Applications of Power Electronics to Power Transmission & Distribution Systems

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Lecture Schedule

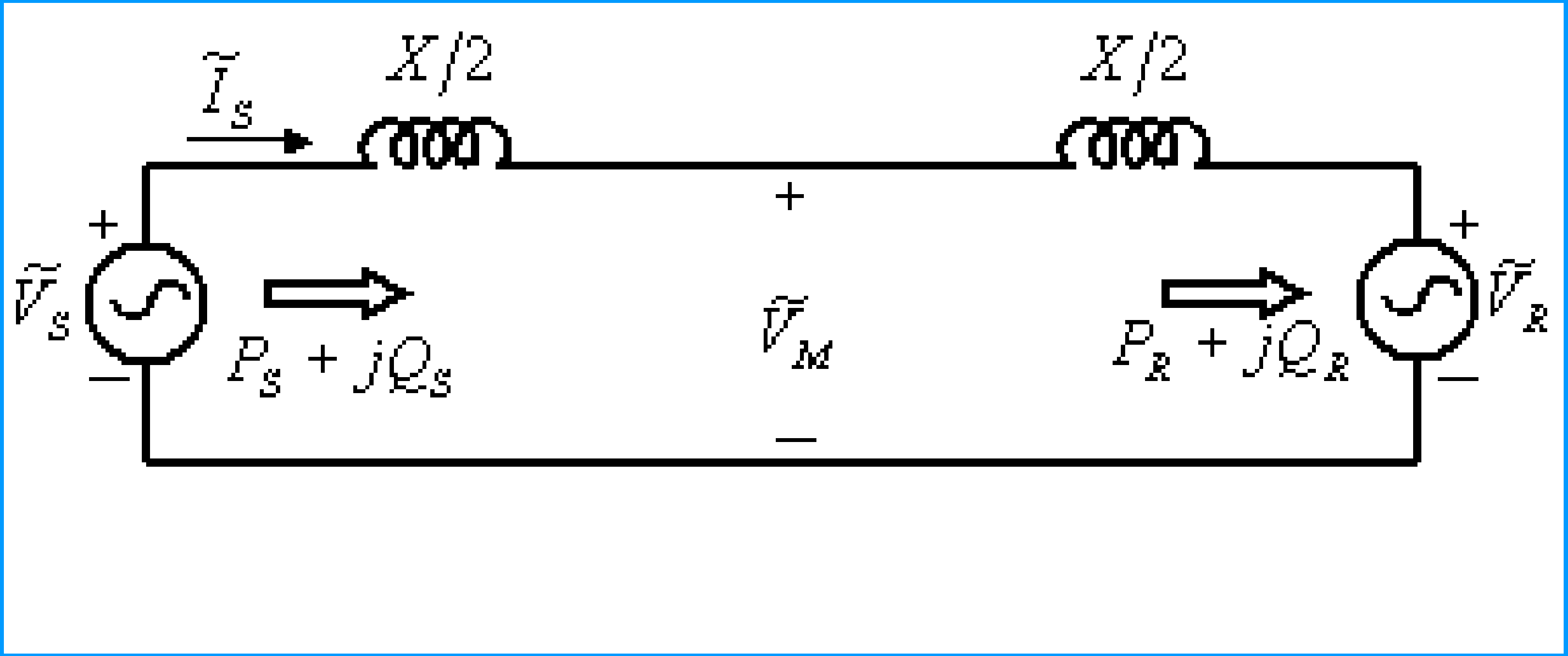
- Day 1: Problems with bulk power transmission & shunt compensation of transmission systems.
- Day2: Series compensation of transmission systems & other FACTS controllers.
- Day 3: Power quality, custom power & network reconfiguring devices.
- Day 4: Distribution STATCOM, Dynamic Voltage Restorer (DVR) & Unified Power Quality Conditioner (UPQC)

Power Transmission Line Characteristics

Transmission lines are represented by:

- Lumped parameter short lines (up to 50 mi).
- Medium lines represented by nominal-π or nominal-T models.
- Long lines represented by distributed parameter models.

Lossless Line Representation



$$\tilde{V}_S = \text{Source Voltage}, \tilde{V}_R = \text{Receiving Voltage},$$

$$\tilde{V}_M = \text{Midpoint Voltage}, X = \text{Total line reactance}$$

Power Flow Over Transmission Line

Let $\tilde{V}_S = V\angle\delta$ and $\tilde{V}_R = V\angle 0^{\text{o}}$

Then $\tilde{I}_S = \dfrac{V(\cos\delta - 1) + jV\sin\delta}{jX}$

We then have

$$P_S + jQ_S = \tilde{V}_S \tilde{I}_S^* = \frac{V^2\sin\delta + jV^2(1-\cos\delta)}{X}$$

Power Flow Over Transmission Line

Similarly

$$P_R - jQ_R = \tilde{V}_R^* \tilde{I}_S = \frac{V^2 \sin\delta - jV^2(\cos\delta - 1)}{X}$$

The real power over the line is

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

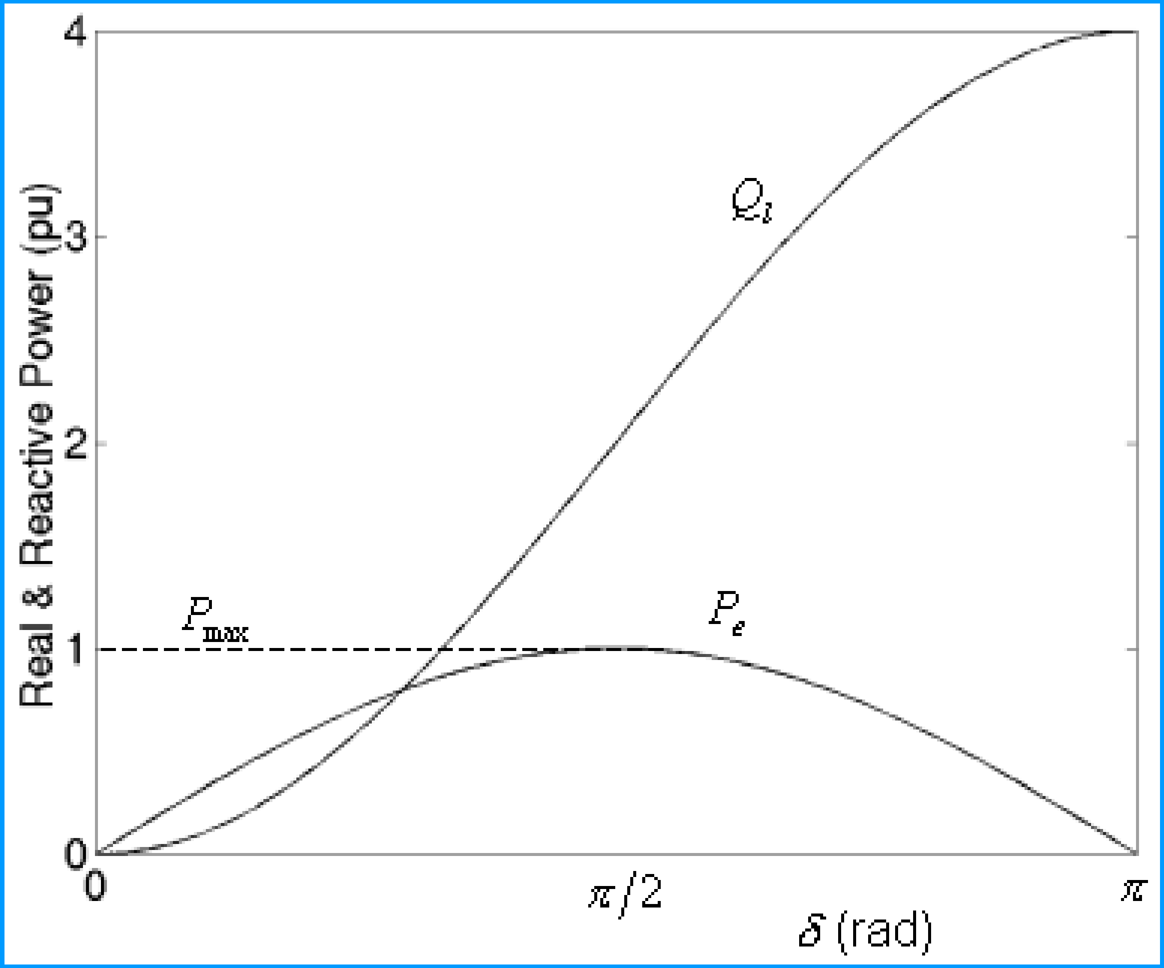
Power Flow Over Transmission Line

The reactive power absorbed by the line

$$Q_l = Q_S - Q_R = \frac{2V^2(1-\cos\delta)}{X}$$

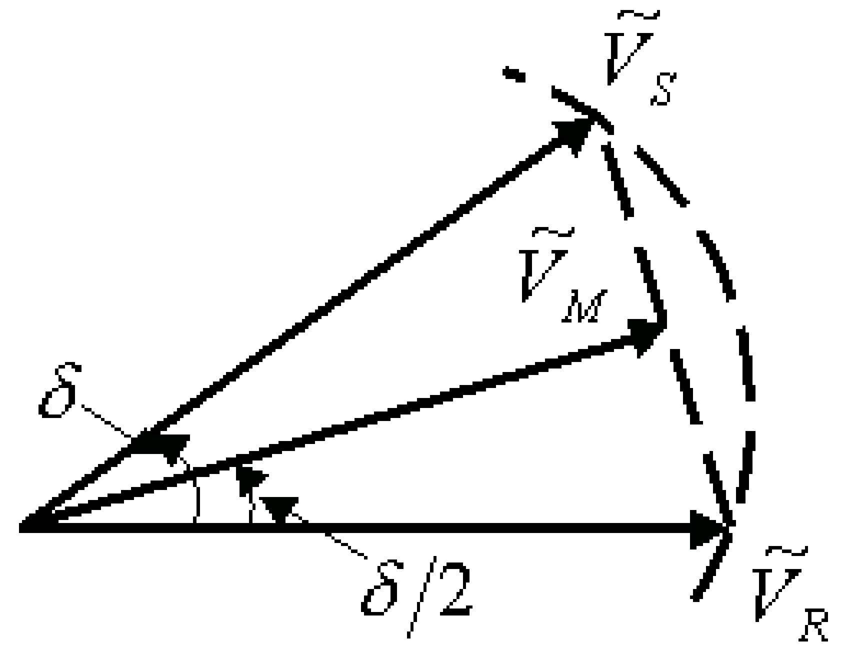
The power-angle curves are shown in the next slide. Note that we have assumed lumped parameter representation of the line. However, a similar pattern also occurs even when the line is modeled using distributed parameters.

Power-Angle Curves



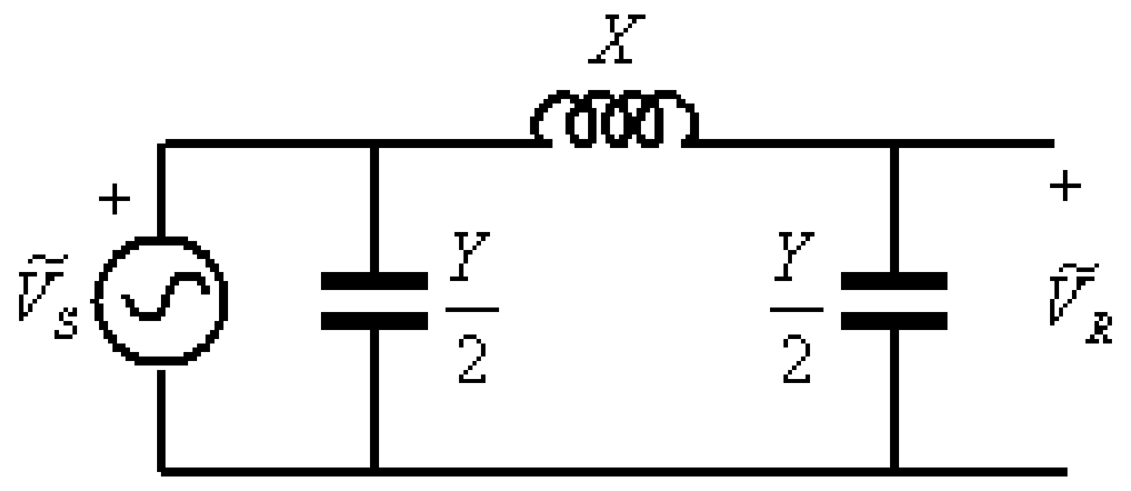
It is assumed that $P_{\max} = \dfrac{V^2}{X} = 1\,\text{pu}$

Midpoint Voltage Sag



$$\tilde{V}_M = V\cos\left(\delta/2\right)\angle\left(\delta/2\right)$$

Ferranti Effect



$$\tilde{V}_R = \frac{(2/Y)}{(2/Y) - X}\tilde{V}_S$$

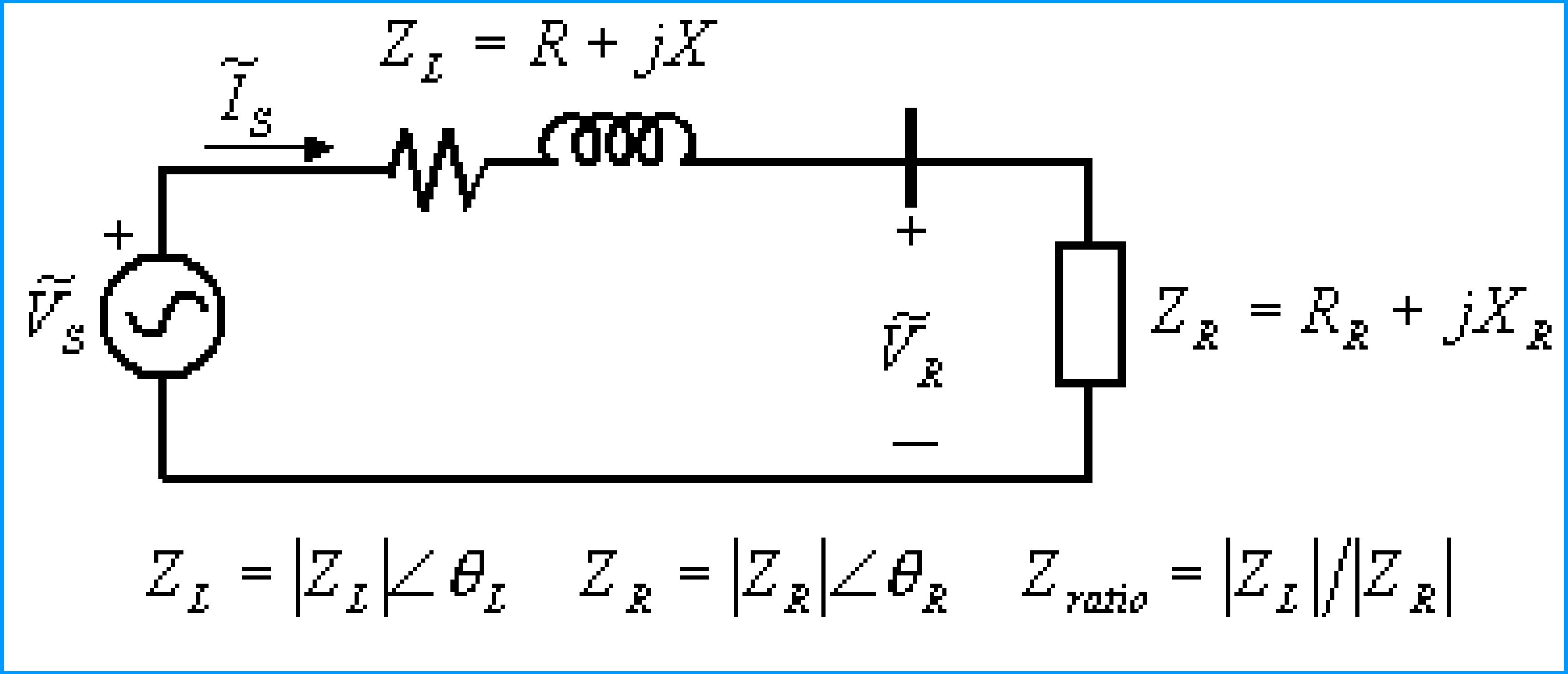
Ferranti Effect

In 500 km long line where per kilometer line reactance and admittance are 0.5145 ohm and 0.0000031734 mho, the receiving end voltage rises 25.64% above the sending end voltage under no-load (or even lightly loaded) condition. Also since the parameters X and Y depend on the line length, the receiving end voltage will be different for different line lengths. In fact the longer the line, the more is the voltage rise.

Voltage Stability

- ***Voltage stability*** is the ability of the power system to return to the nominal (pre-fault) voltages of all buses following a disturbance in the system.
- In addition, the system shall also be able to maintain the nominal voltage at buses in the steady state.
- Conversely, the voltage instability occurs when the voltages at different buses drop continuously following a disturbance or load change.

Voltage Stability



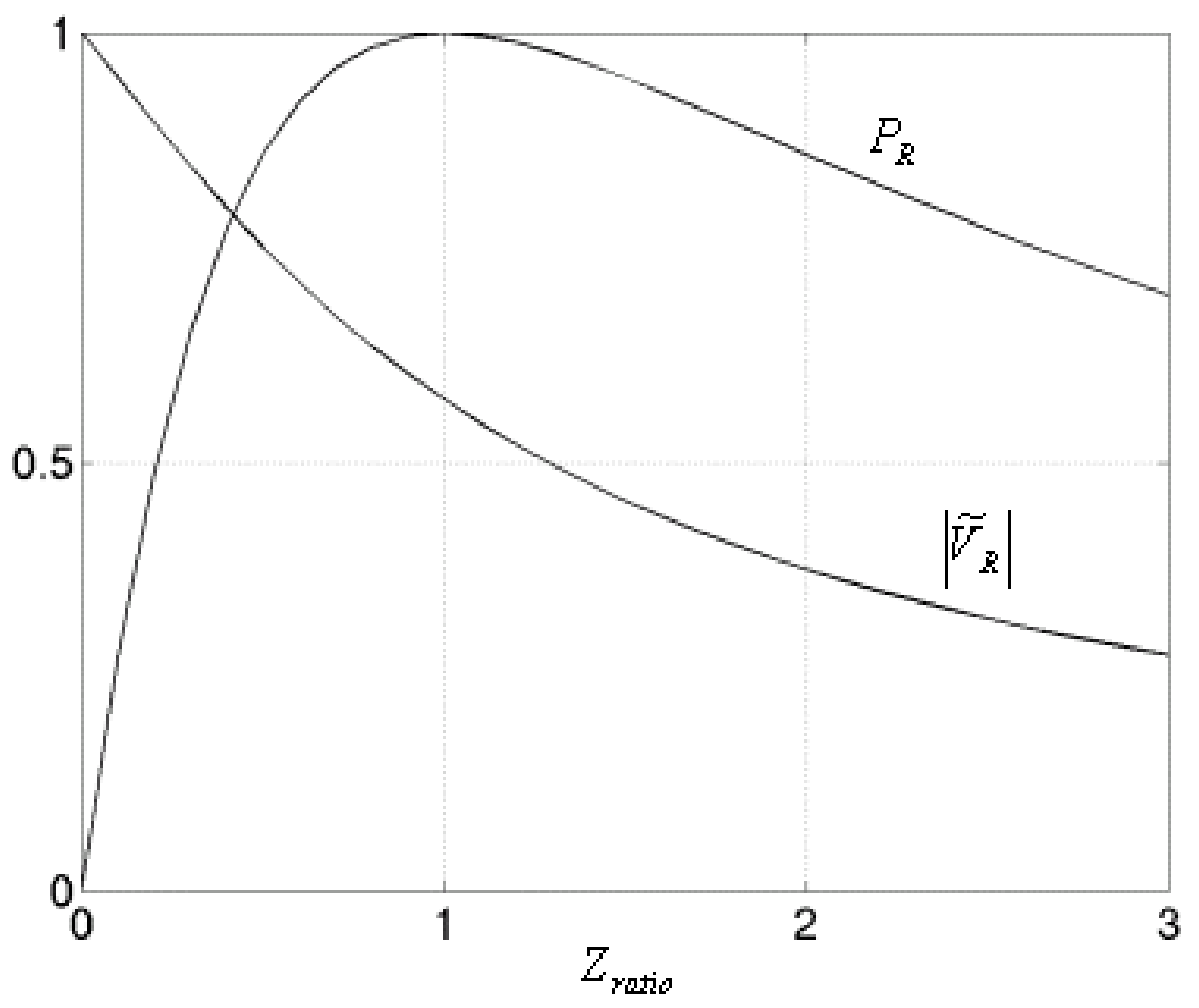
$$\tilde{V}_R = \frac{1}{1 + Z_{ratio}\angle(\theta_L - \theta_R)} \text{ pu when } \tilde{V}_S = 1\angle 0^{\circ}$$

Voltage Stability

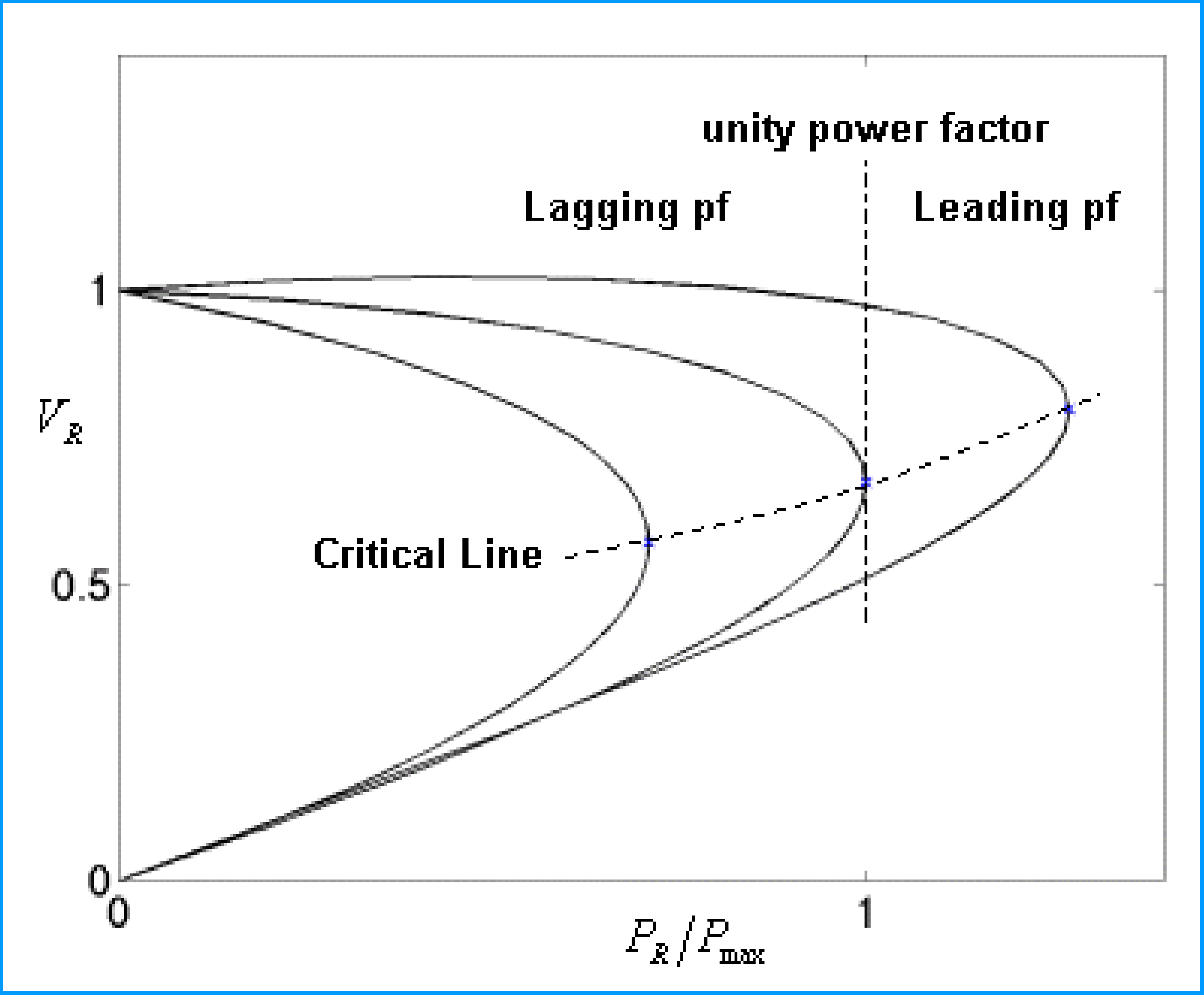
$$P_R = \frac{2Z_{ratio}^2\left\{1+\cos\left(\theta_R-\theta_L\right)\right\}}{1+Z_{ratio}^2+Z_{ratio}\cos\left(\theta_R-\theta_L\right)}$$

The transmission line impedance is fixed for a given line. Therefore Zratio decreases as the load impedance increases. The maximum power occurs when the load and line impedances are same. The power decreases after that and the voltage monotonically decreases.

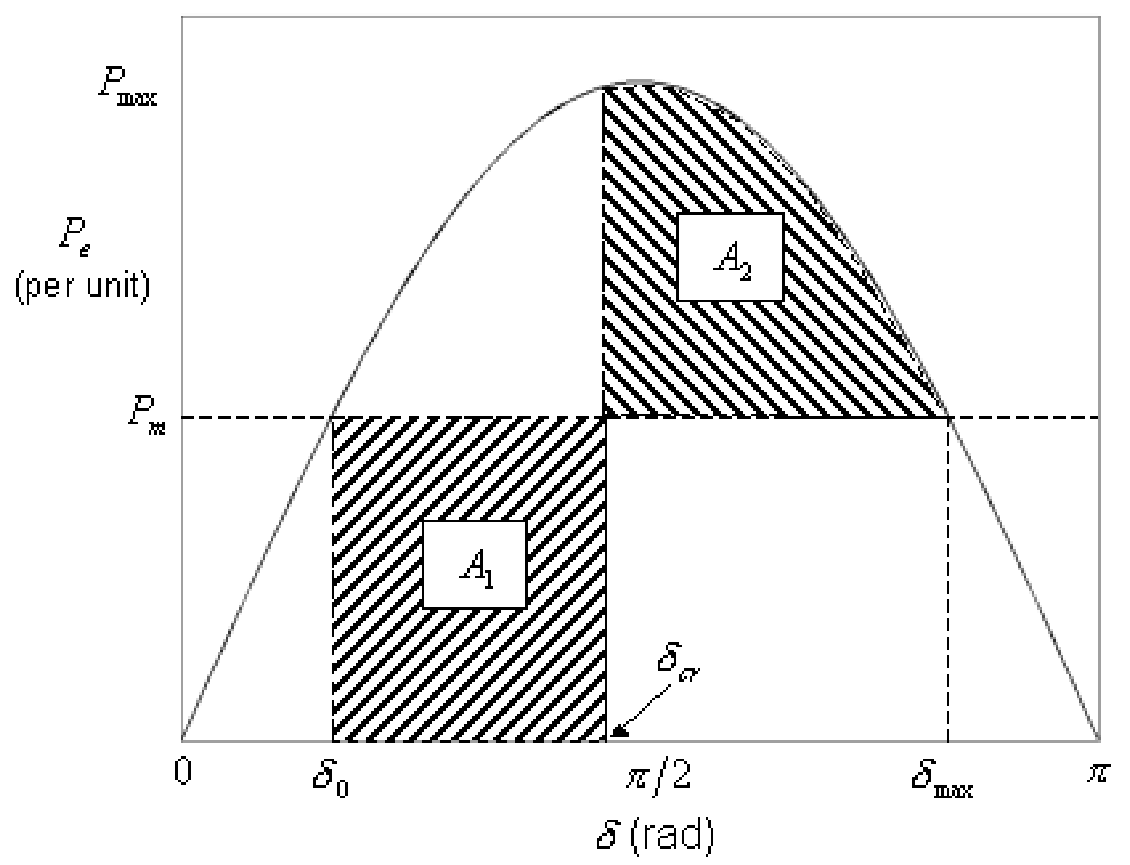
Voltage Stability



Voltage Stability

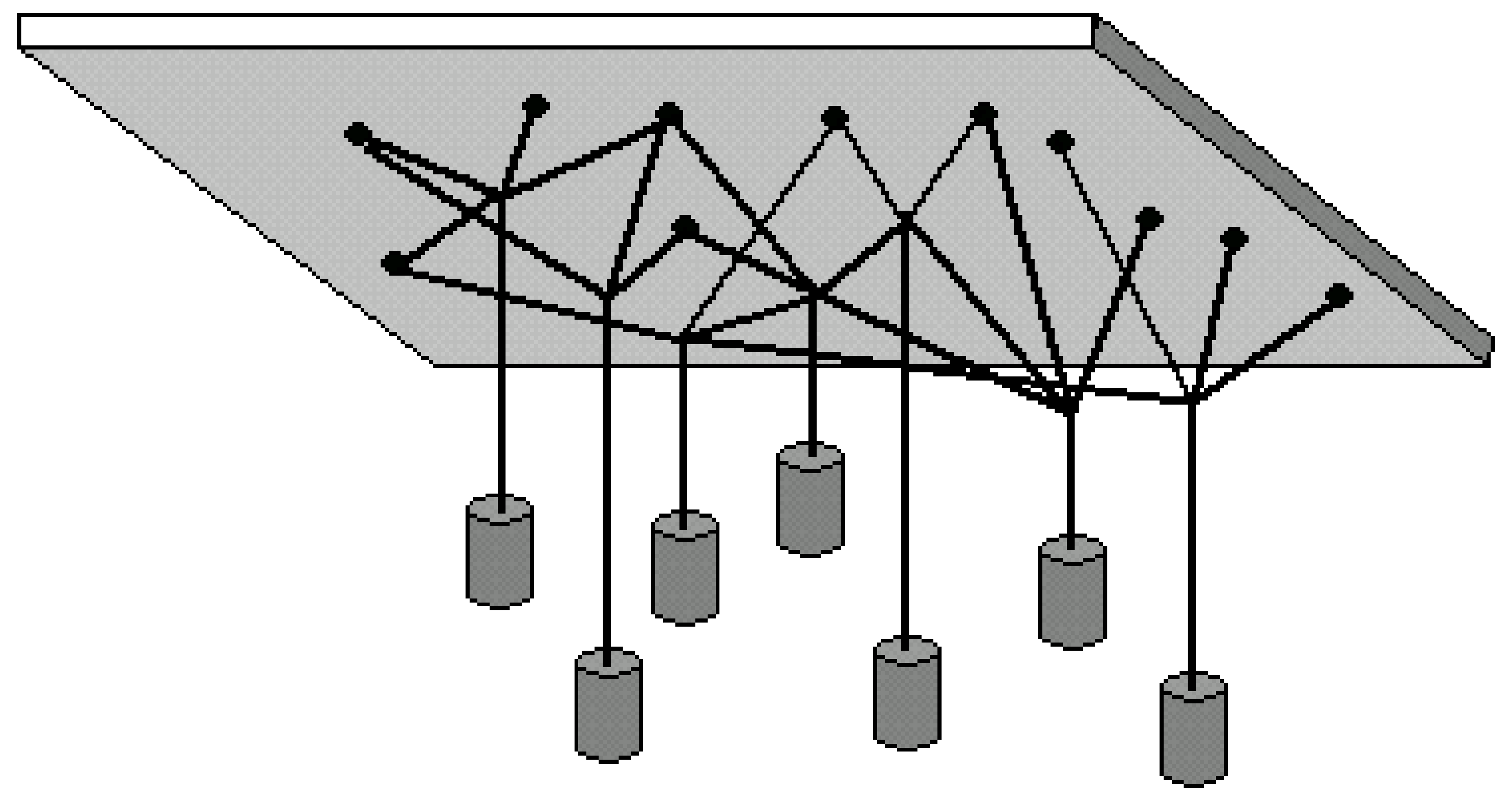


Angle Stability



- P_m = Mechanical power
- P_e = Electrical power

Multimachine Stability



Multimachine Stability

- Modern power systems are interconnected and operate close to their stability limits. In large interconnected systems it is common to find a natural response of a group of closely coupled machines oscillating against other groups of machines.
- These oscillations have a frequency range of 0.1 Hz to 3 Hz.
- The lowest frequency mode involves all generators of the system. This oscillation groups the system into two parts with generators in one part oscillating against the other part (inter-area oscillation).

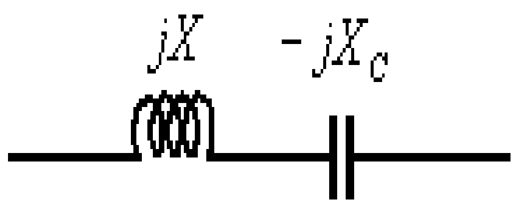
Multimachine Stability

- The higher frequency modes are usually localized with small groups oscillating against each other (local modes).
- Unfortunately, the inter-area oscillation can be initiated by a small disturbance in any part of the system.
- These small frequency oscillations fall under the category of dynamic stability and are analyzed in linear domain through the linearization of the entire interconnected systems model.

Power System Stabilizer (PSS)

- An AVR regulates the generator terminal voltage and also reduces the peak of the first swing following any disturbance.
- However, its high gain contributes to negative damping to the system and this results in the low frequency oscillations in the system.
- These oscillations are the results of the periodic interchange of kinetic energy between different generator rotors.
- A PSS provides positive damping to these small oscillations through negative feedback of the changes in rotor kinetic energy.

Subsynchronous Resonance (SSR)



SSR usually occurs in series capacitor compensated transmission systems. For a radial series compensated system, the natural undamped frequency is

$$f_n = f_0 \sqrt{\frac{X_C}{X}}$$

$$\text{Complement frequency} = f_0 - f_n$$

f_0 being the nominal system frequency

Subsynchronous Resonance (SSR)

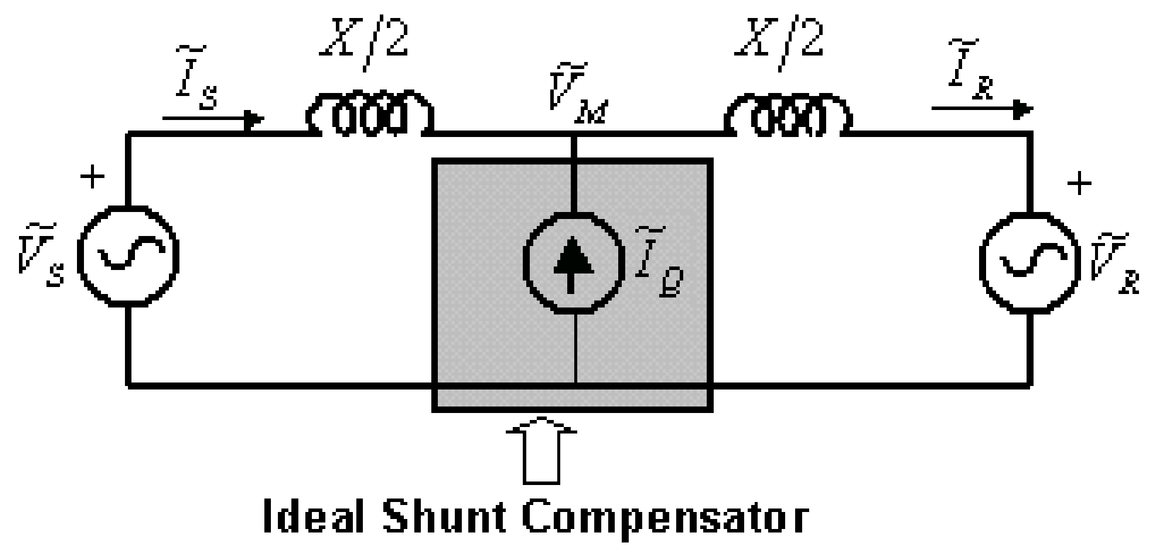
- SSR occurs when the complement frequency is close to one of the torsional frequencies of the turbine-generator shaft system.
- A small voltage induced by rotor oscillation can result in large subsynchronous currents that produce an oscillatory component of rotor torque whose phase is such that it enhances the rotor oscillations.
- If this torque overcomes the mechanical damping, the oscillation in the shaft system grows and can reach damaging levels.

Shunt Compensation of Transmission Systems

A device that that is connected in parallel with a transmission line is called a ***shunt compensator***. It is referred to as a compensator since it compensates for the reactive power in the ac system. It can

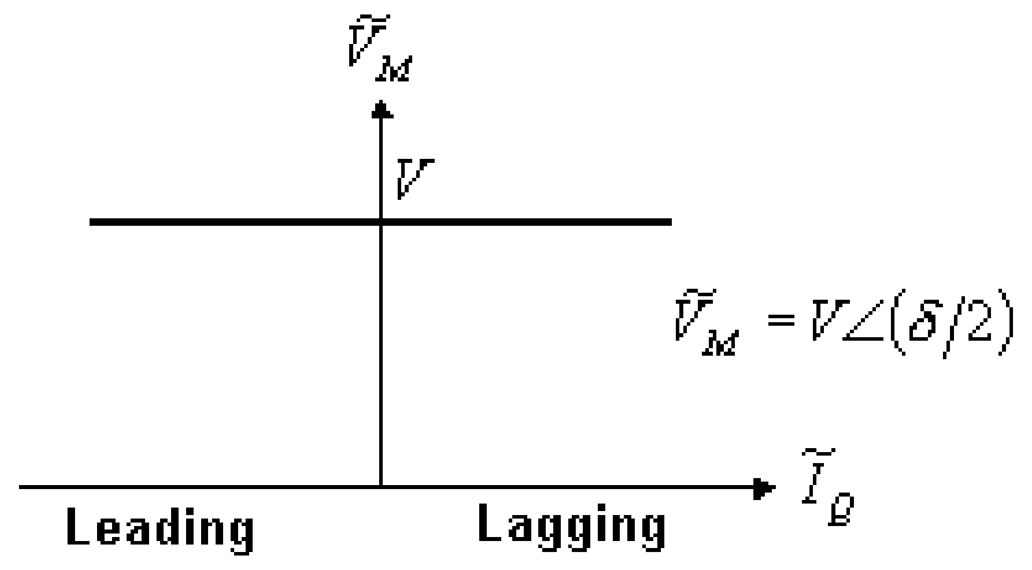
- Improve the voltage profile
- Improve the power-angle characteristics
- Improve the stability margin
- provide damping to power oscillations

Ideal Shunt Compensator



The ideal shunt compensator is represented by an ideal current source that supplies only reactive power and no real power. Let us assume that it is connected at the ***midpoint*** of a lossless line.

Voltage Profile Improvement



The figure shows the ideal voltage-current characteristics of an ideal shunt compensator in which the midpoint voltage held constant irrespective of the current injected.

Injected Current

$$\text{For } \tilde{V}_S = V\angle\delta, \tilde{V}_R = V, \tilde{V}_M = V\angle(\delta/2)$$

$$\tilde{I}_S = \frac{V\angle\delta - V\angle(\delta/2)}{jX/2}, \quad \tilde{I}_R = \frac{V\angle(\delta/2) - V}{jX/2}$$

$$\text{Since } \tilde{I}_Q = \tilde{I}_R - \tilde{I}_S$$

$$\tilde{I}_Q = -j\frac{4V}{X}\{1-\cos(\delta/2)\}\angle(\delta/2)$$

We thus have to generate a current that is phase quadrature with the midpoint voltage. As a consequence the real power injected by the compensator is zero.

Real & Reactive Power

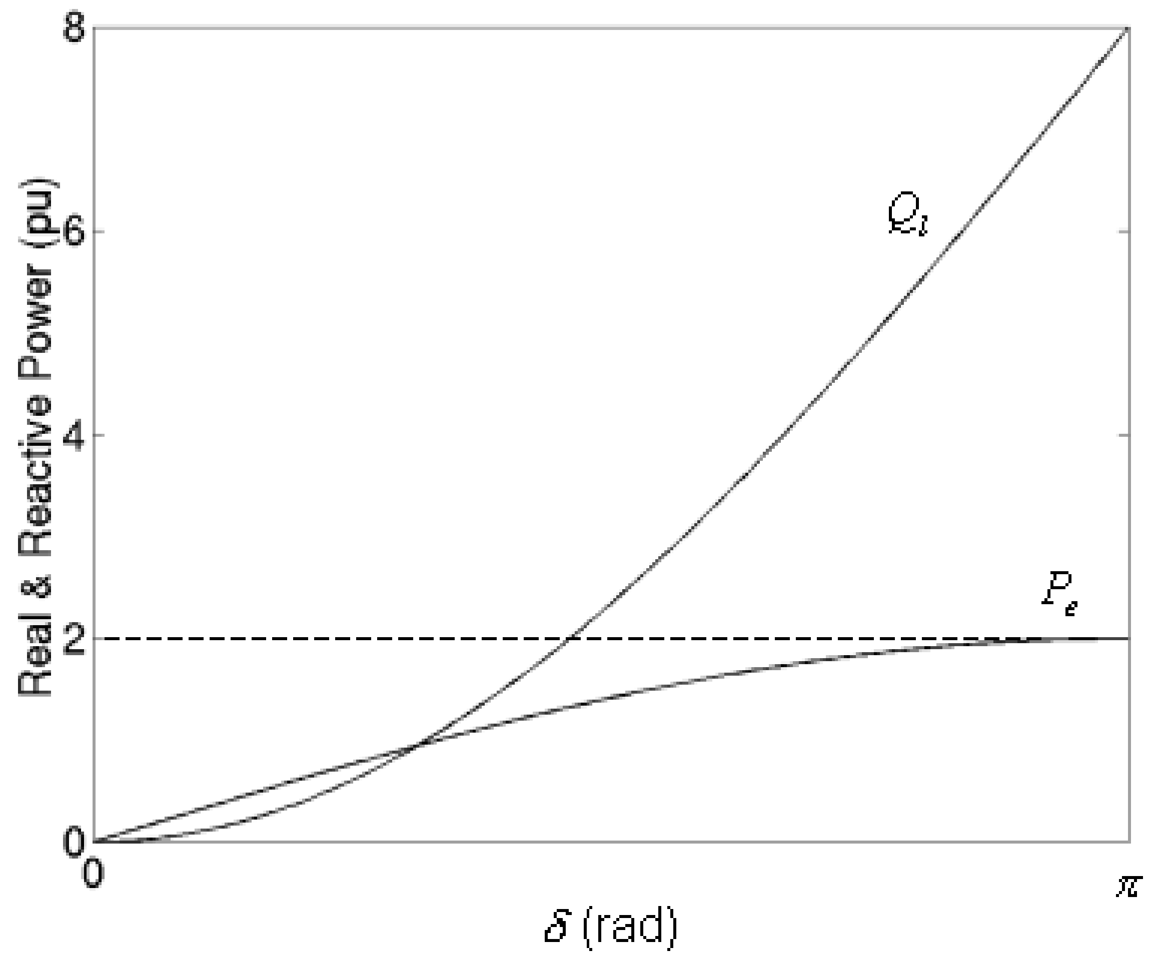
Midpoint shunt compensation improves the power flow over a line. The real power flowing through and the reactive power absorbed by the line are

$$P_e = \frac{2V^2}{X}\sin(\delta/2), \quad Q_l = \frac{8V^2}{X}[1-\cos(\delta/2)]$$

The reactive power generated by the shunt compensator is

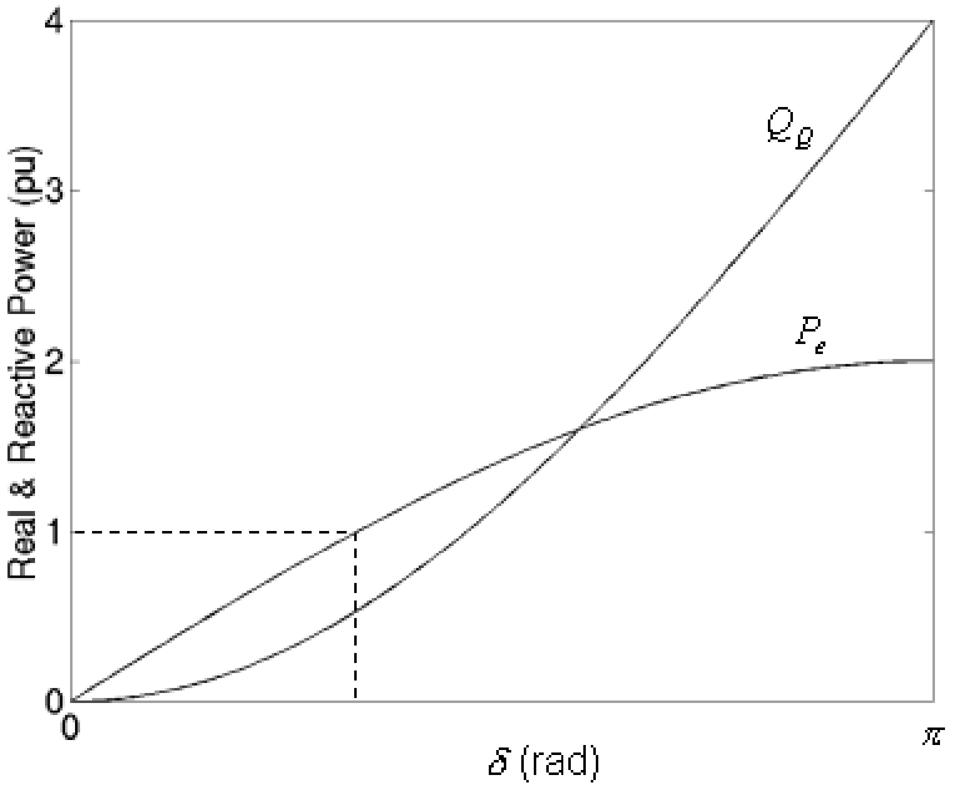
$$Q_Q = \frac{4V^2}{X}[1-\cos(\delta/2)]$$

Power Angle Characteristic



It is assumed that $V^2/X = 1\,\text{pu}$

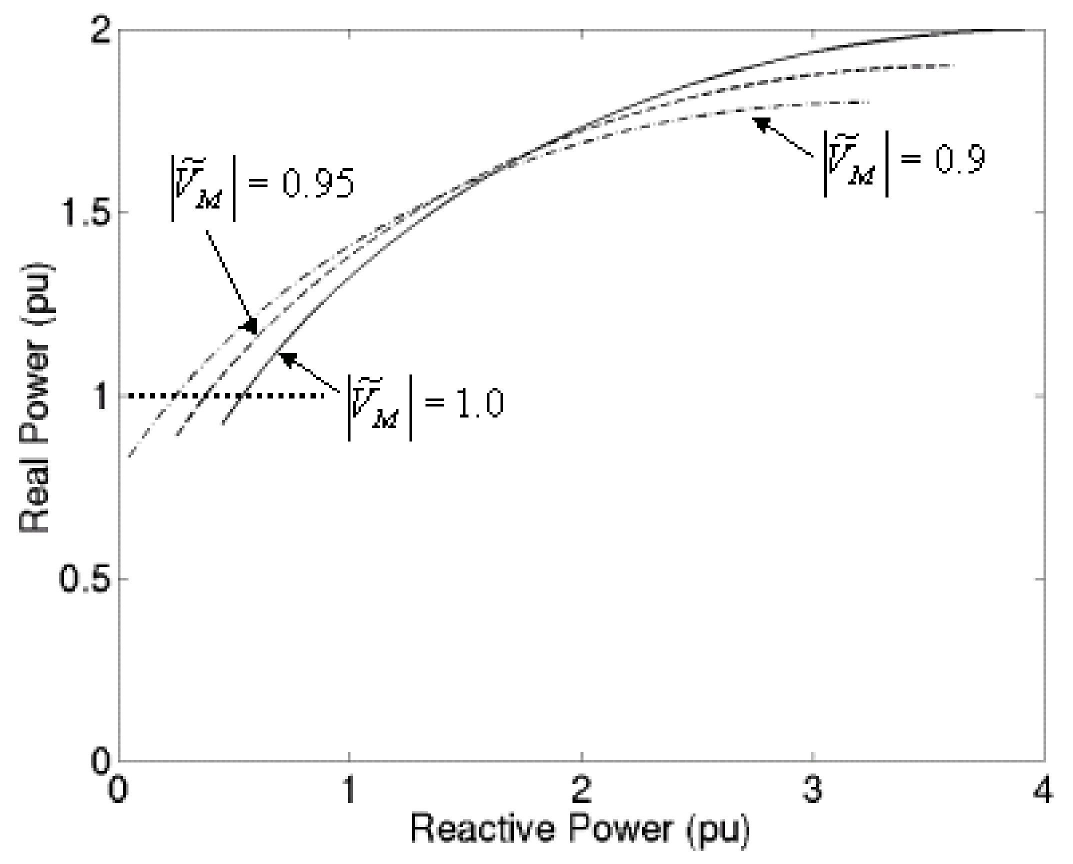
Reactive Power Requirement



- For a real power transfer of 1.0 per unit, a reactive power injection of roughly 0.5359 per unit will be required from the shunt compensator.
- However for 2.0 per unit real power an injection of 4.0 per unit is needed.

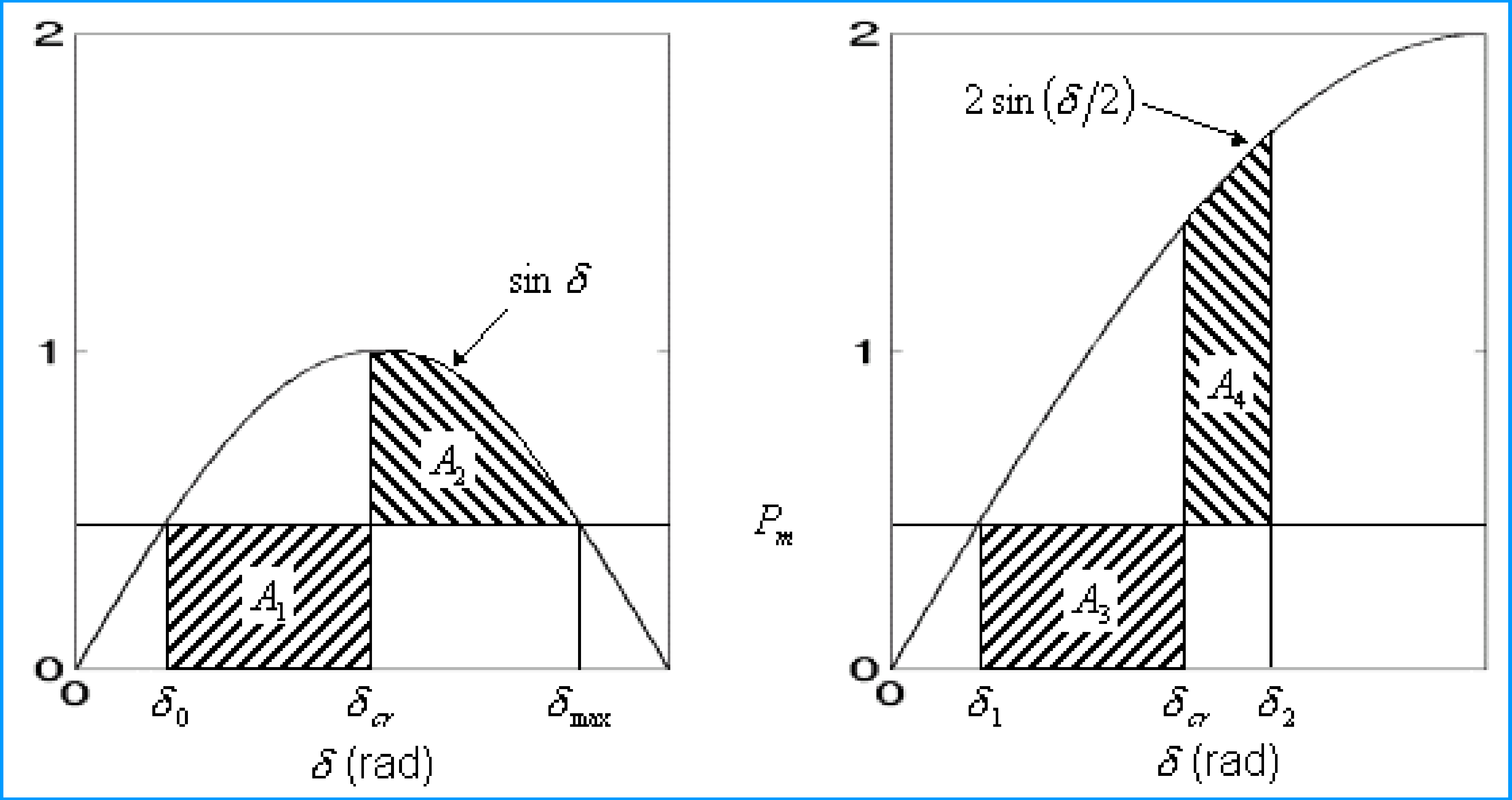
It is assumed that $V^2/X = 1\,\text{pu}$

Reactive Power Requirement



For a real power transfer of 1.0 per unit, the reactive power injection can be lowered by lowering the midpoint voltage.

Improvement of Stability Margin



Power Swing Damping

The swing equation is given by

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e\left(\delta, \left|\tilde{V}_M\right|\right)$$

where P_m is the mechanical power input. Note that the electrical power P_e is define as a function of the load angle δ and the magnitude of the midpoint voltage. This is because both these quantities can alter the power transmitted over a transmission line, for constant voltage at the two ends.

Power Swing Damping

The linearization of the swing equation gives

$$\frac{2H}{\omega_s}\frac{d^2\Delta\delta}{dt^2}+\frac{\partial P_e}{\partial\left|\tilde{V}_M\right|}\Delta\left|\tilde{V}_M\right|+\frac{\partial P_e}{\partial\delta}\Delta\delta=0$$

The regulation of the midpoint voltage implies that the magnitude of V_m is held constant and hence

$$\Delta\left|\tilde{V}_M\right|=0$$

Therefore we get

$$\frac{2H}{\omega_s}\frac{d^2\Delta\delta}{dt^2}+\frac{\partial P_e}{\partial\delta}\Delta\delta=0$$

Power Swing Damping

- The roots of the above equation are located on the imaginary axis of the s-plane. This implies that the load angle will oscillate with a constant frequency of

$$\sqrt{\frac{\omega_s}{2H}\frac{\partial P_e}{\partial \delta}}$$

- Obviously this solution is not acceptable. We must therefore add a derivative of the load angle in the linearized swing equation.

Let us vary the midpoint voltage according to

$$\Delta\left|\tilde{V}_M\right| = K_M \frac{d\Delta\delta}{dt}$$

We therefore get

$$\frac{2H}{\omega_s}\frac{d^2\Delta\delta}{dt^2} + \frac{\partial P_e}{\partial\left|\tilde{V}_M\right|}K_M\frac{d\Delta\delta}{dt} + \frac{\partial P_e}{\partial\delta}\Delta\delta = 0$$

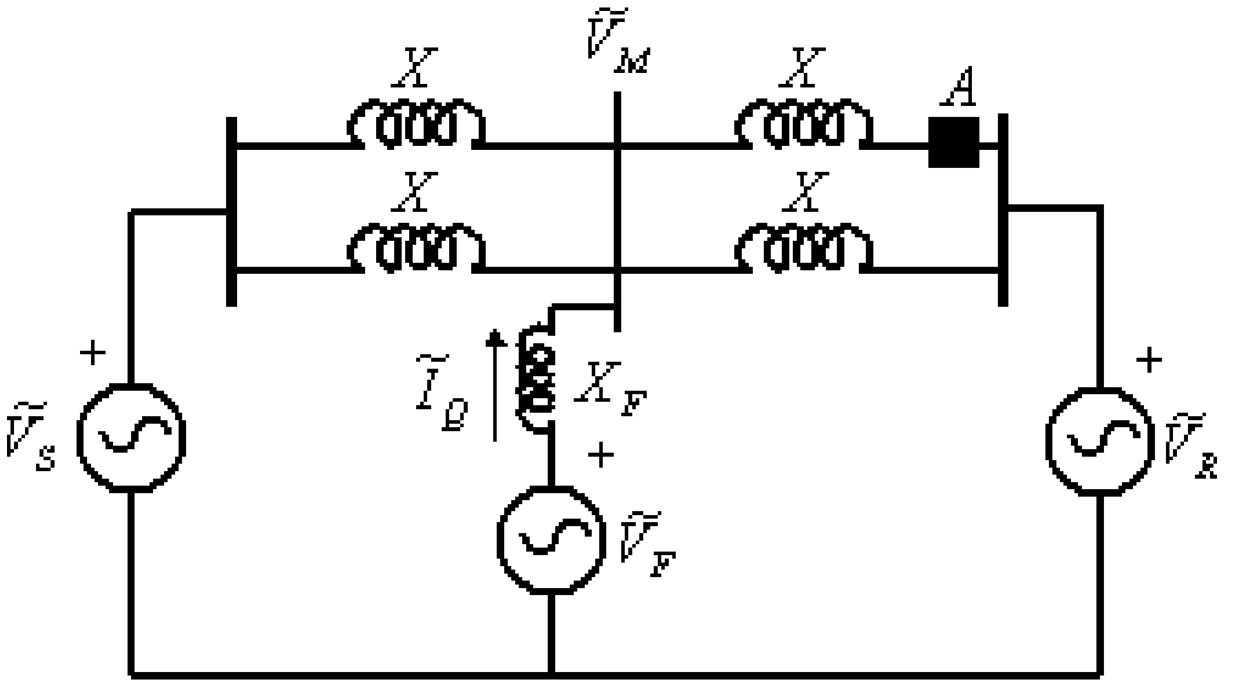
This is the equation of a 2nd order system in which

$$2H/\omega_s > 0, \quad \partial P_e \Big/ \partial\left|\tilde{V}_M\right| > 0, \quad \partial P_e/\partial\delta > 0$$

Therefore a stable solution is guaranteed if

$$K_M > 0$$

An Example



$$\tilde{V}_S = 1\angle 40^{\circ}\ \text{pu}, \quad \tilde{V}_R = 1\angle 0^{\circ}\ \text{pu}, \quad \omega = 100\pi\ \text{rad/s}$$

$$X = 0.5\ \text{pu}, \quad X_F = 0.3\ \text{pu}, \quad H = 4.0\ \text{MJ/MVA}$$

Example (Continued)

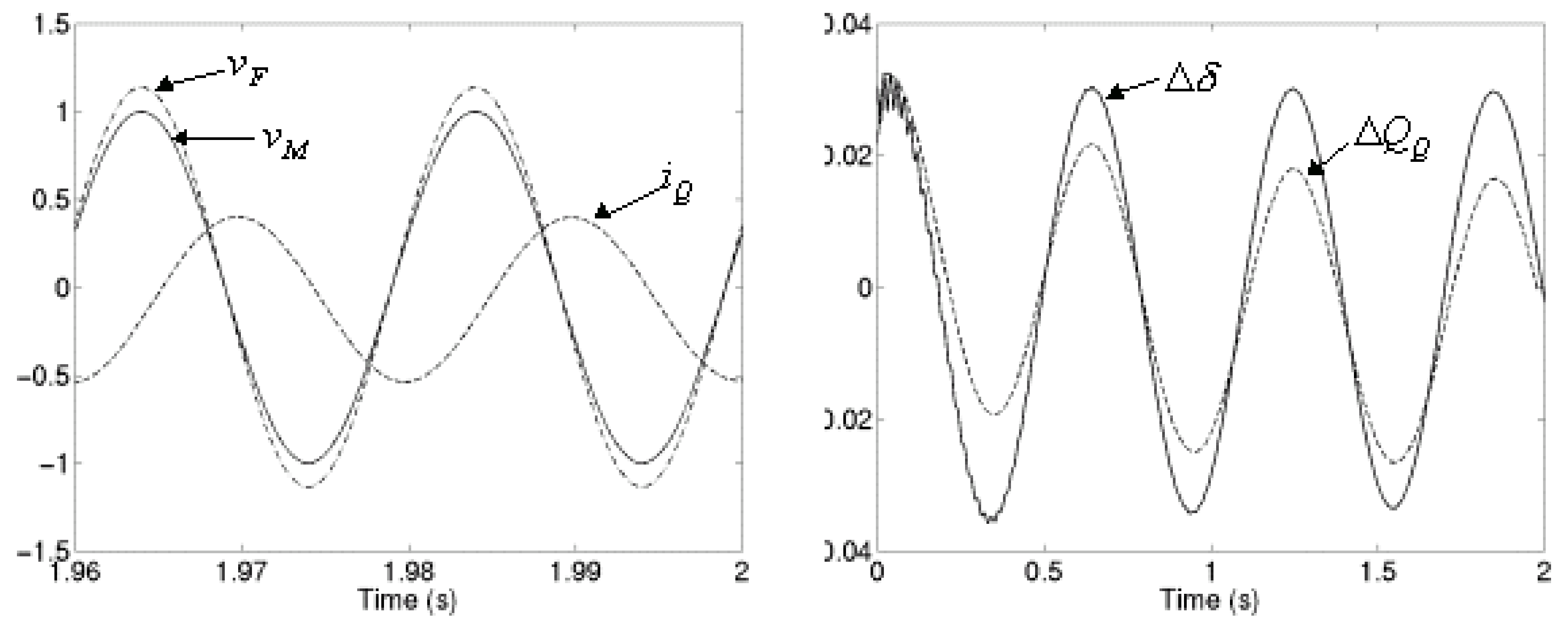
Note that for purely reactive injection by the shunt compensator, the angle of the voltage source is set such that it is in phase with the midpoint voltage, i.e.,

$$\tilde{V}_F = \frac{\tilde{V}_M}{\left|\tilde{V}_M\right|} \times \left|\tilde{V}_P\right|$$

Let us regulate the midpoint voltage to 1.0 per unit using a PI controller of the form

$$\left|\tilde{V}_F\right| = K_P\left(1-\left|\tilde{V}_M\right|\right) + K_I \int \left(1-\left|\tilde{V}_M\right|\right) dt$$

Example (Continued)



System response to a perturbation

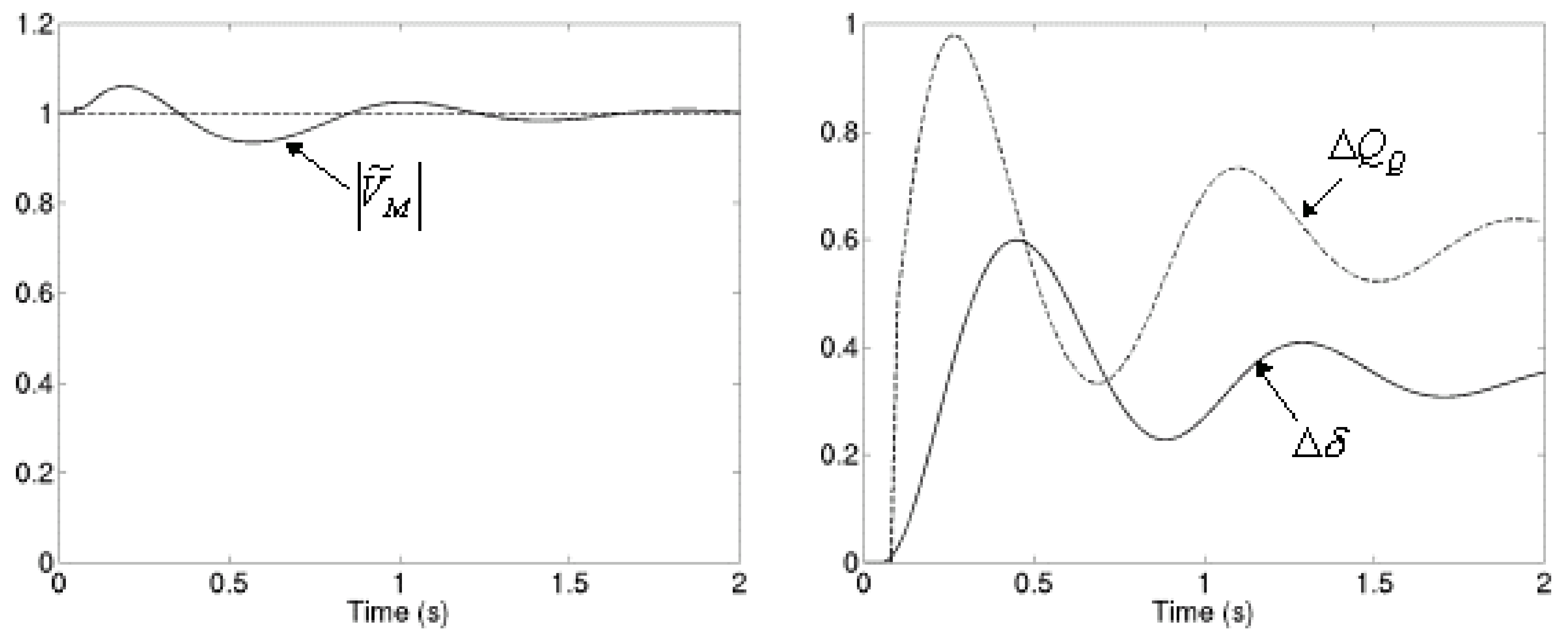
Example (Continued)

To improve damping, we now introduce a term that is proportional to the deviation of machine speed in the feedback loop such that the control law is given by

$$\left|\tilde{V}_F\right| = K_P\left(1-\left|\tilde{V}_M\right|\right)+K_I\int\left(1-\left|\tilde{V}_M\right|\right)dt+C_P\frac{d\Delta\delta}{dt}$$

The last term adds damping to the system.

Example (Continued)



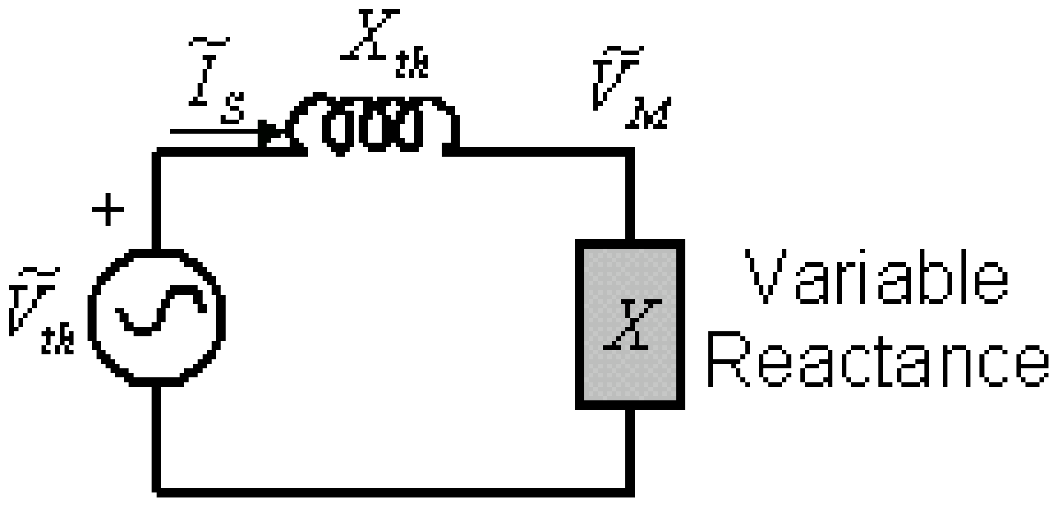
System response when the breaker A opens inadvertently.

Practical Shunt Compensator

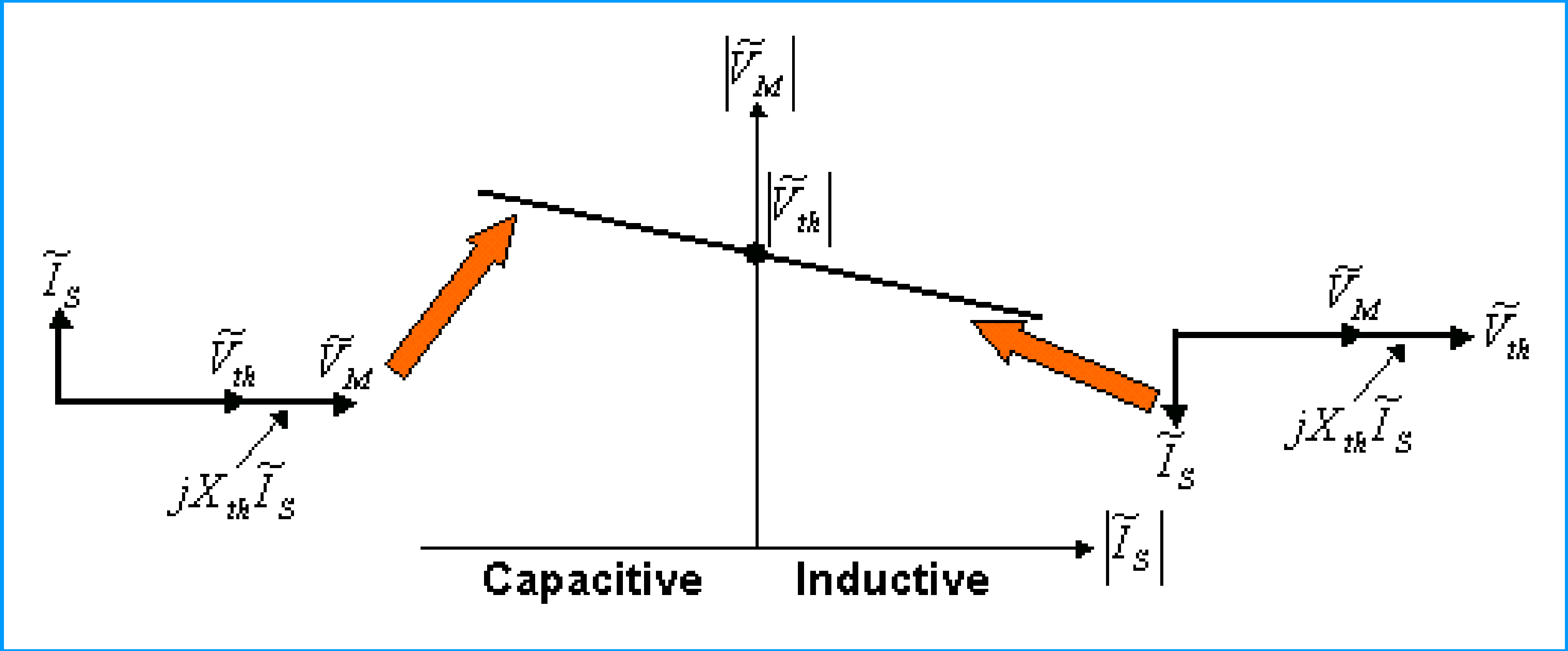
- The above example demonstrates the functioning of a *Static Compensator (*STATCOM) that produces a voltage, the fundamental component of which is in phase with the midpoint voltage. It consists of an inverter based Synchronous Voltage Source (SVS) and a connecting transformer.
- The first generation shunt compensator is the *Static VAr Compensator* (SVC). It actually is a variable reactance.

Uncompensated System

In the figure below the power system is represented by its Thevenin equivalent looking from the midpoint. It is assumed that a variable reactive load is connected at the midpoint.

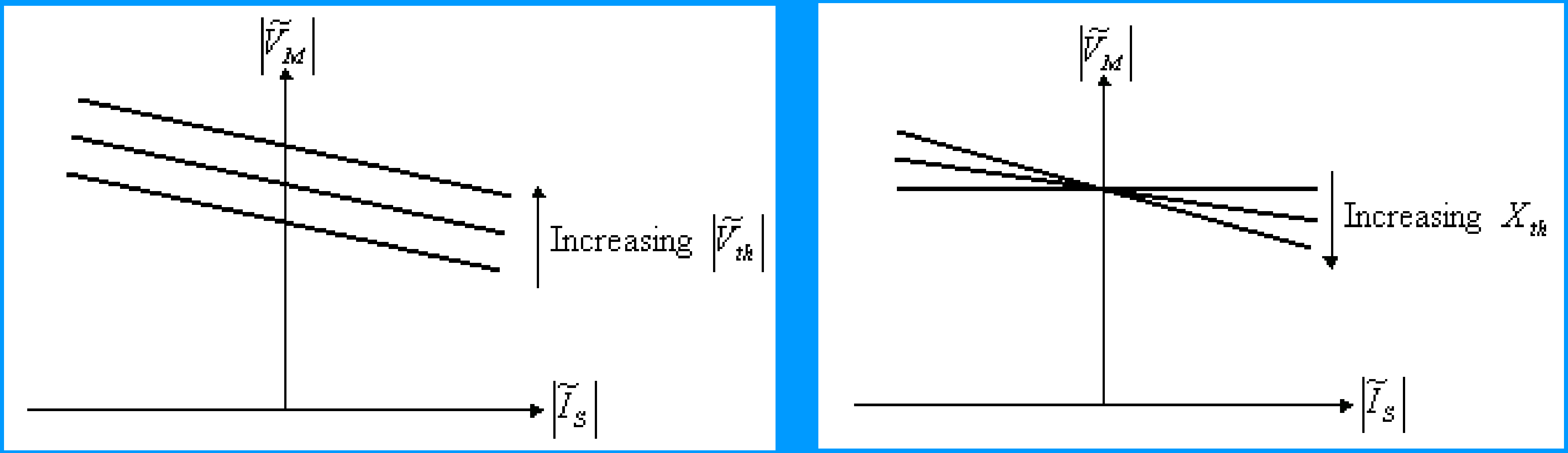


VI Curve



The midpoint voltage increases linearly with capacitive load current and decreases with inductive load current.

VI Curve



Effects of increasing V_{th} (left) and X_{th} (right).

Components of SVC

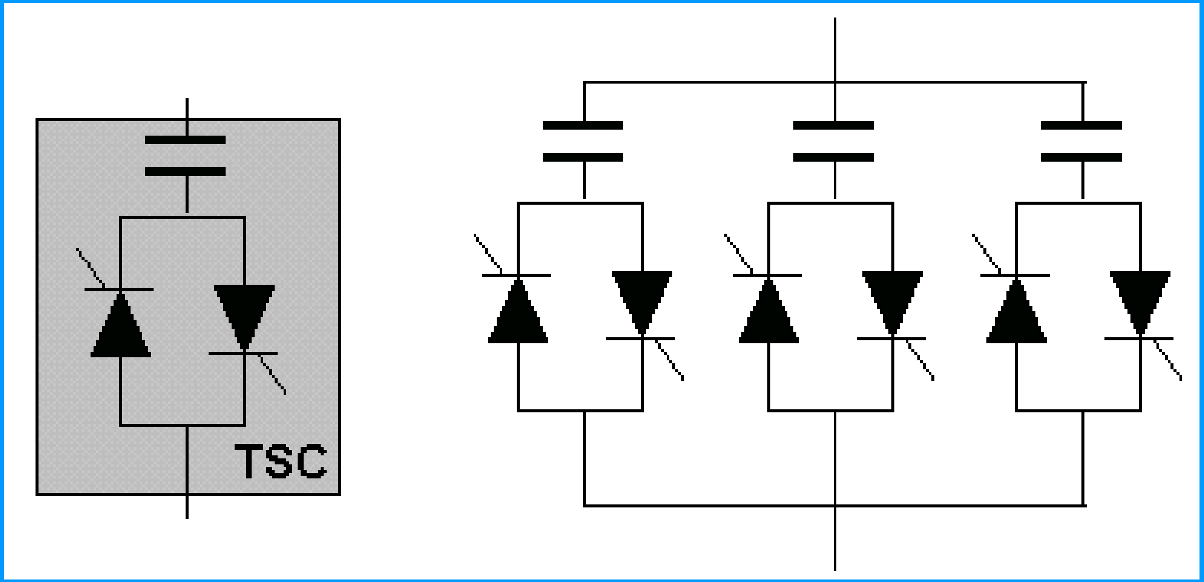
The building blocks of an SVC are

- Saturated Reactor
- **Thyristor Switched Capacitor (TSC)**
- **Thyristor Controlled Reactor (TCR)**
- Thyristor Switched Reactor
- Thyristor Controlled Transformer

An SVC is made of the combination of one or more than one of the above components and fixed capacitor banks.

Thyristor Switched Capacitor (TSC)

In a TSC a capacitor is connected in series with two opposite pole thyristors. A current flows through the capacitor when the opposite poled thyristors are gated.



TSC - Equivalent Reactance

TSCs always come in a pack. The effective reactance of the TSC pack can be changed by switching a TSC on or off. For example in an *n*-pack TSC, the effective reactance is

$$X_{eq} = -j\frac{1}{k\omega C}, k = 0,1,\ldots,n$$

where *k* is the number of TSCs conducting.

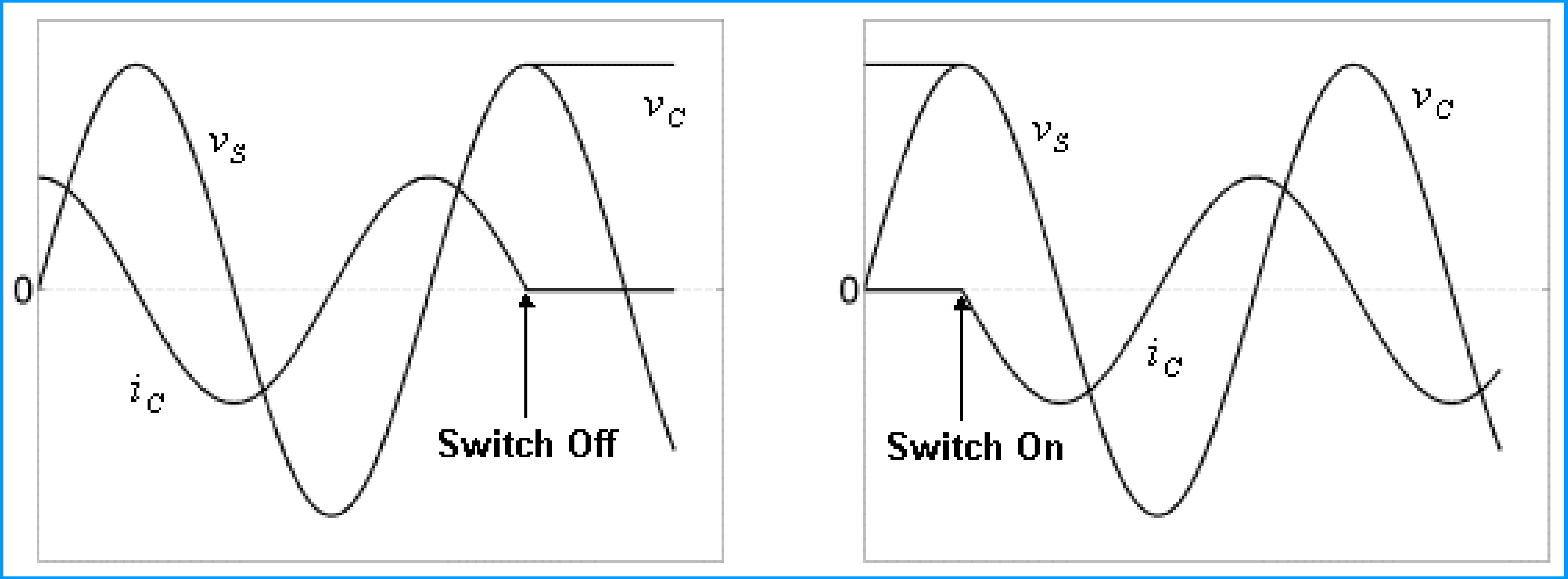
TSC - Transient-free Switching

- TSC suddenly blocks current or allows the current through it.
- Hence severe switching transients occurs if a TSC is switched off while the current thorough it is not zero.
- Similarly, the device must be switched on at a particular instant of the voltage cycle.
- For example, let us consider that a TSC is supplied by a voltage source v_S and has a capacitor voltage v_C and a current i_C through the capacitor.

TSC - Transient-free Switching

- Then as $i_C = C\,(dv_C / dt)$, the current is zero when $dv_C / dt = 0$, i.e., when the capacitor voltage reaches its peak.
- Thus for transient-free switching, it must be ensured that the capacitor voltage is in either its positive peak or negative peak for either turn on or turn off.
- The transient-free switching is shown in the next slide, in which the instant of switching on and off are also indicated.

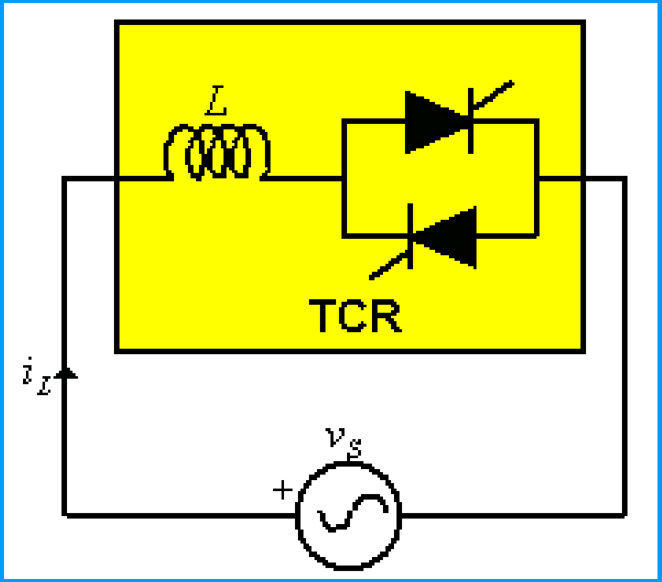
TSC - Transient-free Switching



- The capacitor voltage v_C is kept at the peak of the supply voltage when the switch is off indicating an open circuit.

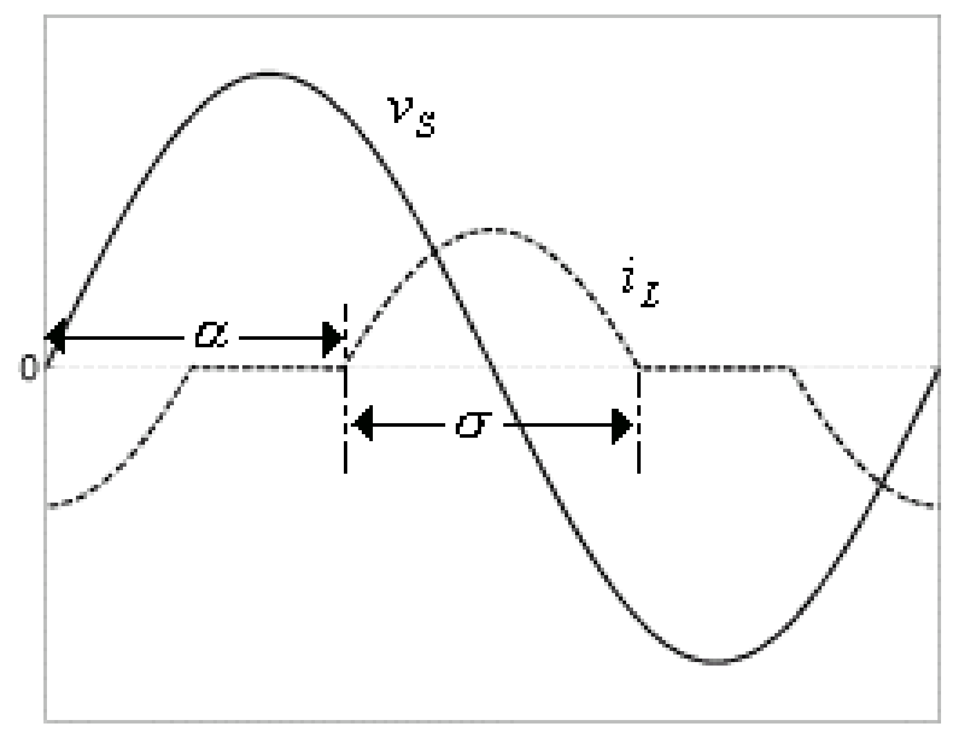
Thyristor Switched Reactor (TCR)

In a TCR a reactor is connected in series to two opposite poled thyristors. One of these thyristors conducts in each half cycle of supply frequency.



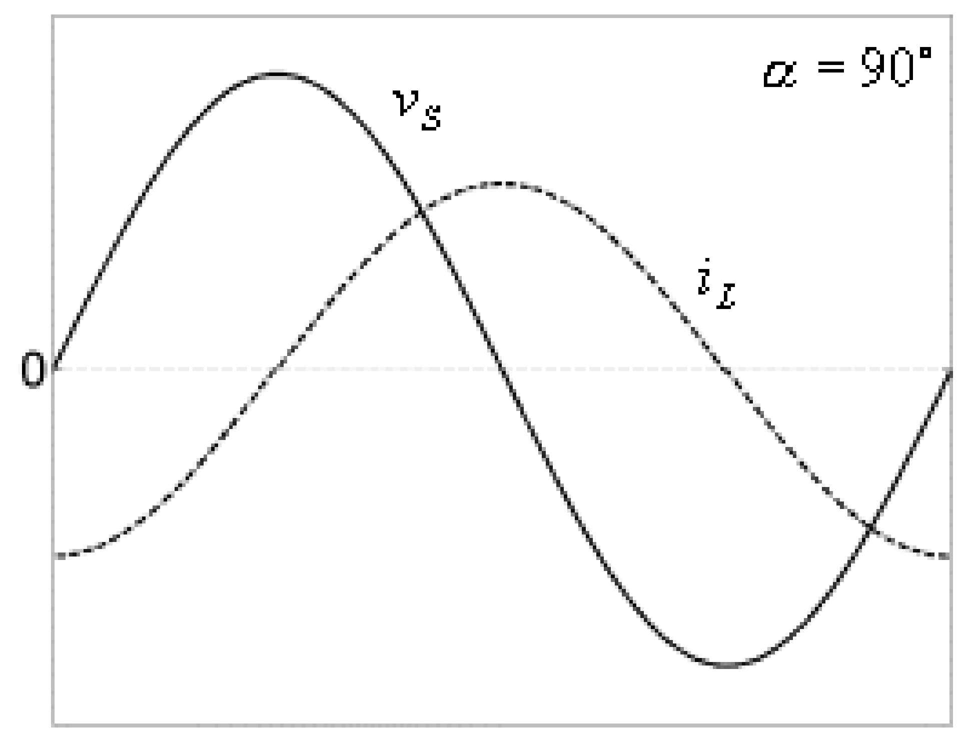
TCR - VI Relationship

- The gating signal to each thyristor is delayed by an angle α (often called the firing or conduction angle) from the zero crossing of the source voltage.



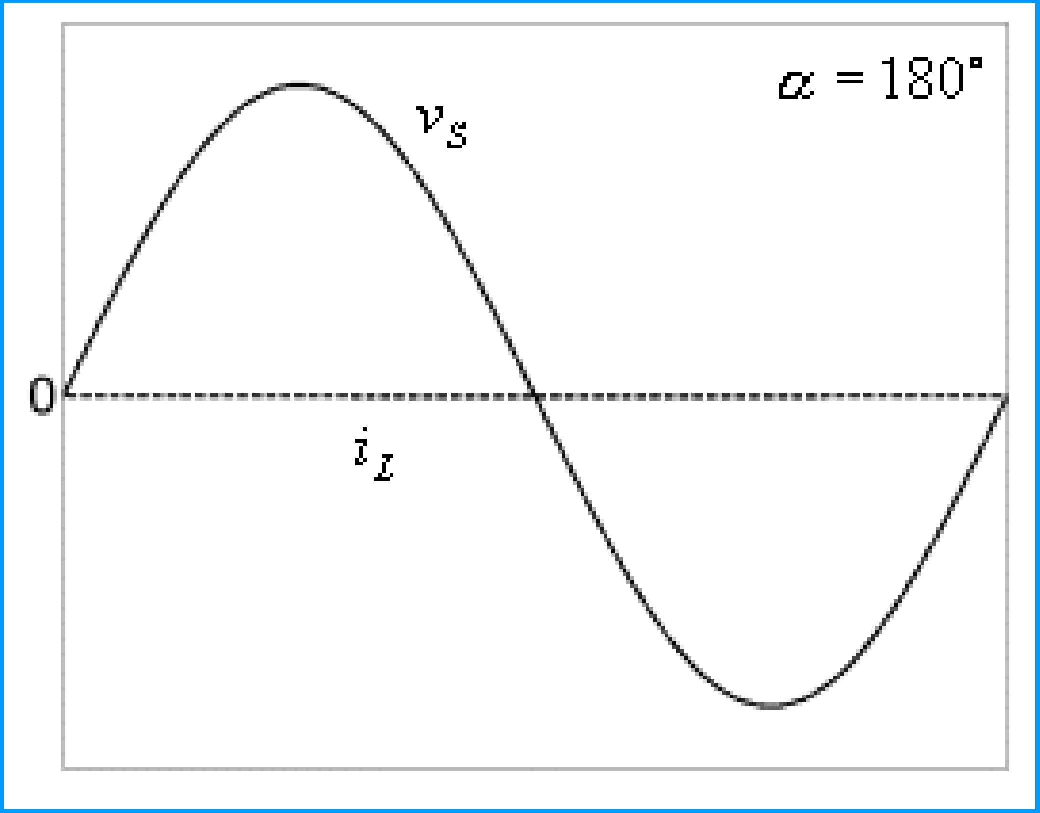
TCR - VI Relationship

- The conduction angle must be in the range 90° $\leq \alpha \leq$ 180°. For α = 90°, the current will have full conduction and will lag the voltage by 90°.



TCR - VI Relationship

- For $\alpha = 180^\circ$, the current will be zero.



TCR - Fundamental Reactance

- The TCR fundamental reactance is derived from the following equation

$$i_L = \begin{cases} \dfrac{1}{L}\displaystyle\int_{\alpha/\omega}^{t} V_m \sin(\omega\lambda)d\lambda = \dfrac{V_m}{\omega L}\left(\cos\alpha - \cos\omega t\right) & \text{for } \alpha \le \omega t < \alpha + \sigma \\ 0 & \text{for } \alpha + \sigma \le \omega t < \alpha + \pi \end{cases}$$

- The fundamental current is given from the above equation as

$$i_{Lf} = \frac{V_m}{\pi X_L}\left(\sigma - \sin\sigma\right)\sin\left(\omega t - 90^\circ\right)$$

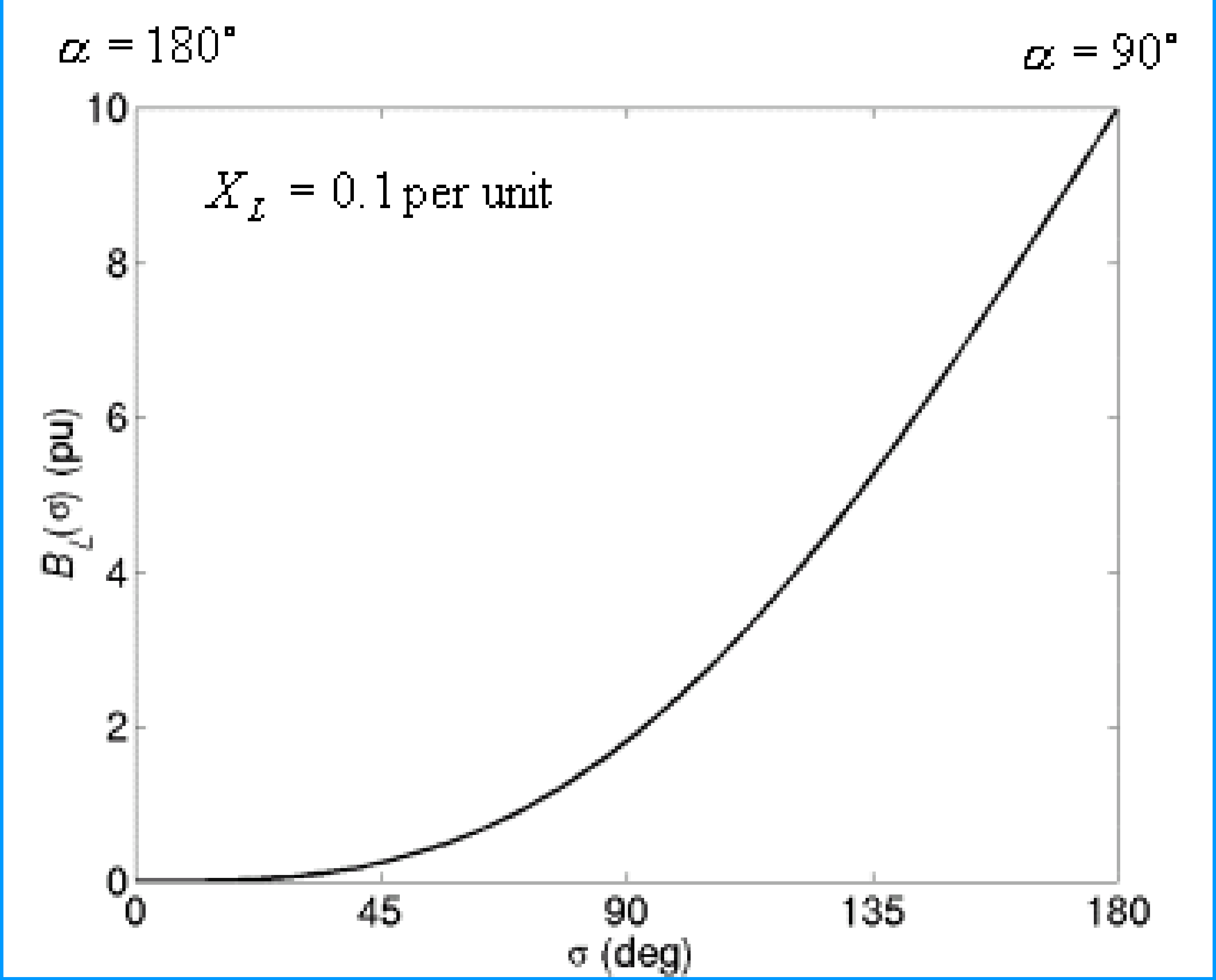
TCR - Fundamental Reactance

- Since the TCR fundamental current must lag the voltage by 90°, we have the fundamental frequency susceptance of the TCR as

$$B_L(\sigma) = \frac{\tilde{I}_{Lf}}{\tilde{V}_s} = \frac{\sigma - \sin\sigma}{\pi X_L}$$

- The susceptance is zero for $\sigma = 0°$ ($\alpha = 180°$) and reciprocal of the chosen value of X_L for $\sigma = 180°$ ($\alpha = 90°$).

TCR - Fundamental Reactance



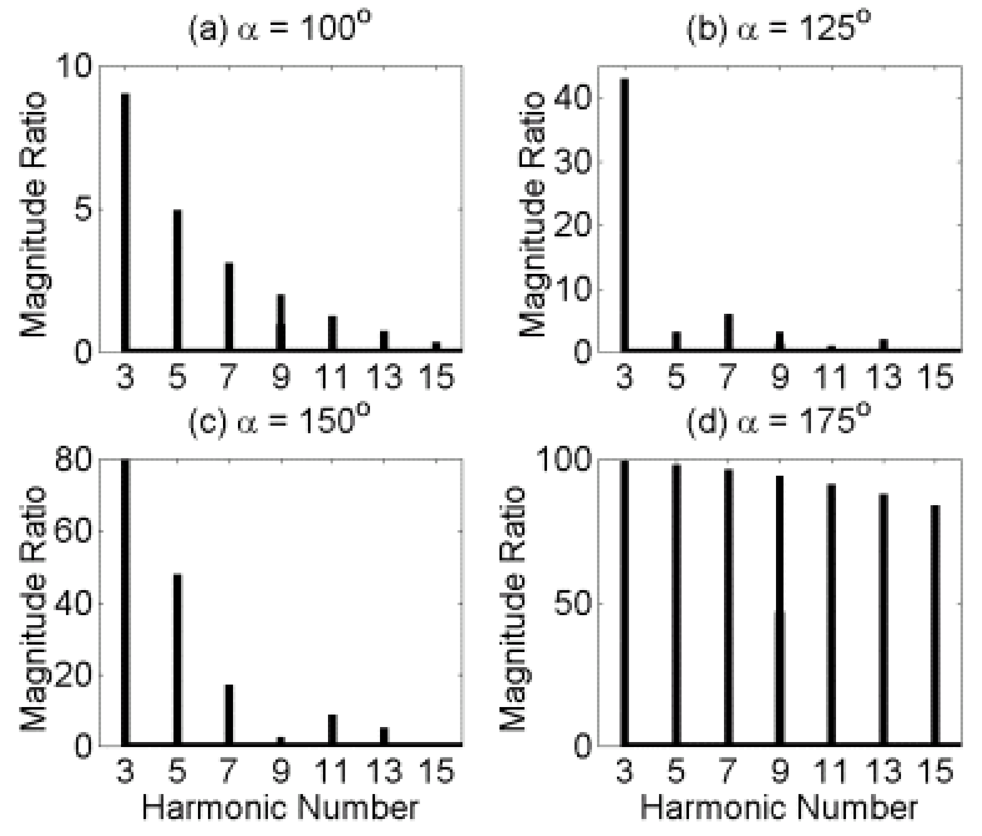
TCR - Harmonics

- The TCR current will not contain any dc or even harmonics, but only the odd harmonics. The peak of the harmonic currents are given by

$$I_{L\_n} = \frac{4V_m}{\pi X_L}\left[\frac{\sin\{(n+1)\alpha\}}{2(n+1)} + \frac{\sin\{(n-1)\alpha\}}{2(n-1)} - \cos\alpha\frac{\sin n\alpha}{n}\right], \quad n = 3,5,\ldots$$

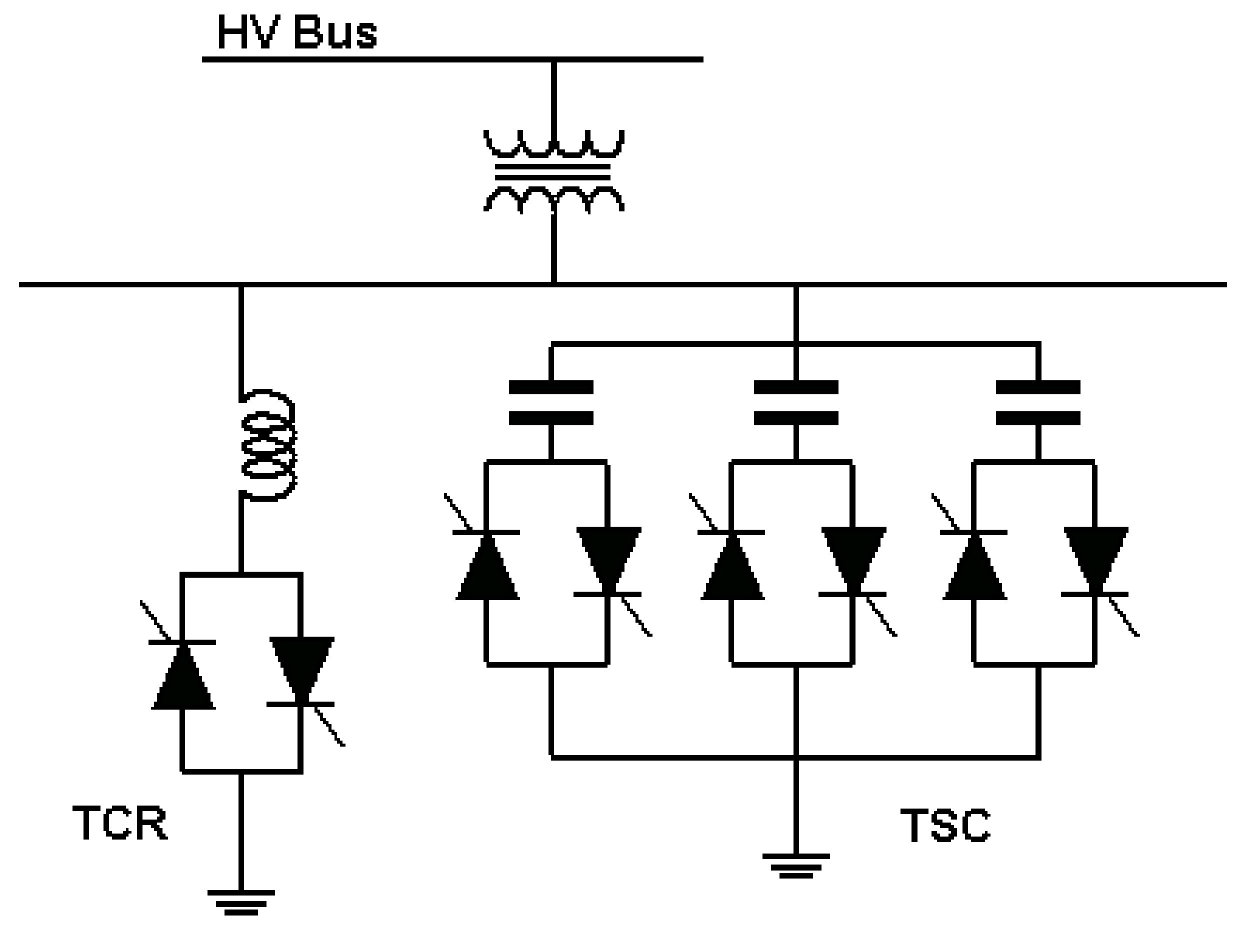
- The normalized harmonic spectrum for various values of α are shown in the next slide.
- As the firing angle increases, the magnitude of the harmonic current increases.

TCR - Harmonics

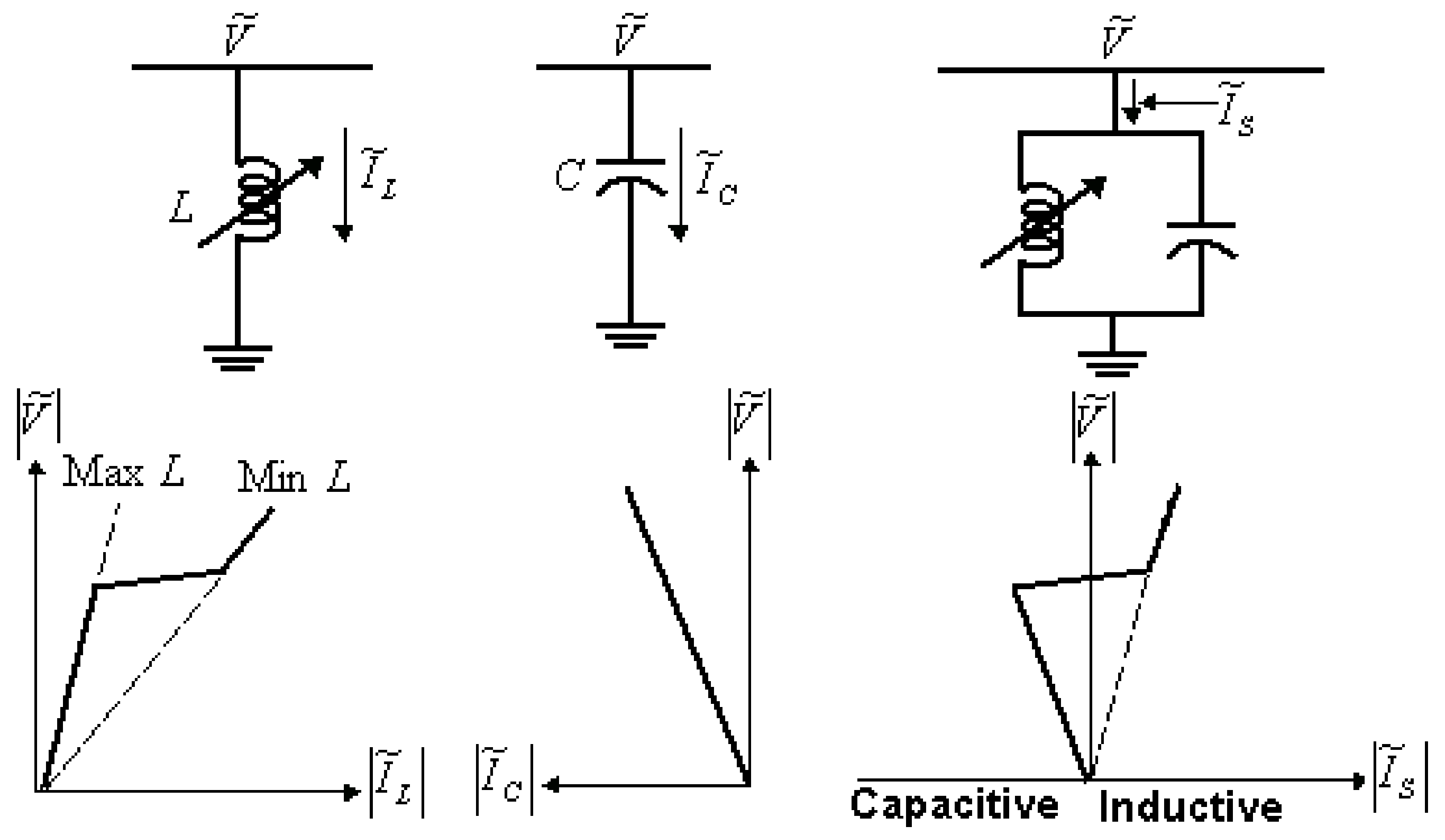


- Both the peak and conduction period *(σ/ω)* decrease with increase in *α* resulting in a reduction of the peak of fundamental current and increase in harmonic contents.

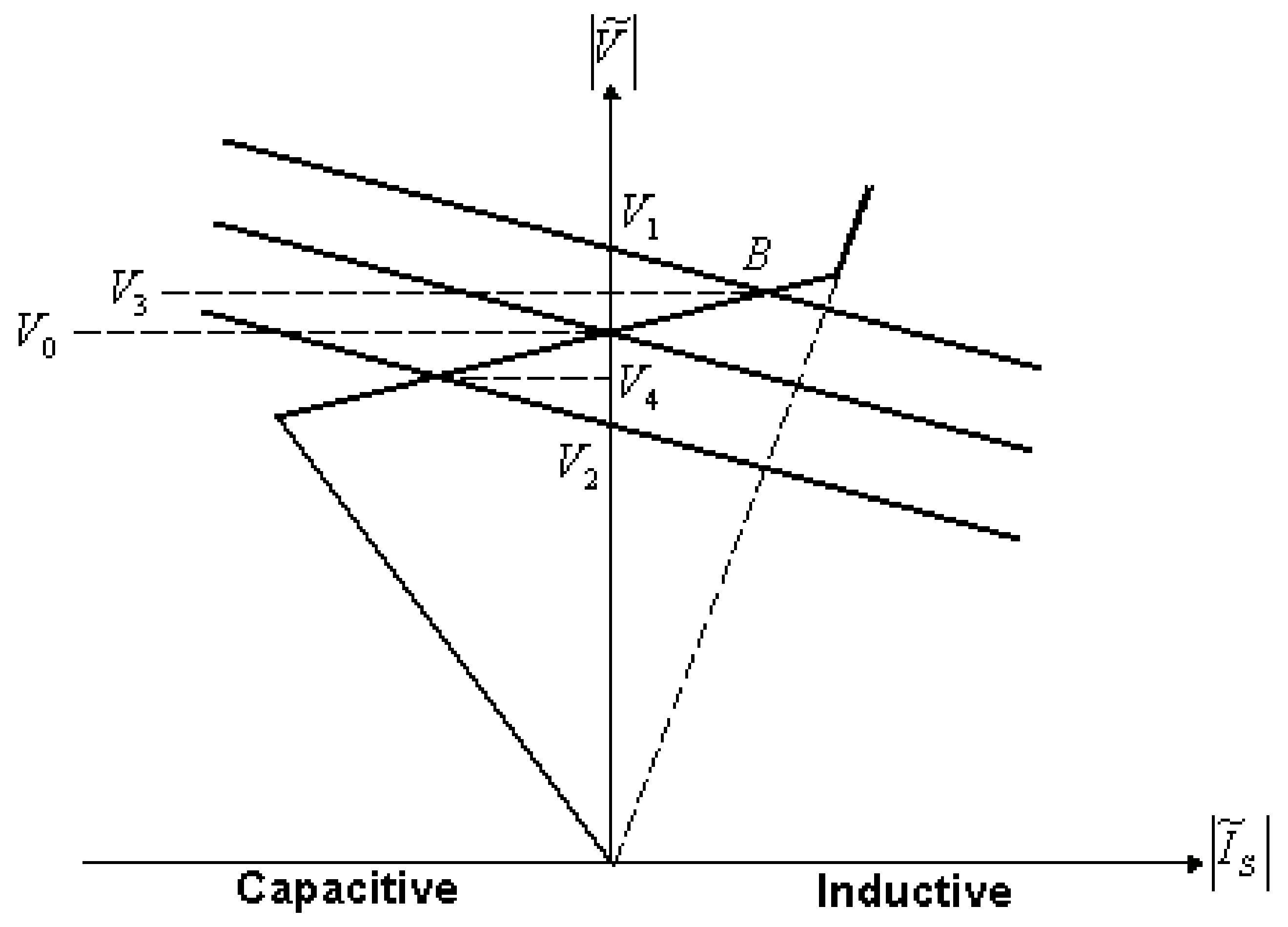
Typical SVC Scheme



SVC VI Characteristics



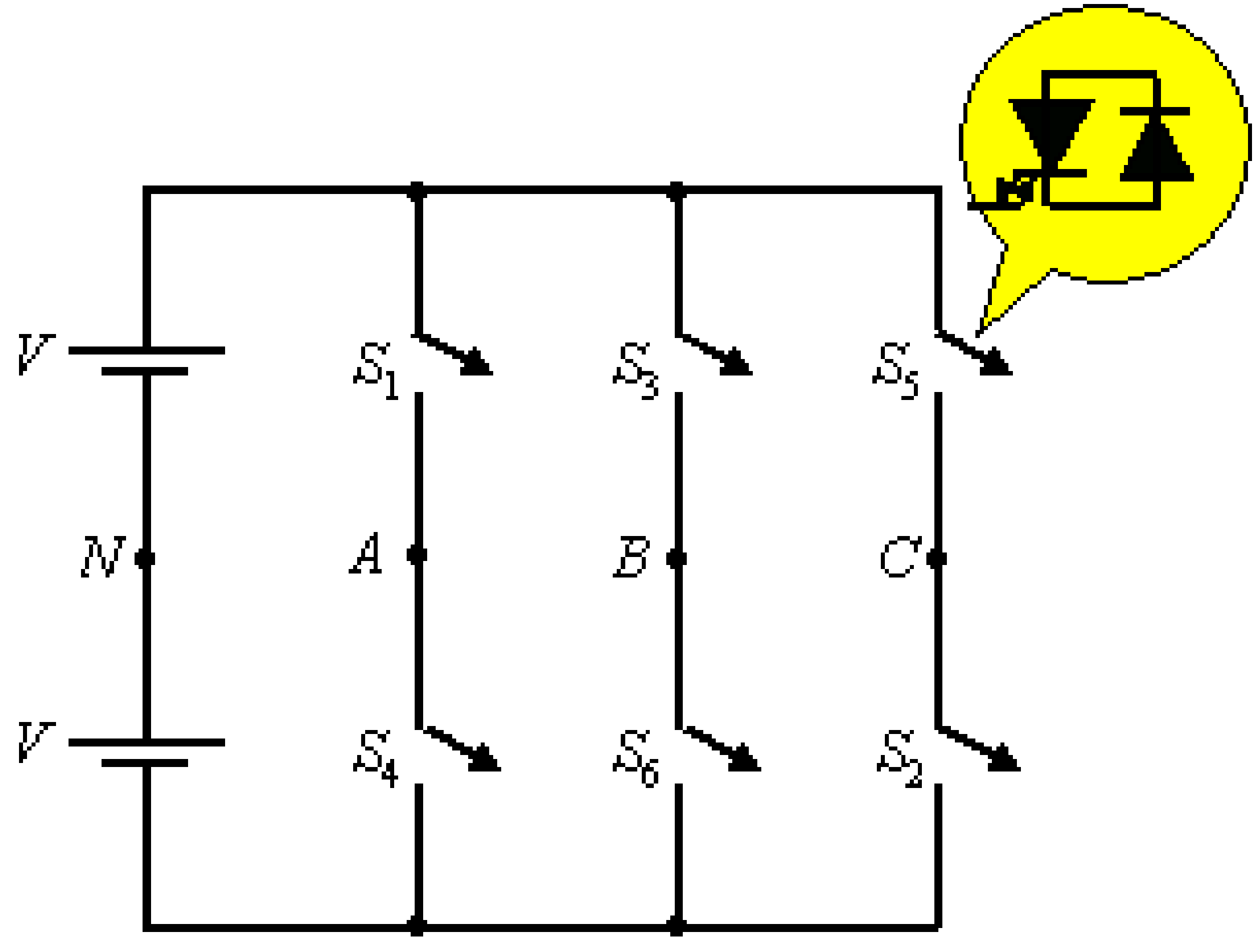
SVC VI Characteristics



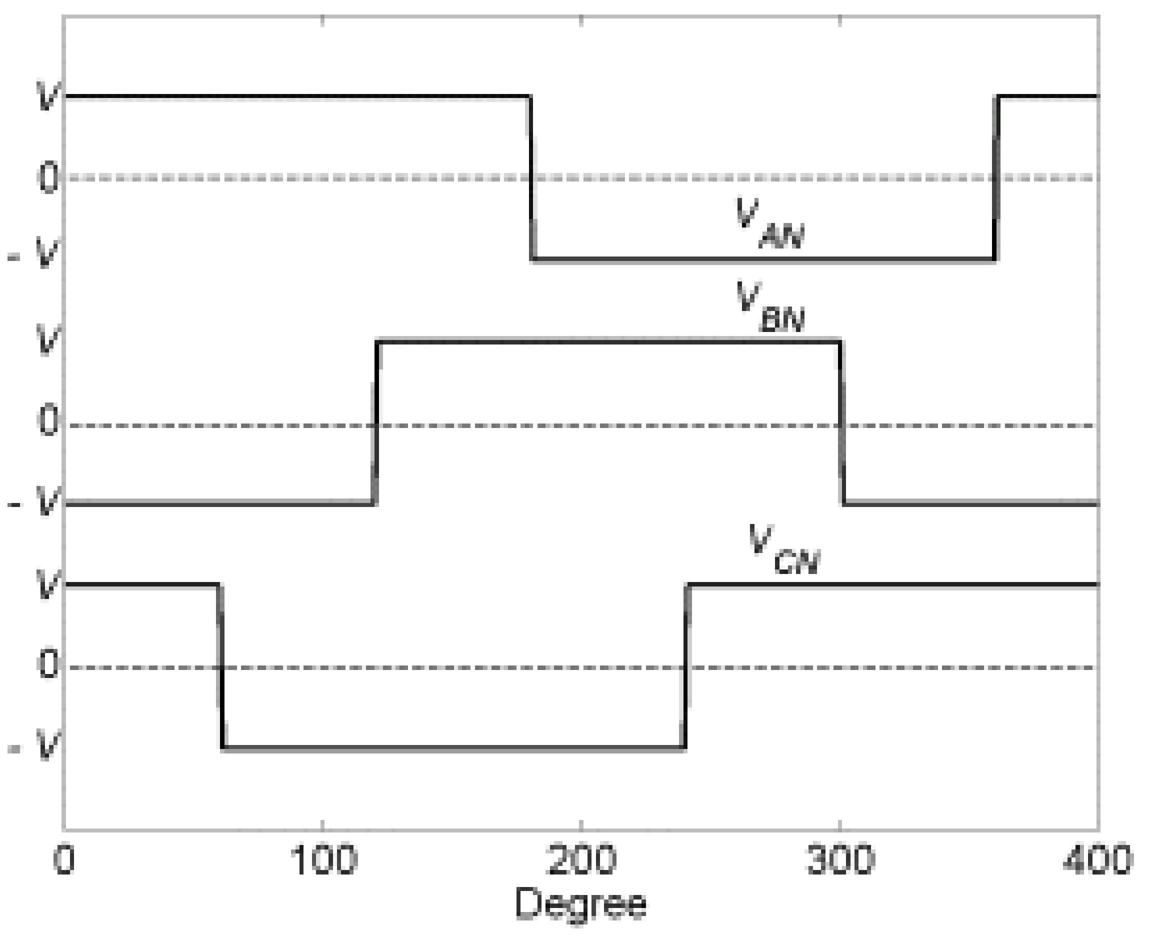
SVC VI Characteristics

- Assume that the system is operating with a voltage V_0.
- If the system voltage increases, V will increase to V_1 without SVC. However the SVC moves the operating point to B by absorbing inductive current and holds the voltage at V_3.
- Similarly the SVC holds the voltage at V_4 for a decrease in the system voltage.

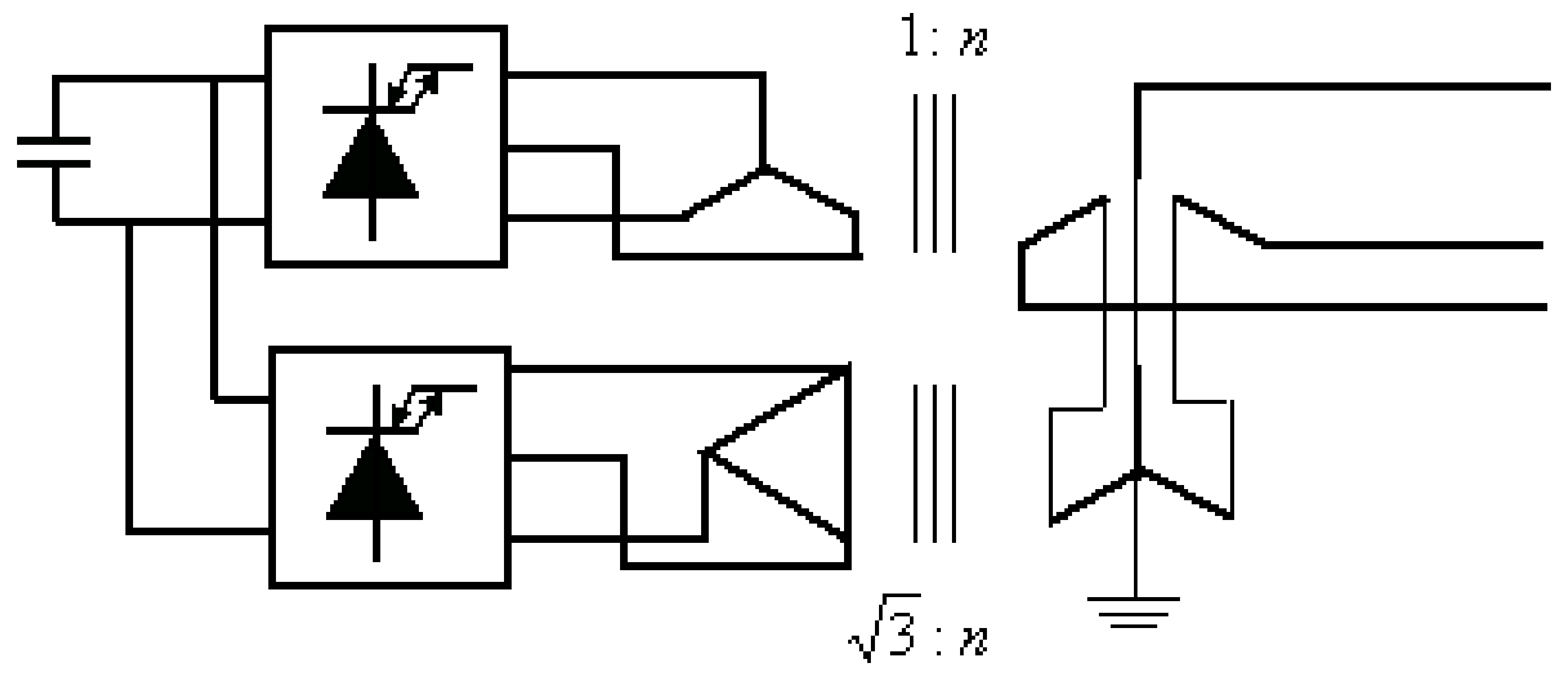
Synchronous Voltage Source (SVS)



SVS - Voltage Waveforms

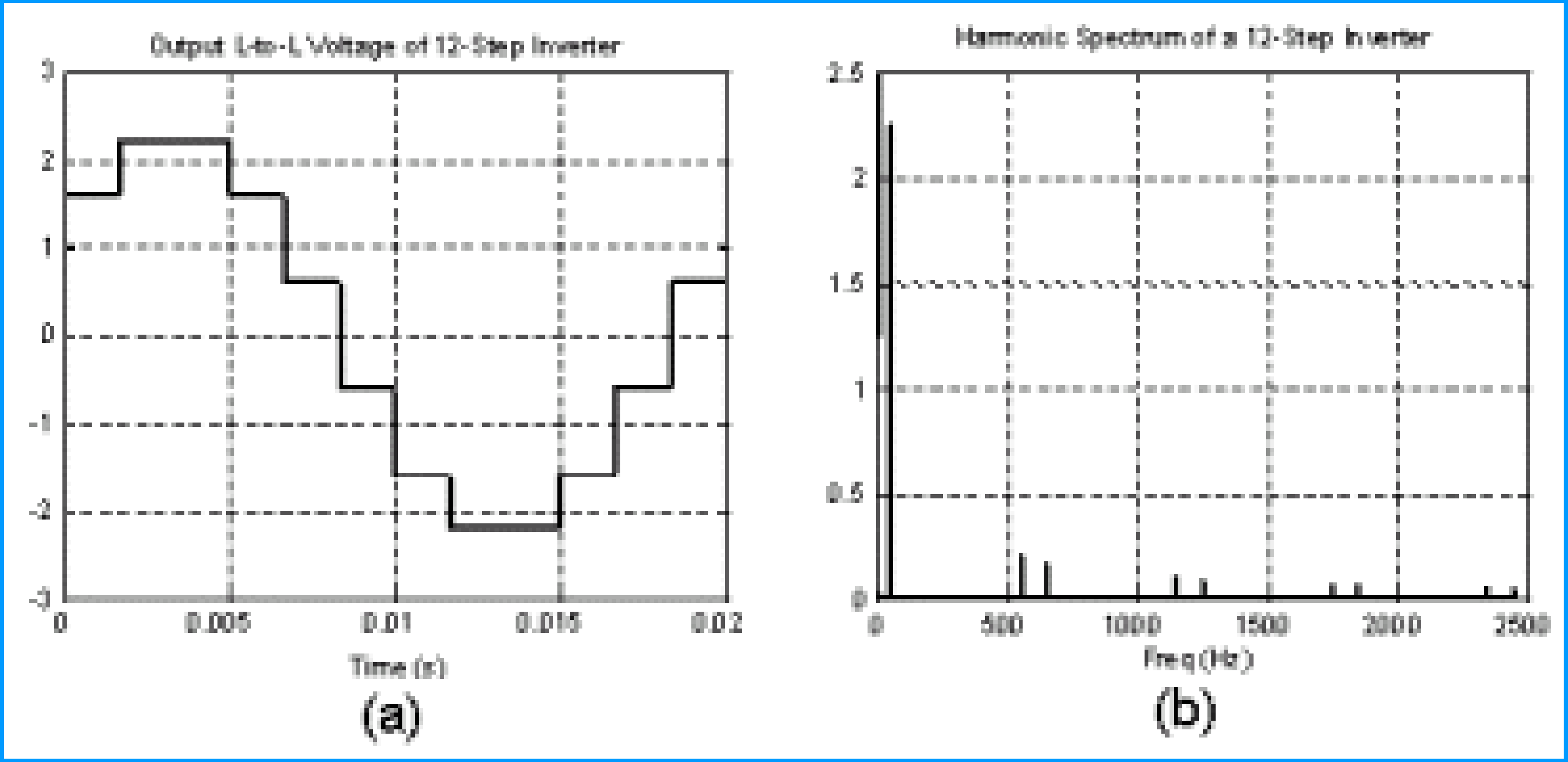


12-Step SVS



The transformer primaries provide a phase shift of 30°.

12-Step Output Waveform and Harmonic Spectrum



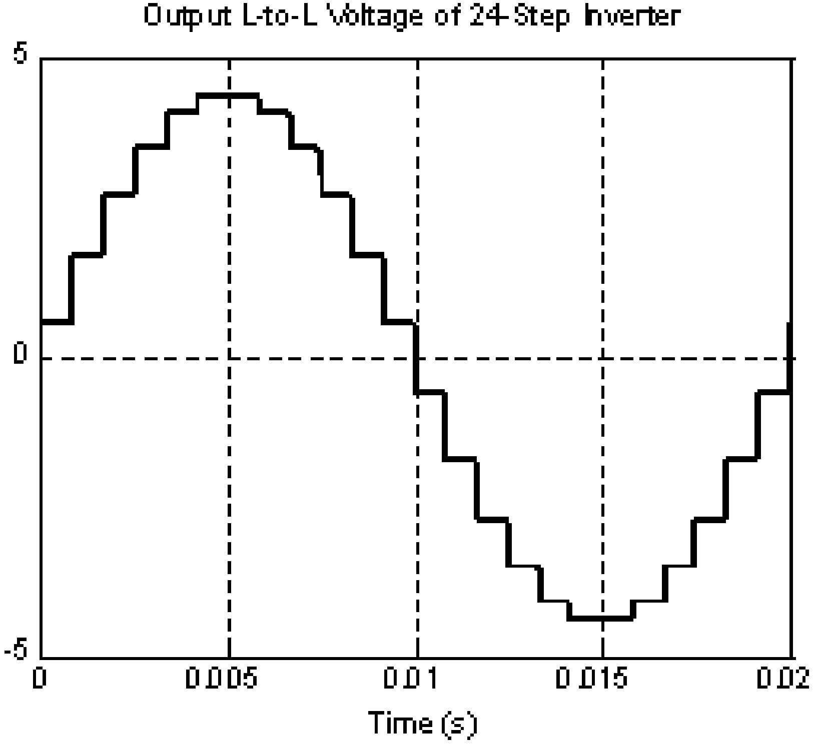
Multi-Step SVS

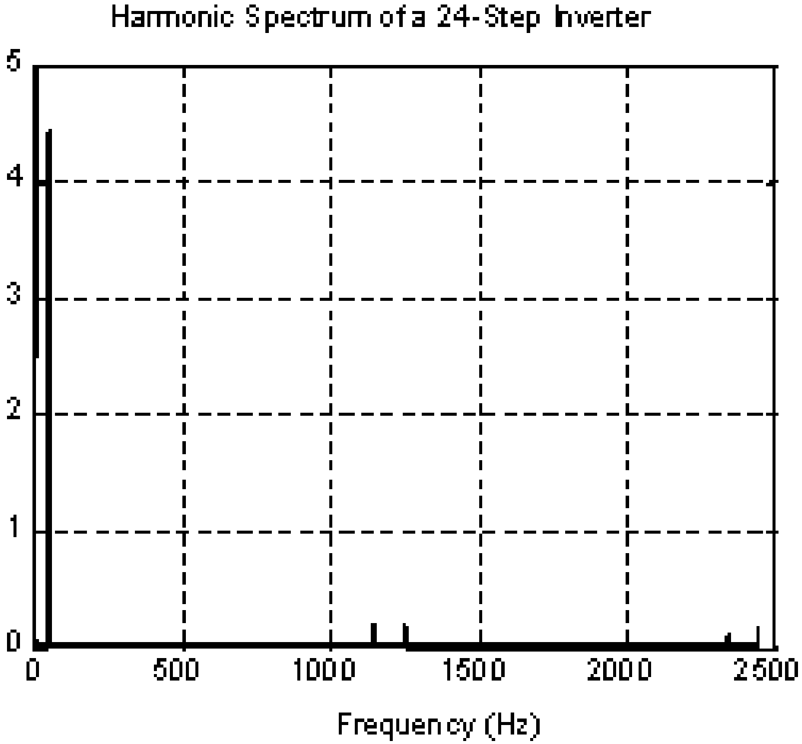
- In a similar way 6*n*-step output voltage can be obtained by connecting *n* basic 6-step inverters and by providing phase shift through transformer connections.
- For example, a 24-step inverter can be constructed by phase shifting each of the four 6-step inverters by 15°.
- Similarly a phase shift of 7.5° between 8 basic inverter output will produce a 48-step output waveform.

Multi-Step SVS

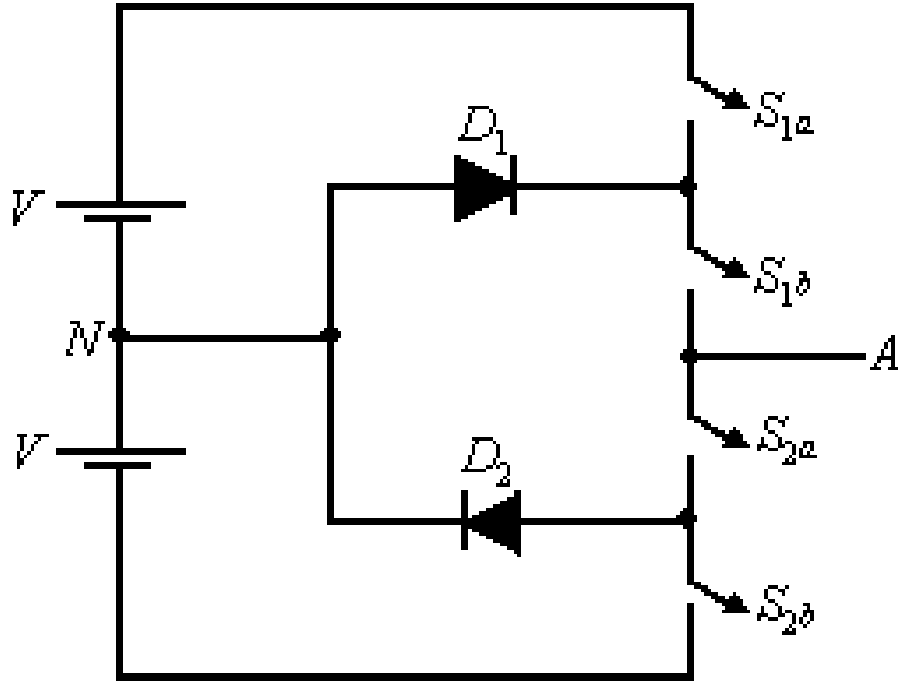
- Note that the firing pulses of the 6-step basic inverters must also be phase shifted by 15° or 7.5° to obtain 24 or 48-step output waveforms respectively.
- The lowest order harmonics in a $6n$-step inverter is $6n \pm 1$ in the ac side and $6n$ in the dc side.

24-Step Output Waveform and Harmonic Spectrum


Output L-to-L Voltage of 24-Step Inverter

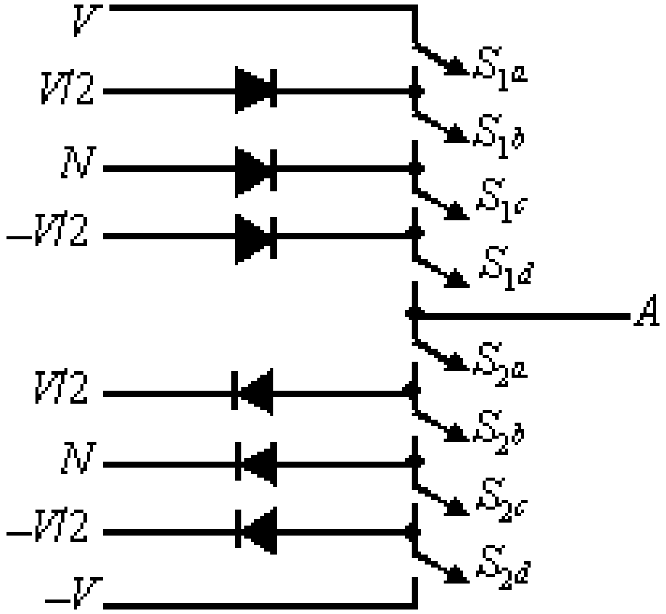

Harmonic Spectrum of a 24-Step Inverter

3-Level Inverter



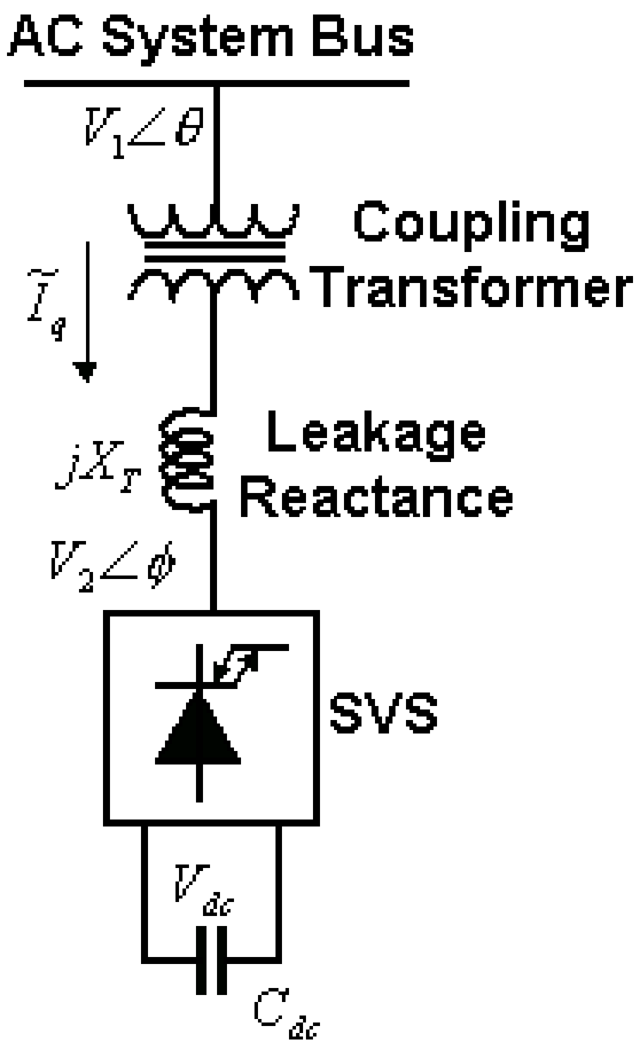
Switch Status				V_{AN}
S_{1a}	S_{1b}	S_{2a}	S_{2b}	
Off	Off	On	On	$-V$
Off	On	On	Off	0
On	On	Off	Off	$+V$

5-Level Inverter



Switch Status								V_{AN}
S_{1a}	S_{1b}	S_{1c}	S_{1d}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	
On	On	On	On	Off	Off	Off	Off	$+V$
Off	On	On	On	On	Off	Off	Off	$+V/2$
Off	Off	On	On	On	On	Off	Off	0
Off	Off	Off	On	On	On	On	Off	$-V/2$
Off	Off	Off	Off	On	On	On	On	$-V$

STATCOM



- A STATCOM consists of a SVS that is supplied by a dc storage capacitor C_{dc}.
- The SVS is connected in shunt with the ac system bus through a coupling transformer with a leakage reactance of X_T.

STATCOM - VAr Generation

If $\angle\theta = \angle\phi$, then the direction of the flow of purely reactive current I_q will depend on the voltage magnitudes V_1 and V_2.

- If $V_1 > V_2$ then the current flows from the ac system to the SVS and the converter absorbs reactive (inductive) power.
- If $V_2 > V_1$ then the current flows from the SVS to the ac system and the converter generates reactive (capacitive) power for the ac system.

STATCOM - DC Capacitor Control

- However pure reactive injection or absorption is neither possible nor desirable.
- Since the converter is supplied by a dc capacitor, the voltage across the capacitor will fall if the STATCOM is not lossless.
- The dc capacitor voltage can be regulated by replenishing the losses due to switching and in the coupling transformer circuit by drawing power from the ac system.
- Therefore $\angle\phi$ must lag $\angle\theta$ by a small amount such that the dc capacitor voltage is held constant.

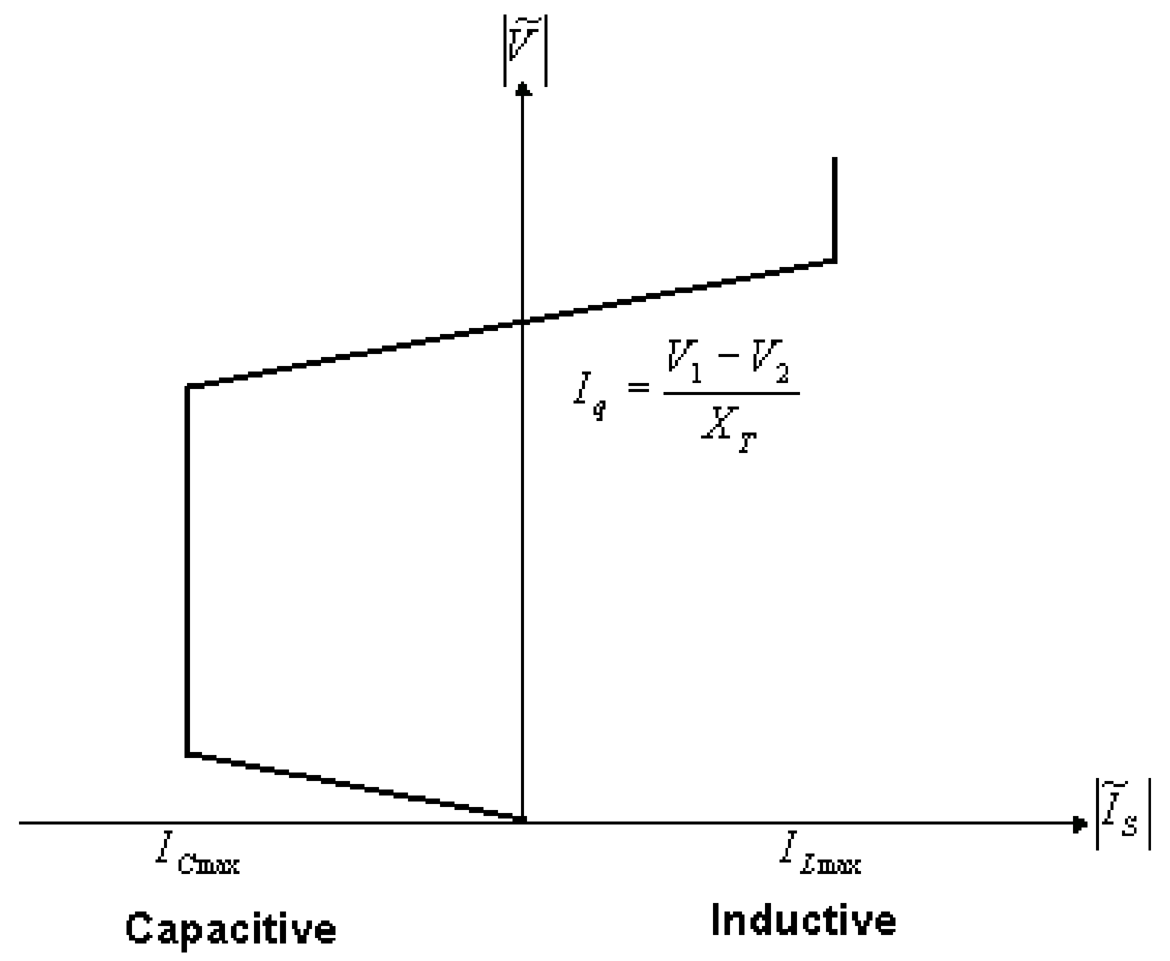
STATCOM - Control

- In a multi-step converter, the fundamental component of the output voltage is determined by the magnitude of the dc capacitor voltage.
- Therefore the voltage magnitude V_2 can be increased or decreased vis-à-vis the magnitude of V_1 by charging or discharging the dc capacitor through the control of ϕ.
- This makes the control loop slow.

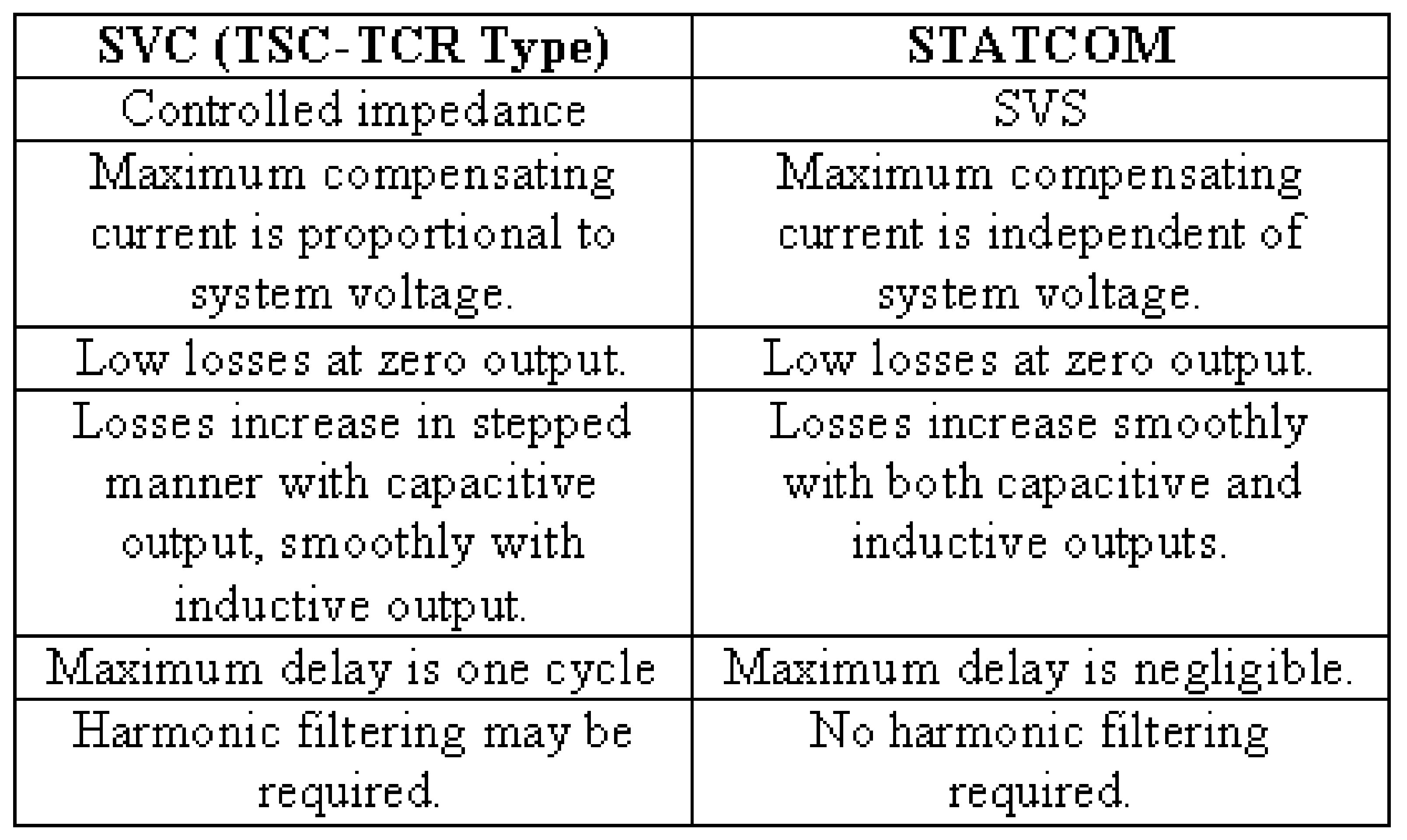
STATCOM - Control

- Pulse width modulation (PWM) can effectively be used in a multilevel converter. This has a better control response.
- In a sinusoidal PWM, the fundamental component of the output voltage magnitude can be changed by changing either the capacitor voltage or the modulation index.
- The capacitor voltage imbalance problem in diode-clamped topology makes its use restrictive. Alternatively flying capacitor topology can be used.

STATCOM - VI Characteristics



Comparison Between SVC and STATCOM



SVC (TSC-TCR Type)	STATCOM
Controlled impedance	SVS
Maximum compensating current is proportional to system voltage.	Maximum compensating current is independent of system voltage.
Low losses at zero output.	Low losses at zero output.
Losses increase in stepped manner with capacitive output, smoothly with inductive output.	Losses increase smoothly with both capacitive and inductive outputs.
Maximum delay is one cycle	Maximum delay is negligible.
Harmonic filtering may be required.	No harmonic filtering required.

For Further Reading

Flexible AC Transmission Systems

The following two books cover most of the aspects of FACTS

[1] N. G. Hingorani and L. Gyugyi, *Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems*, IEEE Press, New York, 2000.
[2] Y. H. Song and A. T. Johns (eds.), *Flexible AC Transmission Systems (FACTS)*, Institute of Electrical Engineers, London, 2001.

The following book mainly deals with thyristor based FACTS devices like SVC and TCSC.

[3] R. M. Mathur and R. K. Varma, *Thyristor Based FACTS Controllers for Electric Power Transmission Systems*, IEEE Press and Wiley Interscience, New York, 2002.

The following book is a classic. It discusses most of the early thyristor based technology.

[4] T. J. E. Miller (ed), *Reactive Power Control in Electric Systems*, John Wiley, New York, 1982.

The following book covers some of the aspects of shunt and series compensation and in general is a good reference book on Power Systems

[5] P. S. Kundur, *Power System Stability and Control*, McGraw-Hill, New York, 1994.

Power Quality and Custom Power

The following books cover many aspects of power quality problems.

[6] R. C. Dugan, M. F. McGranaghan and H. W. Beaty, *Electric Power Systems Quality*, 2nd ed., McGraw-Hill, New York, 2003.
[7] J. Arrillaga, N. R. Watson and S. Chen, *Power Quality Assessment*, John Wiley, New York, 2000.

Voltage sag and interruptions problems have been discussed in great detail in the following book.

[8] M. J. Bolen, *Understanding Power Quality Problems: Voltage Sags and Interruptions*, IEEE Press, 2000.

Various aspects of custom power technology are discussed in

[9] A. Ghosh and G. Ledwich, *Power Quality Enhancement using Custom Power Devices*, Kluwer Academic Publishers, Boston, 2002.