FACTS INTRODUCTION

Classification

- The FACTS device can be classified in TWO ways.

A. Depending on **the type of connection to the network**

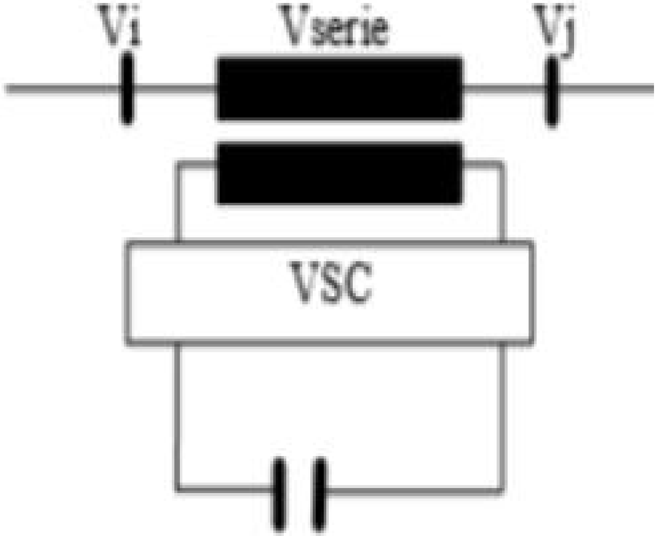
  - Serial controller
  - Derivation controller
  - Serial to serial controller
  - Serial derivation controllers

B. Depending on technological features the FACTS devices can be divided into two generations:

- First generation – uses thyristors (SCR).
- Second generation semiconductors (GTO IGBT etc)

SERIAL CONTROLLERS

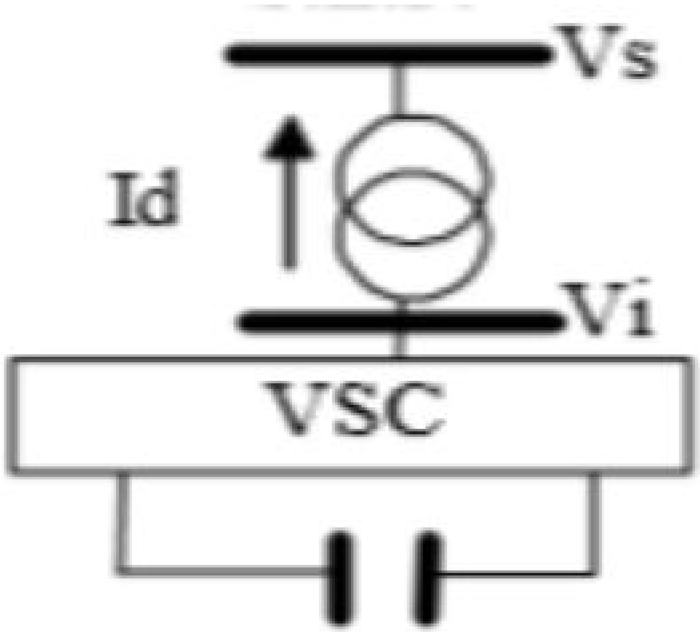
- Consist of a variable impedance as a condenser, coil.
- Inject a serial tension(variable impedance multiplied by the current) to the line.
- Tension is in quadrature with the line current.
- Consumes reactive power.
- Ex: Serial Synchronous Static Compensator (**SSSC**) **or Static Synchronous Series Compensator** (**SSSC**).



CONTROLLERS IN DERIVATION

- Consist of a variable impedance, variable source or a combination of both.
- Inject current to the system in the point of connection. (variable impedance connected to line tension causes variable current flow, thus injecting current to the line).
- While the injected current is in quadrature with the line tension.
- Consumes reactive power.

Ex: Static Synchronous Shunt Compensator (**STATCOM**).



SERIAL – SERIAL CONTROLLERS

- Combination of coordinated serial controllers in a multiline transmission system or can also be an unified controller.
- The serial controllers provide serial reactive compensation for each line also transferring active power between lines through the link of power.
- The term “unified” means that the DC terminals of the converters of all the controllers are connected to achieve a transfer of active power between each other.
- Ex: Interline Power Flow Compensator (**IPFC**).

SERIAL – DERIVATION CONTROLLERS

- Combination of serial and derivations controllers separated, co-ordinately controlled.
- Inject current to the system through the component in derivation of the controller, and serial tension with the line utilizing the serial component.
- When the serial and derivation controllers are unified, they can have an exchange of active power between them through their link.
- Ex: Unified Power Flow Controller (**UPFC**)

DEPENDING ON GENERATIONS

FIRST GENERATION OF FACTS

- Static Compensator of VAR’s (SVC, TCR)
- Tyristor Controlled Series Compensation (TCSC, TCSR)
- Thyristor Controlled phase shifting Transformer (TCPST)
- Thyristor Controlled voltage regulator (TCVR)

SECOND GENERATION OF FACTS

- Synchronous Static Compensator (STATCOM with and without storage)
- Static Synchronous Series Compensator (SSSC with and without storage)
- Unified Power flow Controller (UPFC)
- Interline Power Flow Controller (IPFC)

TYPES OF FACTS CONTROLLERS

SHUNT

- Static Var Compensator (SVC)
- Static Synchronous Shunt Compensator (STATCOM)

SERIES

- Thyristor Controlled Series Capacitor (TCSC)
- Static Synchronous Series Compensator (SSSC)

HYBRID

- Unified Power Flow Controller (UPFC)
- Interline Power Flow Controller (IPFC)

TYPES OF FACTS CONTROLLERS

- FACTS controller can also be classified upon power electronic devices used in the control strategy as,

1. Variable Impedance Type: SVC & TCSC

2. Voltage Source Converter (VSC) Type: STATCOM, SSSC, UPFC

STATIC VARIABLE COMPENSATOR (SVC)

- **SVC is the First Generation FACTS Controller.**
- SVC is an automated impedance matching device. It is designed to bring the system closer to unity power factor.
- SVC is a **variable impedance devices where the current through a reactor is controlled by using back to back connected thyristor valves.**

The applications of SVC is,

1. For **load compensation of fast changing loads** and can provide **dynamic power factor improvement.**
2. It **Improves stability** with fast acting voltage regulation and can Control dynamic over voltages.
3. SVC has no inertia and can be extremely **fast in response**. This enables the faster control of reactive power in its control range.

- Ideally SVC should be located at the electrical centre of the system or midpoint of a transmission line.

SOME OF THE IMPORTANT FACTS DEVICES

- Static VAR Compensator (SVC)
  - Thyristor Controlled Reactor (TCR)
  - Thyristor Switched Capacitor (TSC)
  - TSC – TCR Combined Configuration

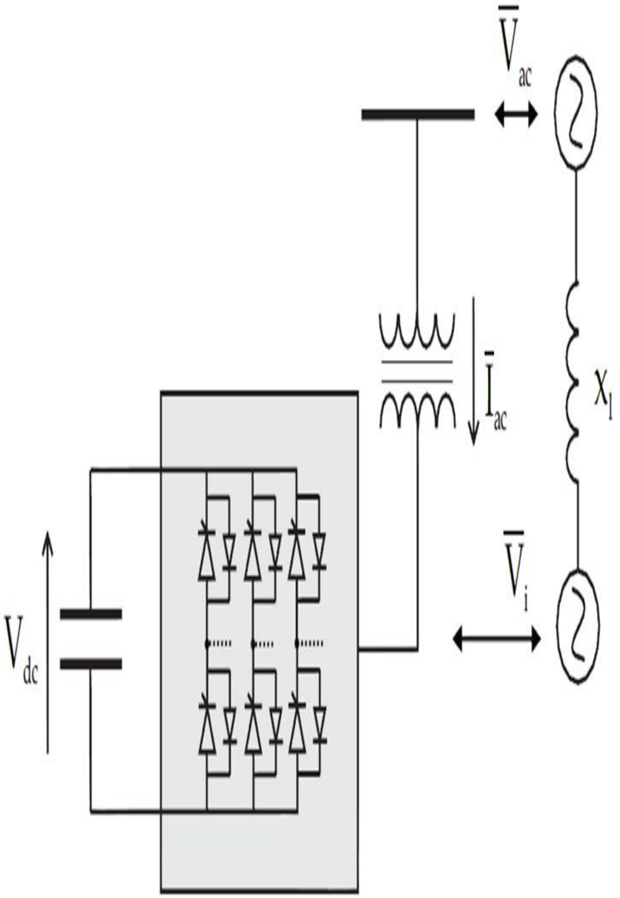
- Thyristor Controlled Series Capacitor (TCSC)
- Static Synchronous Shunt compensator (STATCOM), also known as a static synchronous condenser (STATCON)
- Static Synchronous Series compensator (SSSC)
- Unified Power–Flow Controller (UPFC)

VOLTAGE SOURCE CONVERTER

- Power Electronics based device
- The Voltage source converter is represented as an ideal bi-directional switches.
- It converts voltage and currents from DC to AC, while the exchange of power can be in both directions

1. From AC to DC (rectification mode)
2. From DC to AC (inversion mode).

- The reactive power control can be controlled by using VSC devices.



STATIC SYNCHRONOUS SHUNT COMPENSATOR (STATCOM)

- STATCOM is a **Voltage Source Converter based device**.

STATCOM is generally installed,

- To support electrical networks which have **poor power factor and poor voltage regulation.**
- The voltage source is created from a DC source (capacitor or battery). So, the STATCOM has very little active power capabilities.
- If the terminal voltage of the VSC is higher than the AC voltage at the point of connection, the STATCOM generates reactive power.
- When the amplitude of the voltage source is lower than the AC voltage, it absorbs reactive power.
- The response time of a STATCOM is shorter than that of an SVC, mainly due to the fast switching times provided by

SVC

STATCOM

STATCOM

Introduction

- **Modern power systems are designed to operate efficiently to supply power on demand to various load centers with high reliability**.
- transmission lines carry power from the sources to loads, modern power systems are highly interconnected for economic reasons.
- The interconnected systems benefit by
  - (a) **exploiting load diversity**
  - (b) **sharing of generation reserves and**
  - (c) **economy gained from the use of large efficient units without sacrificing reliability.**

- However, there is also a downside to ac system interconnection –as the security can be adversely affected as the disturbances initiated in a particular area can spread and propagate over the entire system resulting in major blackouts caused by cascading outages.

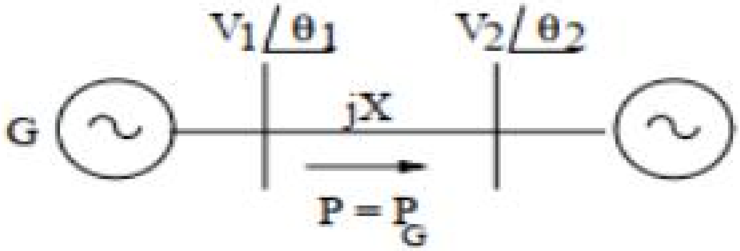
Basics of Power Transmission Networks

- A large majority of power transmission lines are AC lines operating at different voltages (10 kV to 800 kV).
- The distribution networks generally operate below 100 kV while the bulk power is transmitted at higher voltages.
- The lines operating at different voltages are connected through transformers which operate at high efficiency.

Power Flow Control

- Traditionally, AC lines have no provision for the control of power flow.
- The mechanically operated circuit breakers (CB) are meant for protection against faults (caused by flashovers due to overvoltages on the lines or reduced clearances to ground).
- A CB is rated for a limited number of open and close operations at a time and cannot be used for power flow control. (unlike a high power electronic switch such as thyristor, GTO, IGBT, IGCT, etc.).

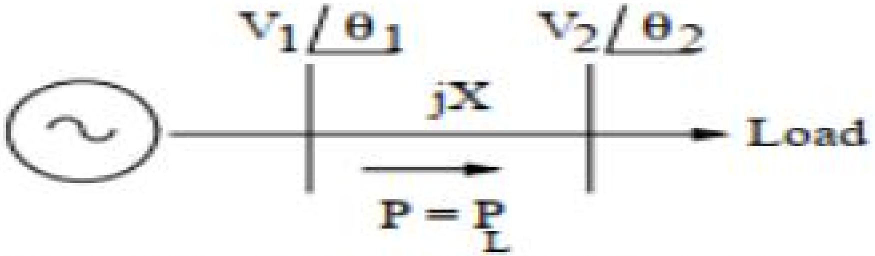
- Ac lines have inherent power flow control as the power flow is determined by the power at the sending end or receiving end.
- For example, consider a transmission line connecting two stations V1 and V2 in Fig.(a)



- Assuming the line to be lossless and ignoring the line charging, the power

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

- Power injected by the power station determines the flow of power in the line.
- The difference in the bus angles is automatically adjusted to enable P = PG (Note that usually there could be more than one line transmitting power from a generating station to a load centre).
- Fig.(b) If one or more lines trip, the output of the power station may have to be reduced by tripping generators, so as to avoid [illegible] operation.

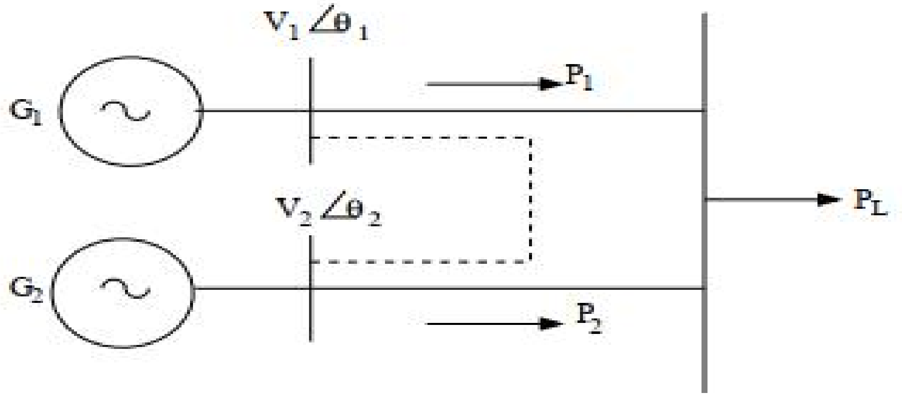


(b) A line supplying power to a load

- Here also the eq. of P applies but the power flow in the line is determined by the load supplied.
- The essential difference between the two situations is that in Fig. (a), the load centre is modeled as an infinite bus which can absorb (theoretically) any amount of power supplied to it from the generating station.
- This model of the load centre assumes that the generation available at the load centre is much higher than the power supplied from the remote power station (obviously, the total load supplied at the load centre is equal to the net generation available at thatbus).

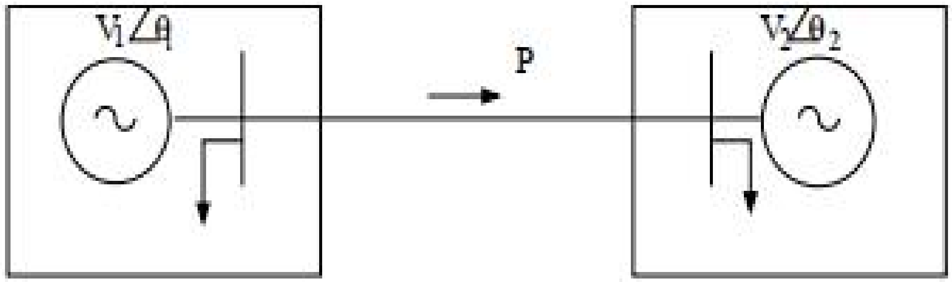
Reliability

- The reliability of the power supply at a load bus can be improved by arranging two (or more) sources of power as shown in Fig



- The addition of an (interconnecting) line can result in increase
of power flow in a line (while decreasing the power flow in some other line).

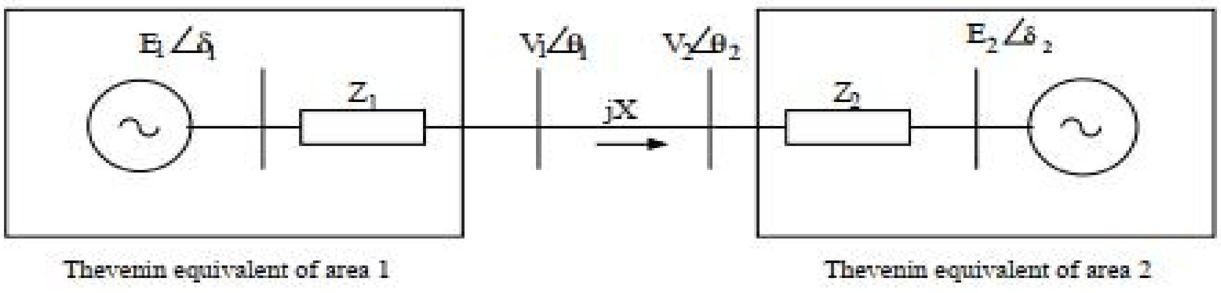
- Consider two power systems, each with a single power station meeting its own local load, interconnected by a tie line as shown in Fig.



(a)Single line diagram

- In this case, the power flow in the tie line (P) in steady state is determined by the mismatch between the generation and load in the individual areas.

- Under dynamic conditions, this power flow is determined from the equivalent circuit shown in Fig.



(b)Equivalent circuit

- If the capacity of the tie is small compared to the size (generation) of the two areas, the angles 1 and 2 are not affected much by the tie line power flow.
- **Thus, power flow in AC tie is generally uncontrolled and it becomes essential to trip the tie during a disturbance, either to protect the tie line or preserve system security.**

Control of Power Flow in AC Transmission Line

- Control the power flow in a AC transmission line to
  - (**a**) **enhance power transfer capacity and**
  - **or(b) to change power flow under dynamic conditions (subjected to disturbances such as sudden increase in load, line trip or generator outage) to ensure system stability and security.**

- The stability can be affected by growing low frequency, power oscillations (due to generator rotor swings), loss of synchronism and voltage collapse caused by major disturbances.

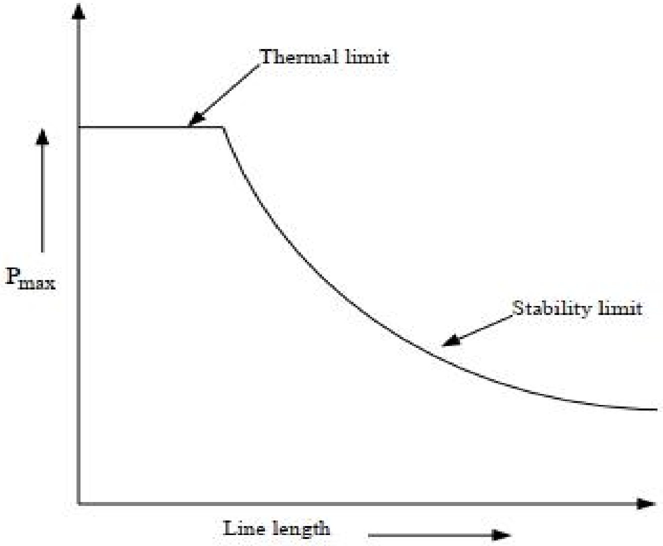
- We have the maximum power (Pmax) transmitted over a line as

$$P_{\max} = \frac{V_1 V_2}{X} \sin \delta_{\max}$$

- where δmax (30–40degree) is selected depending on the stability margins and the stiffness of the terminal buses to which the line is connected.

•For line lengths exceeding a limit, Pmax is less than the thermal limit of the power transfer determined by the current carrying capacity of the conductors (Note this is also a function of the ambient temperature).

• As the line length increases, X increases in a linear fashion and



Power transfer capability

- The series compensation using series connected capacitors increases Pmax as the compensated value of the series reactance (Xc) is given by

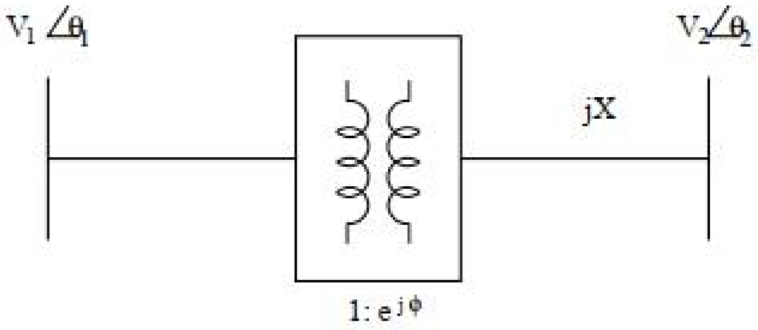
$$X_c = X(1 - k_{se})$$

- where kse is the degree of series compensation.
- The maximum value of kse that can be used depends on several factors including the resistance of the conductors.
- Typically kse does not exceed 0.7.

- **Fixed series capacitors have been used since a long time for increasing power transfer in long lines.**
- They are also most economical solutions for this purpose.
- However, the control of series compensation using thyristor switches has been introduced only 10-15 years ago for fast power flow control.
- The use of Thyristor Controlled Reactors (TCR) in parallel with fixed capacitors for the control of Xc, also helps in overcoming a major problem of Subsynchronous Resonance (SSR) that causes instability of when series compensated lines are used to transmit power from turbo generators in steam power stations.

- In tie lines of short lengths, the power flow can be controlled by introducing Phase Shifting Transformer (PST)
- The power flow in a lossless transmission line with an ideal PST (see Fig. 1.5) is given by

$$P = \frac{V_1 V_2}{X} \sin(\theta \pm \phi)$$



- Again, manually controlled PST is not fast enough under dynamic conditions.
- Thyristor switches can ensure fast control over discrete (or continuous) values of Ø depending on the configuration of PST used.
- Pmax can also be increased by controlling (regulating) the receiving end voltage of the AC line.

- When a generator supplies a unity power factor load the maximum power occurs when the load resistance is equal to the line reactance.
- It is to be noted th and can be expressed as

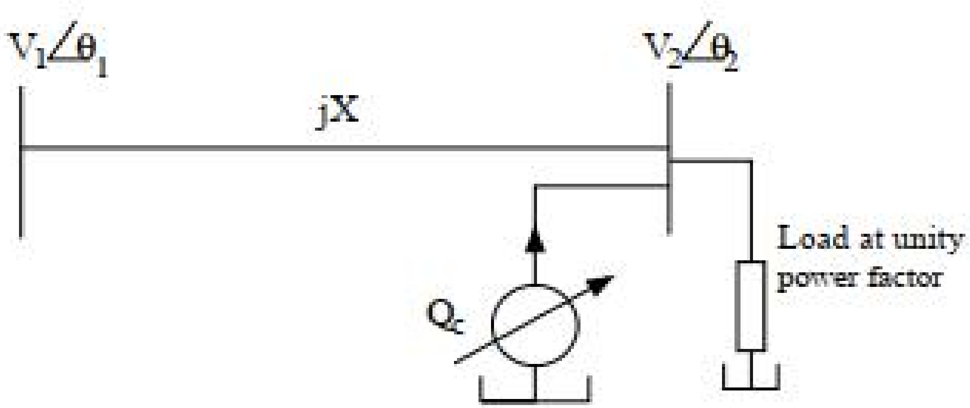
$$V_2 = V_1 \cos(\theta_1 - \theta_2)$$

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

- Substituting in P gives

$$P = \frac{V_1^2 \sin[2(\theta_1 - \theta_2)]}{2X}$$

- By providing dynamic reactive power support at bus (2) as shown in Fig. as shown, it is possible to regulate the bus voltage magnitude



- the maximum power transfer can be doubled just by providing dynamic reactive power support at the receiving end of the transmission line.
- This is in addition to the voltage support at the sending end.

- Steady state voltage support can be provided by mechanically switched capacitors
- the dynamic voltage support requires synchronous condenser or a power electronic controller such as Static Var Compensator (SVC) or STATic synchronous COMpensator (STATCOM)

Reactive Power Compensation

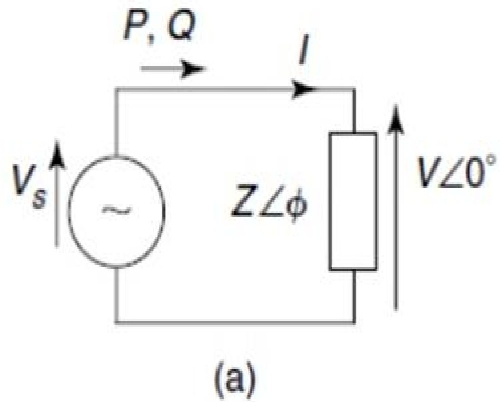
- Reactive power (VAR) compensation is defined as the management of reactive power to improve the performance of ac systems.

REACTIVE POWER CONTROL

- “To make transmission networks operate within desired voltage limits and methods of making up or taking away reactive power is called reactive-power control”.

- Apart from the energy dissipation in resistive components, all energy-coupling devices (e.g: motors and generators) operate based on their capacity to store and release energy.

- Instantaneous power from the voltage source to the load Z∟ *θ, in terms of the instantaneous voltage v and current i,* is given as P=vi
- In the steady state, where ***v= Vmax***
  - ***I = Imax cos(***



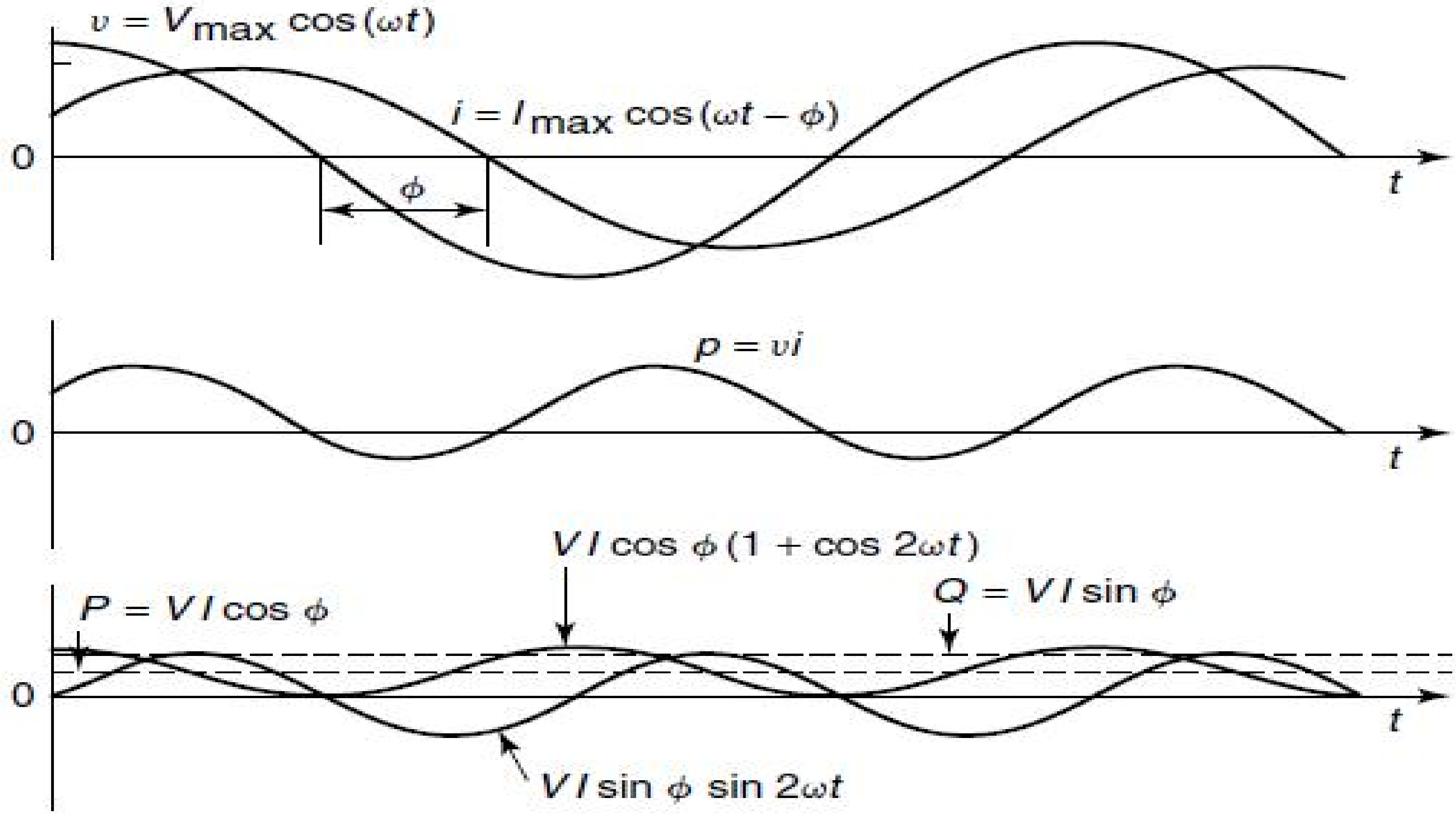
(a)

$$p = \frac{V_{\max} I_{\max}}{2}\,[\cos\phi + \cos(2\omega t - \phi)]$$

$$= VI\cos\phi(1 + \cos 2\omega t) + VI\sin\phi\sin 2\omega t$$

  - where *V and I are the respective root mean square (rms) values of v and i.*

The electrical parameters in an ac network



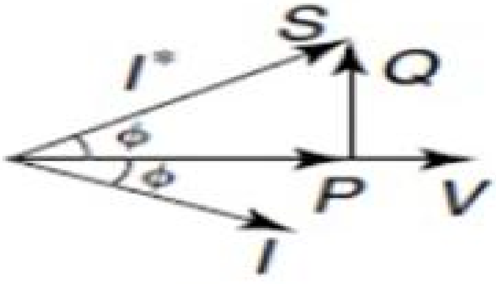
(b)

- In phasor domain, the complex power in the network in Fig. (a) is given by

$$
\begin{aligned}
S &= \overline{V} \cdot \overline{I}^{*} \\
&= P + jQ = VI\cos\phi + jVI\sin\phi
\end{aligned}
$$

- where *P is called the active power, which is measured in watts (W),*
- ***Q is*** **called the reactive power, which is measured in volt–ampere reactives (var).**

- The reactive power is essential for creating the needed coupling fields for energy devices.
- It constitutes voltage and current loading of circuits but does not result in an average (active) power consumption and is, in fact, an important component in all ac power networks
- In high-power networks, active and reactive powers are measured in megawatts (MW) and MVAR, respectively
- Figure(c) shows a commonly used pow



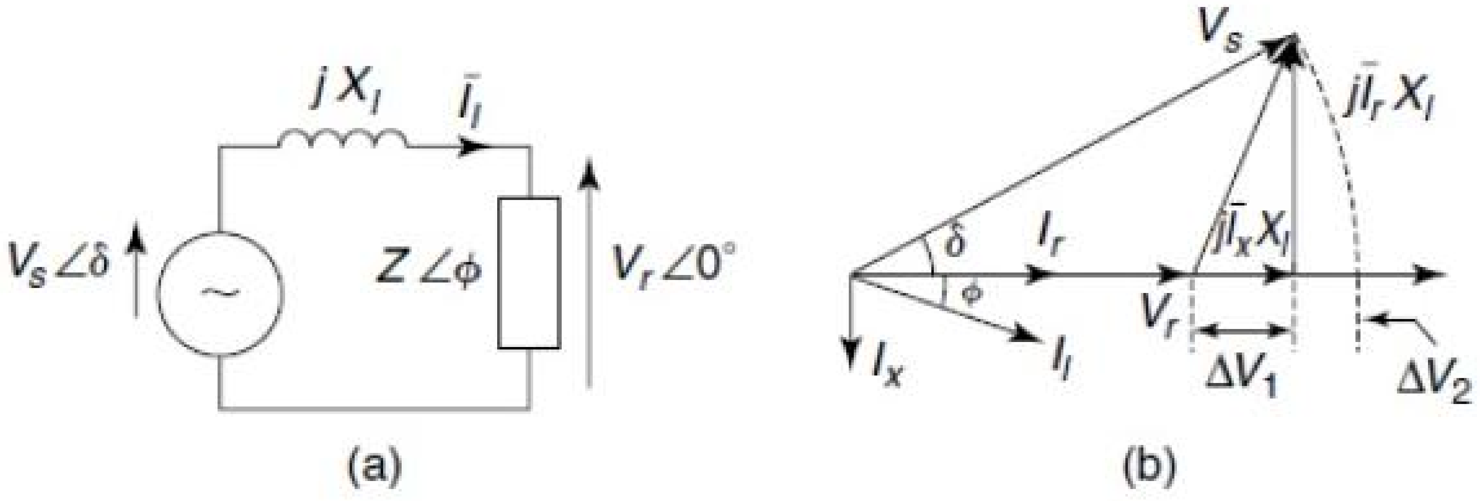
(c)

- **Electromagnetic devices store energy in their magnetic fields.**
  - These devices draw lagging currents, thereby resulting in positive values of *Q; therefore*, they are frequently referred to as the absorbers of reactive power.
- **Electrostatic devices, on the other hand, store electric energy in fields.**
  - These devices draw leading currents and result in a negative value of *Q; thus they are seen to be suppliers* of reactive power.

- The shunt connected devices like shunt capacitors or inductors or synchronous inductors may be fixed or switched (using circuit breaker).

- The smooth control of reactive power is also possible by use of power electronic devices. Example: Static Var Compensator(SVC)” and a Thyristor Controlled Reactor (TCR

Uncompensated Transmission Lines



A short, lossless transmission line feeding a load.

- From the above figure it is clear that between the sending and the receiving end voltages and magnitude variation as well as a phase difference is created and the most significant part of the voltage drop in the line reactance is due to the reactive component of the load current and **to keep the voltages in the network nearly at the rated value two control schemes are**

- Two compensation methods are:
  - 1. Load compensation
  - 2. System compensation

Load compensation

The main objectives are to :-

i) increase the power factor of the system

ii) to balance the real power drawn from the system

iii) compensate voltage regulation

iv) to eliminate current harmonics.

- b) Voltage Support – The main purpose is to decrease the voltage fluctuation at a given terminal of transmission line.
- Therefore the VAR compensation improves the stability of ac system by increasing the maximum active power that can be transmitted.

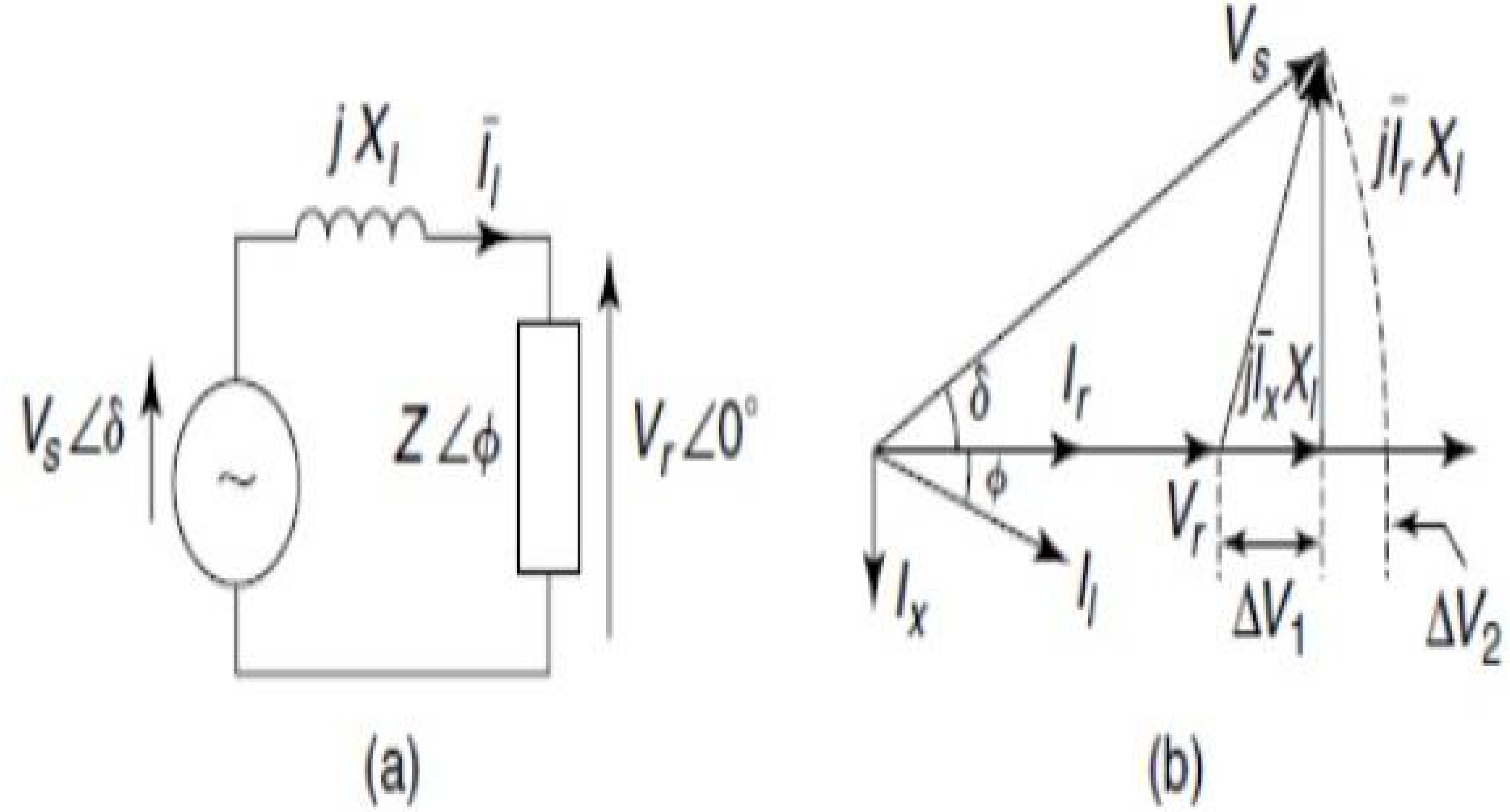
Load Compensation

- It is possible to compensate for the reactive current of the load by adding **a parallel capacitive load so that $I_c = I_x$ and the effective power factor to become unity.**

- **In the figure the absence of I_x eliminates the voltage drop ΔV_1 bringing V_r closer in magnitude to V_s, this condition is called load compensation**
  - and actually by charging extra for supplying the reactive power a power utility company makes it advantageous for customers to use load compensation on their premises.

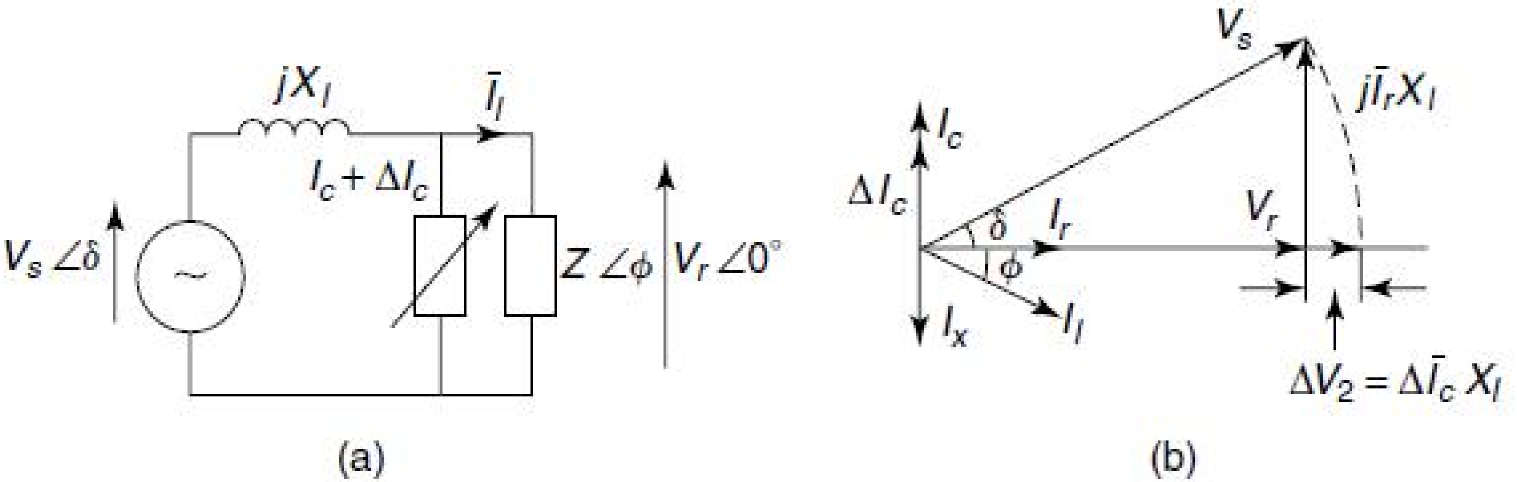
- **Loads compensated to the unity power factor reduce the line drop but do not eliminate it. They**

Load Compensation



System compensation

- **To regulate the receiving-end voltage at the rated value a power utility may install a reactive-power compensator** as shown in the figure
  - **and this compensator draws a reactive current to overcome both components of the voltage drop ΔV_1 and ΔV_2 as a consequence of the load current I through** the line reactance X.



The reactive-power control for voltage regulations

System compensation

- To compensate for ΔV2 an additional capacitive current ΔIc over and above Ic that compensates for Ix is drawn by the compensator.
- When **$\Delta I_c X_1 = \Delta V_2$**
  - the receiving end voltage V_r equals the sending end voltage V_s and such compensators are employed by power utilities to ensure the quality of supply to their customers.

Lossless Distributed Parameter Lines

- Most power transmission lines are characterized by distributed parameters:
  - Series Resistance, Series Inductance, Shunt Conductance and Shunt Capacitance all per-unit length
  - and these parameters all depend on the conductor size, spacing, and clearance above the ground, frequency and temperature of operation.

- In addition these parameters depend on the bundling arrangement of the line conductors and the nearness to other parallel lines.

Lossless Distributed Parameter Lines

- The characteristic behavior of a transmission line is dominated by its *l and c parameters. Parameters r and g account for the transmission losses. The fundamental* equations governing the propagation of energy along a line are the following wave equations:

$$\frac{d^2\overline{V}}{dx^2} = zy\overline{V}$$

$$\frac{d^2\overline{I}}{dx^2} = zy\overline{I}$$

- where $zy = (r + jql)(g + jqc)$.

Lossless Distributed Parameter Lines

$$\overline{V}(x) = \overline{V}_s \cos \beta x - j Z_0 \overline{I}_s \sin \beta x$$

$$\overline{I}(x) = \overline{I}_s \cos \beta x - j \frac{\overline{V}_s}{Z_0} \sin \beta x$$

- These equations are used to calculate voltage and current anywhere on line, at a distance x *from the sending end, in terms of the sending-end voltage and* current and the line parameters

Lossless Distributed Parameter Lines

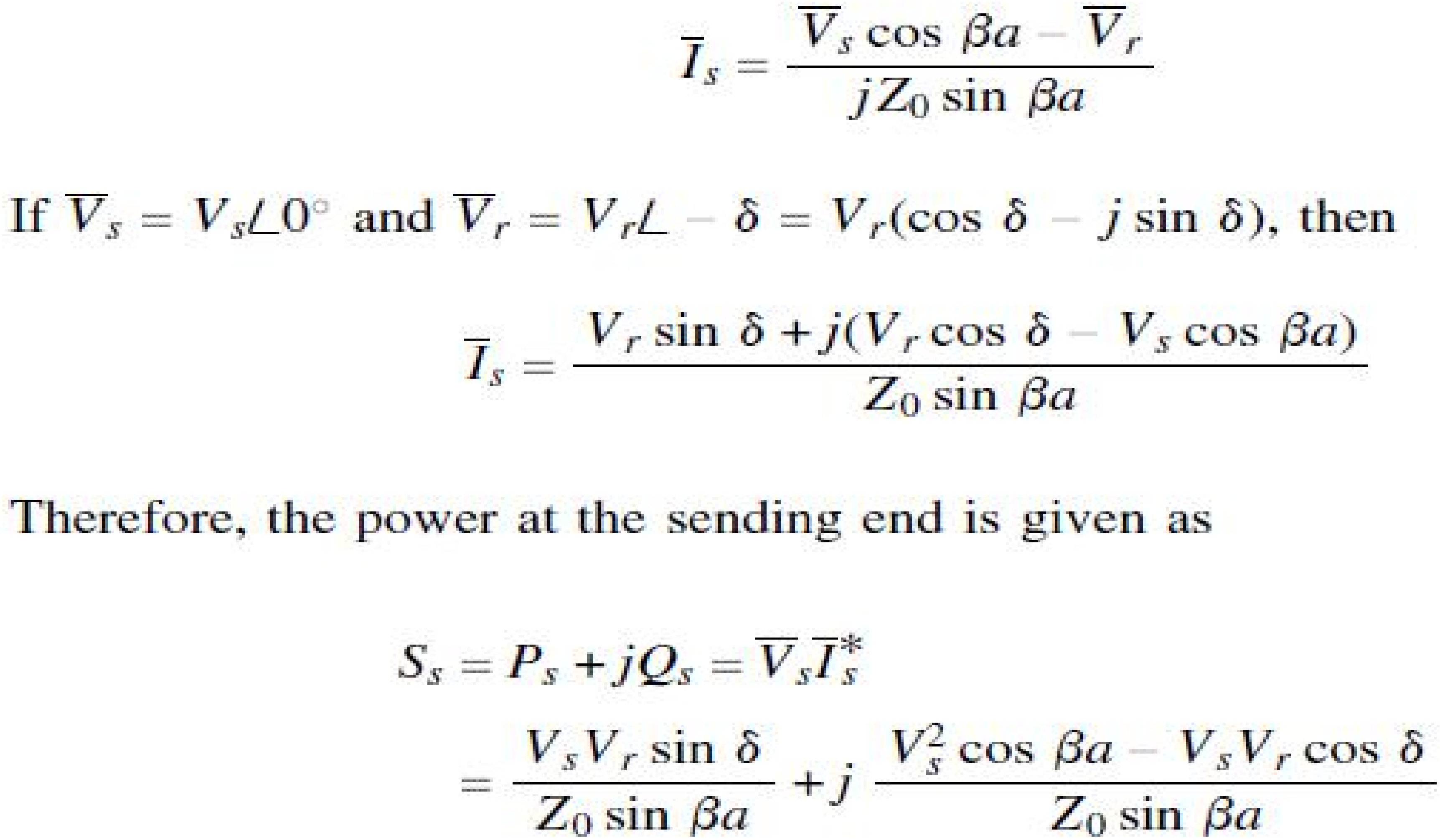
$$Z_0 = \sqrt{\frac{l}{c}}\ \Omega = \text{the surge impedance or characteristic impedance}$$

$$\beta = \omega\sqrt{lc}\ \text{rad/km} = \text{the wave number}$$

$$\beta a = \omega\sqrt{lca}\ \text{rad} = \text{the electrical length of an } a\text{-km line}$$

- where *l is the line inductance in henries per kilometer (H/ km), c is the line shunt* capacitance in farads per kilometer (F/ km), and $1\sqrt{lc}$ *is the propagation* velocity of electromagnetic effects on the transmission line. (It is less than the velocity of light.)

Lossless Distributed Parameter Lines



$$\overline{I}_s = \frac{\overline{V}_s \cos \beta a - \overline{V}_r}{jZ_0 \sin \beta a}$$

If $\overline{V}_s = V_s \angle 0^\circ$ and $\overline{V}_r = V_r \angle - \delta = V_r(\cos \delta - j \sin \delta)$, then

$$\overline{I}_s = \frac{V_r \sin \delta + j(V_r \cos \delta - V_s \cos \beta a)}{Z_0 \sin \beta a}$$

Therefore, the power at the sending end is given as

$$S_s = P_s + jQ_s = \overline{V}_s \overline{I}_s^*$$

$$= \frac{V_s V_r \sin \delta}{Z_0 \sin \beta a} + j \frac{V_s^2 \cos \beta a - V_s V_r \cos \delta}{Z_0 \sin \beta a}$$

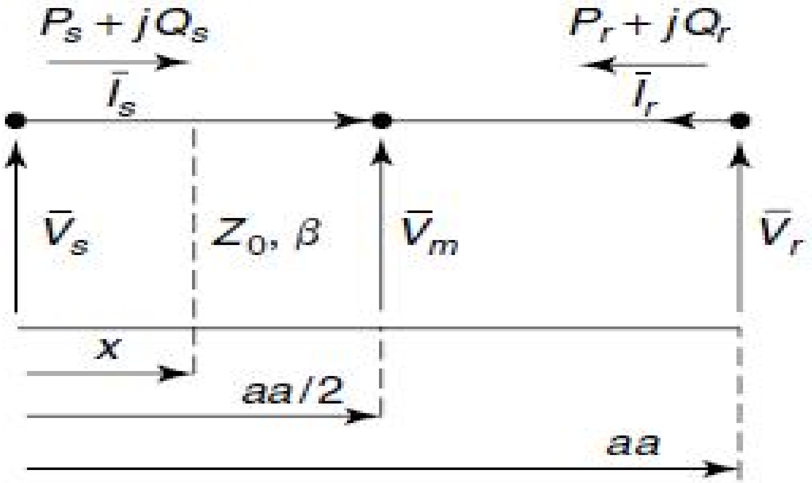


Figure 2.4 The power on a lossless distributed line.

$$S_r = P_r + jQ_r = -\frac{V_s V_r \sin\delta}{Z_0 \sin\beta a} + j\,\frac{V_r^2 \cos\beta a - V_s V_r \cos\delta}{Z_0 \sin\beta a}$$

Comparing Eqs. (2.7) and (2.8) and taking the directional notation of Fig. 2.4 into account, it is concluded that for a lossless line, *Ps c − Pr , as expected.* However, *Qs Qr because of the reactive-power absorption/generation in the* line.

Lossless Distributed Parameter Lines

- From Eqs. the power flow from the sending end to the receiving end is expressed as

$$P = \frac{V_s V_r \sin \delta}{Z_0 \sin \beta a}$$

Symmetrical Lines

When the voltage magnitudes at the two ends of a line are equal that is

- **$V_s = V_r = V$, the line is said to be symmetrical because power networks operate as voltage sources attempts are made to hold almost all node voltages at nearly rated values.**

- Therefore a symmetrical line presents a realistic situation.

PASSIVE COMPENSATION

- **Reactive-power control for a line is often called reactive-power compensation.**
- **External devices or subsystems that control reactive power on transmission lines are known as compensators.**
- A compensator mitigates the undesirable effects of the circuit parameters of a given line

The objectives of line compensation are invariably

1. **to increase the power-transmission capacity of the line, and/ or**
2. **to keep the voltage profile of the line along its length within acceptable bounds to ensure the quality of supply to the connected customers as**

Passive reactive–power compensators include

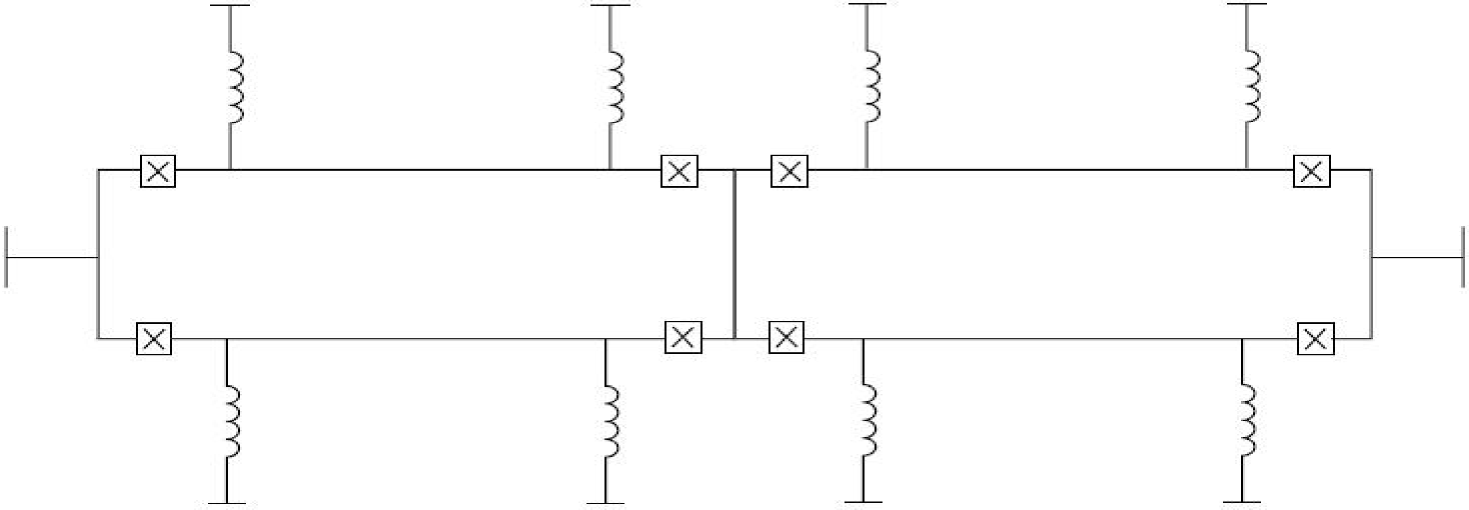
- series capacitors
- and shunt–connected inductors and capacitors

Shunt Compensation

- Changes the natural electrical characteristics of the transmission line to make it more compatible with the prevailing load demand.
  - Thus, **shunt connected, fixed or mechanically switched reactors are applied to minimize line overvoltage under light load conditions, and**
  - **shunt connected, fixed or mechanically switched capacitors are applied to maintain voltage levels under heavy load conditions**
- The ultimate objective of applying reactive shunt compensation in a transmission system is to increase the transmittable power

Shunt Compensation

- Shunt devices may be connected permanently or through a switch.
-
- Figure 2.12 shows the arrangements of shunt reactors on a long-distance, high-voltage ac line.
-



Shunt Compensation

- Many power utilities connect shunt reactors via breakers, thereby acquiring the flexibility to turn them off under heavier load conditions.
- Shunt reactors are generally gapped-core reactors and, sometimes, air-cored.
- Shunt capacitors are used to increase the power-transfer capacity and to compensate for the reactive-voltage drop in the line.

Shunt Compensation

Shunt capacitors

Shunt reactors

- The application of shunt capacitors requires careful system design.

- The circuit breakers connecting shunt capacitors should withstand high-charging in-rush currents and also, upon disconnection, should withstand voltages

- Also, the addition of shunt capacitors creates higher-frequency-resonant circuits and can therefore lead to harmonic overvoltages on some system buses.

Series compensation

- **Series compensation** is defined as insertion of reactive power elements into transmission lines.

- It provides the following benefits:
  - Reduces line voltage drops.
  - Limits load-dependent voltage drops.
  - Increases transfer capability.

Series Compensation

- Series capacitors are used to partially offset the effects of the series inductances of lines.
- **Series compensation results in the improvement of the maximum power-transmission capacity of the line.**
- The net effect is a lower load angle for a given power-transmission level and, therefore, a higher-stability margin

- The reactive-power absorption of a line depends on the transmission current,
    - so when series capacitors are employed, automatically the resulting reactive-power compensation is adjusted proportionately.

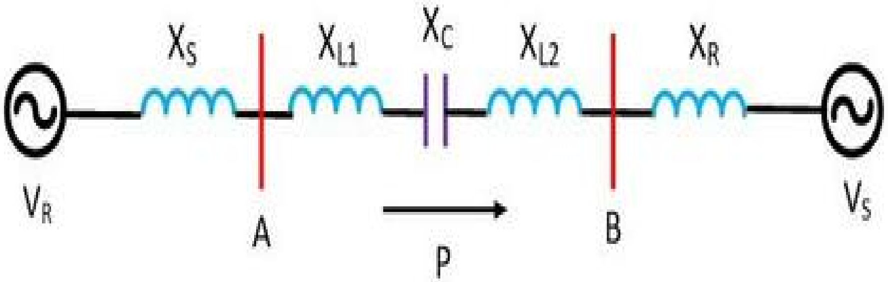
Increase in Power Transfer Capability

- The power transfer over a line is given by

$$P_1 = \frac{V_s V_R}{X_L} \sin\delta$$

- where P_1 – power transferred per phase (W)
  V_s – sending-end phase voltage (V)
  V_r – receiving-end phase voltage
  X_L – series inductive reactance of the line
  δ – phase angle between V_s and V_r

- If a capacitor having capacitance reactance X_c is connected in series with the line, the reactance of the line is reduced from X_L to $(X_L - X_c)$. The power transfer is given by:



$$P_2 = \frac{V_S V_R}{X_L - X_C} \sin\delta$$

$$\frac{P_1}{P_2} = \frac{X_L}{X_L - X_C} = \frac{1}{1 - \frac{X_C}{X_L}} = \frac{1}{1 - k}$$

$$k = \frac{X_C}{X_L}$$

- The factor k is known as a degree of compensation or compensation factor.

$$k = \frac{X_C}{X_L}\ pu$$

- Thus, per unit compensation is given by the equation percentage compensation is given by the equation

$$k = \frac{X_C}{X_L}\ pu \times 100\ \%$$

- Where $X_L =$ total series inductive reactance of the line per phase
$X_C =$ capacitive reactance of the capacitor banck per phase
In practice , k lie k = 0.5,

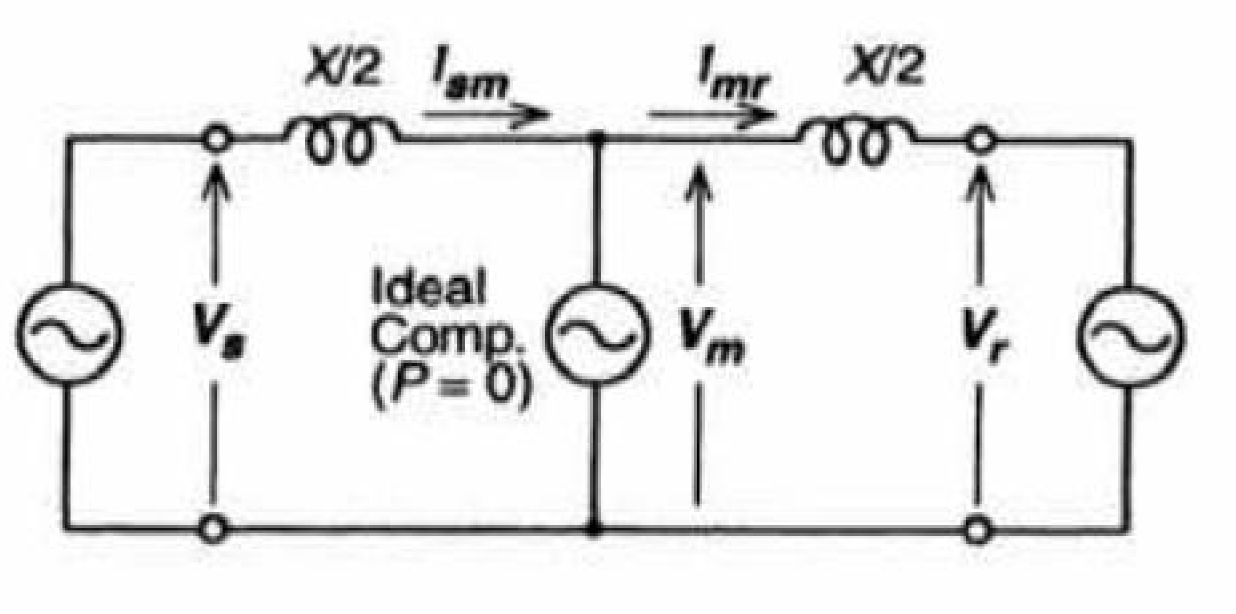
$$\frac{P_2}{P_1} = \frac{1}{1-k} = \frac{1}{1-0.5} = 2$$

- Thus, the power transfer is doubled by $50\ \%$ compensation.

MIDPOINT VOLTAGE REGULATION FOR LINE SEGMENTATION:

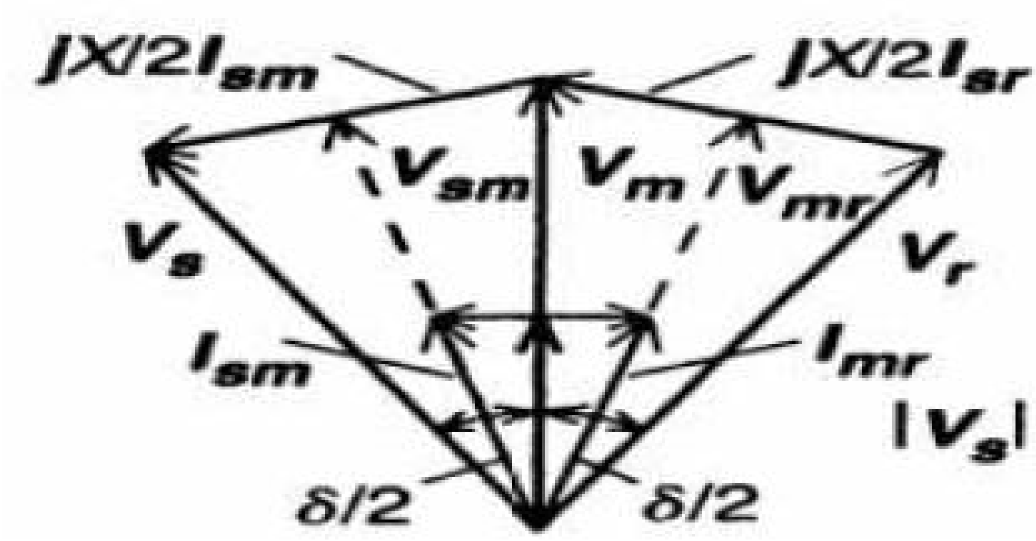
- VAR compensation is thus used for voltage regulation at the midpoint (or some intermediate) to segment the transmission line
- And at the end of the (radial) line to prevent voltage instability, as well as for dynamic voltage control to increase transient stability and ‘damp power oscillations

- Consider the simple two-machine (two-bus) transmission model in which an ideal var compensator is shunt connected at the midpoint of the transmission line,.

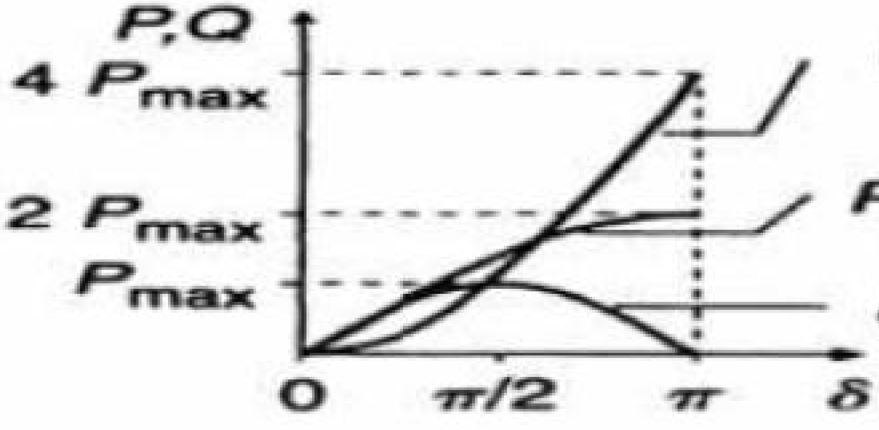


- For simplicity, the line is represented by the series line inductance.
- The compensator is represented by a sinusoidal ac voltage source (of the fundamental frequency), inphase with the midpoint voltage, Vm
- Sending and receiving-end voltages are (Vm = Vs = Vr = V)

- The midpoint compensator in effect segments the transmission line into two independent parts:
  - **The first segment, with an impedance of X/2, carries power from the sending end to the midpoint,**
  - **and the second segment, also with an impedance of X/2, carries power from the midpoint to the receiving end.**
- The midpoint VAR compensator exchanges only reactive power with the transmission line in this process.



$$|V_s| = |V_r| = |V_m| = V$$



$$Q_p = \frac{4V^2}{X}(1 - \cos\delta)$$

$$P_p = \frac{2V^2}{X}\sin\delta/2$$

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

The corresponding equations are

$$V_s = V_m = V\cos\frac{\delta}{4}$$

$$I_s = I_m = I = \frac{4V}{X}\sin\frac{\delta}{4}$$

The transmitted power is

$$P = V_s \; I_s = V_m \; I_m = VI\cos\frac{\delta}{4} = \frac{2V^2}{X}\sin\frac{\delta}{2}$$

$$Q = V_s \; I_s = V_m \; I_m = VI\sin\frac{\delta}{4} = \frac{4V^2}{X}\left(1 - \cos\frac{\delta}{2}\right)$$

- It can be observed that the midpoint shunt compensation can significantly increase the transmittable power (doubling its maximum value) at the expense of a rapidly increasing reactive power demand on the midpoint compensator (and also on the end generators).

Importance of mid point compensation

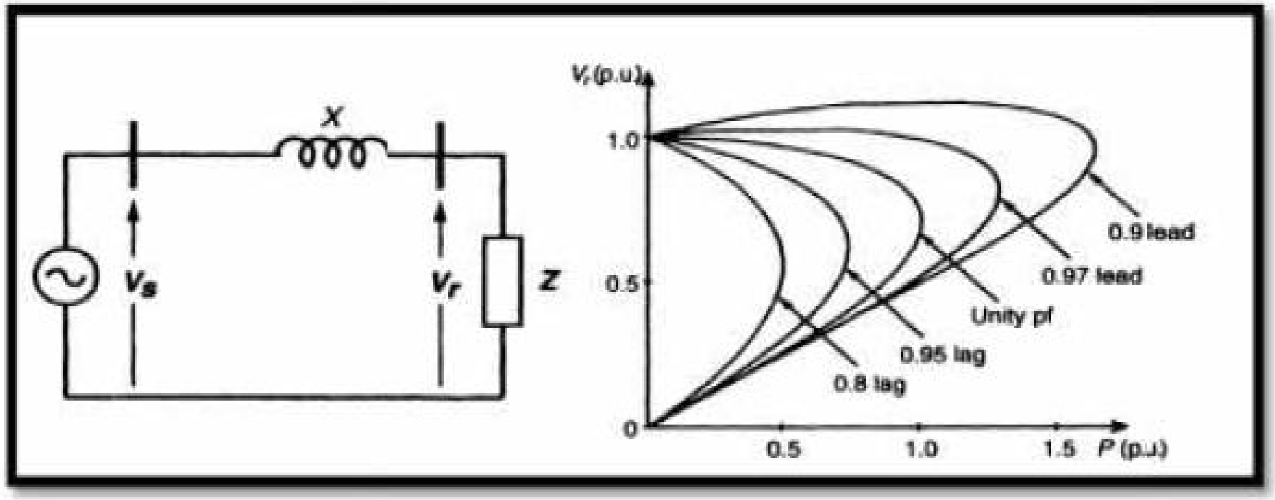
The midpoint of the transmission line is the best location for the compensator.

- This is because the voltage sag along the uncompensated transmission line is the largest at the midpoint.
- Also, **the compensation at the midpoint breaks the transmission line into two equal segments for each of which the maximum transmittable power is the same**.
- For unequal segments, the transmittable power of the longer segment would clearly determine the overall transmission limit

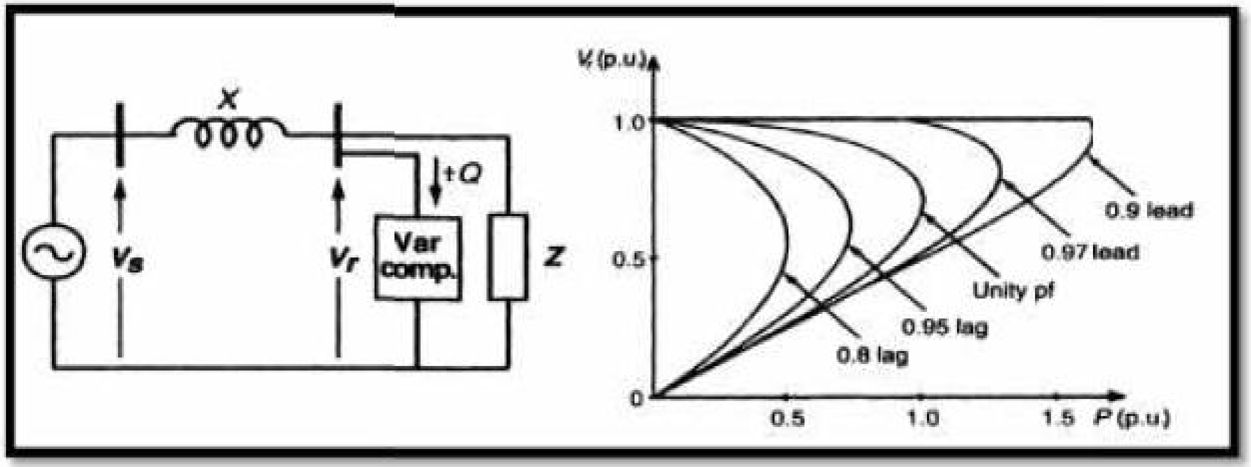
END OF LINE VOLTAGE SUPPORT TO PREVENT VOLTAGE INSTABILITY

- A simple radial system with feeder line reactance of *X and load impedance Z*, together with the normalized terminal voltage *V*, *versus power P plot at various load power* factors, ranging from 0.8 lag and 0.9 lead.
- The ‘nose-point‘ at each plot given for a specific power factor represents the voltage instability corresponding to that system condition.
- **It should be noted that the voltage stability limit decreases with inductive loads and increases with capacitive loads.**
- **The shunt reactive compensation can effectively increase the voltage stability limit by supplying the reactive load and regulating the terminal voltage ($V - Vr = 0$).**

WITHOUT COMPENSATION:



WITH COMPENSATION:



- It is evident that for a radial line, the end of the line, where the largest voltage variation is experienced, is the best location for the compensator.
  - (Recall that, by contrast, the midpoint is the most effective location for the line interconnecting two ac system buses.)

Summary

- The compensator must stay in synchronous operation with the AC system at the compensated bus under all operating conditions including major disturbances.
- The compensator must be able to regulate the bus voltage for **voltage support and improved transient stability**, or control it for **power oscillation damping and transient stability enhancement**, on a priority basis as system conditions may require.
- For a transmission line connecting two systems, the best location for Var compensation is in the middle, whereas for a **radial feed to a load the best location is at the load end**.