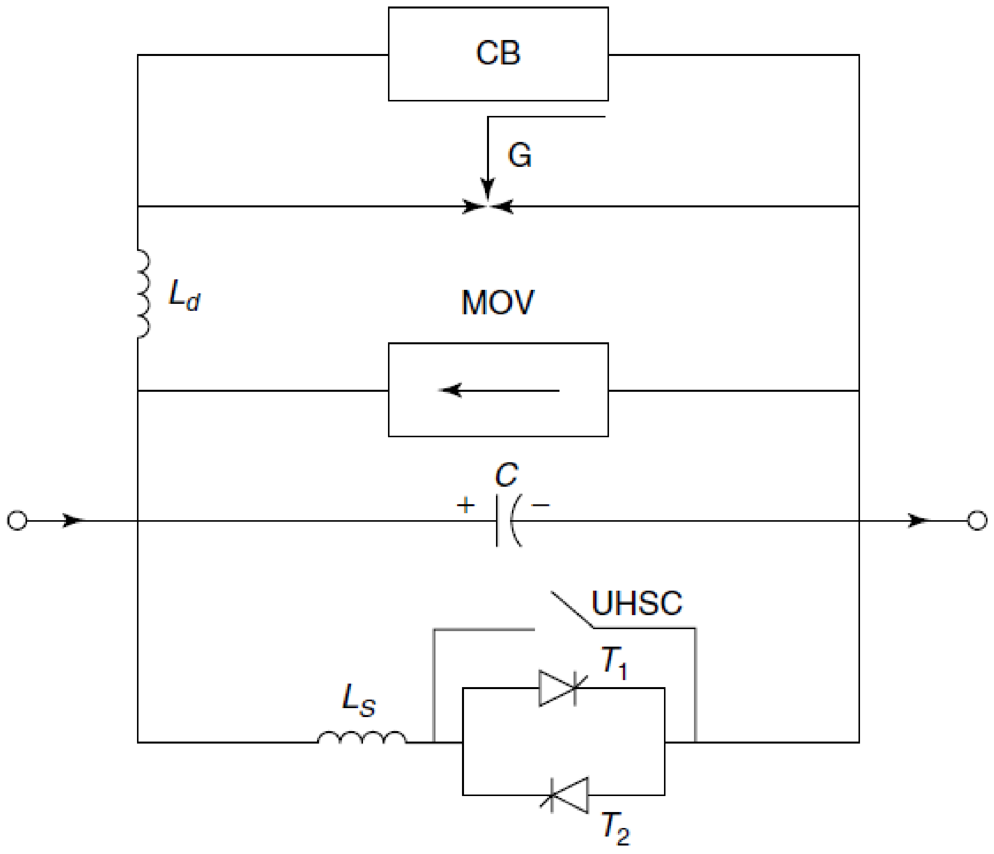


Fig. Practical module

Practical Module:

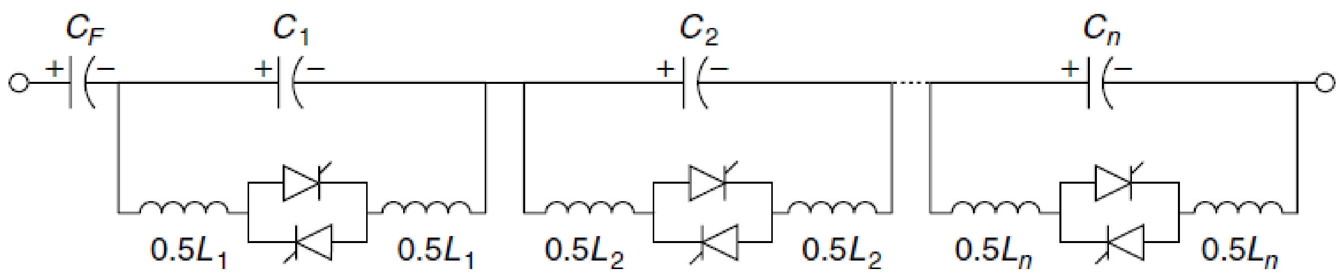
❖ <u>MOV</u>

- To prevent the occurrence of high capacitor voltages
- It improves transient stability

❖ <u>Spark Gap</u> is used to divert transient over voltages safely to earth without affecting Capacitor.

❖ <u>Circuit breakers</u> controls the insertion in line also by pass during faults.

❖ <u>UHSC</u> is to minimize conduction losses



Advantages of the TCSC:

- Continuous control of the transmission-line series-compensation level.
- Dynamic control of power flow in selected transmission lines within the network to enable optimal power-flow conditions and prevent the loop flow of power.
- Suppression of sub synchronous oscillations.
- Decreasing dc-offset voltages.
- Enhanced level of protection for series capacitors.
- Voltage support.
- Reduction of the short-circuit current. During events of high short-circuit current, the TCSC can switch from the controllable-capacitance to the controllable-inductance mode, thereby restricting the short-circuit currents.

Variable-Series Compensation:

1. Enhanced base-power flow and loadability of the series-compensated line.

2. Additional losses in the compensated line from the enhanced power flow.

3. Increased responsiveness of power flow in the series-compensated line from the outage of other lines in the system.

Basic Principle:

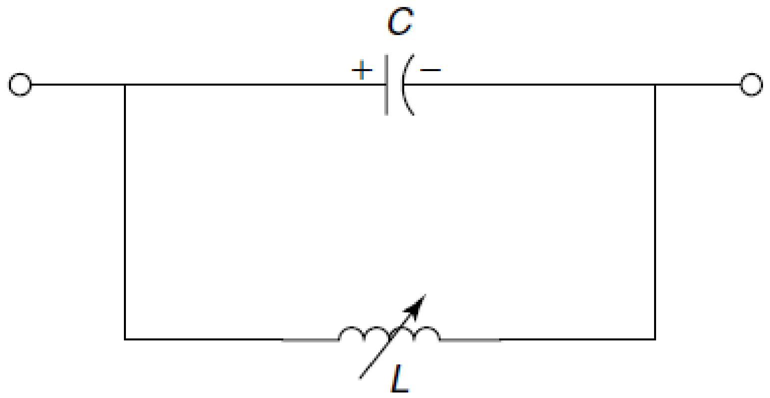


Fig. A variable inductor connected in shunt with an FC.

The equivalent impedance Z_{eq} is

$$Z_{eq} = \left(j\frac{1}{\omega c}\right) \Big\| (j\omega L) = -j\frac{1}{\omega C - \frac{1}{\omega L}}$$

$\omega C - (1/\omega L) > 0$ Provides variable capacitive reactance

$\omega C - (1/\omega L) < 0$ Provides variable inductive reactance

Basic Principle:

The behavior of the TCSC is similar to that of the parallel *LC* combination. The difference is that the *LC*-combination analysis is based on the presence of pure sinusoidal voltage and current in the circuit, whereas in the TCSC, because of the voltage and current in the FC and thyristor-controlled reactor (TCR) are not sinusoidal because of thyristor switching.

Mode of TCSC Operation:

There are essentially three modes of TCSC operation.

- Bypassed Thyristor Mode
- Blocked Thyristor Mode
- Partially Conducting Thyristor or Vernie

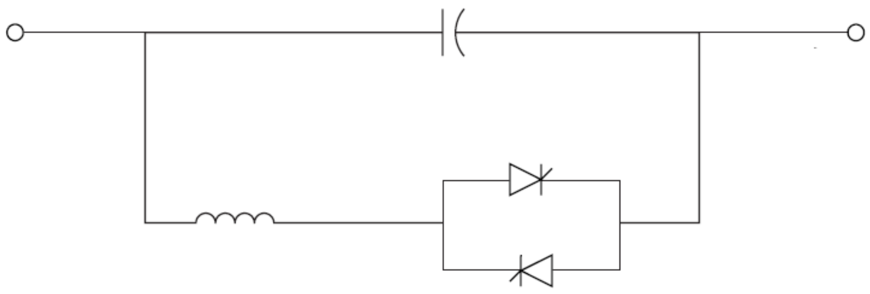
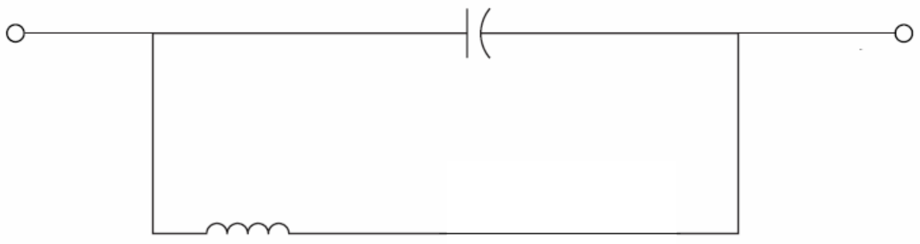


Fig. TCSC Equivalent circuit

Reactor is chosen to be greater than that of the capacitor

Bypassed Thyristor Mode:

In this bypassed mode, the thyristors are made to fully conduct with a conduction angle of 180 degree. Gate pulses are applied as soon as the voltage across the thyristors reaches zero and becomes positive, resulting in a continuous sinusoidal of flow current through the thyristors valves.



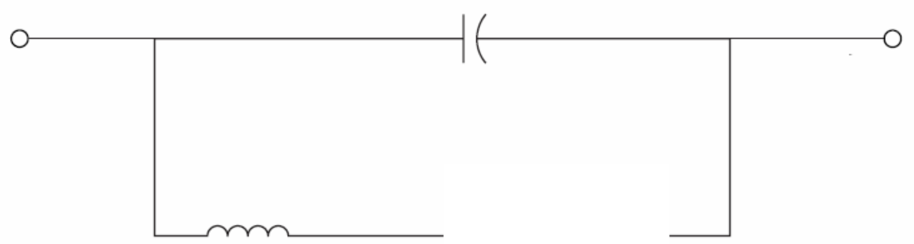
The TCSC module behaves like a parallel capacitor–inductor combination. However, the net current through the module is inductive, for the susceptance of the reactor is chosen to be greater than that of the capacitor.

$$Z_{\mathrm{eq}} = \left(j\,\frac{1}{\omega c}\right) \Big\| \,(j\omega L) = -j\,\frac{1}{\omega C - \dfrac{1}{\omega L}}$$

Blocked Thyristor Mode:

- In this mode, also known as the *waiting* mode, the firing pulses to the thyristor valves are blocked. If the thyristors are conducting and a blocking command is given, the thyristors turn off as soon as the current through them reaches a zero crossing.

- The TCSC module is thus reduced to a fixed-series capacitor, and the net TCSC reactance is capacitive.



- In this mode, the dc-offset voltages of the capacitors are monitored and quickly discharged using a dc-offset control without causing any harm to the transmission-system transformers.

Partially Conducting Thyristor or Vernier Mode:

- This mode allows the TCSC to behave either as a continuously controllable capacitive reactance or as a continuously controllable inductive reactance. It is achieved by varying the thyristor-pair firing angle in an appropriate range.

A smooth transition from the capacitive to inductive mode is not permitted
because of the resonant region between the two modes.

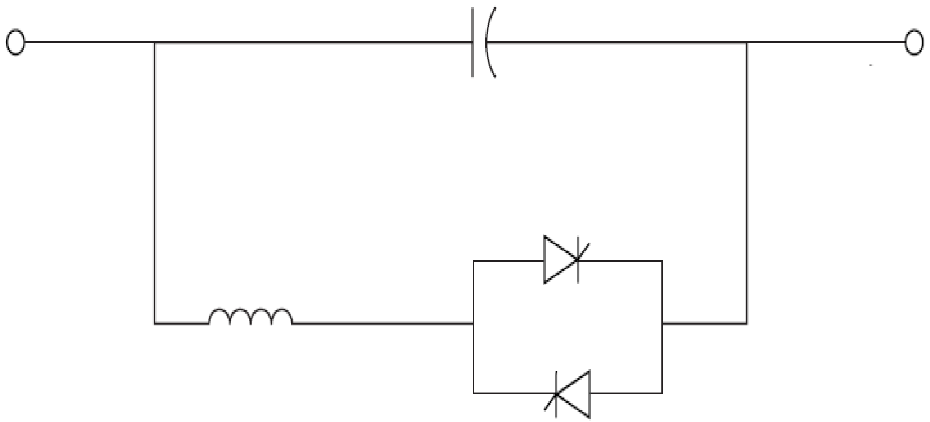
- Capacitive-vernier-control mode
- inductive-vernier mode

Partially Conducting Thyristor or Vernier Mode:

- *Capacitive-vernier-control* mode, in which the thyristors are fired when the capacitor voltage and capacitor current have opposite polarity.

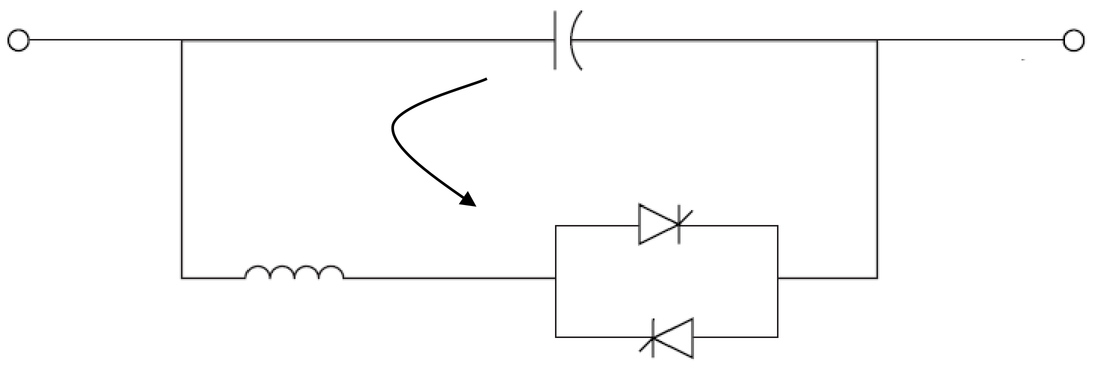
- This condition causes a TCR current that has a direction opposite that of the capacitor current, thereby resulting in a loop-current flow in the TCSC controller.

- This loop current increases the voltage across the FC, effectively enhancing the series compensation level.



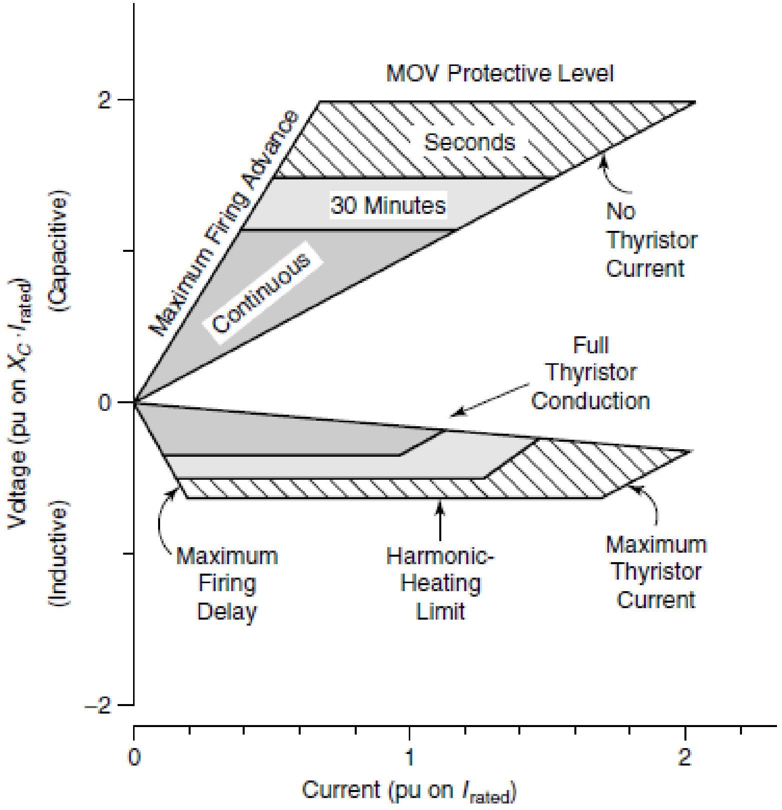
Inductive-Vernier Mode:

- Another variant is the *inductive-vernier mode*, in which the TCSC can be operated by having a high level of thyristor conduction. In this mode, the direction of the circulating current is reversed and the controller presents a net inductive impedance.



V-I CHARACTERISTICS OF TCSC:

V-I capability characteristics for a single-module TCSC



V-I CHARACTERISTICS OF TCSC:

- In the capacitive region, the maximum apparent capacitive reactance is chosen based on the TCSC design so that the TCSC does not venture close to or into the inherently unstable resonant point. The maximum *X*TCSC is typically
2–3 pu, as expressed in per units of *XC*.

The minimum TCSC capacitive reactance is obtained when the thyristors are blocked, corresponding to alpha=180 and the absence of thyristor-current flows and relating to X_{TCSC} =1 pu.

As the line current increases, the TCSC voltage increases until the maximum voltage limit of the TCSC is reached.

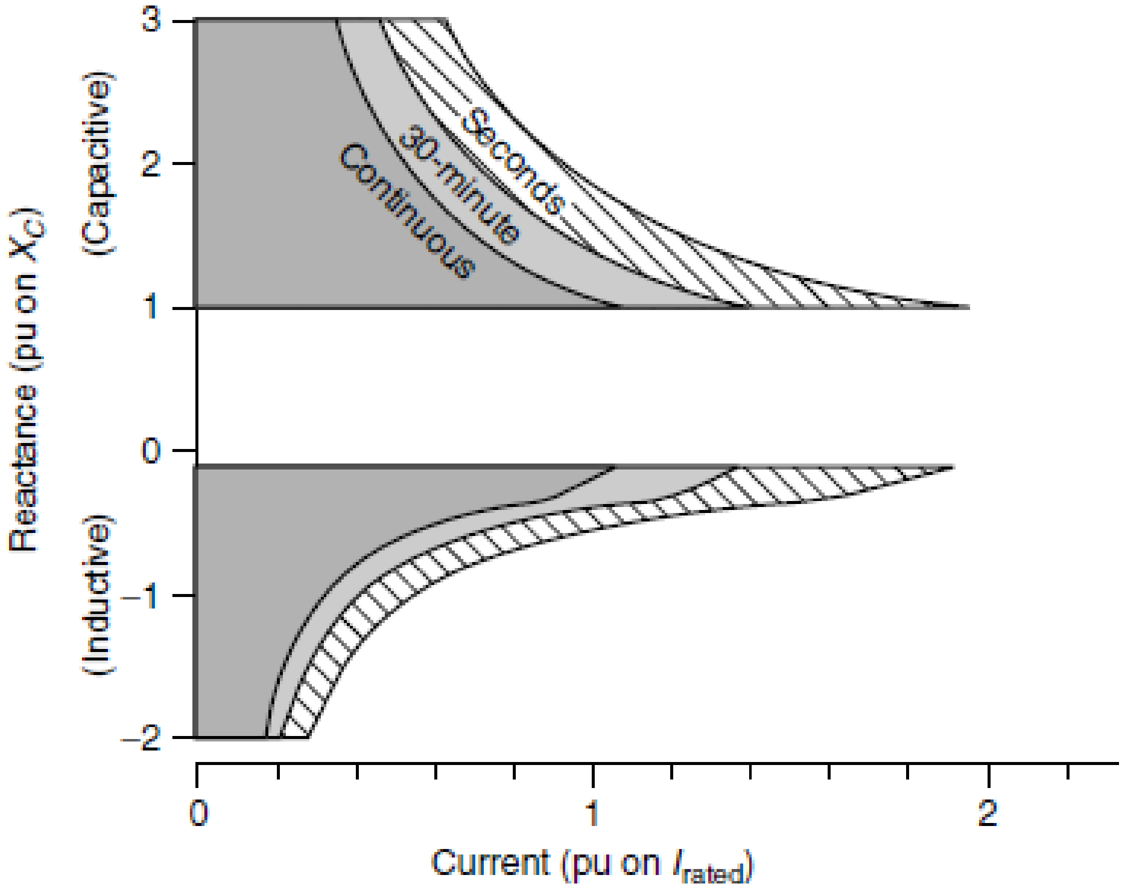
V-I CHARACTERISTICS OF TCSC:

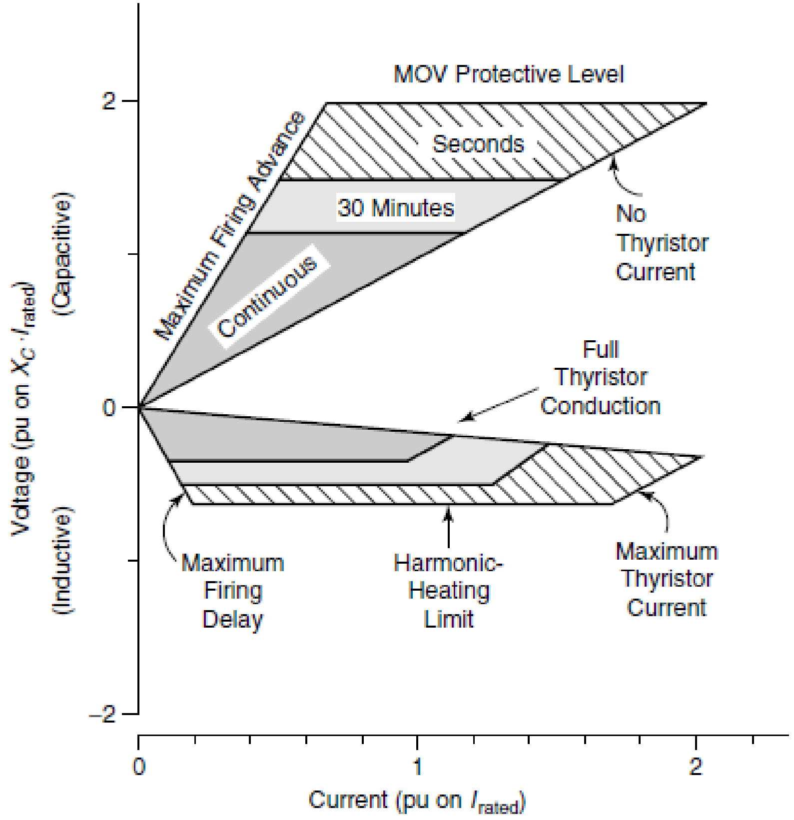
- In the inductive-reactance zone, the maximum reactance limit is also selected to prevent the TCSC from operating in the resonant region. This limit is attained at low line currents and is expressed in terms of the maximum firing-delay angle.

A maximum inductive reactance of 2 pu is typical;

the minimum inductive reactance limit is reached when the thyristors are fully conducting, corresponding to alpha=90 degree.

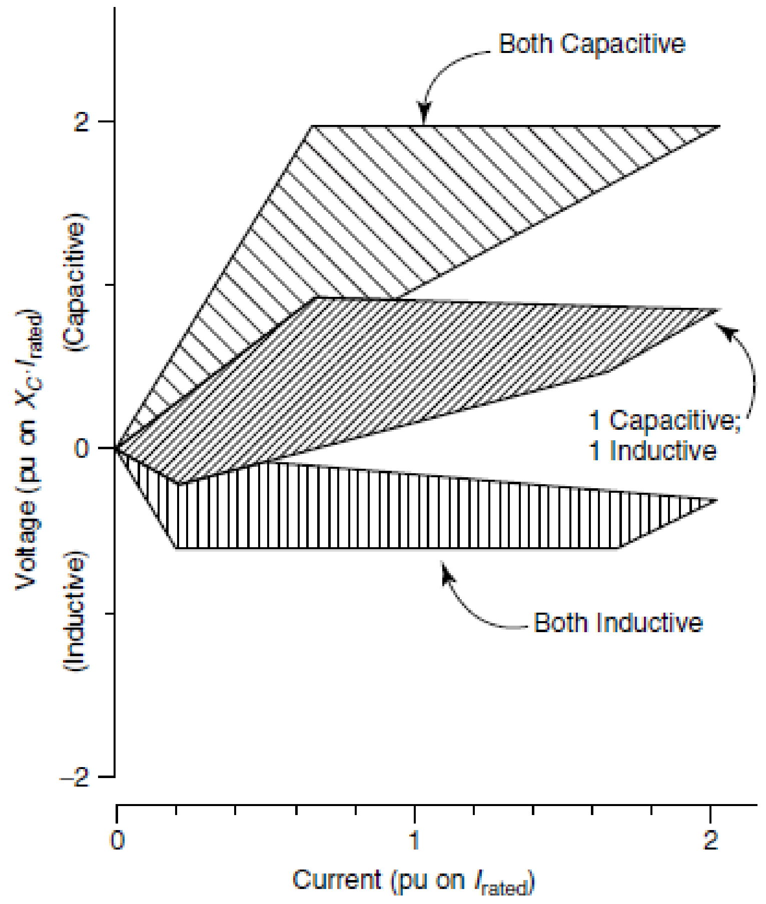
X-I CAPABILITY CHARACTERISTIC FOR A SINGLE-MODULE TCSC.





the TCSC capability can be expressed in a reactance–line-current plane

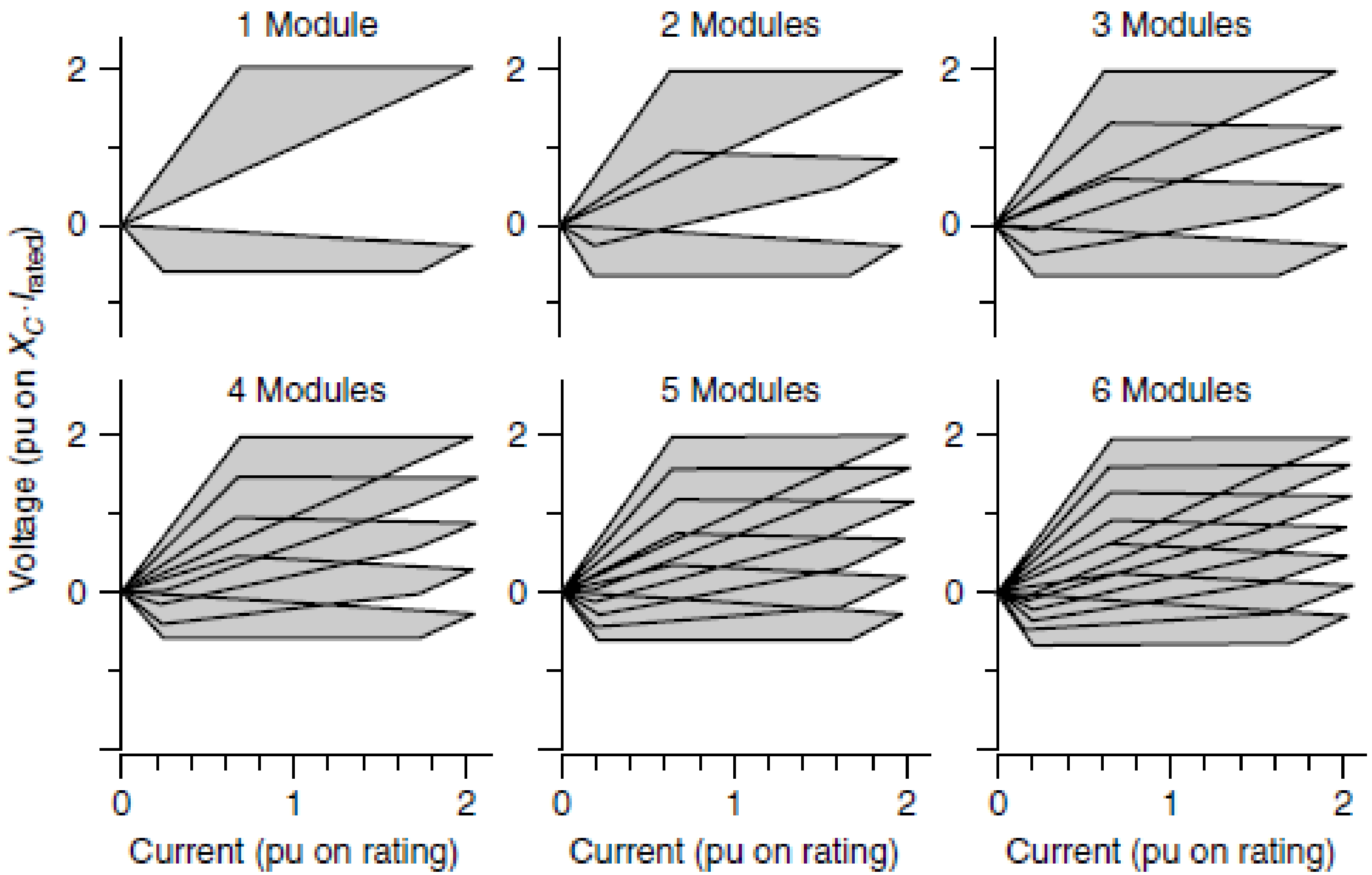
The *V-I* capability characteristics for a two-module TCSC:



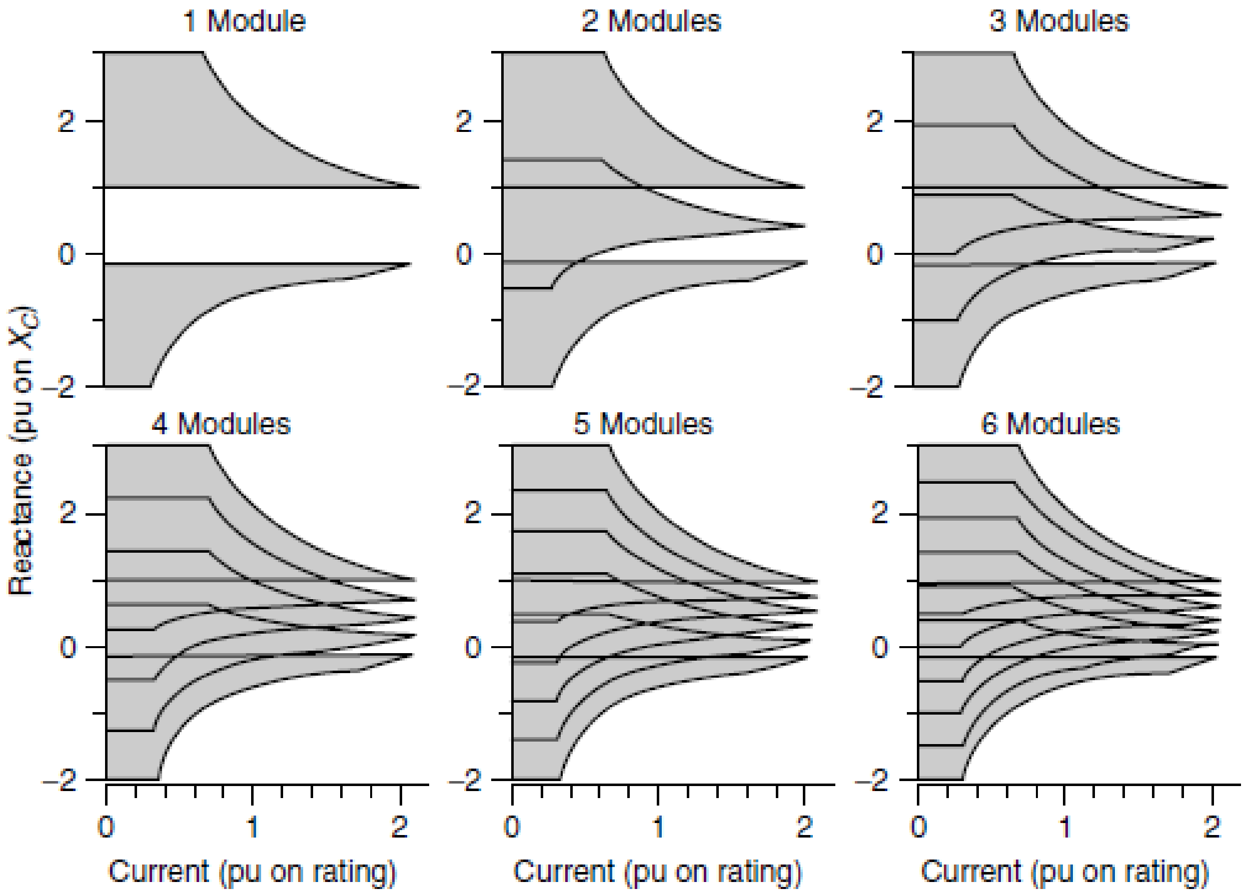
- A smooth variation in the line reactance is desirable that can be achieved by splitting a single TCSC into multiple modules and operating them independently in the inductive and capacitive modes.

- Splitting a single TCSC into two modules, each with a half-MVA rating, results in a *V-I* capability curve with both similar and dissimilar operation, as noted in Fig

The *V-I* capability characteristics for a multi-module TCSC:



The *X-I* capability characteristic for a multimodule TCSC:



MODELING OF THE TCSC:

A TCSC involves continuous-time dynamics, relating to voltages and currents in the capacitor and reactor, and nonlinear, discrete switching behavior of thyristors.

- **Variable-Reactance Model**
- **Firing angle Model**

Assumption:

- The transmission system operates in a sinusoidal steady state, with the only dynamics associated with generators and PSS.
- The variable-reactance TCSC model assumes the availability of a continuous-reactance range and is therefore applicable for multi module TCSC configurations.

The variable-reactance model of the TCSC for Transient Stability Studies

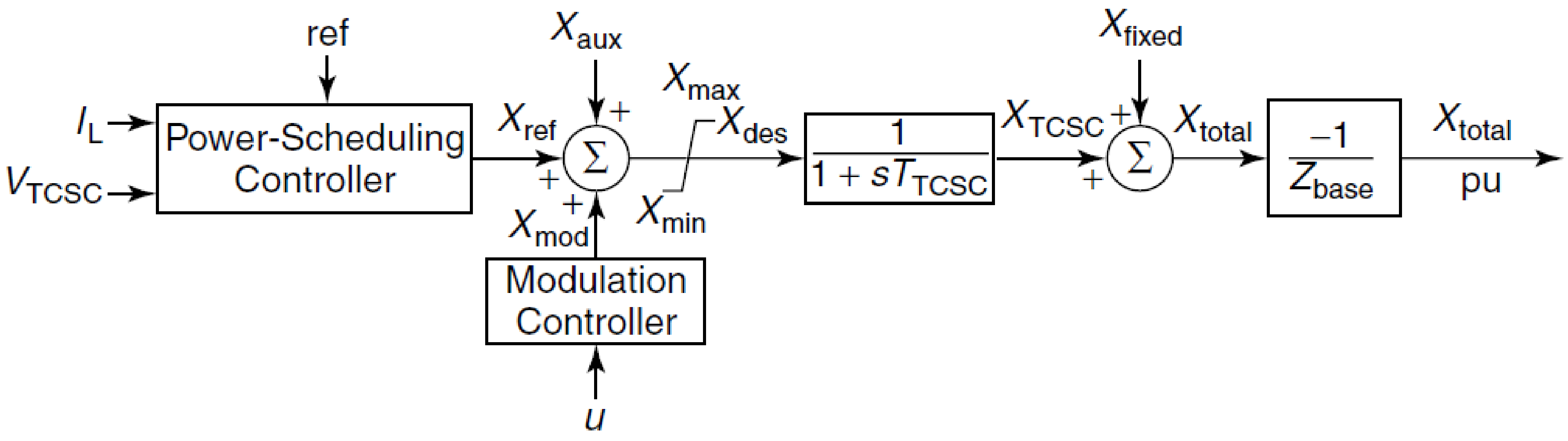


Fig. A block diagram of the variable-reactance model of the TCSC

$$Z_{base} = \frac{(kV_{TCSC})^2}{MVA_{sys}}$$

kV_{TCSC} = the rms line–line voltage of the TCSC in kilovolts (kV)

MVA_{sys} = the 3-phase MVA base of the power system

The variable-reactance model of the TCSC for Transient Stability Studies

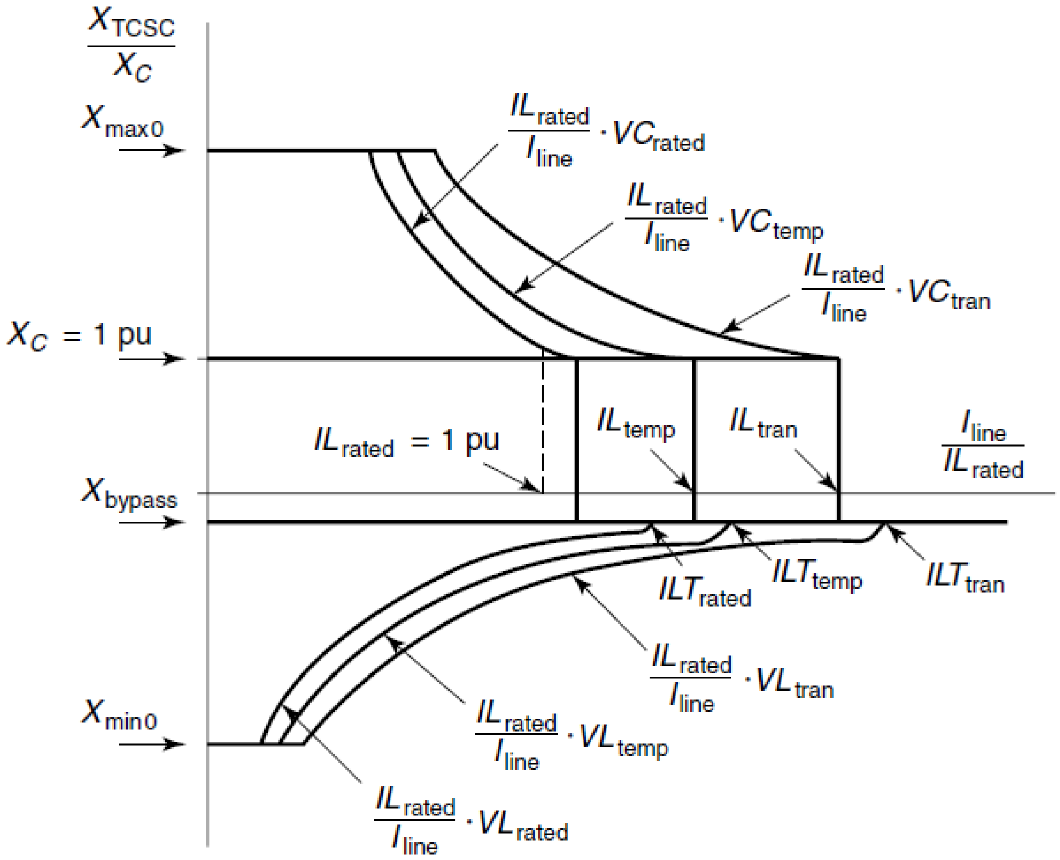
Long Term Stability Model:

Capability curves of TCSC depends on the duration of V and I operating conditions

Two time limited regions are

- ❖Transient Over load region
- ❖Temporary Overload region

Both are followed by continuous region

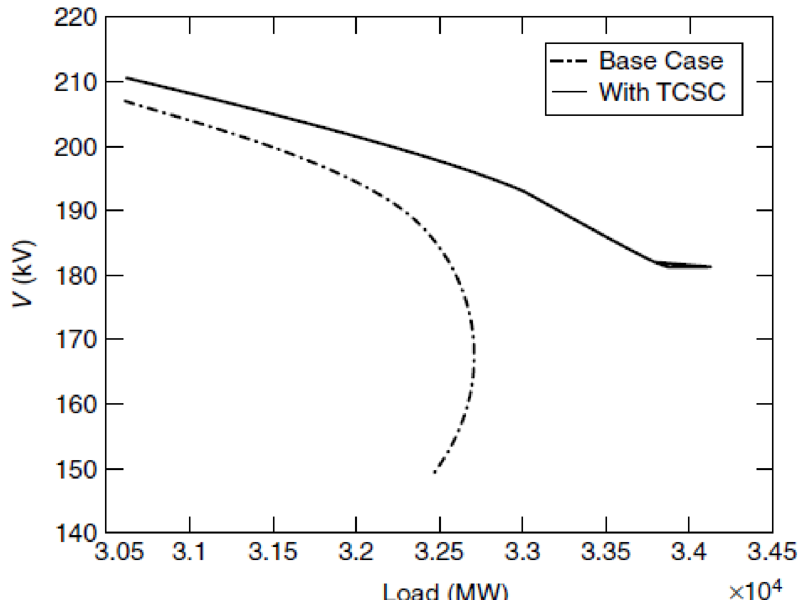


APPLICATIONS OF TCSC
Voltage Collapse Prevention:

- An application of the TCSC is tested on European power system.

- The system faces voltage collapse or a maximum loading point corresponding to a 2120-MW increase in the net load.

- If a TCSC is installed to provide 50% compensation of the line experiencing the highest increase in power at the point of collapse, the maximum loadability will be enhanced to 3534 MW.



$$P = \frac{V_1 \times V_2}{x} \times \sin\delta$$

$$Q = \frac{V_1 \times V_2}{x} \times \cos\delta - \frac{V_2^2}{x}$$

VOLTAGE COLLAPSE PREVENTION:

Performance factor, Fp -Indicates the maximum increase in loadability, for a given percent of line compensation

$$f_p = \frac{\lambda_0 \text{ [MW]}}{X_{\text{ref}} \text{ [\% compensation of } X_{\text{line}}\text{]}}$$

λ_0 = System loadability (MW)

where X_{ref} = the reactance-reference setting of the TCSC

X_{line} = the line reactance

This index can be gainfully employed to obtain the best location of the TCSC in a system.

VOLTAGE COLLAPSE PREVENTION:

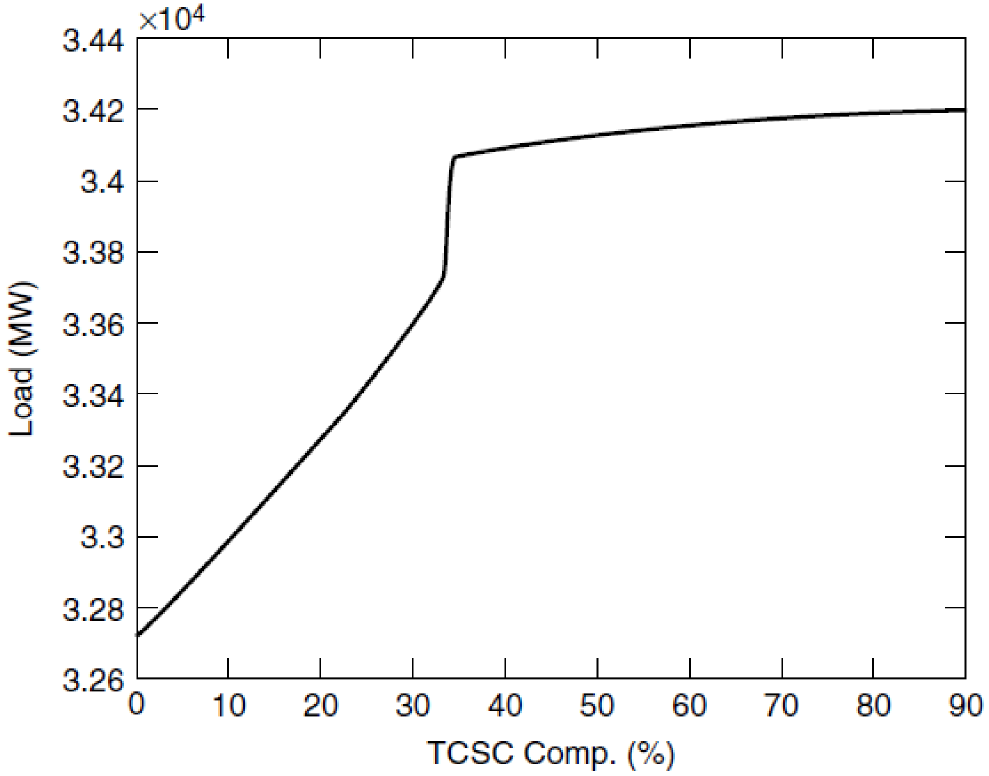


Fig. The loading margin

VOLTAGE COLLAPSE PREVENTION:

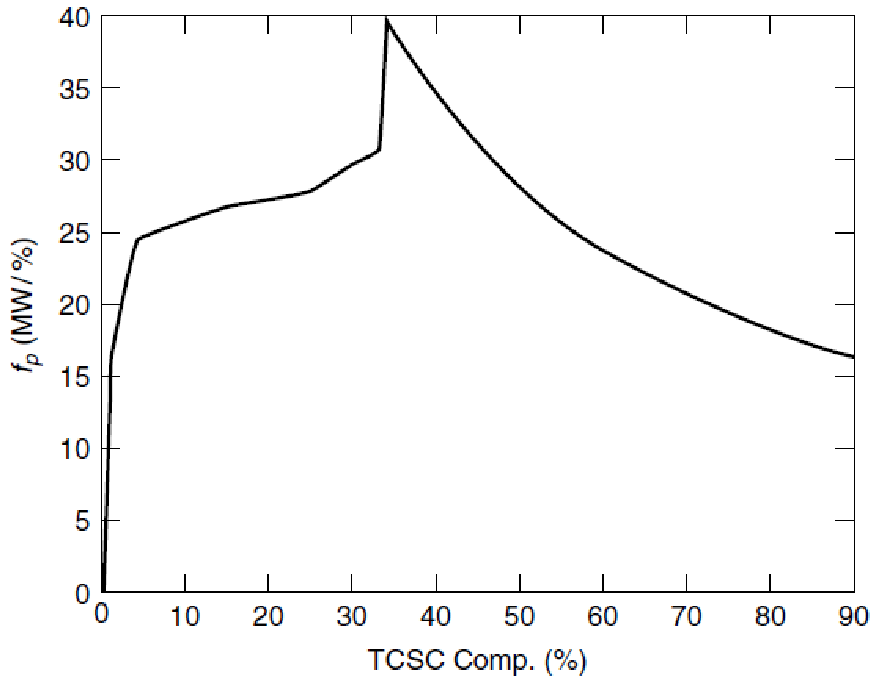


Fig. The performance measure, *f p*.

It is suggested that TCSC reactance-modulation schemes based on line current or line power, or on the angular difference across lines, may prove unsuccessful for voltage-stability enhancement. The reason is that these controls constrain any variation in the corresponding variables that may be necessary with changing loads, thereby limiting any power-flow enhancement on the line.

APPLICATIONS OF TCSC
Enhancement of System Damping:

Generally, the damping control of a TCSC or any other FACTS controller should generally do the following:

1. Stabilize both post disturbance oscillations and spontaneously growing oscillations during normal operation

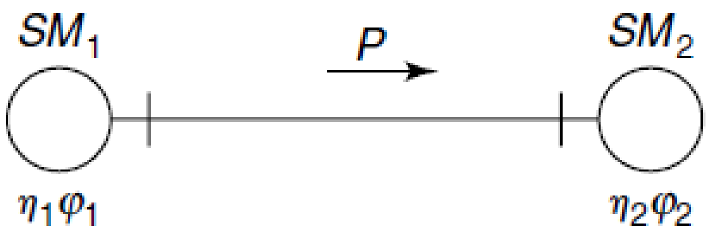
2. Prevent the adverse interaction with high-frequency phenomena in power
systems, such as network resonances

3. Prevent local instabilities within the controller bandwidth

4. Robust, reliable

APPLICATIONS OF TCSC
Enhancement of System Damping:

Principle of Damping



Let the speed and rotor angle of machine *SM*1 be denoted by η1 and Φ1, respectively; of machine *SM*2, denoted by η2 and Φ2, respectively

- When the receiving end–machine speed is lower than the sending end–machine speed, that is, Δη (= η2− η1) is negative, the TCSC should increase power flow in the line.
- On the other hand, when Δη is positive, the TCSC must decrease the power transmission in the line.

APPLICATIONS OF TCSC
Enhancement of System Damping:

The incremental variation of the line-power flow ΔP, given in megawatts (MW), with respect to ΔQ_{TCSC}, given in MVAR, is as follows

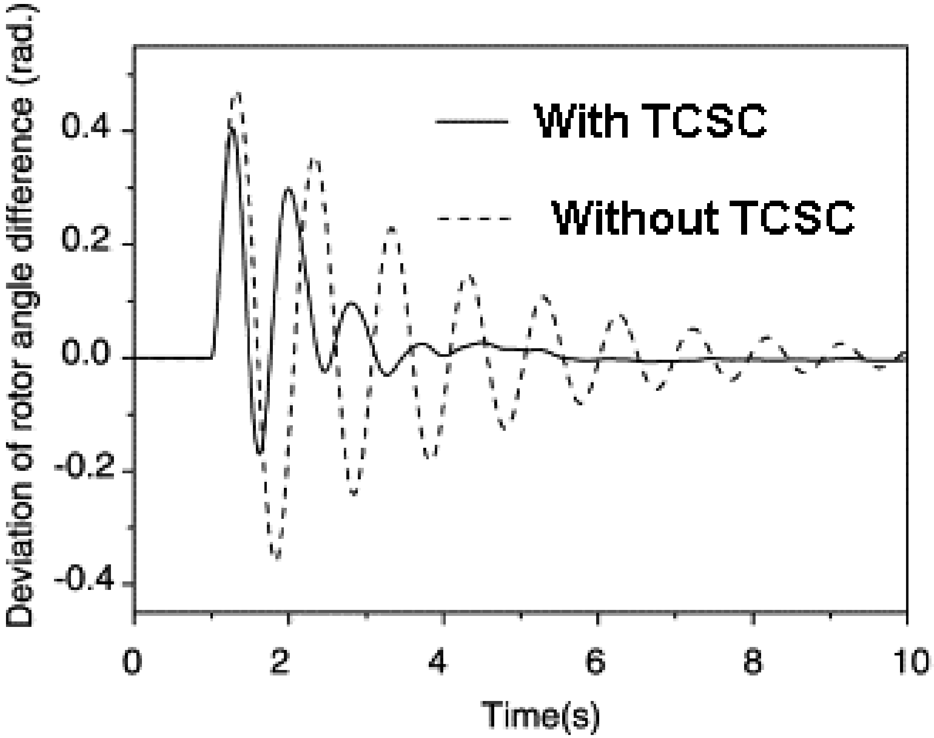
$$\frac{\Delta P}{\Delta Q_{TCSC}} = \frac{1}{2\tan\delta/2}\left(\frac{I}{I_N}\right)^2$$

where δ = the angular difference between the line-terminal voltages
I = the operating-point steady-state current
I_N = the rated current of the TCSC

Thus the TCSC action is based on the variation of line-current magnitude and is irrespective of its location.

The required series compensation in a line is therefore usually split into a fixed-capacitor component and a controllable TCSC component.

APPLICATIONS OF TCSC
Enhancement of System Damping:



UNIT-4
VOLTAGE SOURCE CONVERTER BASED FACTS CONTROLLERS

STATIC VAR COMPENSATOR (SVC):

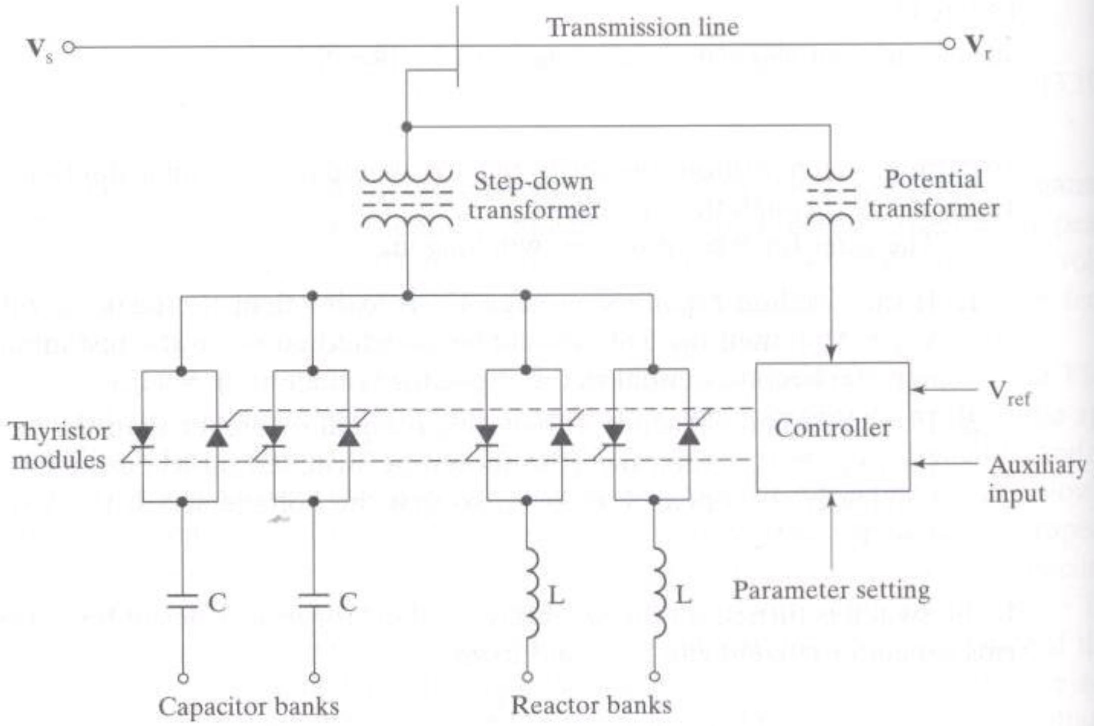
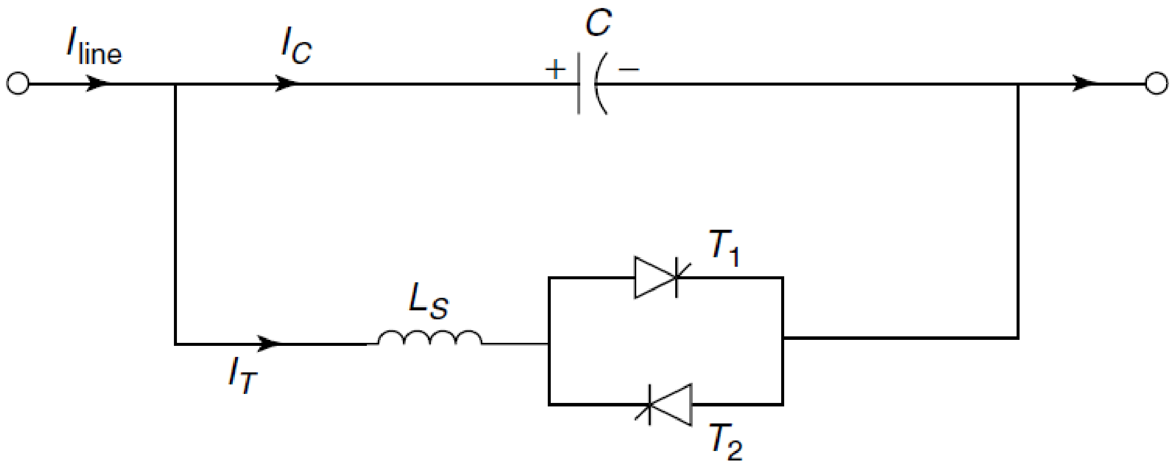


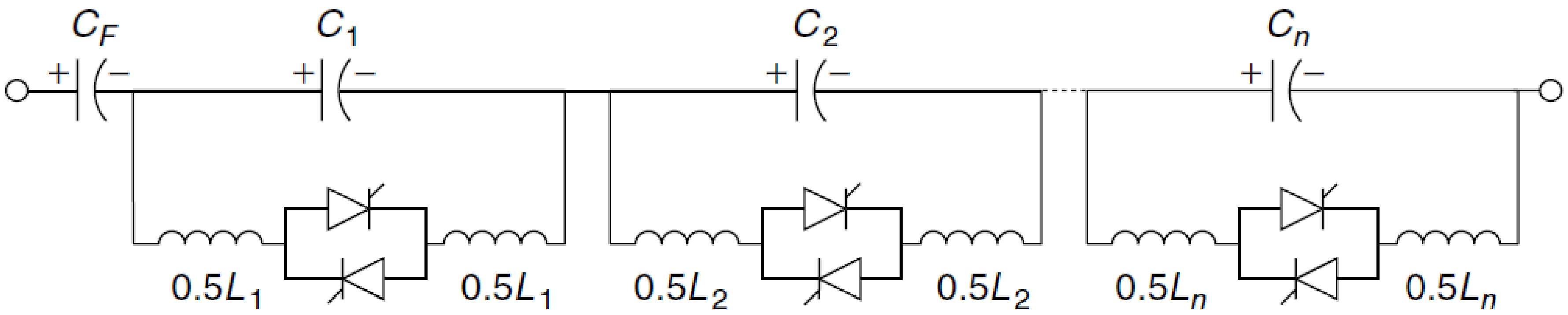
FIGURE 13.6

General arrangement of static VAR compensator [Ref. 4].

TCSC CONTROLLER:



A basic TCSC module



A typical TCSC system.

STATCOM - Static Synchronous Compensator:

It is a solid-state switching converter, capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source.

STATCOM is considered as voltage-source converter that, from a given input of dc voltage, produces a set of 3-phase ac-output voltages, each in phase with and coupled to the corresponding ac system voltage through a relatively small reactance

STATCOM - Static Synchronous Compensator:

STATCOM can improves:

1. the dynamic voltage control in transmission and distribution systems;
2. the power-oscillation damping in power-transmission systems;
3. the transient stability;
4. the voltage flicker control; and
5. the control of not only reactive power but also (if needed) active power in the connected line, requiring a dc energy source.

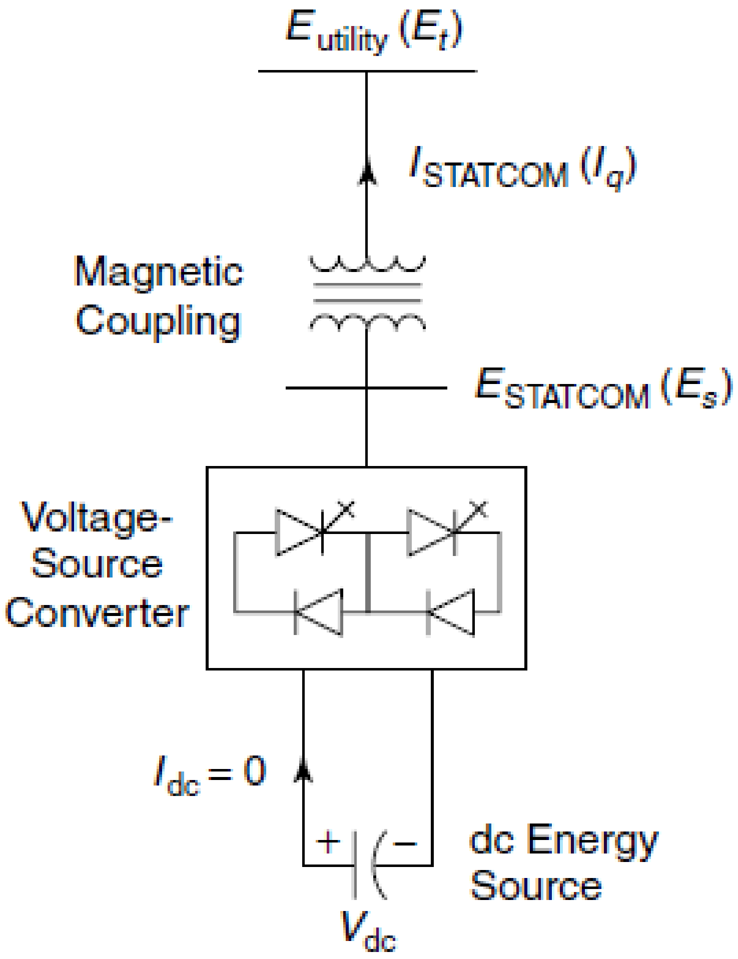
STATCOM - Static Synchronous Compensator:

STATCOM structure:

1. it occupies a small footprint,
2. it factory-built equipment, thereby reducing site work and commissioning time;
3. it uses encapsulated electronic converters, thereby minimizing its environmental impact.

STATCOM - Static Synchronous Compensator:

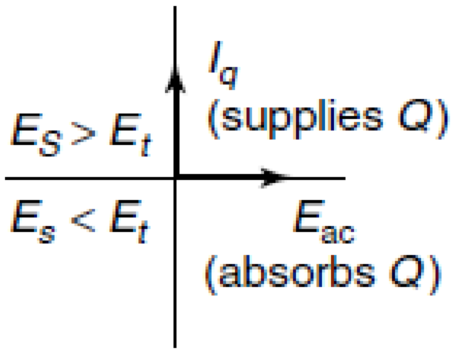
STATCOM power circuit



Reactive Power Generation

Magnitude Es>Et → Generates reactive power

Magnitude Es<Et → Absorbs reactive power



STATCOM - Static Synchronous Compensator:

When supplying/absorbing Reactive Power

If the amplitude of the output voltage is increased above that of the utility bus voltage, *Et*, then a current flows through the reactance from the converter to the ac system and the converter generates capacitive-reactive power for the ac system.

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

If the output voltage equals the ac system voltage, the reactive-power exchange becomes zero, in which case the STATCOM is said to be in a floating state.

In reactive power generation, the real power provided by the dc source as input to the converter must be zero. The primary need for the capacitor is to provide a circulating-current path as well as a voltage source.

STATCOM - Static Synchronous Compensator:

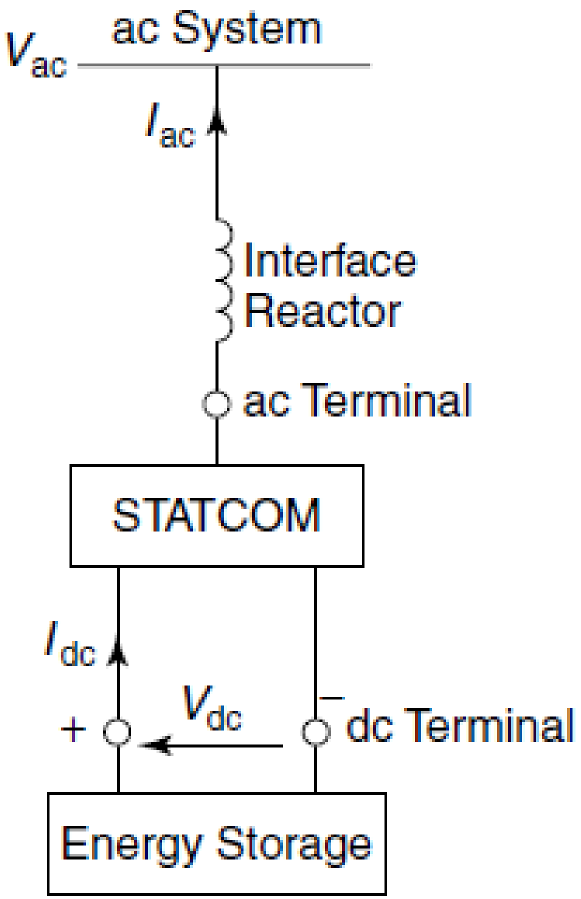
When supplying/absorbing Reactive Power

In practice, the semiconductor switches of the converter are not lossless, so the energy stored in the dc capacitor is eventually used to meet the internal losses of the converter, and the dc capacitor voltage diminishes.

Hence by making the output voltages of the converter lag behind the ac-system voltages by a small angle (usually in the 0.1–0.2 degree range), the converter absorbs a small amount of real power from the ac system to meet its internal losses and keep the capacitor voltage at the desired level.

STATCOM - Static Synchronous Compensator:

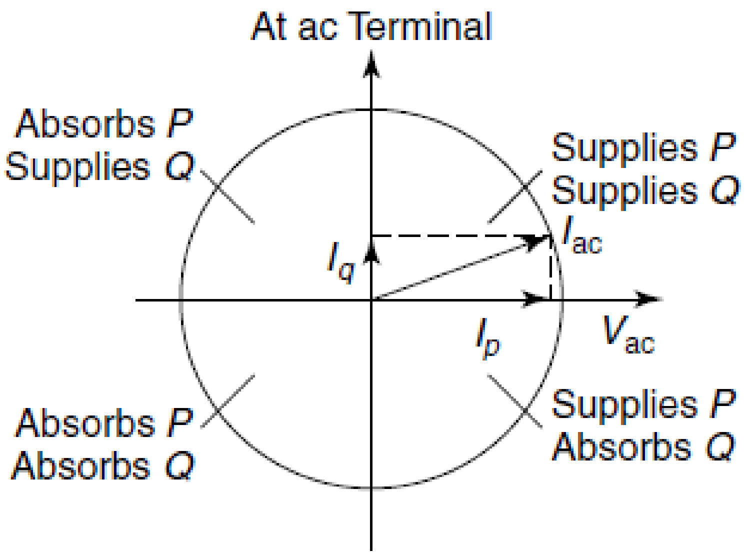
STATCOM power circuit with energy storage



Real Power Generation

Phase Es leads Et → Generates real power

Phase Es lags Et → Absorbs real power



STATCOM - Static Synchronous Compensator:

When supplying/absorbing Real Power

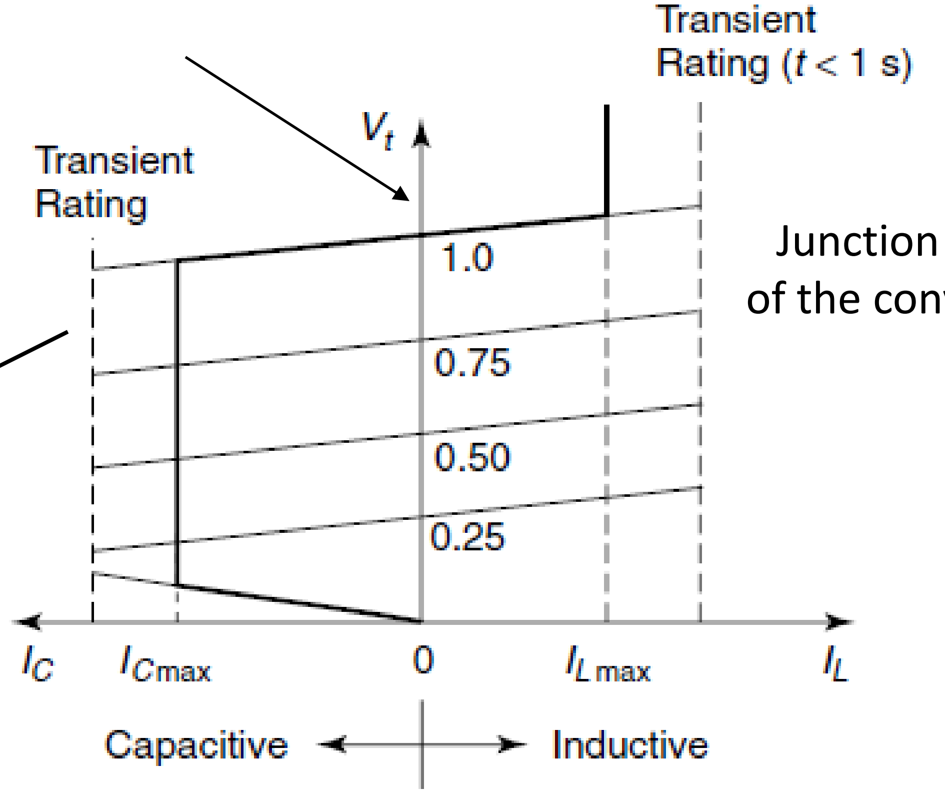
Adjusting the phase shift between the converter-output voltage and the ac system voltage can similarly control real-power exchange between the converter and the ac system.

If the converter-output voltage is made to lead the ac-system voltage, then the converter can supply real power to the ac system from its dc energy storage.

If its voltage lags behind the ac-system voltage, then the it absorb real power from the ac system for the dc system

STATCOM - Static Synchronous Compensator:

V-I Characteristic



Junction temperature
of the converter switches

Maximum turn
off capability
of converter switches

STATCOM can supply both the capacitive and the inductive compensation and is able to independently control its output current over the rated maximum capacitive or inductive range irrespective of the amount of ac-system voltage. That is, the STATCOM can provide full capacitive-reactive power at any system voltage—even as low as 0.15 pu.

STATCOM - Static Synchronous Compensator:

The characteristic of a STATCOM reveals another strength of this technology:

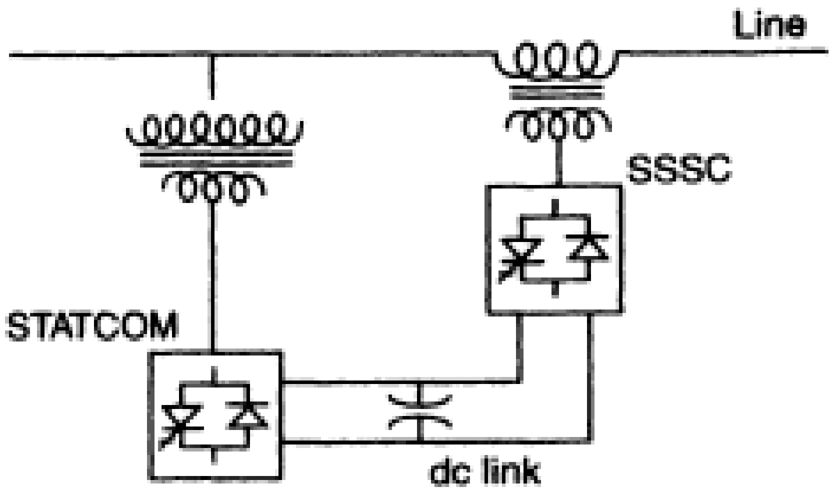
- It is capable of yielding the full output of capacitive generation almost independently of the system voltage.

- Hence it supports the system voltage during and after faults where voltage collapse would otherwise be a limiting factor.

The maximum attainable transient overcurrent in the capacitive region is determined by the maximum current turn-off capability of the converter switches. In the inductive region, the converter switches are naturally commutated;

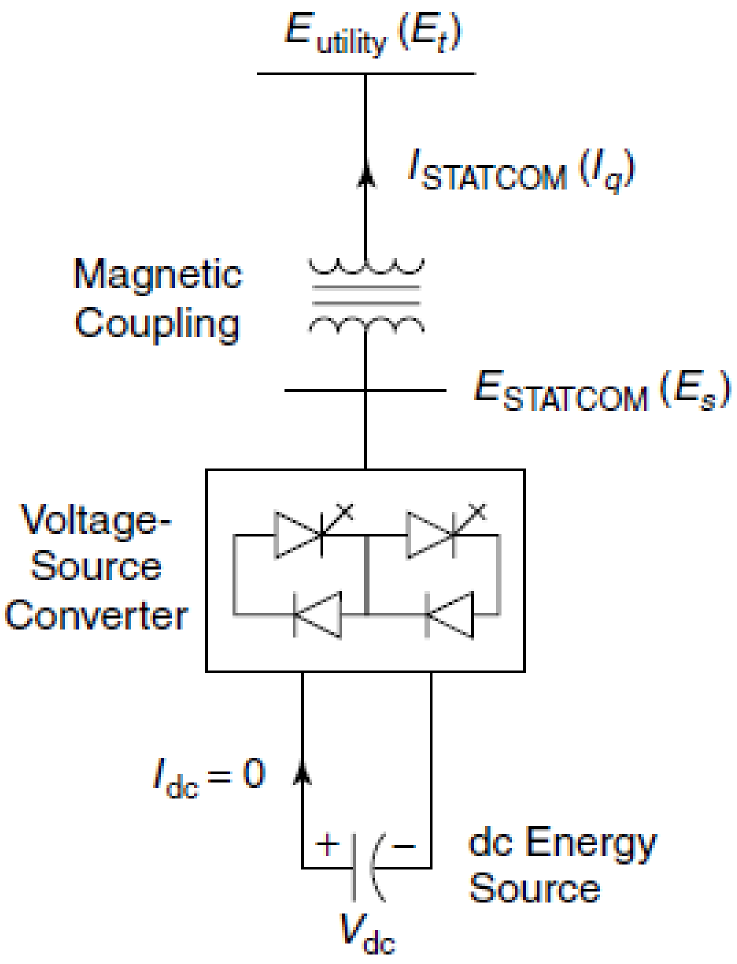
Unified Power Flow Controller (UPFC):

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/reactive power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM.



- STATCOM
- SSSC

STATCOM Operation:



Reactive Power Generation

Magnitude Es>Et → Generates reactive power

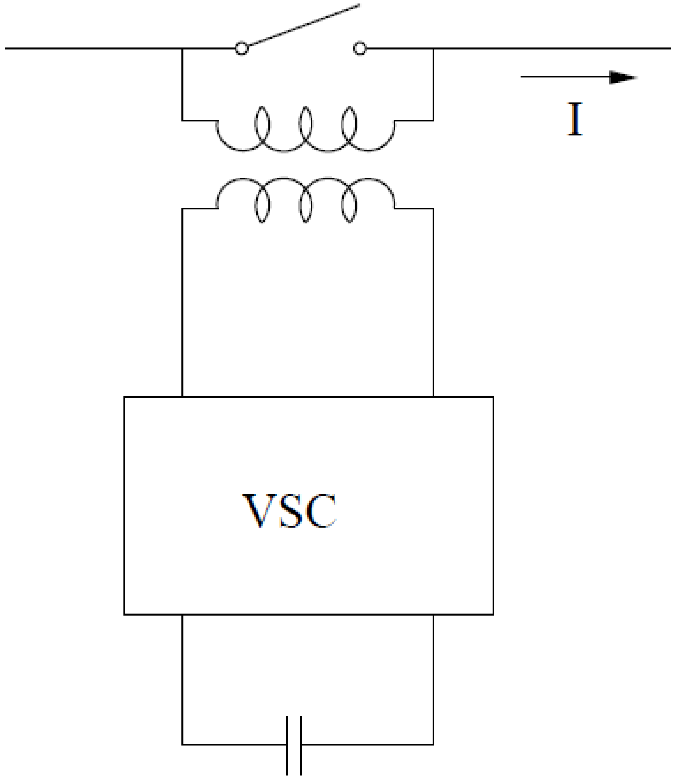
Magnitude Es<Et → Absorbs reactive power

Real Power Generation

Phase Es leads Et → Generates real power

Phase Es lags Et → Absorbs real power

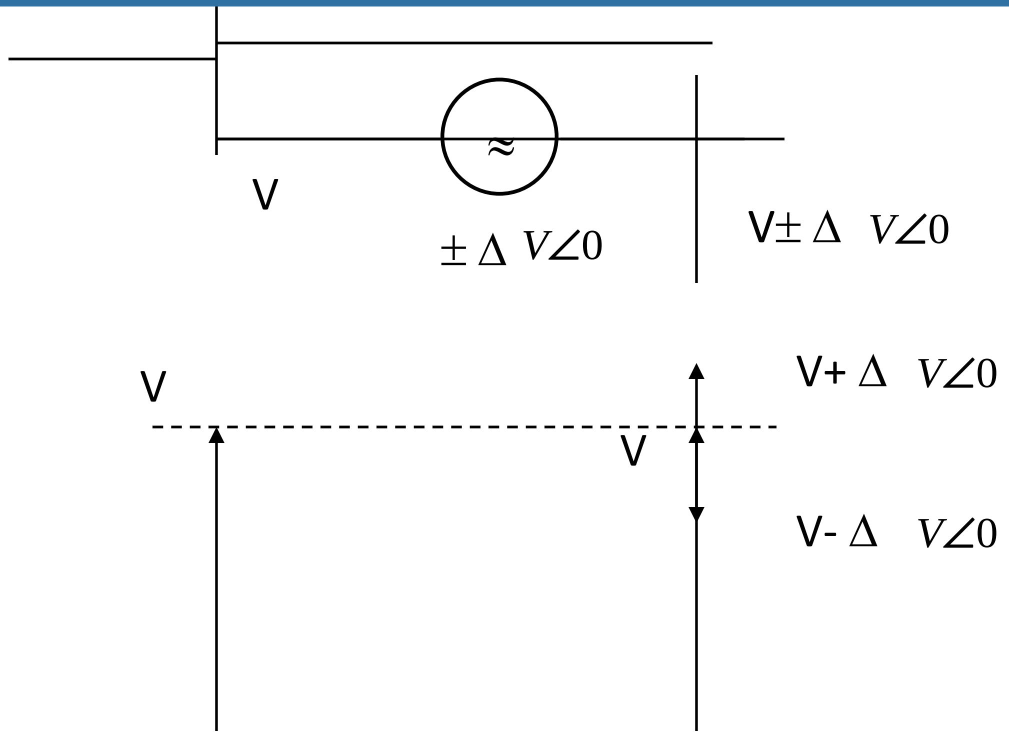
SSSC Operation:



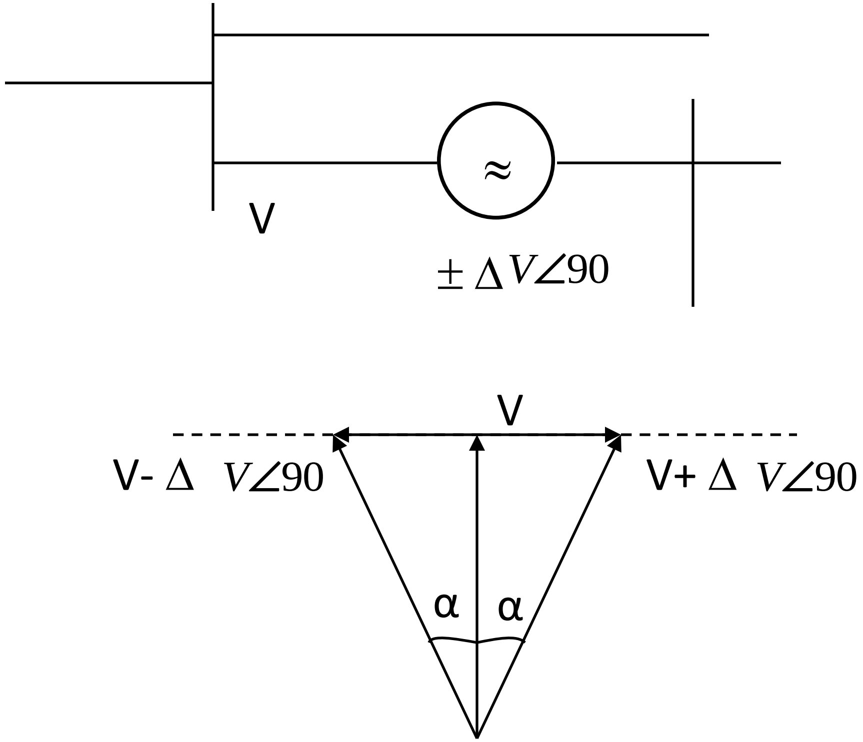
If the injected voltage is in phase with the line current, then the voltage would exchange real power.

On the other hand, if a voltage is injected in quadrature with the line current, then reactive power—either absorbed or generated—would be exchanged.

SSSC Operation:



In-phase Voltage injection

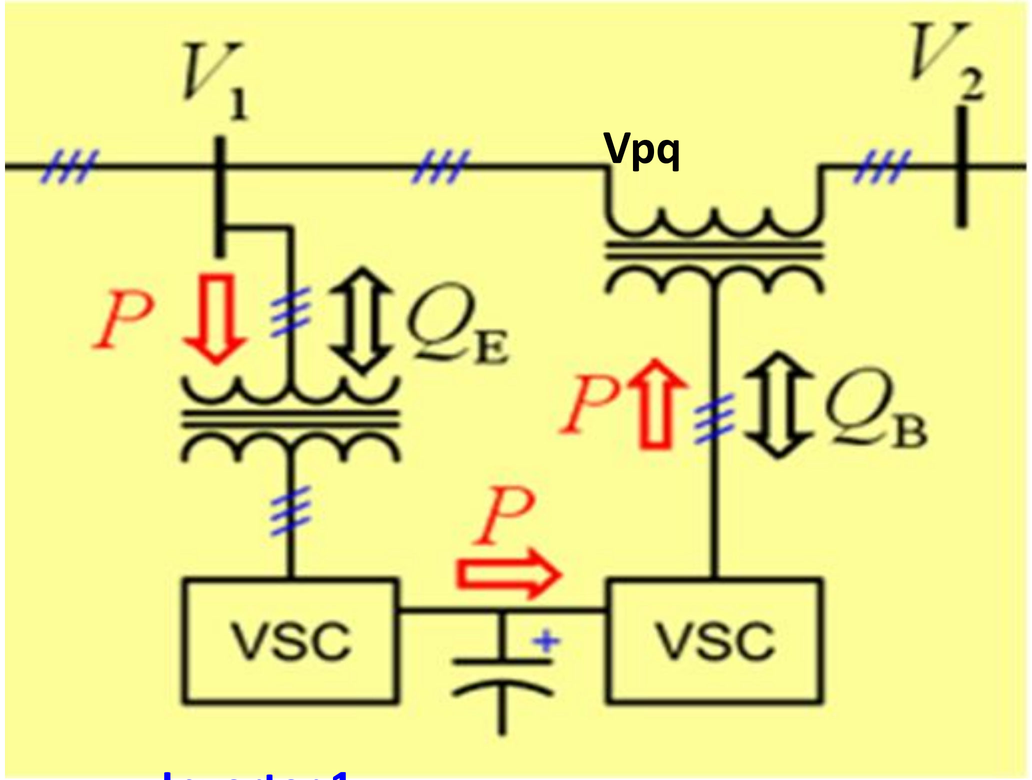


Quadrature Voltage injection

Here, reactive power control through voltage adjustment

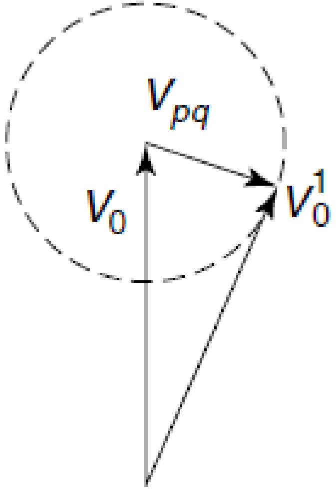
Here, real power control through phase angle adjustment

UPFC operation:



Inverter 1
STATCOM

Inverter 2
SSSC



0<Vpq<Vpqmax

Phase angle

0 to 360 degree

UPFC operation:

- One VSC—converter 1—is connected in shunt with the line through a coupling transformer, the other VSC—converter 2—is inserted in series with the transmission line through an interface transformer.

- The dc voltage for both converters is provided by a common capacitor bank.

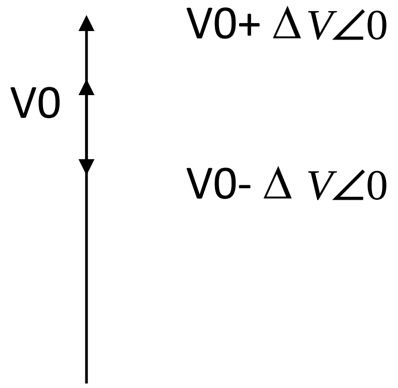
- The series converter is controlled to inject a voltage phasor, *Vpq*, in series with the line Thereby the series converter exchanges both real and reactive power with the transmission line.

- The reactive power is internally generated/ absorbed by the series converter, the real-power generation.

- The shunt-connected converter 1 is used mainly to supply the real-power demand of converter 2, which it derives from the transmission line

UPFC operation:

Phasor Diagram for series voltage injection

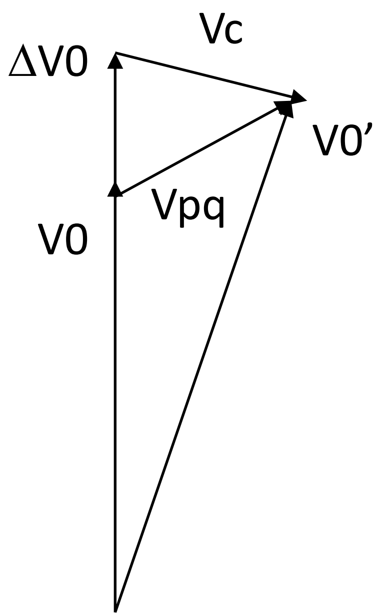


Various Power Function of UPFC

- Voltage regulation
- Series Compensation
- Phase Shifting

Phasor Diagram for Series Compensation

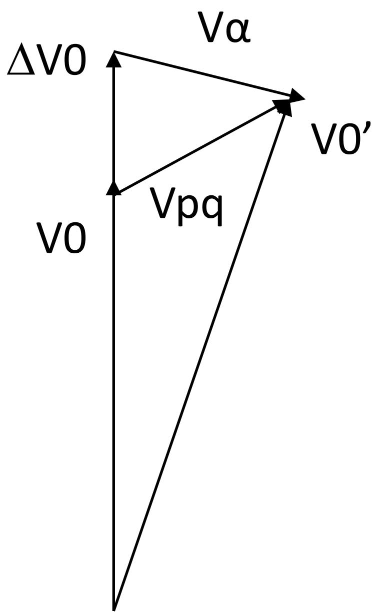
Here, Vpq is the sum of a voltage regulating component ∆V0 and a series compensation providing voltage component Vc that lags behind the line current by 90 degree.



∆V0 – Voltage regulating components
Vc – Series compensation providing voltage component Vc that lag behind the line current by 90.

Phasor Diagram for Phase Shifting:

In the phase-shifting process, the UPFC-generated voltage *Vpq* is a combination of voltage-regulating component Δ*V*0 and phase-shifting voltage component *V*α



UPFC:

The UPFC operates with constraints on the following variables:

1. the series-injected voltage magnitude;
2. the line current through series converter;
3. the shunt-converter current;
4. the minimum line-side voltage of the UPFC;
5. the maximum line-side voltage of the UPFC; and
6. the real-power transfer between the series converter and the shunt converter

UPFC Modes Of Operation:

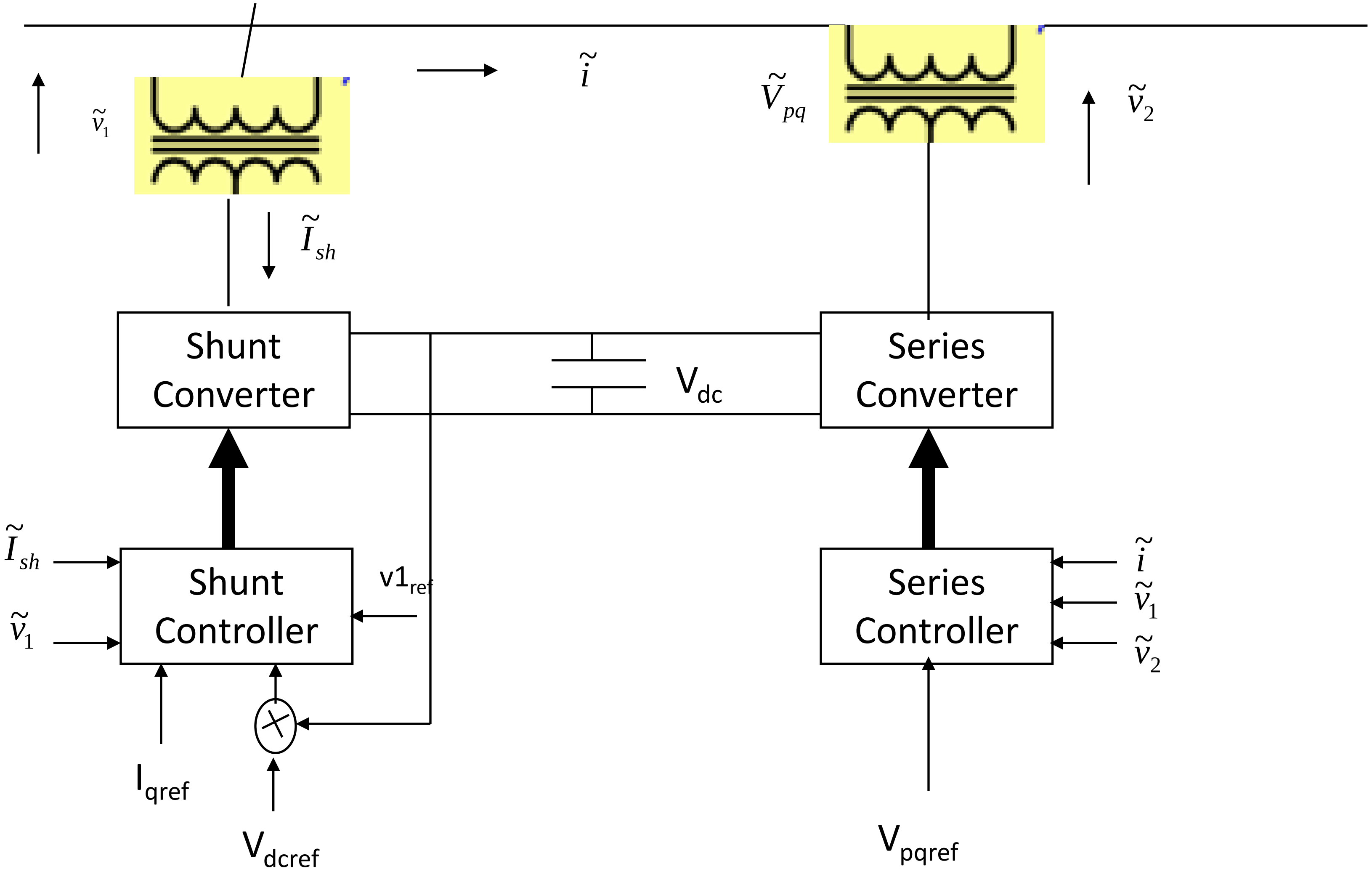
Shunt Converter (STATCOM) Control Mode

- Reactive Power Control Mode
- Automatic Voltage control mode

Series Converter (SSSC) Control Mode

- Direct Voltage Injection Mode
- Bus Voltage regulation and control mode
- Phase angle regulation mode
- Automatic Power flow control mode

UPFC Control Scheme for different modes of Operation:



UPFC Modes Of Operation:

Reactive Power Control Mode

- Reference inputs are used to generate inductive and capacitive VAR request
- Shunt converter control converts the VAR reference into the corresponding shunt current request by adjusting the gate pulse of the converter.

Automatic Voltage control mode

- Uses feed back signal v1
- Shunt converter reactive current is automatically regulated to maintain transmission line voltage to reference value at the point of connection.

UPFC Modes Of Operation:

Direct Voltage Injection Mode:

Simply generates Vpq with magnitude and phase angle requested

By reference input.

Vpq in phase with V → voltage magnitude control

Vpq quadrature with V → real power control

Bus Voltage Regulation Mode:

Vpq is kept in phase with v1 angle, its magnitude is controlled to maintain

the magnitude output bus voltage v2 at the given reference value.

UPFC Modes Of Operation:

Phase Angle Regulation Mode:

Vpq is controlled w.r.t voltage magnitude v1. Hence v2 is phase shifted without any magnitude change relative to the angle specified by the vi reference value.

Automatic Power Flow Control Mode:

Magnitude and angle of Vpq is controlled so as to force a line current, that results in desired real and reactive power flow in the line.

Vpq is determined automatically and continously by closed loop control system to ensure desired P and Q.

Modeling of UPFC for Load Flow Studies:

Load flow Studies

Basic Power Flow Equations at any bus i is calculated using

$$P_i = \sum_{k=1}^{n} |Y_{3i}||V_i||V_k| \cos(\theta_i - \theta_k - \gamma_{ik})$$

$$Q_i = \sum_{k=1}^{n} |Y_{3i}||V_3||V_i| \sin(\theta_i - \theta_k - \gamma_{ik})$$

Modeling of UPFC for Load Flow Studies:

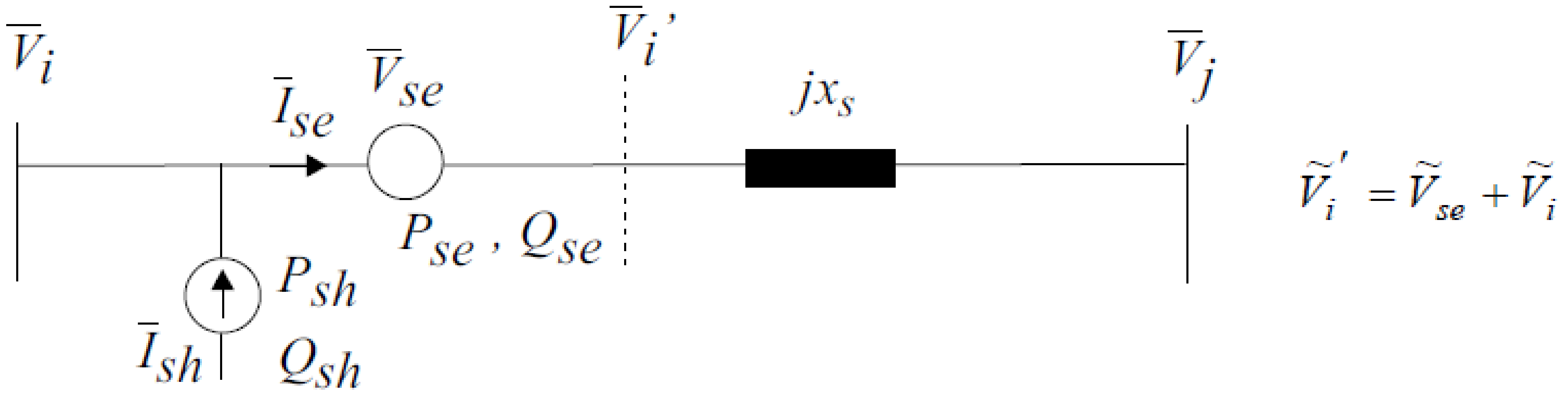


Fig. The UPFC electric circuit arrangement

Series connected voltage source is modeled by an ideal series voltage Vse which is controllable in magnitude and phase, that is, $Vse = r*V_k*ej^{\zeta}$ where $0 \le r \le r_{max}$ and $0 \le \zeta \le 360$.

UNIT-5
CO-ORDINATION OF FACTS CONTROLLERS

Controller interactions

Controller interactions can occur in the following combinations

1. Multiple FACTS controllers of a similar kind.

2. Multiple FACTS controllers of a dissimilar kind.

3. Multiple FACTS controllers and HVDC converter controllers.

The term *coordinated* implies that the controllers have been tuned simultaneously to effect an overall positive improvement of the control scheme

Controller interactions

The frequency ranges of the different control interactions have been classified as follows

- 0 Hz for steady-state interactions
- 0–3/ 5 Hz for electromechanical oscillations
- 2–15 Hz for small-signal or control oscillations
- 10–50/ 60 Hz for sub synchronous resonance (SSR) interactions
- >15 Hz for electromagnetic transients, high-frequency resonance or harmonic resonance interactions, and network-resonance interactions

Steady State interactions

- Steady-state interactions between different controllers occur between their system-related controls.

- These interactions are related to issues such as the stability limits of steady-state voltage and steady-state power; adequacy of reactive-power support at buses.

- Load-flow and stability programs with appropriate models of FACTS equipment and HVDC links are generally employed to investigate the foregoing control interactions.

Electromechanical oscillations

- Electromechanical-oscillation interactions between FACTS controllers also involve synchronous generators, compensator machines, and associated power system stabilizer controls.

- *Local mode* oscillations- typically in the range of 0.8–2 Hz,
- *Inter-area mode* oscillations- typically in the range of 0.2–0.8 Hz.

- Eigen value analysis programs are employed for determining the frequency and damping of sensitive modes.

Small-signal or control oscillations

- ✓ Control interactions between individual FACTS controllers and the network or between FACTS controllers and HVDC links may lead to the onset of oscillations in the range of 2–15 Hz.

- ✓ Oscillations are largely dependent on the network strength and the choice of FACTS controller parameters

- ✓ Frequency-scanning programs, electromagnetic-transient programs are employed for determining the higher frequency oscillations.

SVC-SVC Interactions

- Interaction analysis performed through eigen value analyses and root-loci plots.

- Effect of Electrical Coupling and Short-Circuit Levels
- System Without Series Compensation
- System With Series Compensation
- High-Frequency Interactions

Coordination of multiple controllers using Linear-control techniques

- The term *coordination* does not imply centralized control;

- It implies the simultaneous tuning of the controllers to attain an effective, positive improvement of the overall control scheme.

- It is understood that each controller relies primarily on measurements of locally available quantities and acts independently on the local FACTS equipment.

The Basic Procedure for Controller Design

The controller-design procedure involves the following steps:

1. derivation of the system model;

2. enumeration of the system-performance specifications;

3. selection of the measurement and control signals;

4. coordination of the controller design; and

5. validation of the design and performance evaluation.

Derivation of the System Model

- A reduced-order nonlinear system model must be derived for the original power system.

- The model is linearized around an operating point to make it amenable to the application of linear-control design techniques.

- In situations where linearized-system models may not be easily obtainable, identification techniques are employed to derive simple linear models from time-response information.