Day-2
Series Compensation & Other FACTS Controllers

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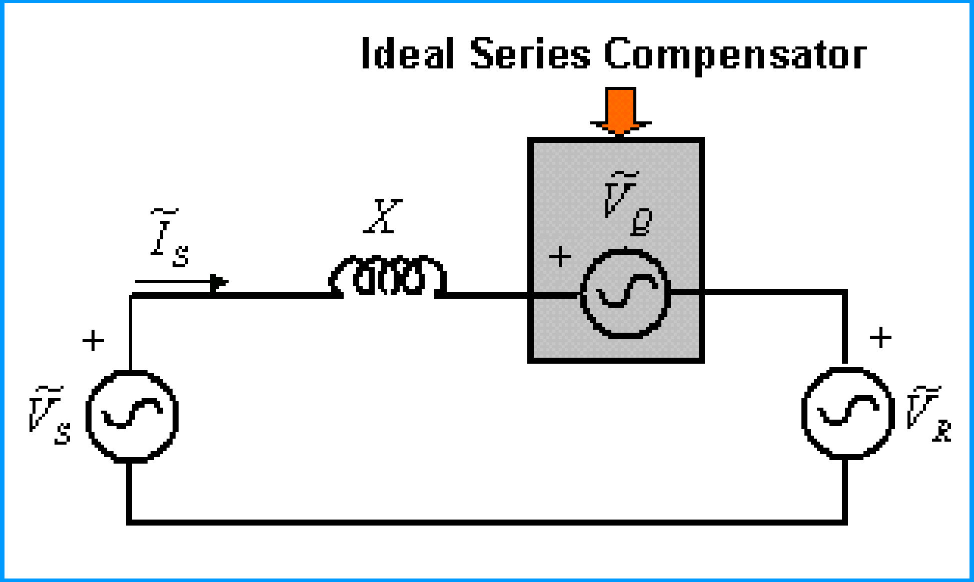
Series Compensation of Transmission Systems

A device that is connected in series with the transmission line is called a ***series compensator***. In the analysis given below, we shall investigate the effect of the series compensator on

- the voltage profile
- the power-angle characteristics
- the stability margin
- the damping of power oscillations

Ideal Series Compensator



- The ideal series compensator is represented by a voltage source that only supplies reactive power and no real power.
- The location of the series compensator is not crucial, and it can be placed anywhere along the transmission line.

Voltage Profile

- The series voltage must be injected in such a way that the series compensator does not absorb any real power in the steady state. The injected voltage is then

$$\tilde{V}_Q = \lambda \tilde{I}_S e^{\mu j90^\circ}$$

  where λ is a proportionality constant.
- The ratio λ / X is called the ***compensation level***. For example, we call the compensation level to be 50% when $\lambda = X/2$.

Voltage Profile

Let us assume

$$\tilde{V}_S = V\angle\delta, \quad \tilde{V}_R = V\angle 0^\circ.$$

Then

$$\tilde{I}_S = \frac{\tilde{V}_S - \tilde{V}_R - \tilde{V}_Q}{jX} = \frac{V\angle\delta - V}{j\left(X \,\mu\, \lambda\right)}$$

The choice of sign of the injected voltage vis-à-vis that of the current plays an important role in the operation of the series compensator.

Mode of Operation

$$\mathbf{Case-1:}\quad \tilde{V}_Q=\lambda\tilde{I}_S e^{-j90^\circ}\Rightarrow \tilde{I}_S=\frac{V\angle\delta-V}{j(X-\lambda)}$$

The above choice corresponds to the voltage source acting as a pure capacitor. Hence we call this as the ***capacitive mode of operation***.

$$\mathbf{Case-2:}\quad \tilde{V}_Q=\lambda\tilde{I}_S e^{+j90^\circ}\Rightarrow \tilde{I}_S=\frac{V\angle\delta-V}{j(X+\lambda)}$$

Since the voltage source in this case acts as a pure inductor, we call this as the ***inductive mode of operation***.

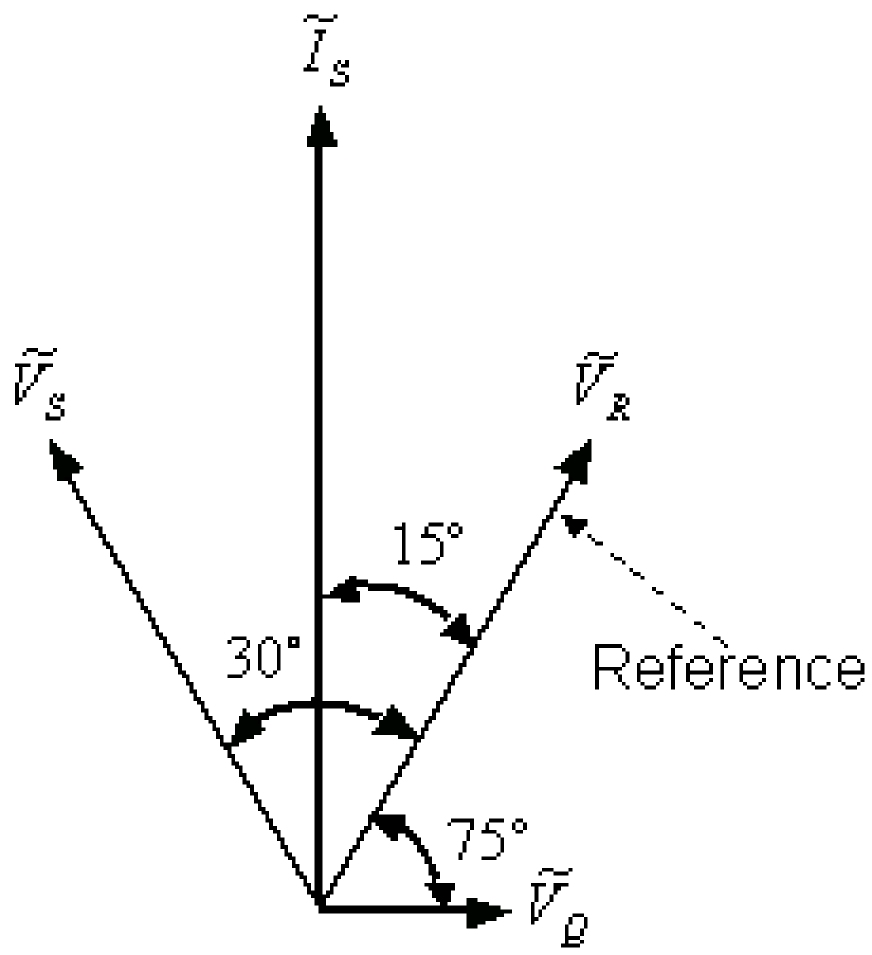
An Example

Consider a system with sending and receiving end voltages being $1\angle 30^\circ$ and $1\angle 0^\circ$ per unit respectively, $X = 0.5$ per unit and $\lambda = 0.15$ per unit. Let us assume that the series compensator operates in the capacitive mode. Then we have

$$\tilde{I}_S = 1.479\angle 15^\circ \text{ per unit}$$

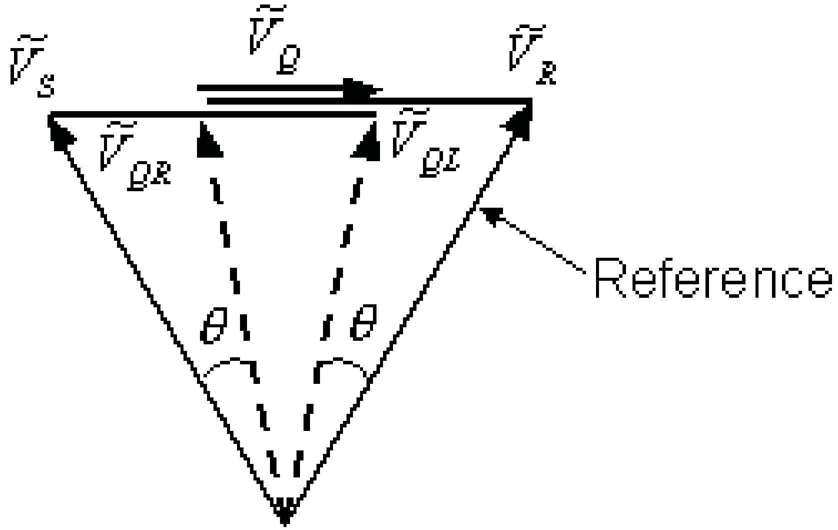
$$\tilde{V}_Q = 0.2248\angle -75^\circ \text{ per unit}$$

Example (Continued)



The phasor diagram is given left. Let us now investigate the impact of the location compensator placement on the voltage profile. We shall denote the voltage on the left of the compensator by V_{QL} and on the right of the compensator by V_{QR}.

Case-1: Compensator in middle



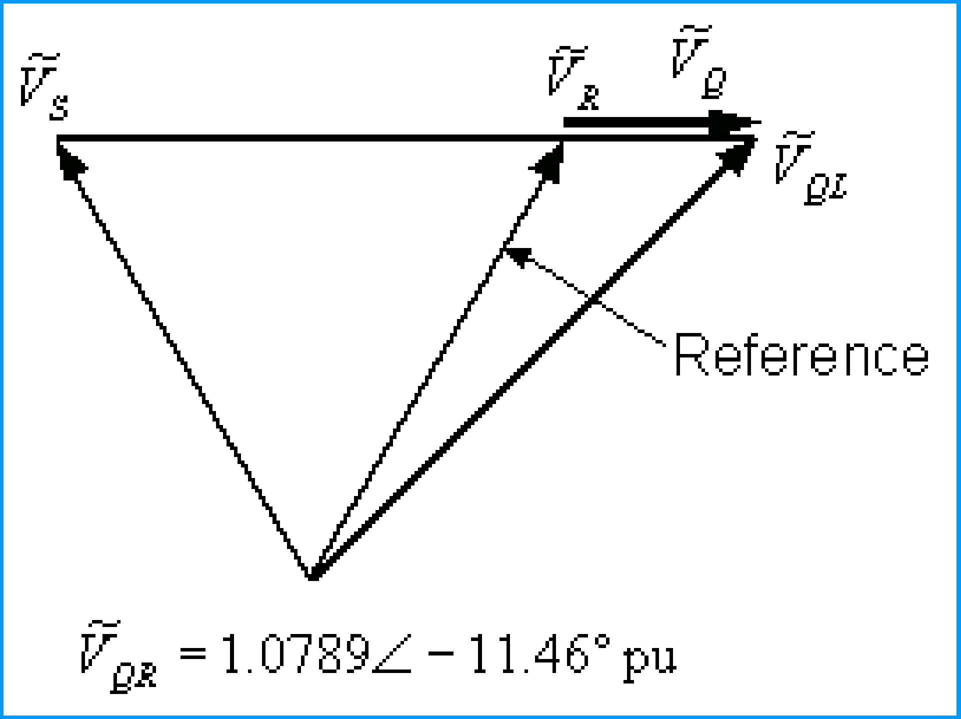
Voltage on the left $\tilde{V}_{QL} = 0.9723\angle 8.45°$ pu

Voltage on the right $\tilde{V}_{QR} = 0.9723\angle 21.55°$ pu

$\theta = 8.45°$

- The series compensator is placed in the middle.
- The worst voltage sag occurs at each side of the series compensator where the voltage vector aligns with the current vector.

Case-2: Compensator before the infinite bus



- The series compensator is placed just before the infinite bus.
- The maximum voltage rise occurs just before the compensator.
- The worst voltage sag still occurs where the voltage vector aligns with the current vector.

Power-Angle Curve

The real and reactive powers at the sending and receiving end are given by

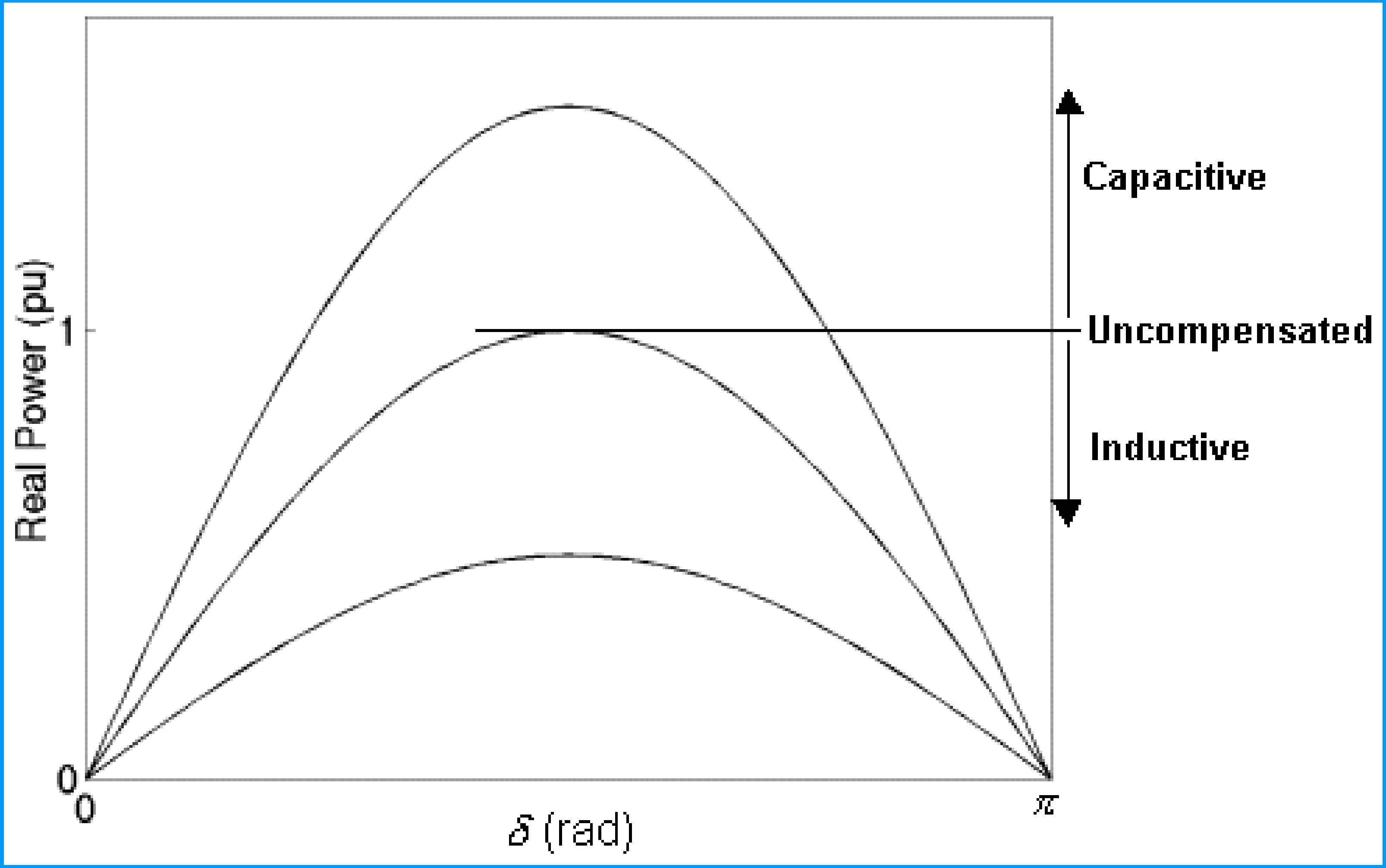
$$P_S + jQ_S = \frac{V^2 \sin\delta}{X \mu \lambda} + j\frac{V^2(1 - \cos\delta)}{X \mu \lambda}$$

$$P_R + jQ_R = \frac{V^2 \sin\delta}{X \mu \lambda} + j\frac{V^2(\cos\delta - 1)}{X \mu \lambda}$$

The real power flow is then

$$P_e = P_S = P_R = \frac{V^2 \sin\delta}{X \mu \lambda}$$

Power-Angle Curve



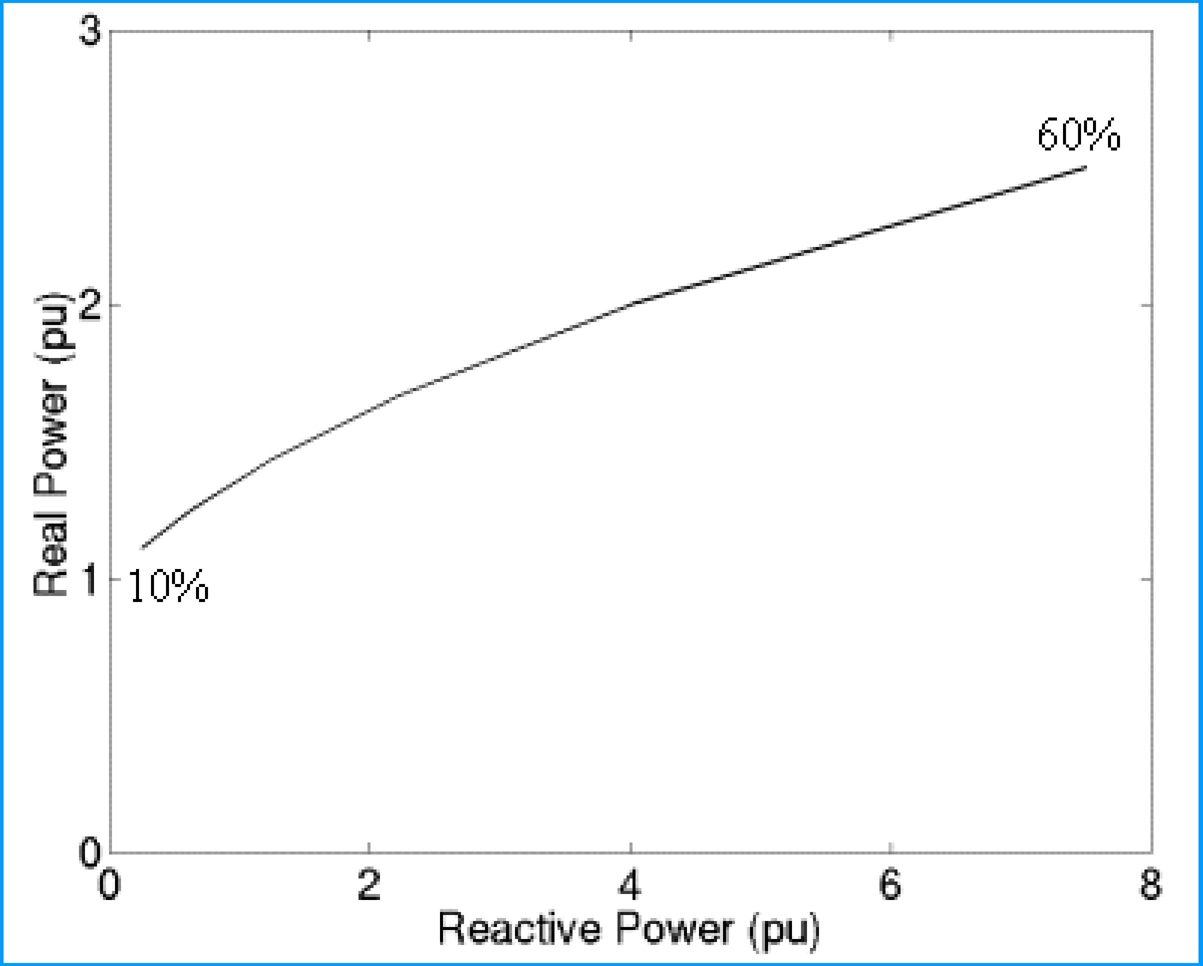
Reactive Power

Since the injected voltage and line current are in quadrature,

- the real power supplied by the compensator is zero.
- the reactive power supplied by the compensator operating in the capacitive mode is

$$Q_Q = \mathrm{Im}\left(\tilde{V}_Q \tilde{I}_S^{\,*}\right) = j\,\frac{2\lambda V^2}{(X-\lambda)^2}\left(\cos\delta - 1\right)$$

Reactive Power



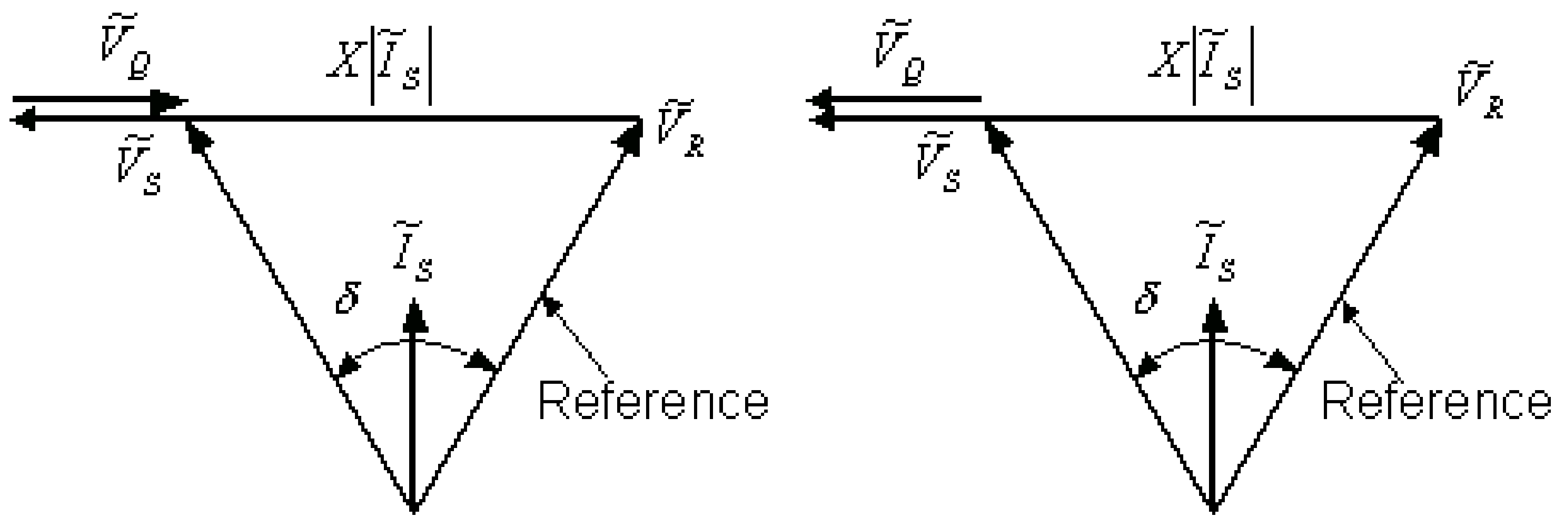
Both the real power transfer and the reactive injection requirement increase with the increase in the compensation level (λ / X).

Alternate Method of Voltage Injection

- The series compensator injects a voltage that is in quadrature with the line current.
- So far we have assumed that the injected voltage magnitude is proportional to the magnitude of the line current.
- If we now relax the assumption, then the magnitude of the injected voltage is given by

$$\tilde{V}_Q = \frac{\tilde{I}_S}{\left|\tilde{I}_S\right|} e^{\mu j 90^\circ}$$

Phasor Diagrams



Capacitive Operation **Inductive Operation**

Note that it is assumed that

$$\tilde{V}_R = V\angle 0^\circ, \quad \tilde{V}_S = V\angle\delta$$

Expression for Power

For the capacitive operation

$$X\left|\tilde{I}_S\right| = \left|\tilde{V}_Q\right| + 2V\sin(\delta/2)$$

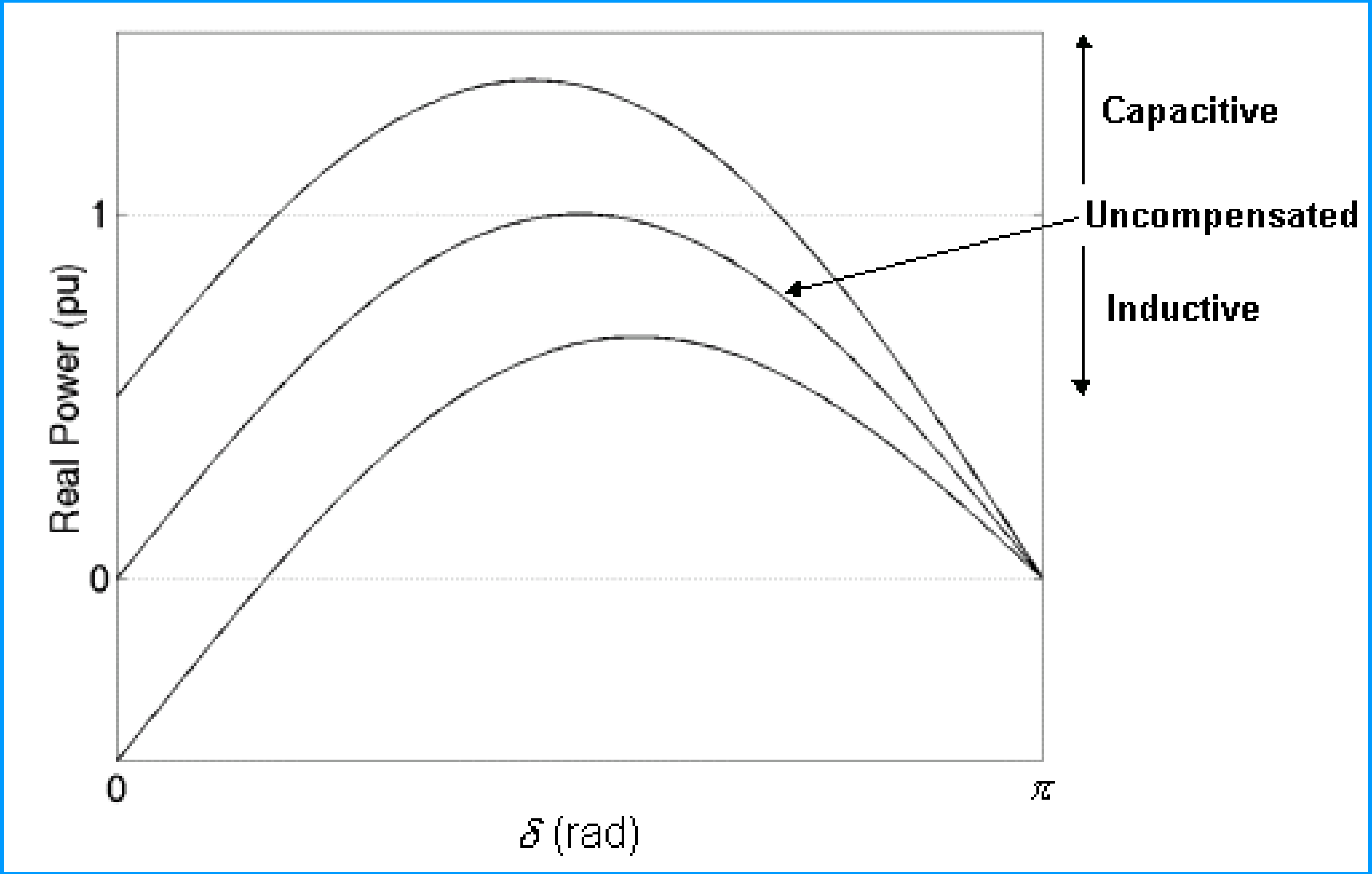
For the inductive operation

$$X\left|\tilde{I}_S\right| = -\left|\tilde{V}_Q\right| + 2V\sin(\delta/2)$$

The power flow is then given by

$$P_e = \frac{V^2}{X}\sin\delta \pm \frac{V}{X}\left|\tilde{V}_Q\right|\cos(\delta/2)$$

Power-Angle Curve



Series Compensator Modes of Operation

With appropriate control, the series compensator operates in two modes:

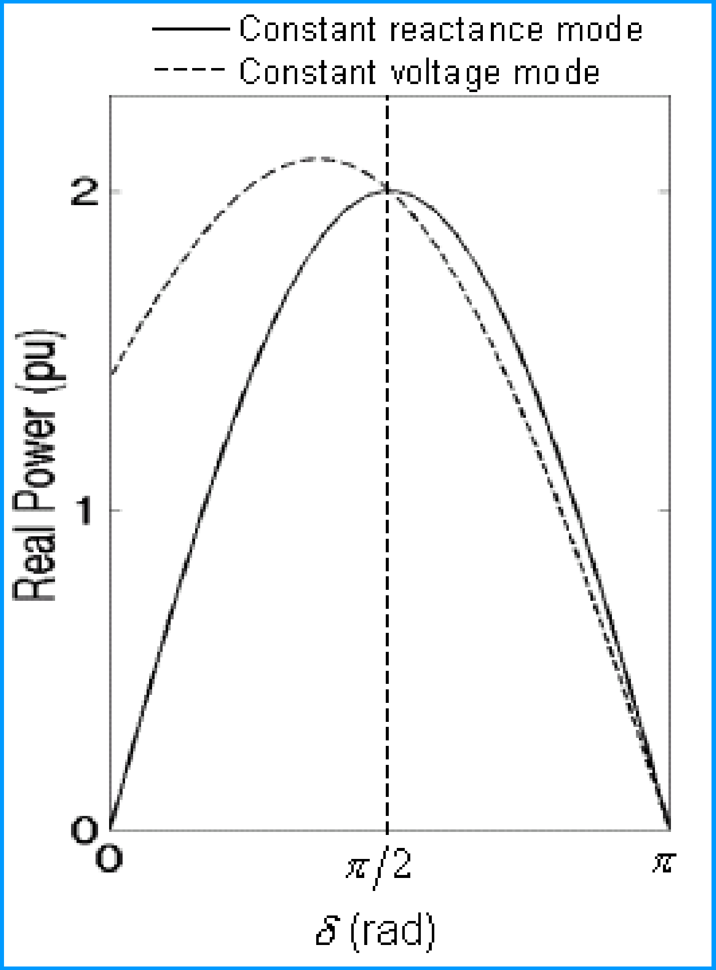
- Constant Reactance

$$\tilde{V}_Q = \lambda \tilde{I}_S e^{\mu j 90^\circ}$$

- Constant Voltage

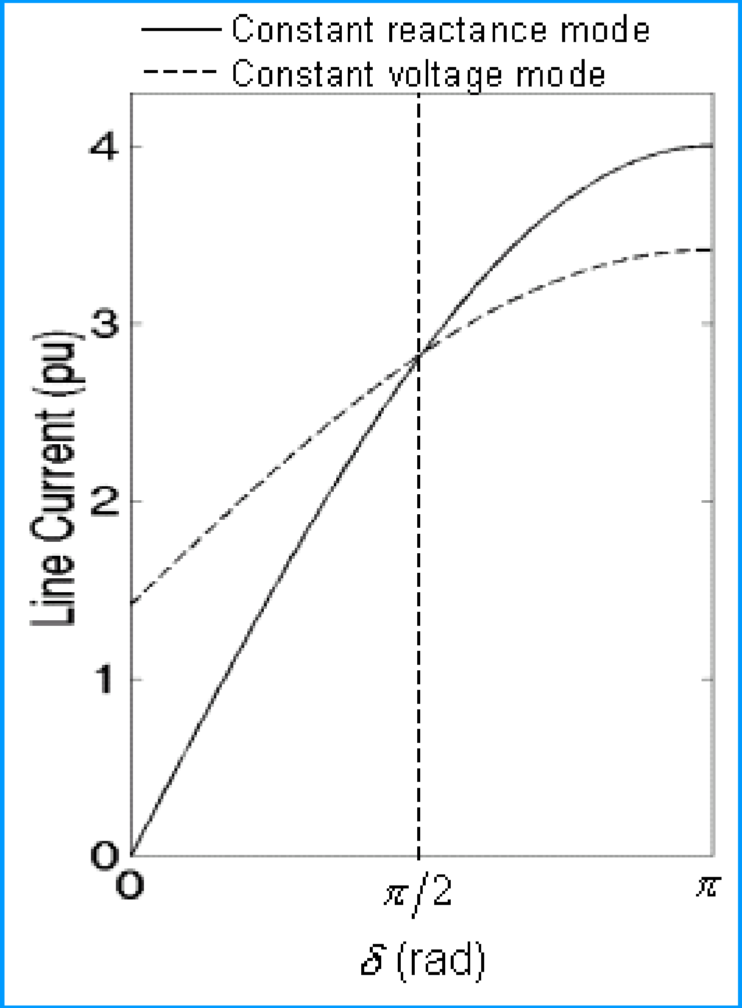
$$\tilde{V}_Q = \frac{\tilde{I}_S}{\left|\tilde{I}_S\right|} e^{\mu j 90^\circ}$$

Comparison Between the Modes of Operation



- The two curves match at $\pi/2$.
- The maximum power for constant voltage case occurs earlier than $\pi/2$.
- The power transfer for constant voltage case for δ = 0 is greater than zero.

Comparison Between the Modes of Operation



- The increase in line current in either case is monotonic.
- However the rate of rise in the constant voltage mode is lower than constant reactance mode.
- Constant voltage is the more desirable mode of operation

Power Flow Control and Power Swing Damping

Let us consider an example to illustrate

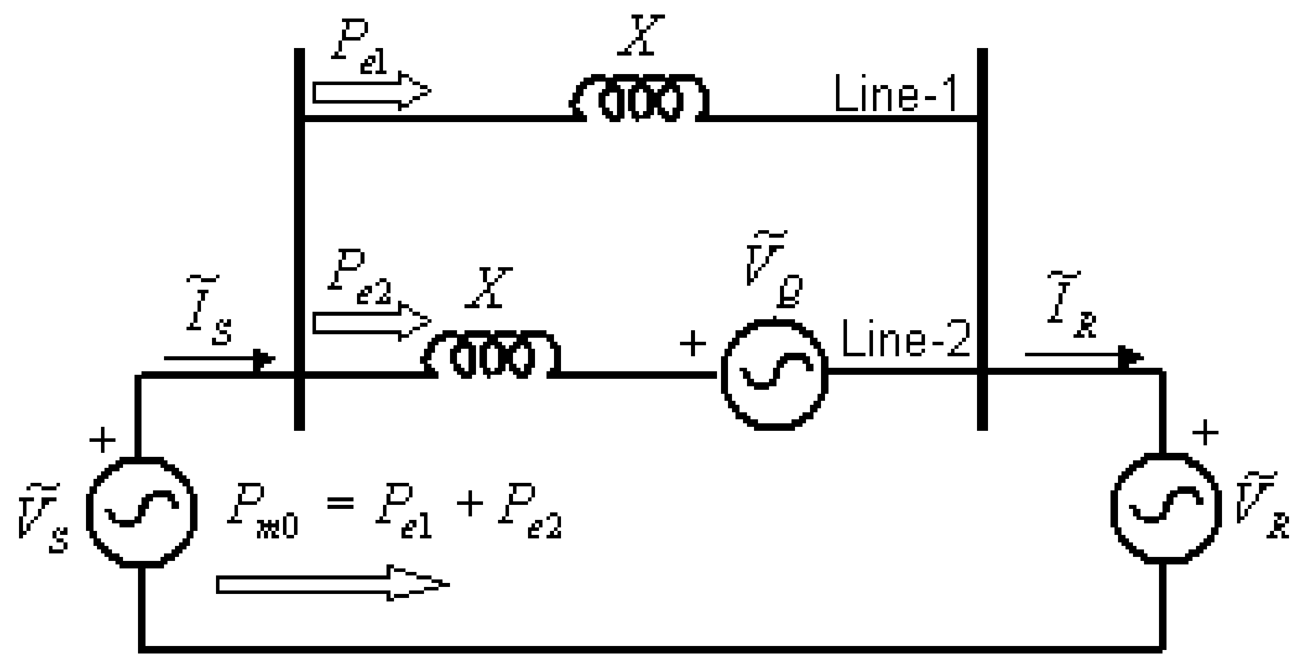
- the power flow control and
- The power swing damping

capabilities of ideal series compensator.

The system contains

- a double circuit transmission line
- one of the two lines compensated by an ideal series compensator.

An Example



$$\left|\tilde{V}_S\right| = \left|\tilde{V}_R\right| = 1.0 \text{ pu}, X = 0.5 \text{ pu}, \delta_0 = 30°$$

Constant reactance mode with $\lambda = 0.15$ pu

$$P_{e1} = 1.0 \text{ pu}, P_{e2} = 1.43 \text{ pu}, P_{m0} = 2.43 \text{ pu}$$

Example (Continued)

For any increase or decrease in the power flow, the series compensator can be controlled in one of the following two modes.

- ***Regulating Control***: Channeling the increase (or decrease) in power through line-1. In this case the series compensator holds the power flow over line-2 constant.
- ***Tracking Control***: Channeling the increase (or decrease) in power through line-2. In this case the series compensator helps in holding constant the power flow over line-1.

Example (Continued)

- The input to the control system is the power flow over line-2 (P_{e2}).
- P_{e2} is compared with the reference value P_{ref} and the error is passed through a PI controller.
- In addition, a damping controller is also added to the feedback loop.
- The output of the controller is the compensation level C_I (=λ / X).

$$C_I = K_P\left(P_{ref} - P_{e2}\right) + K_I \int \left(P_{ref} - P_{e2}\right)dt + C_P \frac{d\Delta\delta}{dt}$$

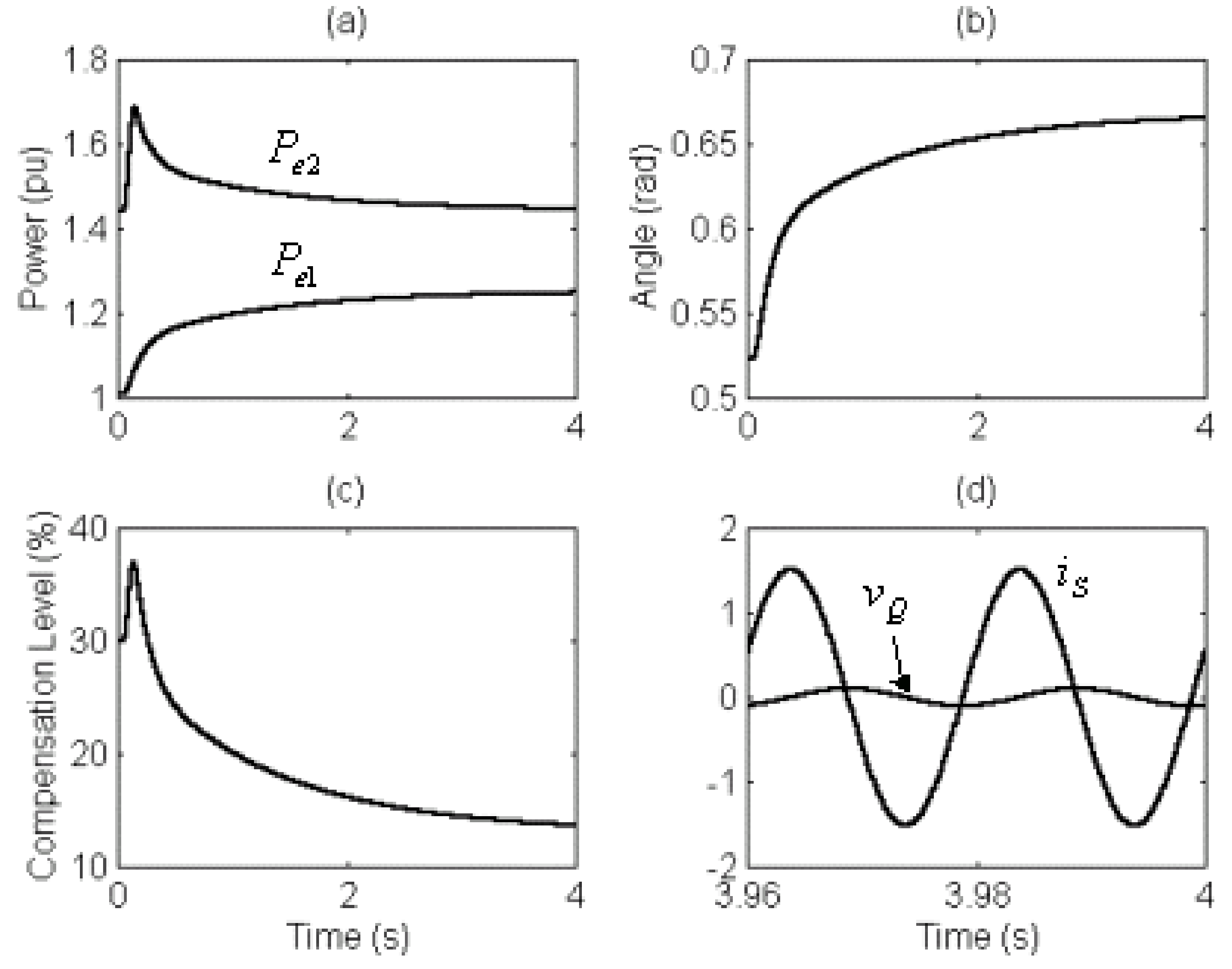
The controller parameters are

$$K_P = 0.1, \quad K_I = 1 \text{ and } C_P = 75$$

Example:
Regulating Control

- The system is in the nominal steady state with P_{m0} = 2.43 per unit.
- The mechanical power input is suddenly raised by 10% (i.e., 0.243 per unit).
- It is expected that the series compensator will hold the power through line-2 constant at P_{e2} such that entire power increase is channeled through line-1.
- We then expect that the power P_{e1} will increase to 1.243 per unit and the load angle to go up to 0.67 rad.
- The compensation level will then change to 13%.

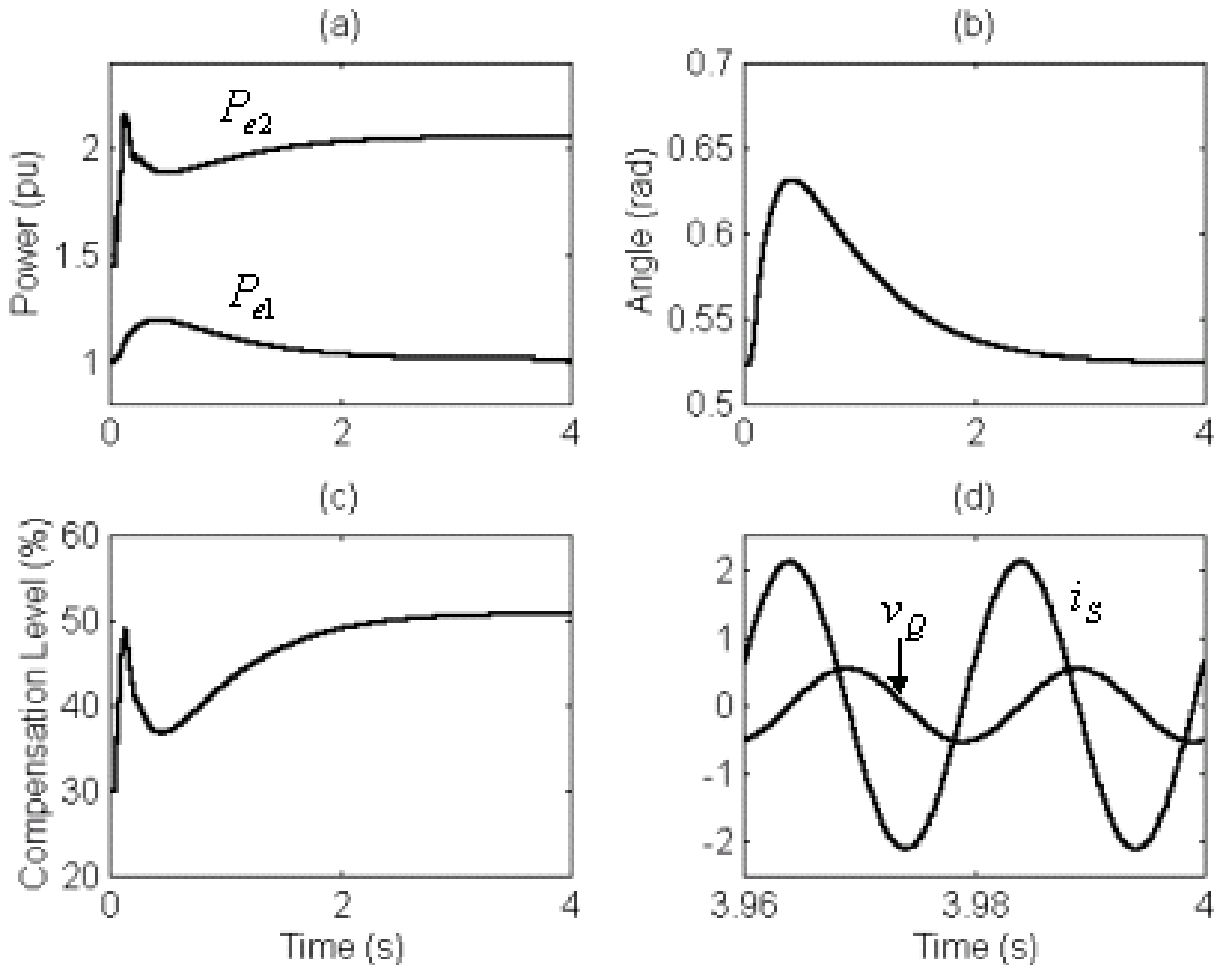
Example: Regulating Control



Example: Tracking Control

- The system is in the nominal steady state with P_{m0} = 2.43 per unit.
- The mechanical power input is suddenly raised by 25% (i.e., 0.6 per unti).
- It is expected that the series compensator will make the entire power increase to flow through line-2.
- Then both P_{e1} and load angle are maintained constant at their nominal values.
- The power, P_{e2}, through line-2 will then increase to about 2.04 per unit and the compensation level will change to 51%.

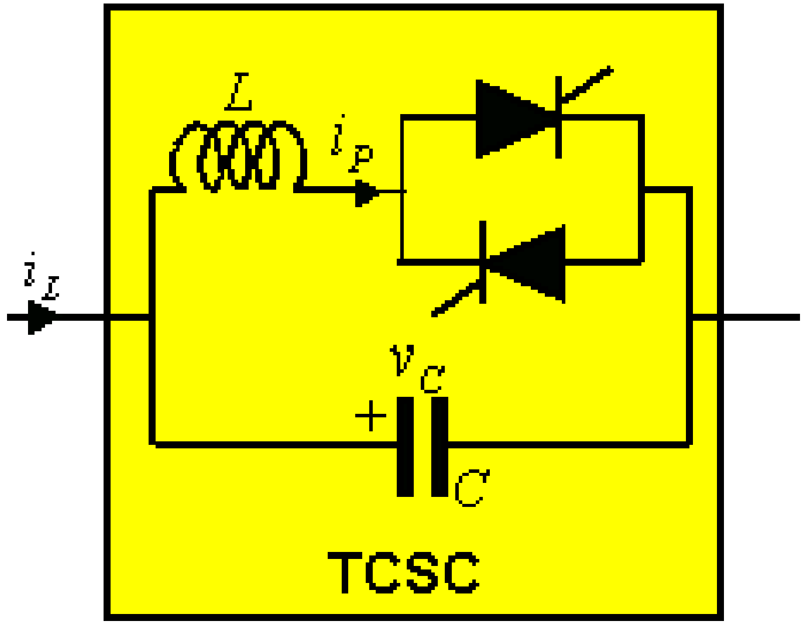
Example: Tracking Control



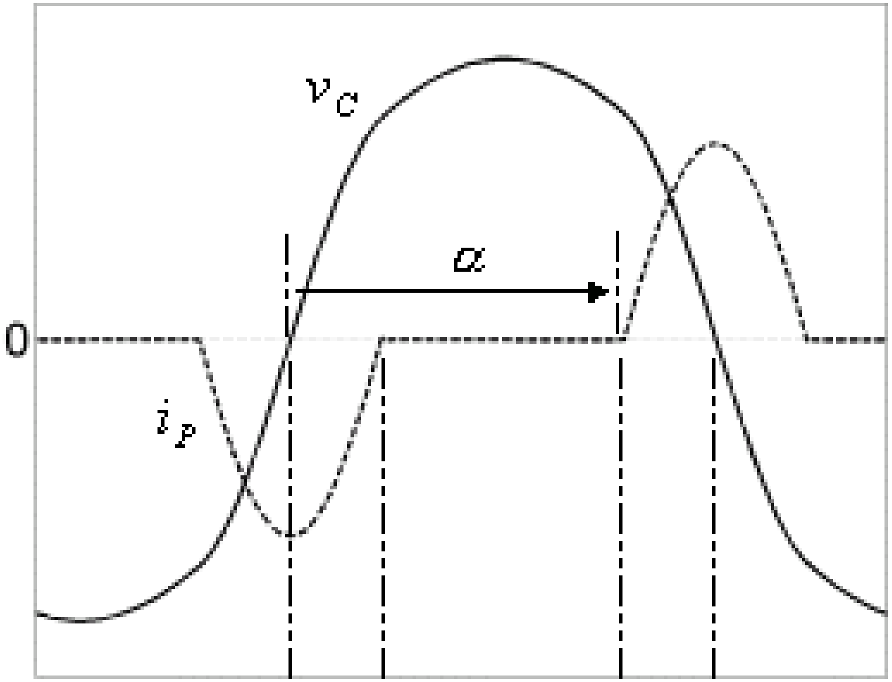
Practical Series Compensator

- The series compensator structure assumed throughout this section is essentially that of a ***static synchronous series compensator*** or ***SSSC***. Like in the case of STATCOM, the SSSC includes an SVS (supplied by a dc capacitor) and a coupling transformer.
- A ***thyristor controlled series compensator*** or ***TCSC*** is an older thyristor and passive element based devices that controls the fundamental reactance. We shall discuss it first.

Thyristor Controlled Series Compensator (TCSC)



Equivalent Circuit



Voltage-Current Waveforms

TCSC - Circuit Equations

The TCSC voltage and currents are combination of two piecewise linear models. Let the system state vector be $x^T = [v_c \ \ i_P]$. Then when the thyristor is on

$$\dot{x} = \begin{bmatrix} 0 & -\dfrac{1}{C} \\ \dfrac{1}{L} & 0 \end{bmatrix} x + \begin{bmatrix} \dfrac{1}{C} \\ 0 \end{bmatrix} i_L$$

TCSC - Circuit Equations

Similarly when the thyristor is off

$$\dot{x} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} x + \begin{bmatrix} \dfrac{1}{C} \\ 0 \end{bmatrix} i_L$$

The waveform of v_C is a combination of the solution of these two state equations and therefore is not a smooth sinusoidal function. Therefore both the inductor current and capacitor voltage are the solutions of two piece-wise linear models.

TCSC - Fundamental Characteristics

- A TCSC is a parallel combination of a fixed capacitor and a thyristor controlled reactor.
- Therefore the steady state fundamental impedance of the TCSC is given by

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

- We can therefore see that by varying the conduction angle, the fundamental frequency reactance of the TCSC can be made inductive or capacitive.

TCSC - Fundamental Reactance

The fundamental reactance of the TCSC is given by

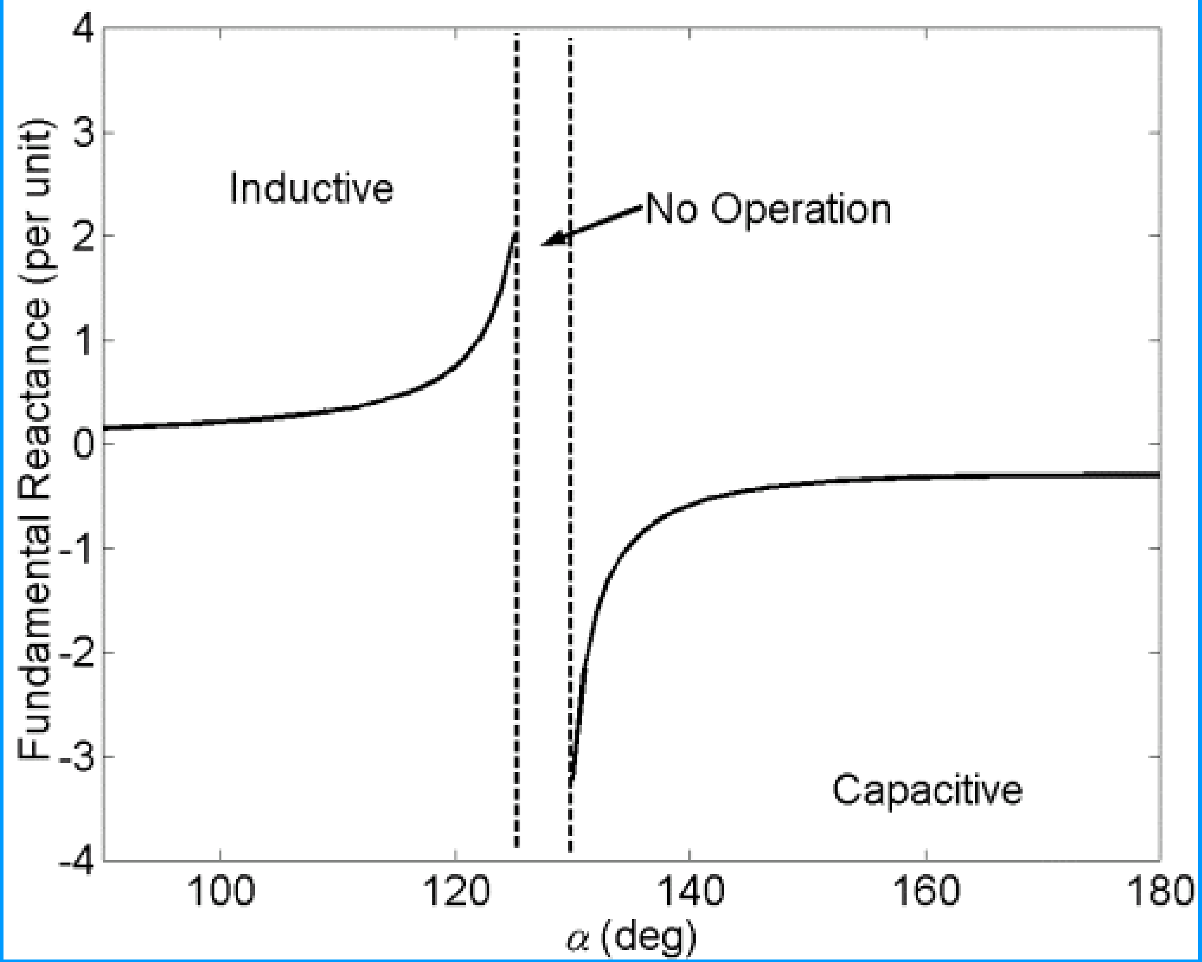
$$X_{TCSC} = \beta_1 \left(X_C + \beta_2 \right) - \beta_4 \beta_5 - X_C$$

$$\beta_1 = \frac{2(\pi - \alpha) + \sin 2(\pi - \alpha)}{\pi}, \quad \beta_2 = \frac{X_C X_P}{X_C - X_P}, \quad \beta_3 = \sqrt{\frac{X_C}{X_P}}$$

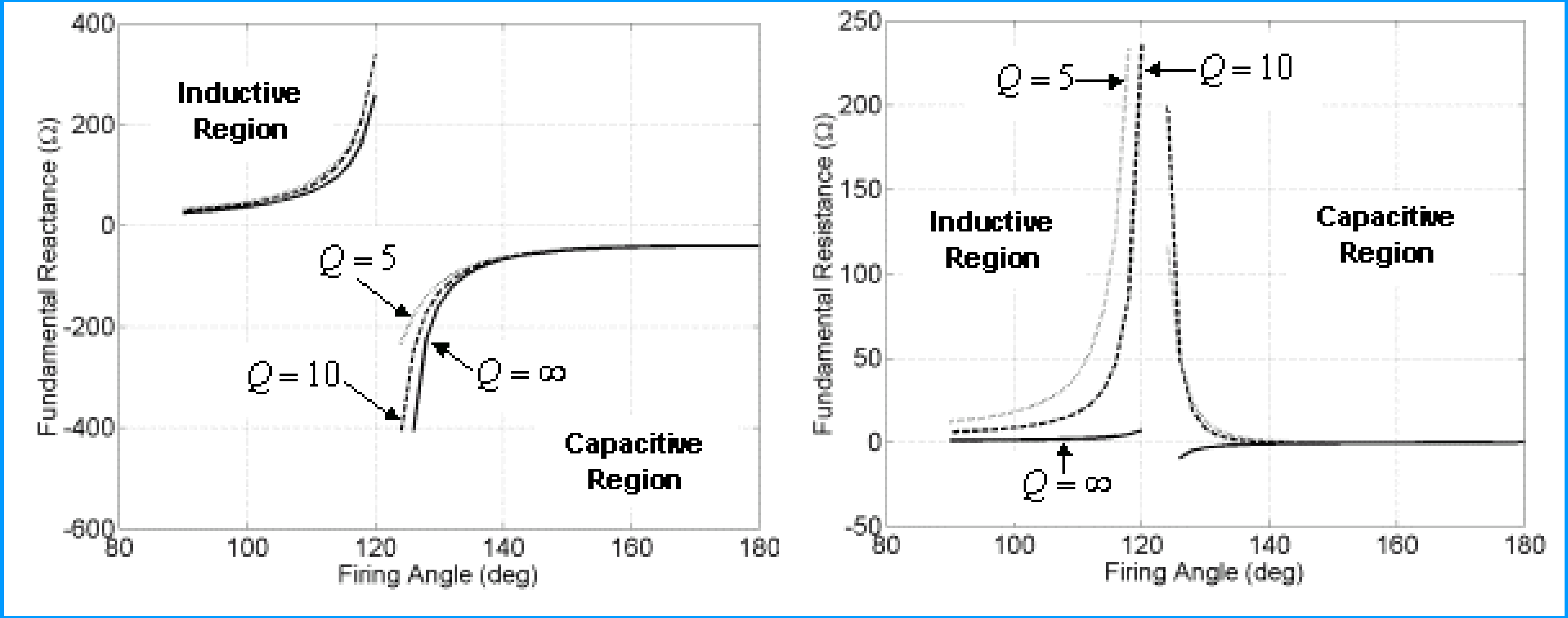
$$\beta_4 = \beta_3 \tan[\beta_3 (\pi - \alpha)] - \tan(\pi - \alpha), \quad \beta_5 = \frac{4 \beta_2^2 \cos^2 (\pi - \alpha)}{\pi X_P}$$

- α is the firing angle
- X_C and X_P respectively are the reactances of the capacitor and parallel inductor.

TCSC - Fundamental Reactance Plot

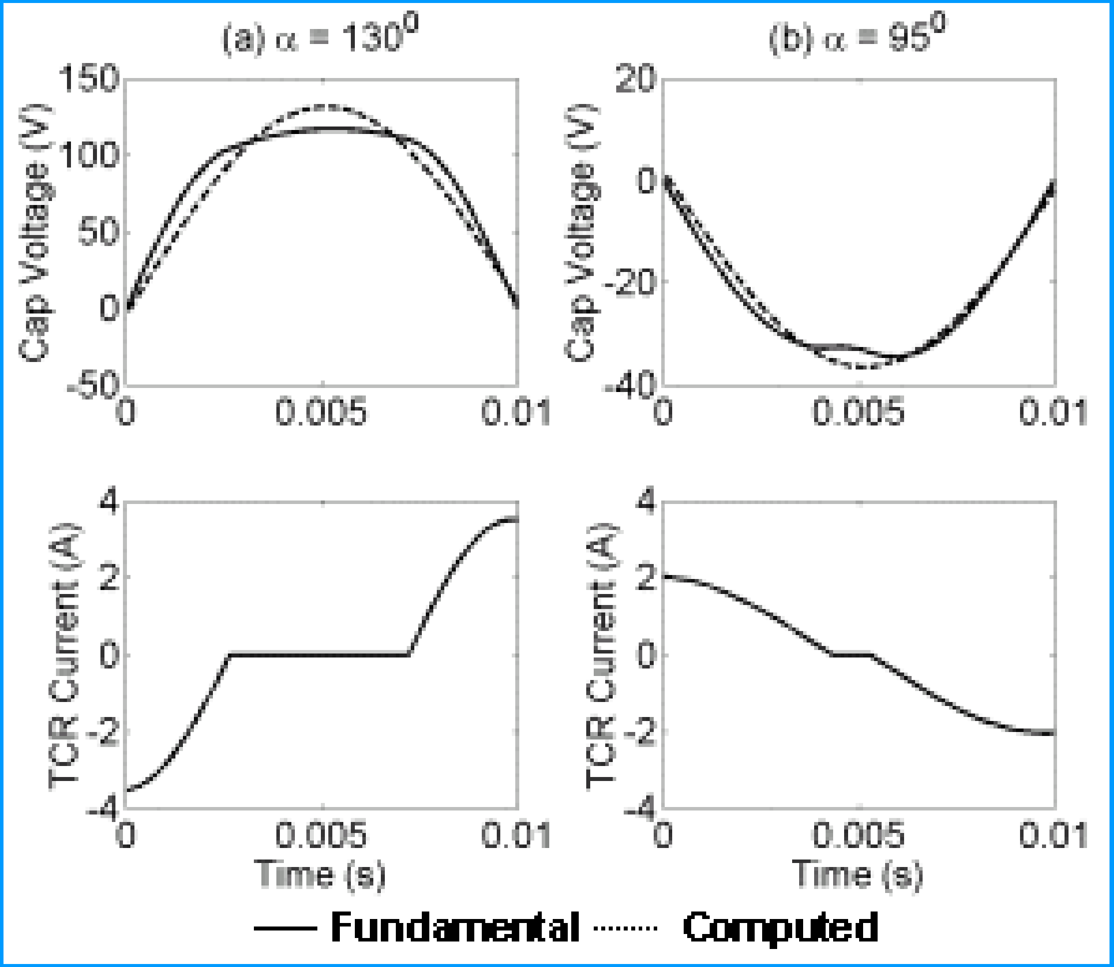


TCSC - Fundamental Impedance Plots for Finite Q



- The fundamental reactance and resistance change with the quality factor of the coil.
- The above design curves can be used for characterizing the TCSC.

TCSC Waveforms for Finite Q Factor



TCSC Control

A TCSC can be controlled in three modes.

Blocking Mode:

- The thyristors are not gated (i.e., the TCR is blocked).
- The line current passes through the capacitor.
- The TCSC performs the task of a fixed series capacitor.

Bypass Mode:

- The thyristors are gated for full conduction of inductor current.
- The TCSC behaves as a parallel of fixed capacitor and inductor.

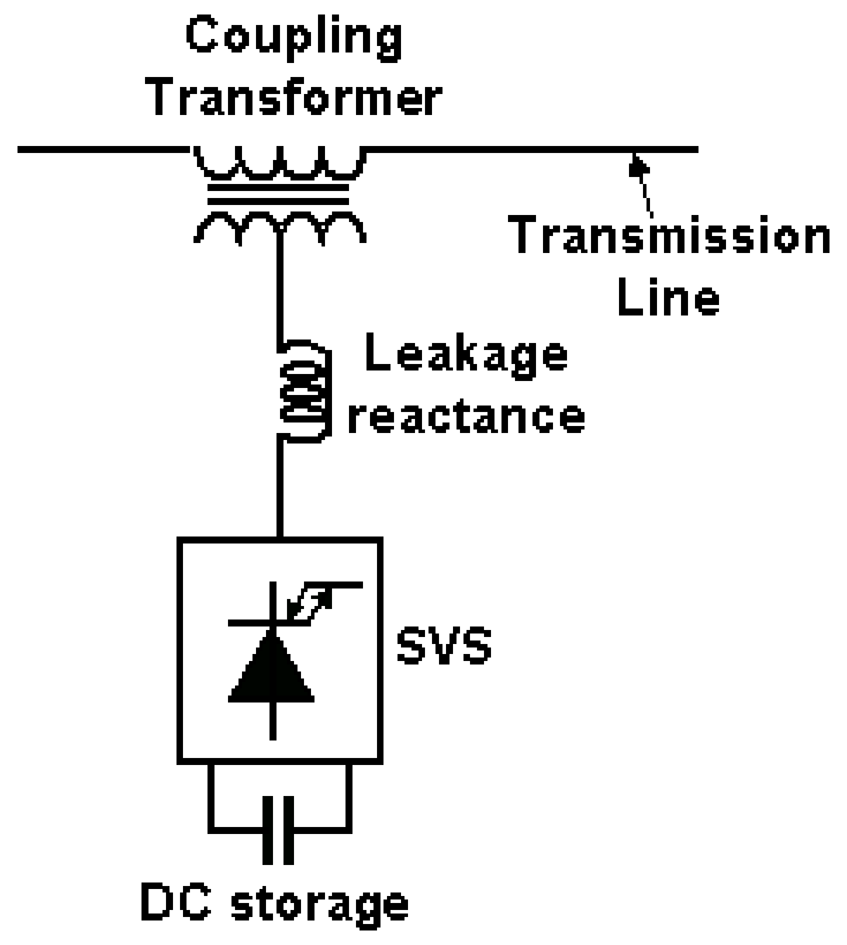
Bypass Mode (continued):

- The capacitor voltage is less for a given line current.
- Therefore this mode is utilized to reduce capacitor stress during faults.

Vernier Control Mode:

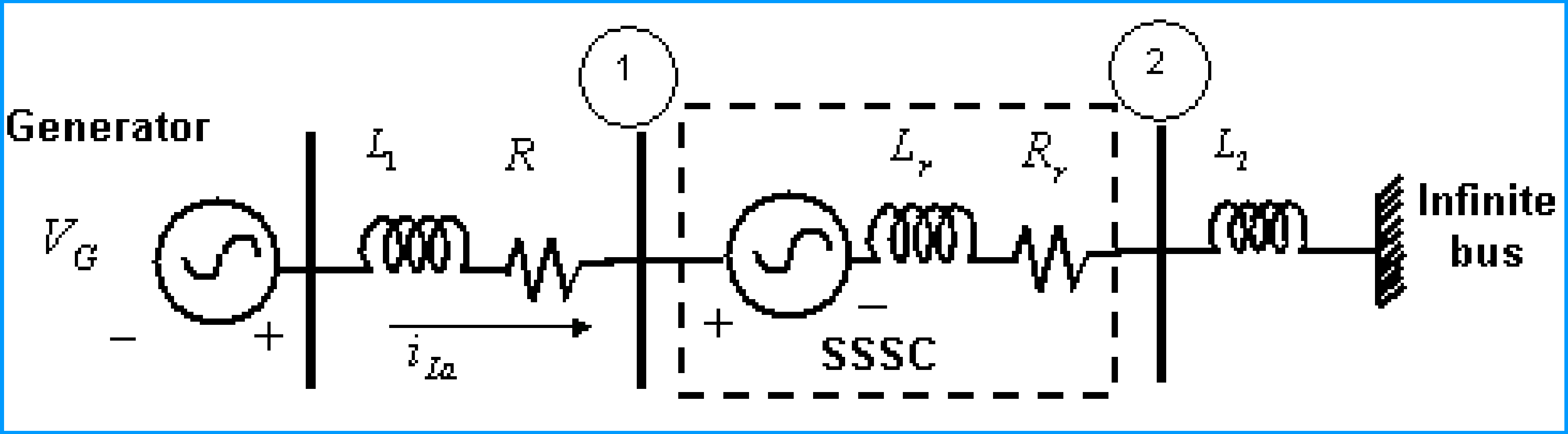
- The conducting angle of the TCSC is continuously varied to operate in either capacitive boost or inductive boost modes.
- In this mode the TCSC follows the fundamental reactance curve shown earlier.

Static Synchronous Series Compensator (SSSC)



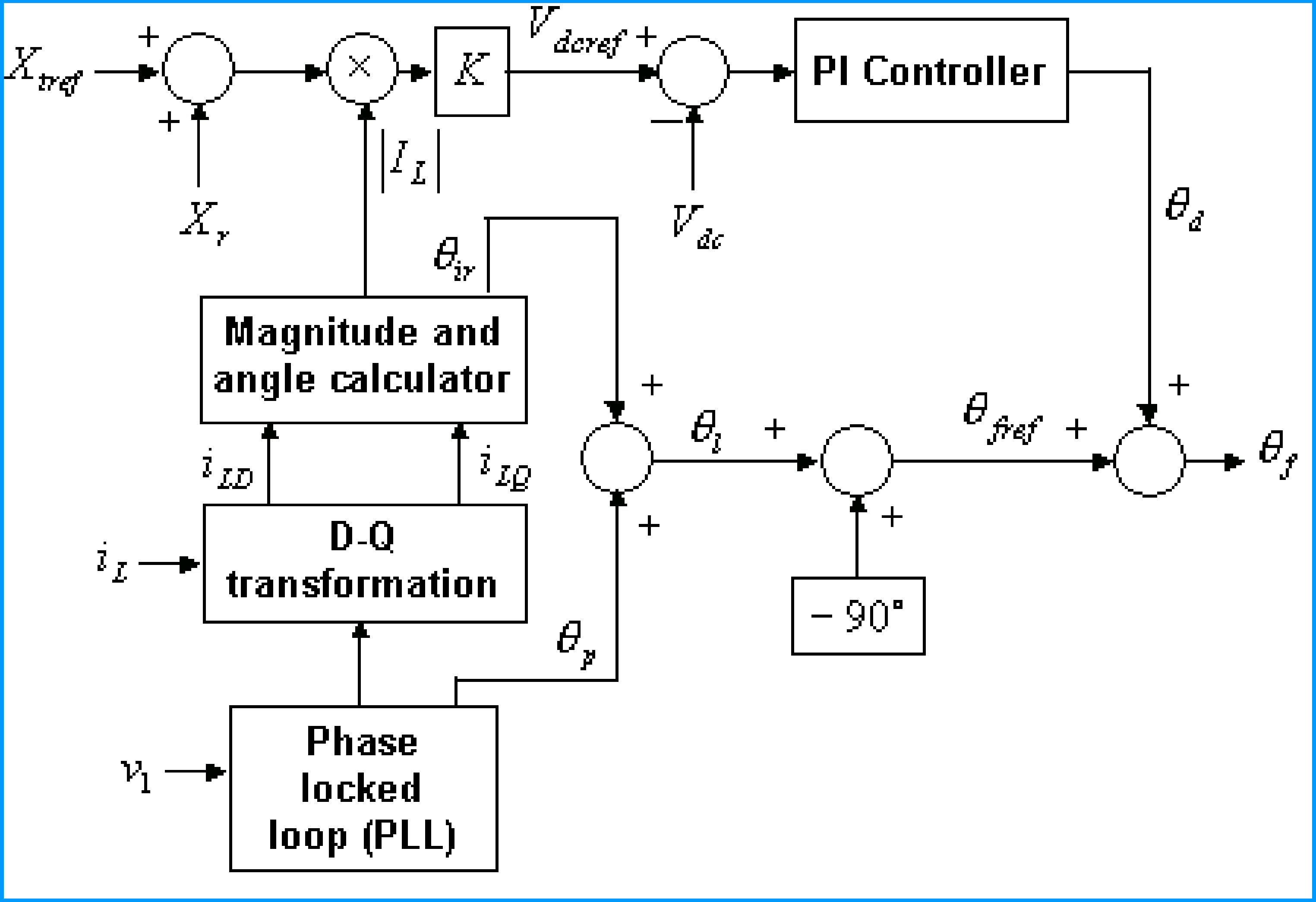
- An SSSC contains an SVS and a coupling transformer that is connected in series with the line.
- The SSSC is operated such that the injected voltage is almost in phase quadrature with the line current.

Equivalent Circuit of SSSC Compensated System



- In the equivalent circuit of an SSSC compensated system, the SSSC is represented by a voltage source and impedance (L_r,R_r).
- The SSSC is connected between buses 1 and 2.
- The pair (L_1,R) represent the line and L_2 represents a transformer.

SSSC Control



SSSC Control

- An instantaneous 3-phase set of line voltages at bus 1 is used to calculate the angle θ that is phase locked to the phase-a of the line voltage.
- An instantaneous 3-phase set of measured line currents is first decomposed into real and reactive components.
- The amplitude and the relative angle of the line current θ_{ir} are then calculated.
- The phase locked angle θ_p and θ_{ir} are added to obtain the angle θ_i which is the angle of the line current.

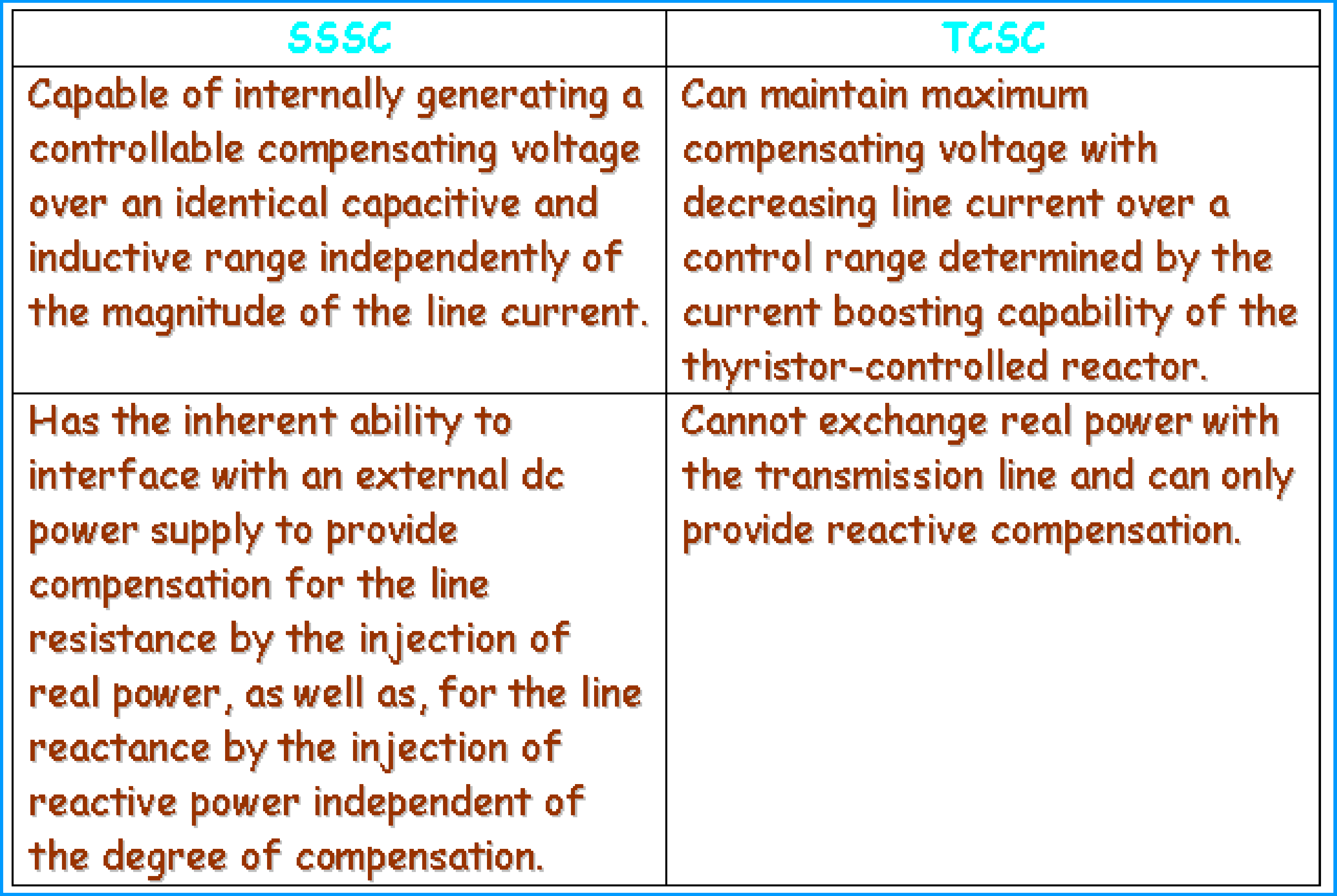
SSSC Control

- The are two control loops.
- Since the SSSC voltage must lag the line current by 90°, a fixed angle equal to -90° is added to θ_l to obtain θ_{fref} in the main loop.
- In the auxiliary loop, the reactance demand X_{tref} is added to X_r of SSSC.
- The sum is multiplied by the magnitude of the line current and a constant to obtain V_{dcref}.
- The error between V_{dcref} and the actual value of V_{dc} is passed through a PI controller to obtain θ_d.
- This quantity is then added to θ_{fref} to obtain θ_f of the inverter.

SSSC Control

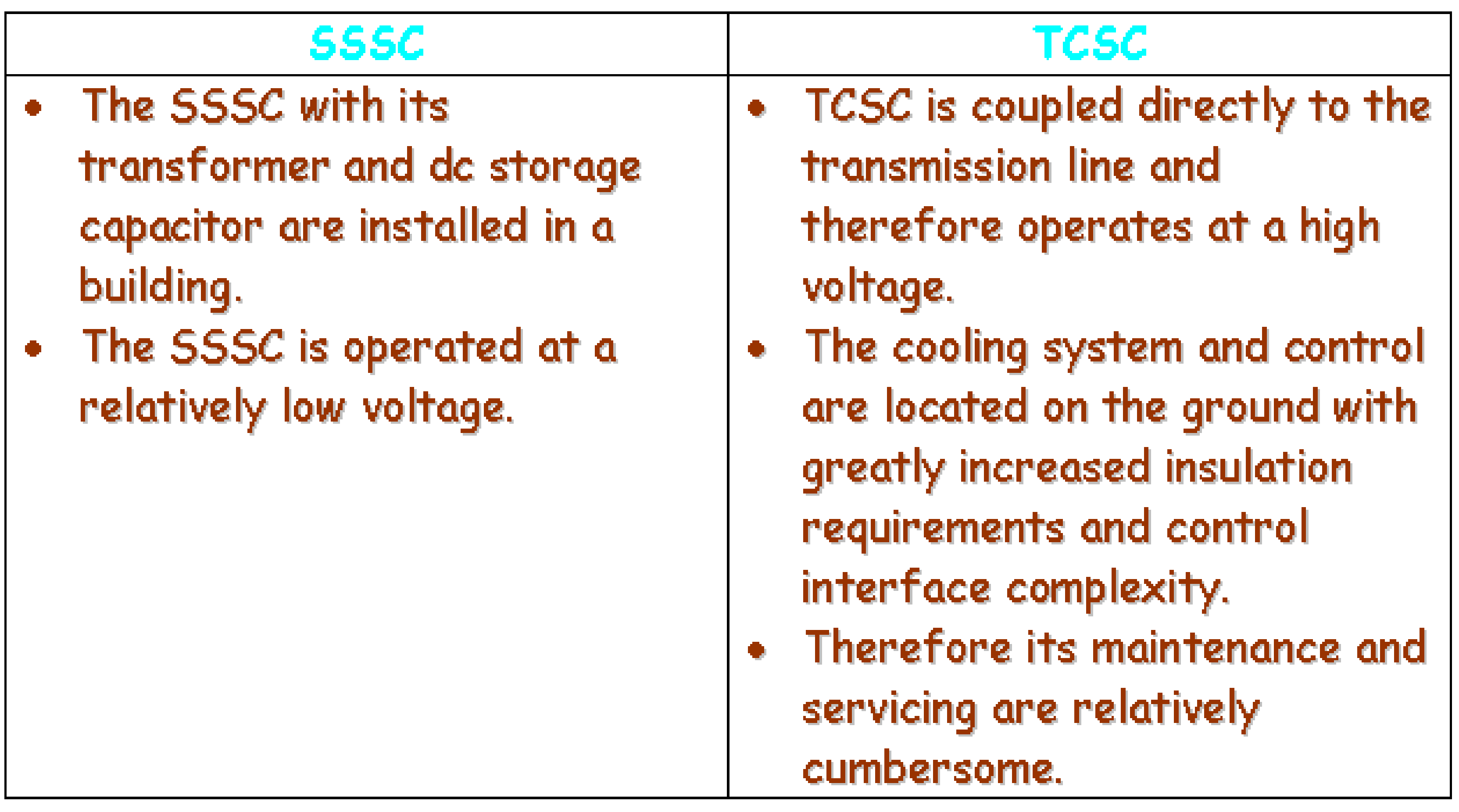
- The PI controller retains the charge on the dc capacitor by injecting a voltage nearly in quadrature with the line current.
- The real power exchange between the ac system and SSSC takes place if the injected voltage is not in quadrature with the line current, which either charges or discharges the dc capacitor.
- The PI controller then advances or retards the phase of the injected voltage relative to line current in order to adjust the power at ac terminals and keep the dc voltage constant.

Comparison Between SSSC and TCSC



SSSC	TCSC
Capable of internally generating a controllable compensating voltage over an identical capacitive and inductive range independently of the magnitude of the line current.	Can maintain maximum compensating voltage with decreasing line current over a control range determined by the current boosting capability of the thyristor-controlled reactor.
Has the inherent ability to interface with an external dc power supply to provide compensation for the line resistance by the injection of real power, as well as, for the line reactance by the injection of reactive power independent of the degree of compensation.	Cannot exchange real power with the transmission line and can only provide reactive compensation.

Comparison (Continued)



SSSC	TCSC
- The SSSC with its transformer and dc storage capacitor are installed in a building. - The SSSC is operated at a relatively low voltage.	- TCSC is coupled directly to the transmission line and therefore operates at a high voltage. - The cooling system and control are located on the ground with greatly increased insulation requirements and control interface complexity. - Therefore its maintenance and servicing are relatively cumbersome.

Comparison (Continued)

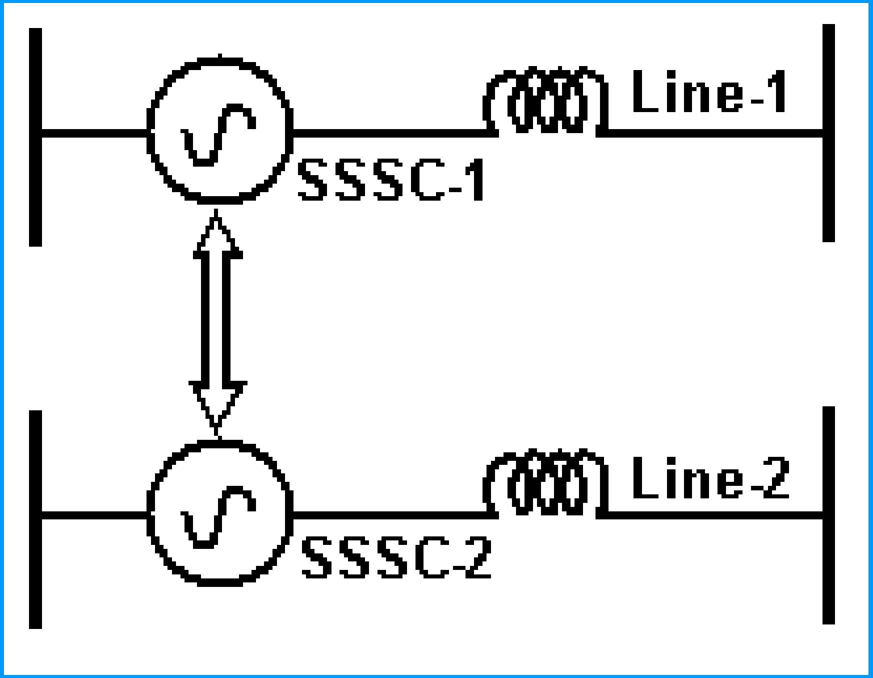
SSSC	TCSC
The SSSC is more effective in power oscillation damping. This is achieved by modulating the series reactive compensation to increase and decrease the transmitted power, and by concurrently injecting an alternating virtual positive and negative real impedance to absorb and supply real power from the line in sympathy with the prevalent machine swings.	The TCSC can damp oscillation only by modulating the reactive compensation thereby affecting the transmitted power.
SSSC uses GTO thyristors, which have lower voltage and current ratings. Their short-term surge current rating capacity is low. They may need external fast protection during severe line faults by an auxiliary conventional thyristor bypass switch.	TCSC employs conventional thyristors with no internal turn-off capability. These thyristors are available with the highest current and voltage ratings, and they have the highest surge current capability.

Other FACTS Controllers

There are many other FACTS controllers that use the power electronic technology. We shall briefly discuss the following:

- Interline Power Flow Controller (IPFC)
- Thyristor Controlled Braking Resistor (TCBR)
- Thyristor Controlled Phase Angle Regulator (TCPAR)
- Unified Power Flow Controller (UPFC)

Interline Power Flow Controller (IPFC)



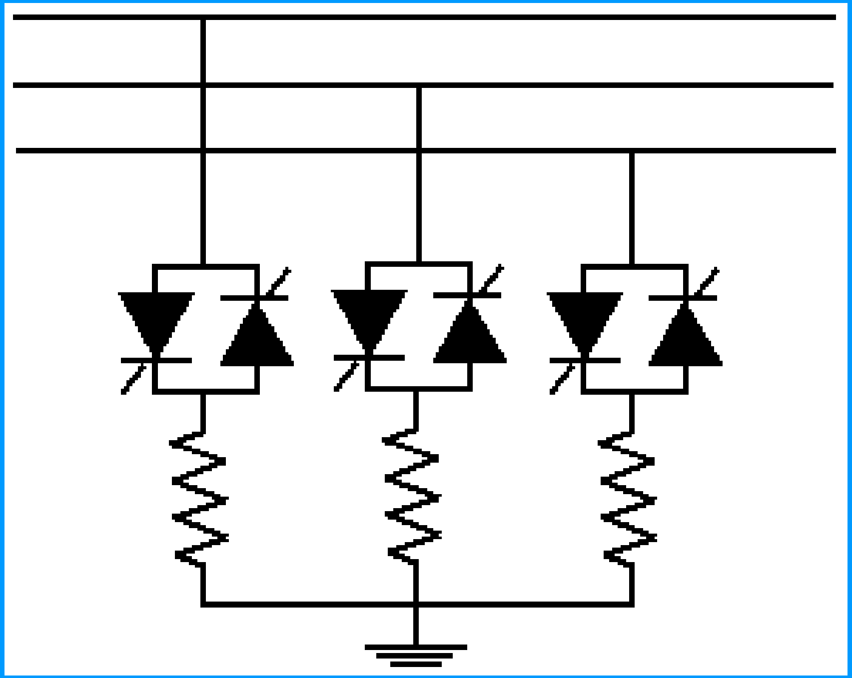
An IPFC contains two or more SSSCs that are connected to a common dc bus to facilitate real power exchange between them.

IPFC (Continued)

- Each individual SSSC can provide controllable series compensation to the line it is connected.
- In addition, it can also exchange power between them.
- Example: Assume that Line-1 is lightly loaded while Line-2 is heavily loaded.
- SSSC-1 then absorbs power to charge the dc capacitor.
- SSSC-2 is then supplied real power by the dc capacitor.
- In this way the load sharing between the lines can be equalized.

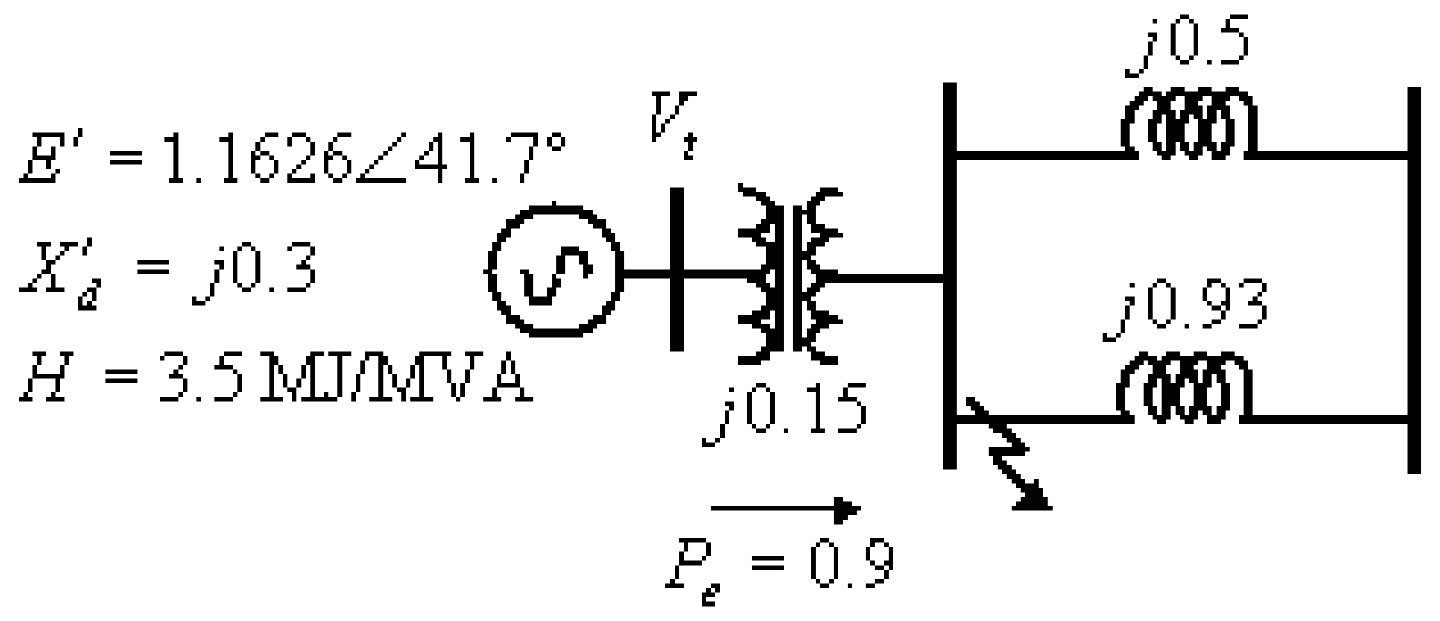
Thyristor Controlled Braking Resistor

This is a shunt connected thyristor switched resistor, which is used for minimizing the power acceleration during a fault.



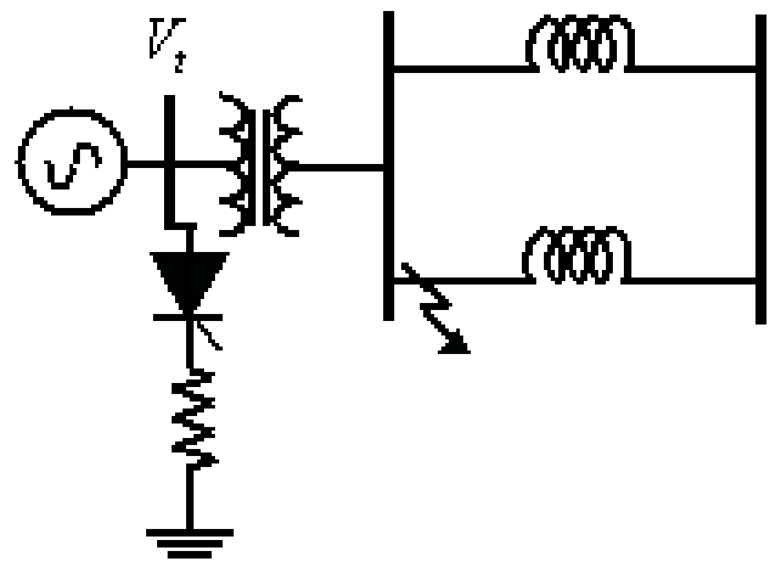
- In the schematic diagram, the thyristors are usually blocked.
- They are switched on when a fault is detected.

Braking Resistor



For the system shown above, the critical clearing angle is computed to be 52.24°. We shall now place a dynamic brake at the generator terminals.

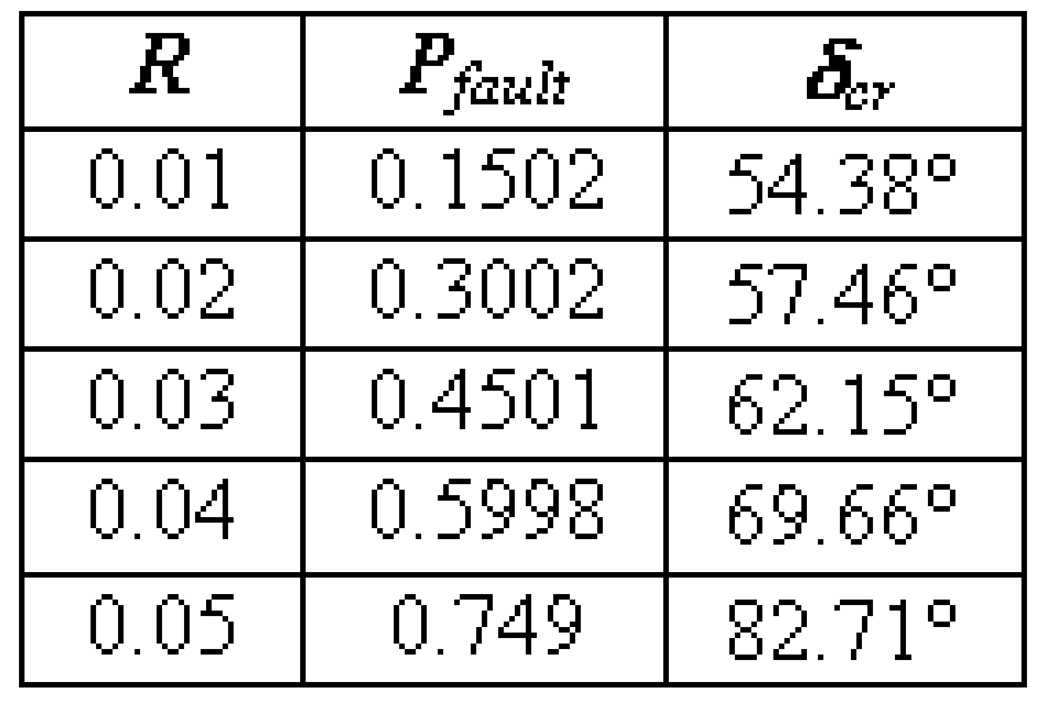
Braking Resistor



We assume that the braking resistor is pressed into service as soon as the fault occurs and is removed as soon as the fault is cleared. Then

$$P_e = \mathrm{Re}\{(E'\angle\delta)I^*\} \approx \frac{E'^2}{10R}$$

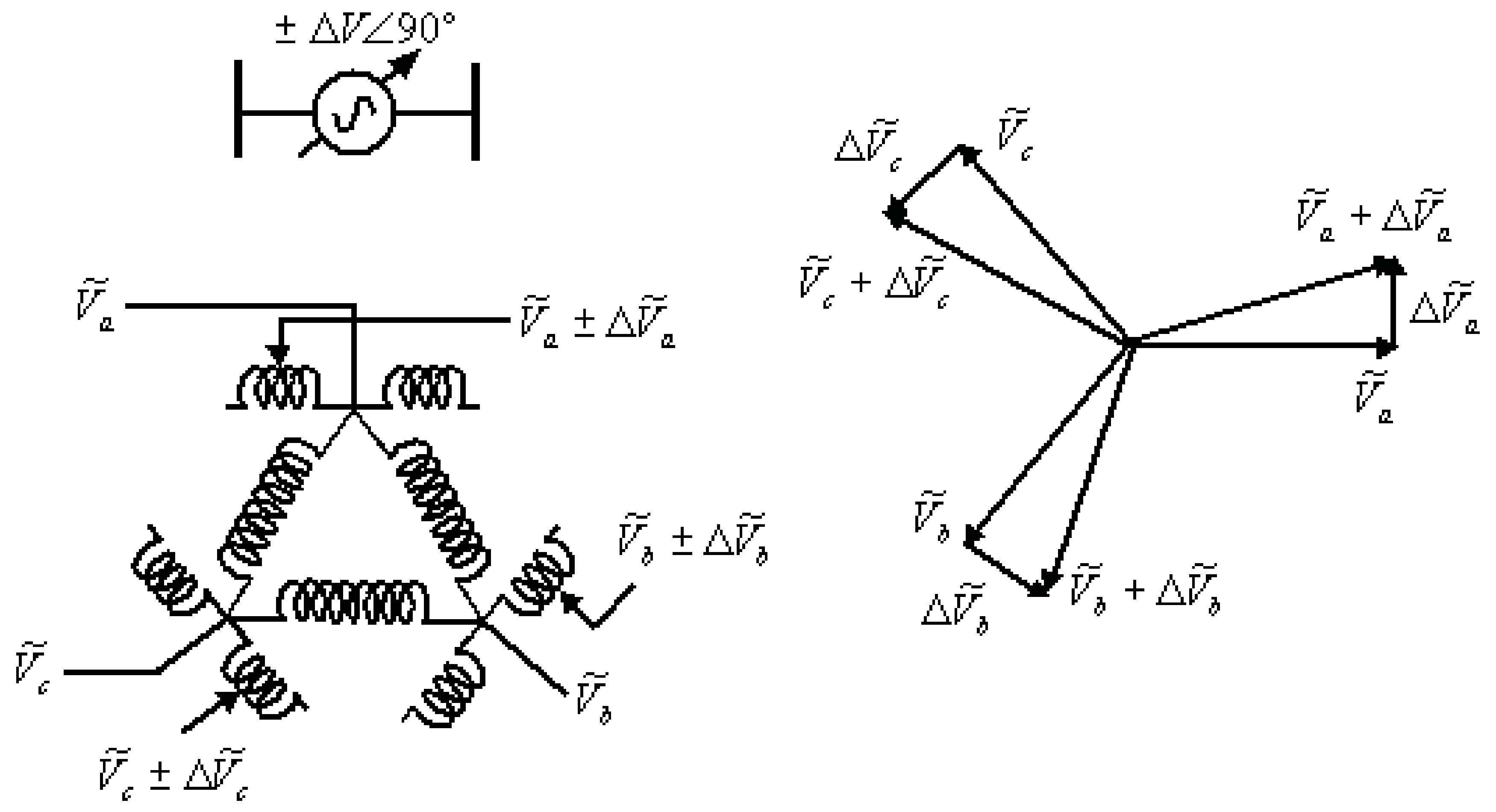
Braking Resistor



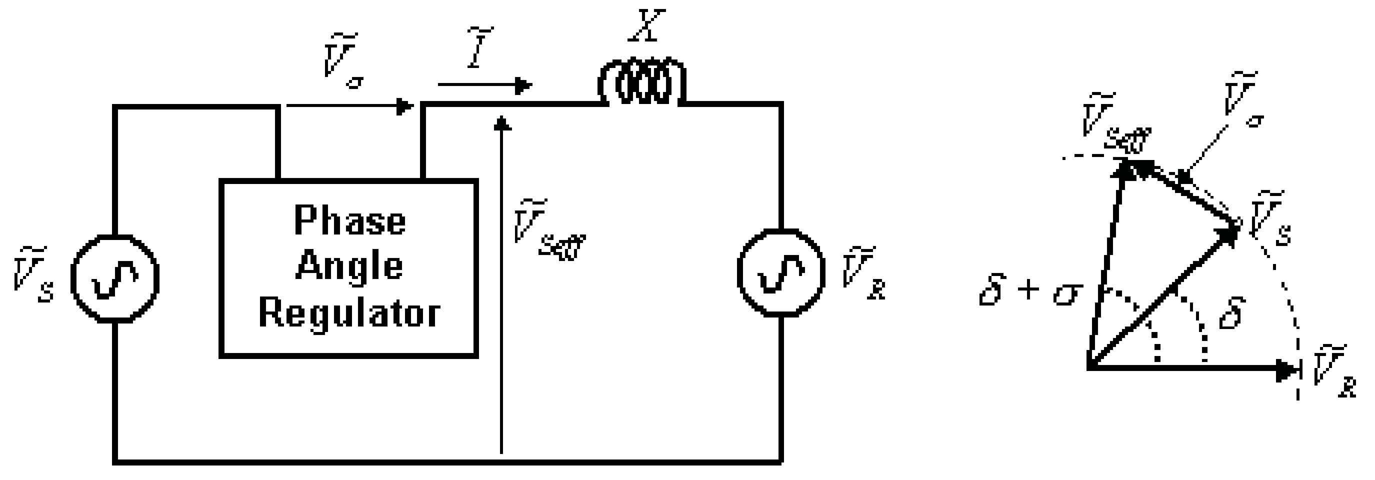
R	P_{fault}	δ_{cr}
0.01	0.1502	54.38°
0.02	0.3002	57.46°
0.03	0.4501	62.15°
0.04	0.5998	69.66°
0.05	0.749	82.71°

It can be seen that the critical clearing angle increases with the increase in the value of the resistor.

Phase Angle Regulator (PAR)

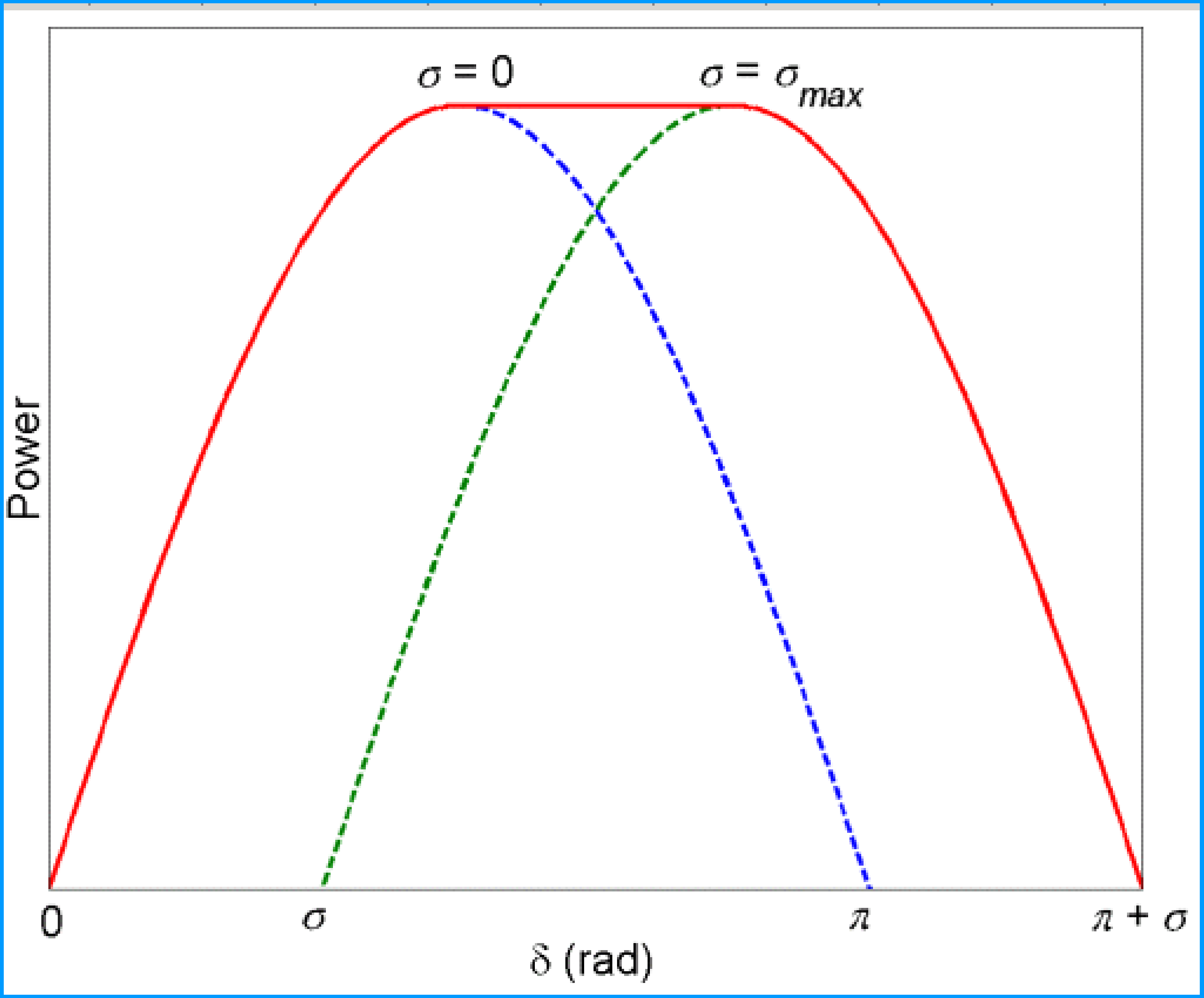


PAR - Operation

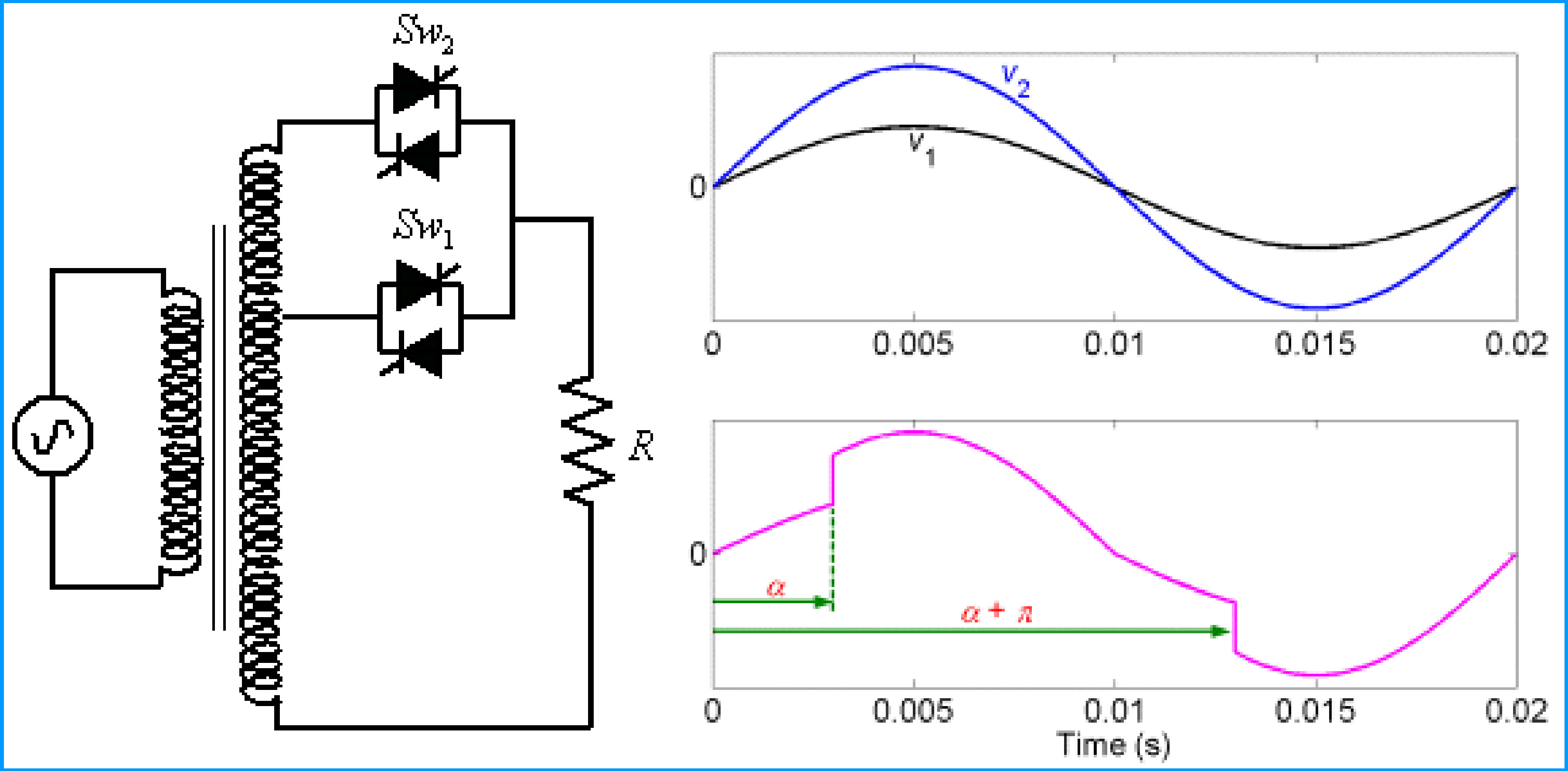


- The PAR is inserted between the sending end and transmission line.
- It is a sinusoidal voltage source with controllable amplitude.
- For an ideal PAR the angle of the phasor V_σ is stipulated to vary such that the magnitude of V_{seff} remains constant.

PAR - Power-Angle Curve



PAR - Phase Shifting



Assume that a resistive load is connected at the output.

PAR - Phase Shifting

The voltages obtained at the lower and upper taps are v_1 and v_2 respectively.

- At the zero crossing of these voltages, the switch Sw_1 is turned on.
- At α the switch Sw_2 is turned on.
- This commutates the current of Sw_1 by forcing a negative anode to cathode voltage across it, thereby making the voltage across the load v_2.
- The switch Sw_2 turns off when the current through it reverses.

PAR - Phase Shifting

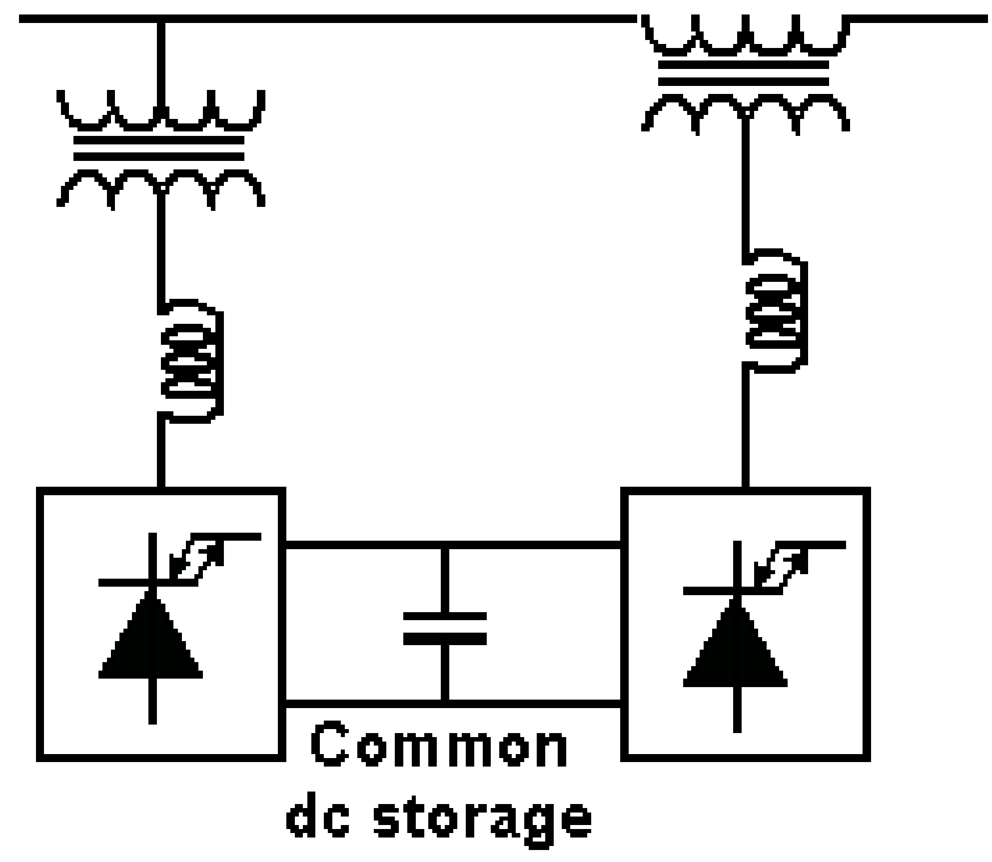
The voltage thus obtained contains harmonics. The fundamental component of the voltage is given by

$$\tilde{V}_0 = \sqrt{a^2 + b^2} \angle \tan^{-1}\left(\frac{a}{b}\right)$$

$$a = \frac{\left|\tilde{V}_2\right| - \left|\tilde{V}_1\right|}{2\pi}(\cos 2\alpha - 1), \quad b = \left|\tilde{V}_1\right| + \frac{\left|\tilde{V}_2\right| - \left|\tilde{V}_1\right|}{2\pi}\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)$$

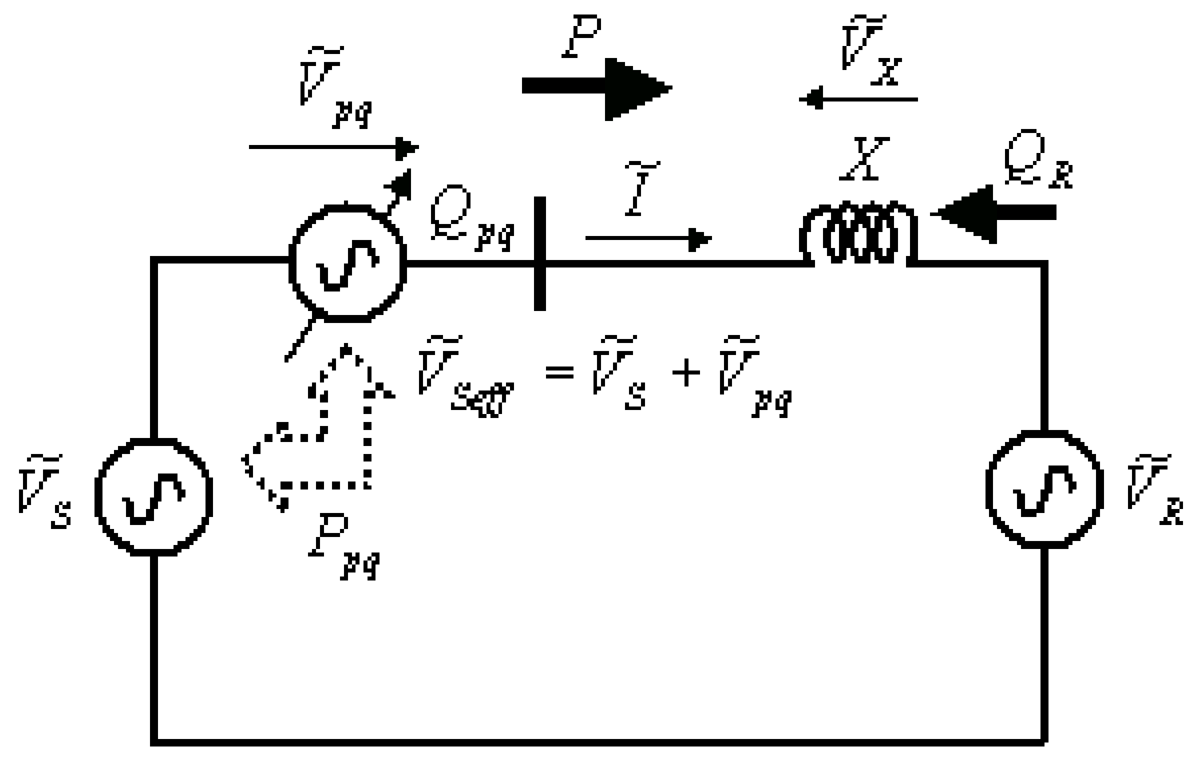
We can therefore vary the fundamental voltage by varying the delay angle α.

Unified Power Flow Controller (UPFC)



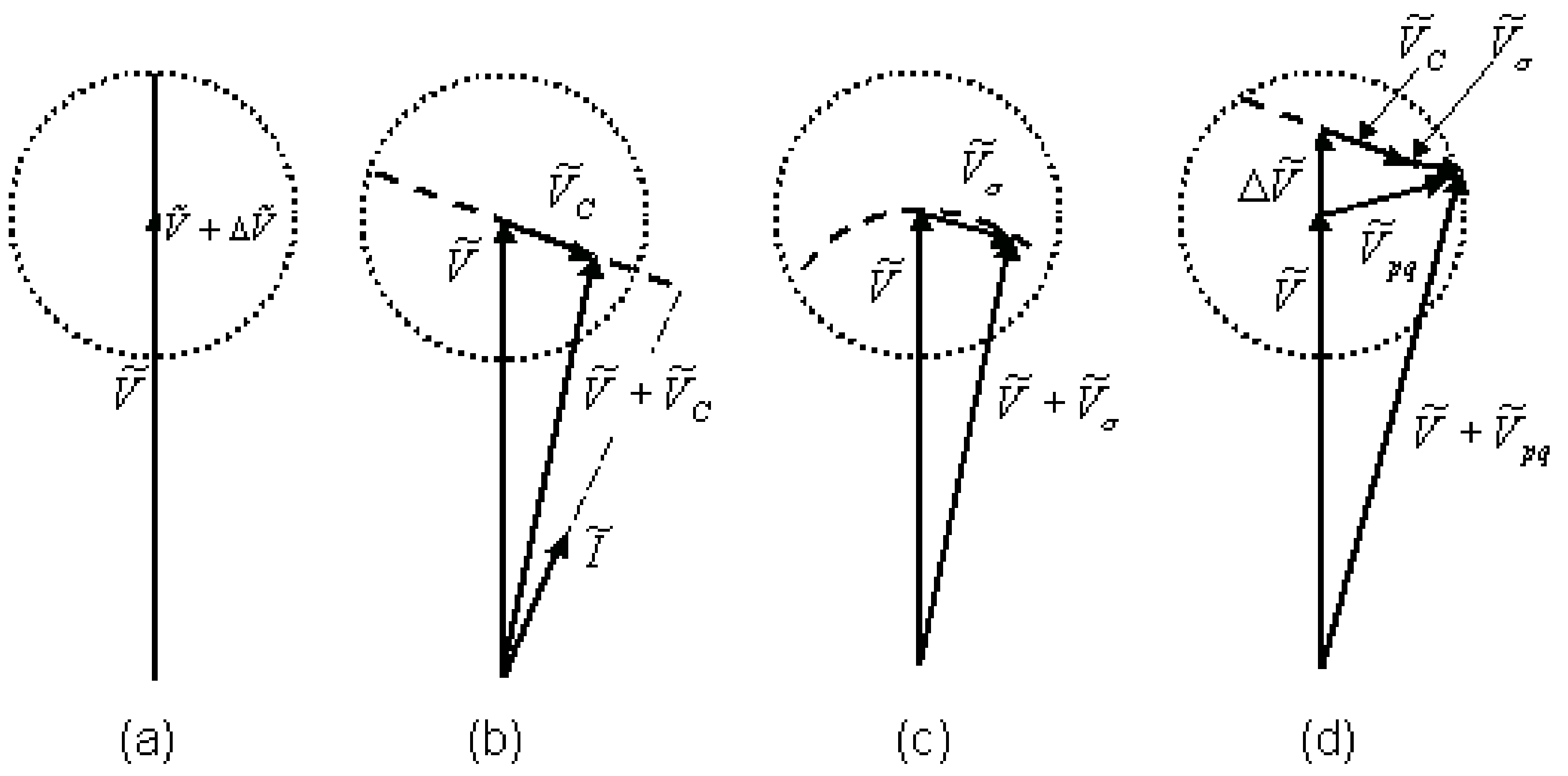
- A UPFC contains a shunt SVS and a series SVS that are connected to a common dc bus such that real power exchange can take place between them.

UPFC - Equivalent Circuit



The term P_{pq} indicates real power exchange between the shunt and series branches.

UPFC - Phasor Diagrams



(a) Voltage Regulation, (b) Line impedance compensation, (c) Phase shifting and (d) simultaneous control.

UPFC - Real & Reactive Power

Let

$$\tilde{V}_S = V\angle 0°, \quad \tilde{V}_R = V\angle -\delta, \quad \tilde{V}_{pq} = V_{pq}\angle -\rho$$

Then for the uncompensated system ($V_{pq} = 0$) we have

$$P = P_0 = \frac{V^2}{X}\sin\delta$$

$$Q_R = -Q_0 = \frac{V^2}{X}\left(\cos\delta - 1\right)$$

UPFC - Real & Reactive Power

For the compensated system

$$P - jQ_R = V\angle -\delta \left[\frac{V - V\angle -\delta + V_{pq}\angle -\rho}{jX} \right]^*$$

Solving we get

$$P = P_0 - \frac{VV_{pq}}{X}\sin(\delta - \rho)$$

$$Q_R = Q_0 - \frac{VV_{pq}}{X}\cos(\delta - \rho)$$

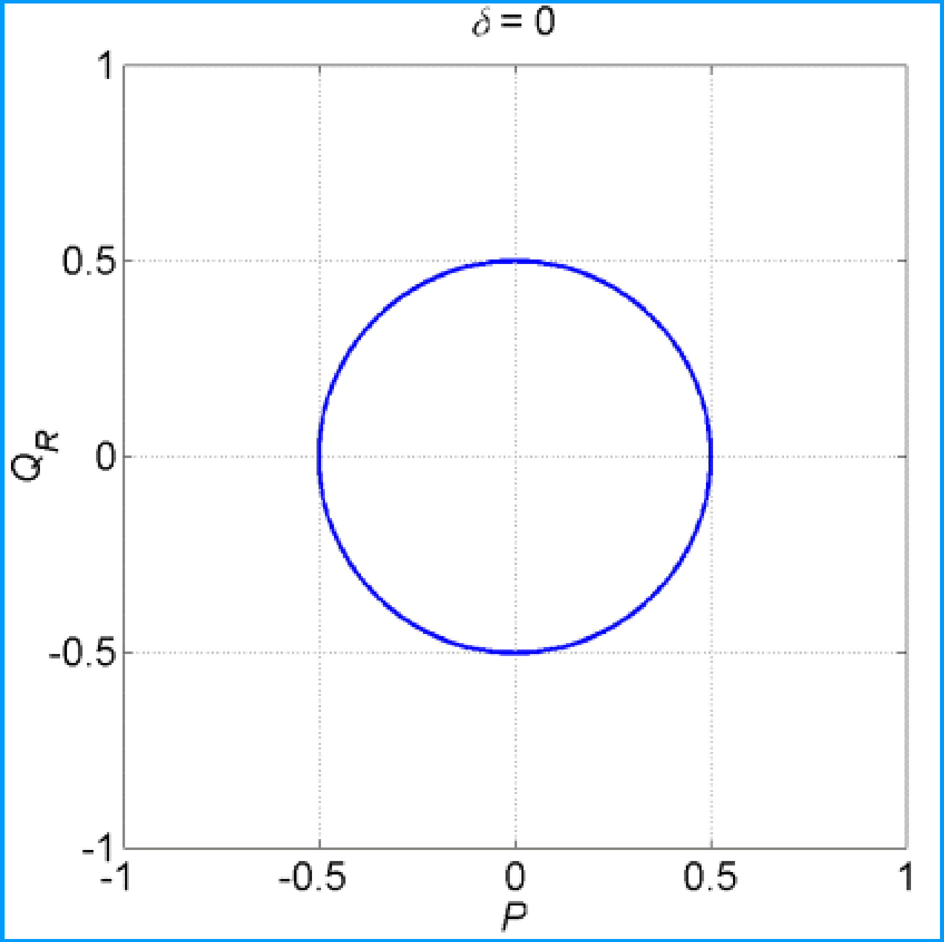
UPFC - Real & Reactive Power

Then

$$\left(P - P_0\right)^2 + \left(Q_R - Q_0\right)^2 = \left(\frac{VV_{pq}}{X}\right)^2$$

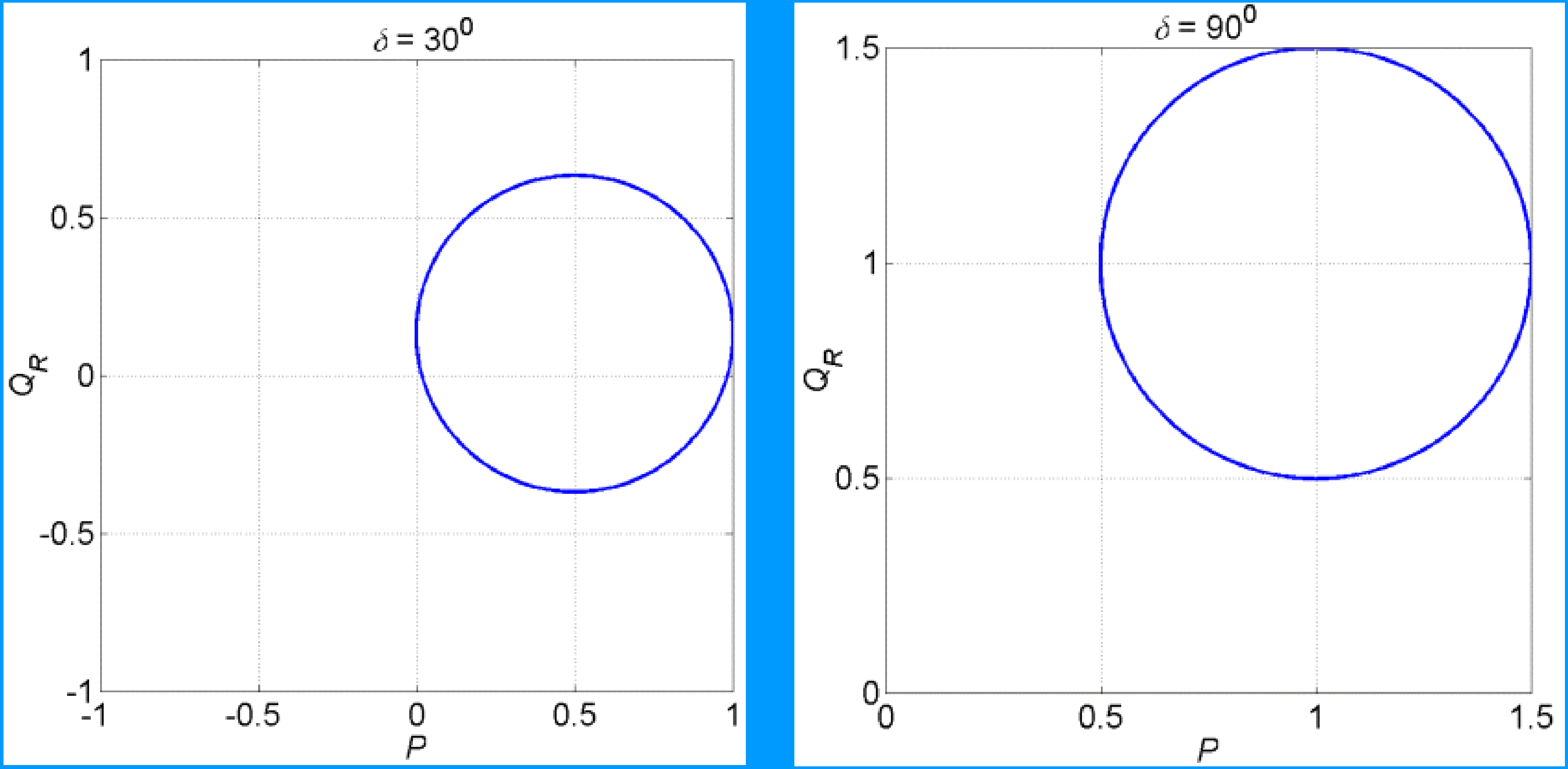
- This is the equation of circle with its center at P_0, Q_0 and radius of VV_{pq}/X.
- Suppose $V^2/X = 1.0$ and $V_{pq} = 0.5\,V$.
- Then $VV_{pq}/X = 0.5$.

Real Versus Reactive Power



- Even though the uncompensated system cannot transfer any power in this case, the UPFC is capable of transmitting power in either direction.

Real Versus Reactive Power



Real vs Reactive Power

- The figures show that the UPFC has the unique capability to control independently the real and reactive power flow at any transmission angle.
- It is however assumed here that the sending and receiving end voltages are provided by independent power systems which are able to supply and absorb real power without any internal angular change.
- In practice the situation will be different depending on the change in load angle.