# Recent Developments in Electric Power Transmission Technology

Dr. Kalyan Sen

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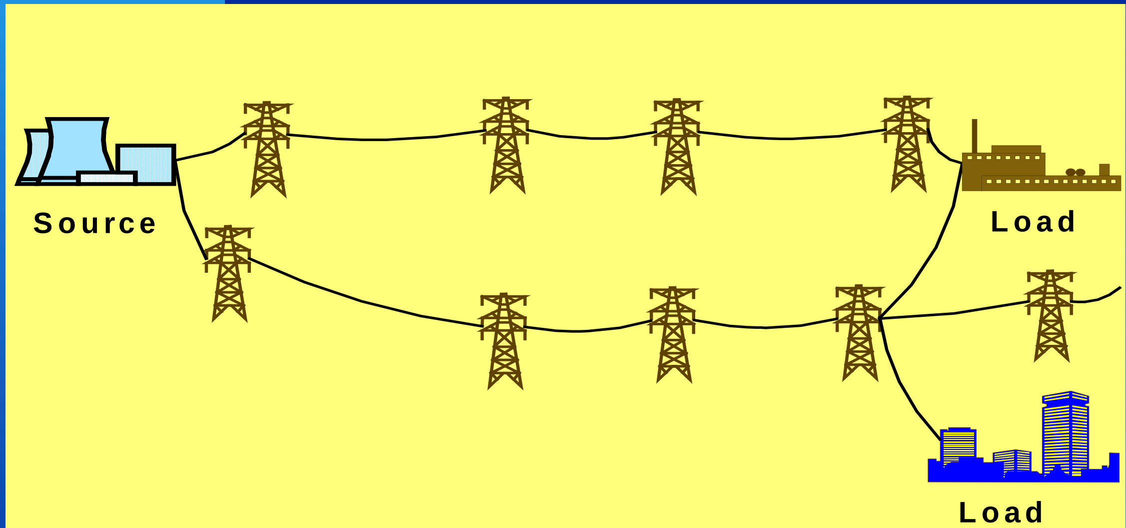
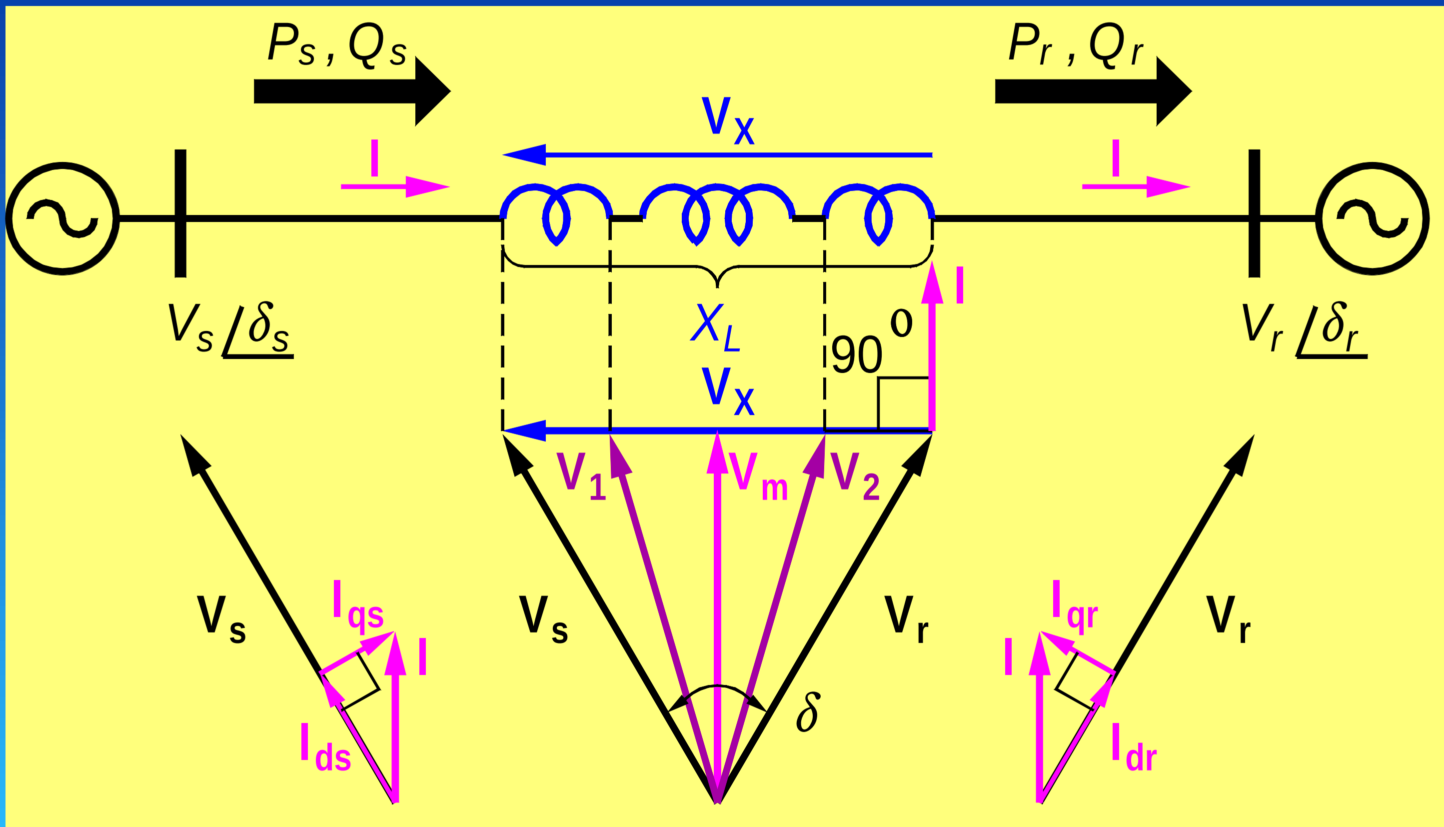
# Issues Facing Power Industry Today



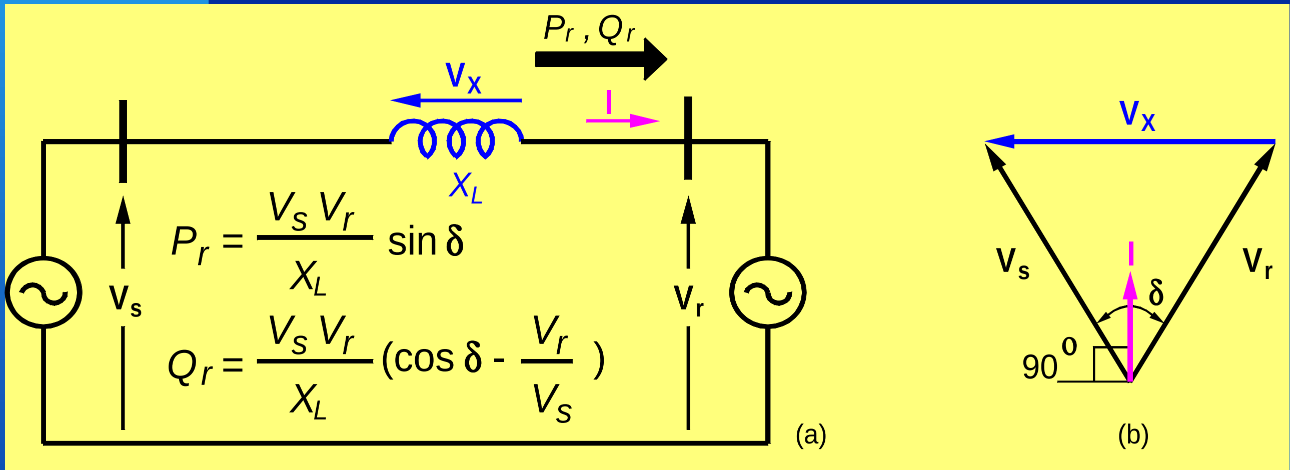

- Demand for electrical energy is increasing.
- “Free Flow” makes particular transmission lines overloaded.
- Construction of new transmission lines has become increasingly difficult and expensive.
- Energy needs to be transported from the generating point to the end-user along the most desirable path.

# Issues Facing Power Industry Today

- Voltage level may need to be restored at a point along the line.



# Principles of Power Flow in a Transmission Line

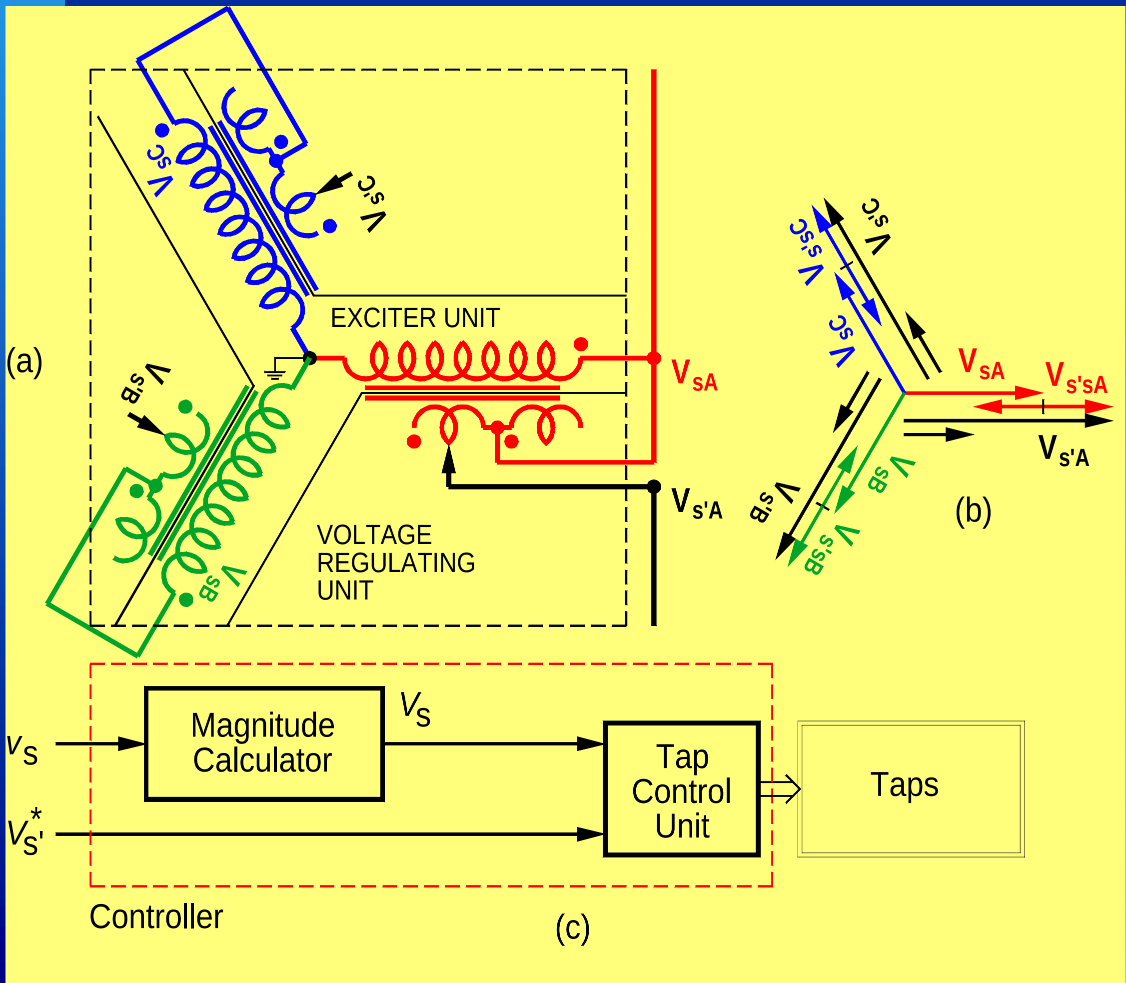



- Power flow in a transmission line depends on
  - impedance
  - voltage
  - phase angle.
- Leading voltage sends active power to the lagging voltage.

# Available Solutions

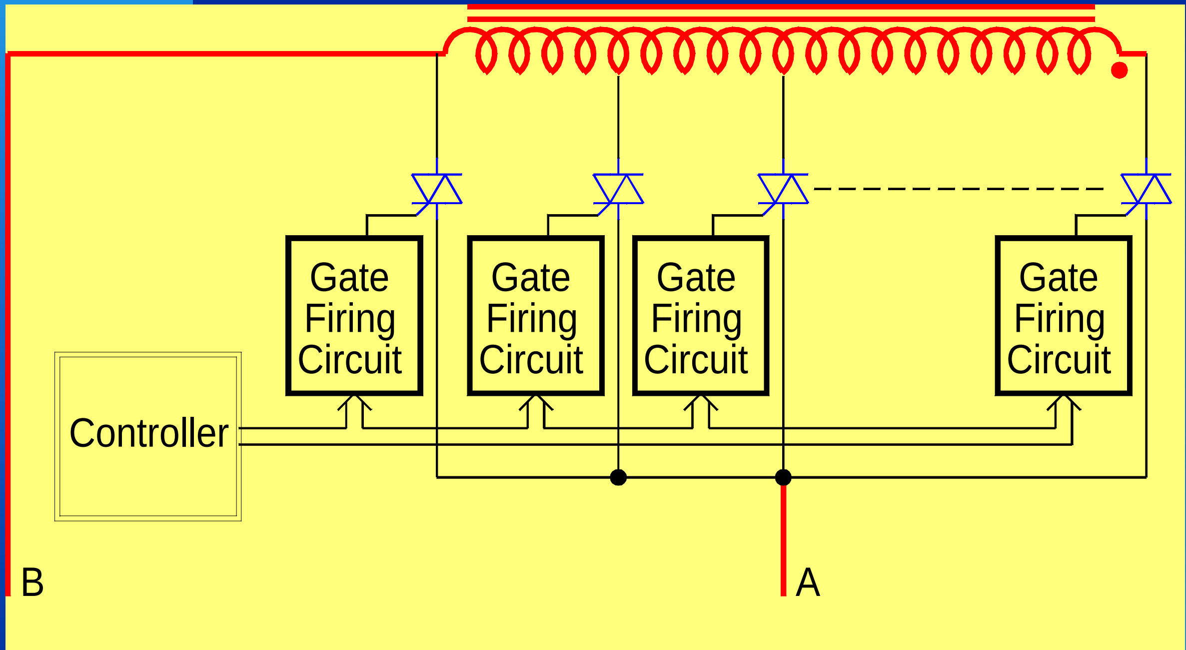
- Traditional Technology
  - Voltage-Regulating Transformer
  - Shunt Inductor/Capacitor
  - Series Inductor/Capacitor
  - Phase Angle Regulator
- Voltage-Sourced Converter Based Technology
  - STATic synchronous COMpensator (STATCOM)
  - Static Synchronous Series Compensator (SSSC)
  - Unified Power Flow Controller (UPFC)

# Voltage-Regulating Transformer



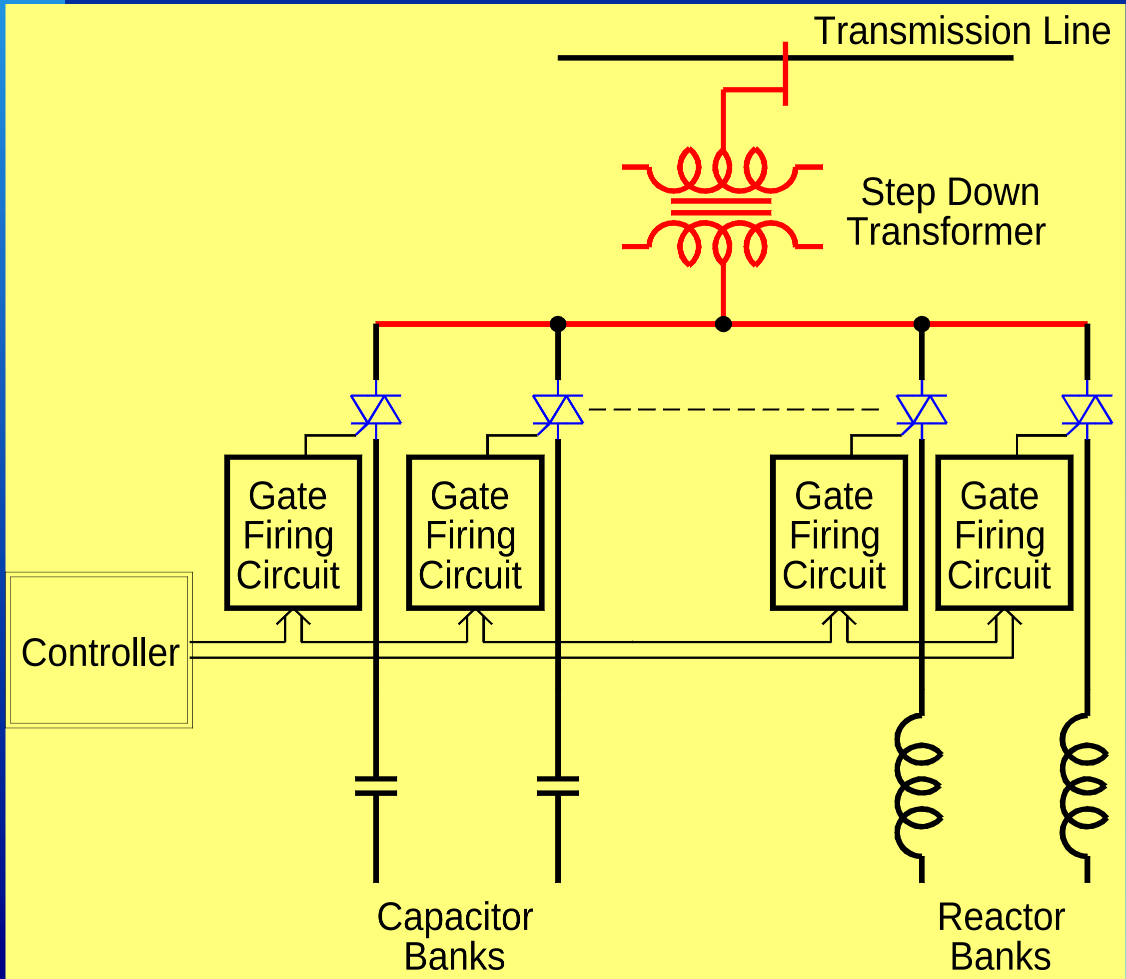

- Regulates the line voltage in small steps by adding or subtracting a compensatng voltage in series with the transmission line.

# Voltage-Regulating Transformer



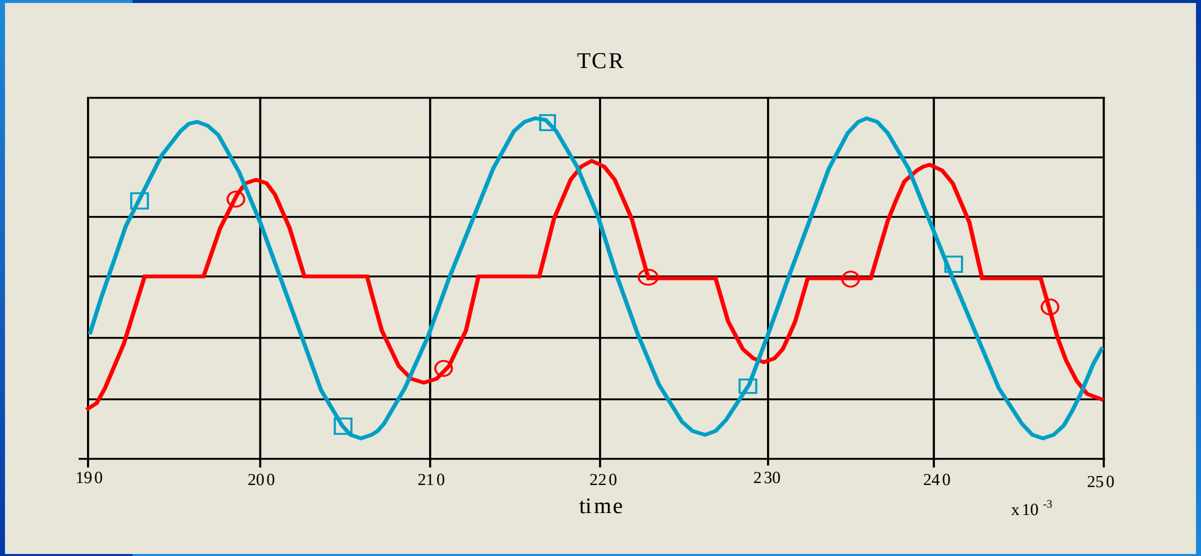

- Produces a variable voltage.

# Thyristor-Controlled Static Var Compensator



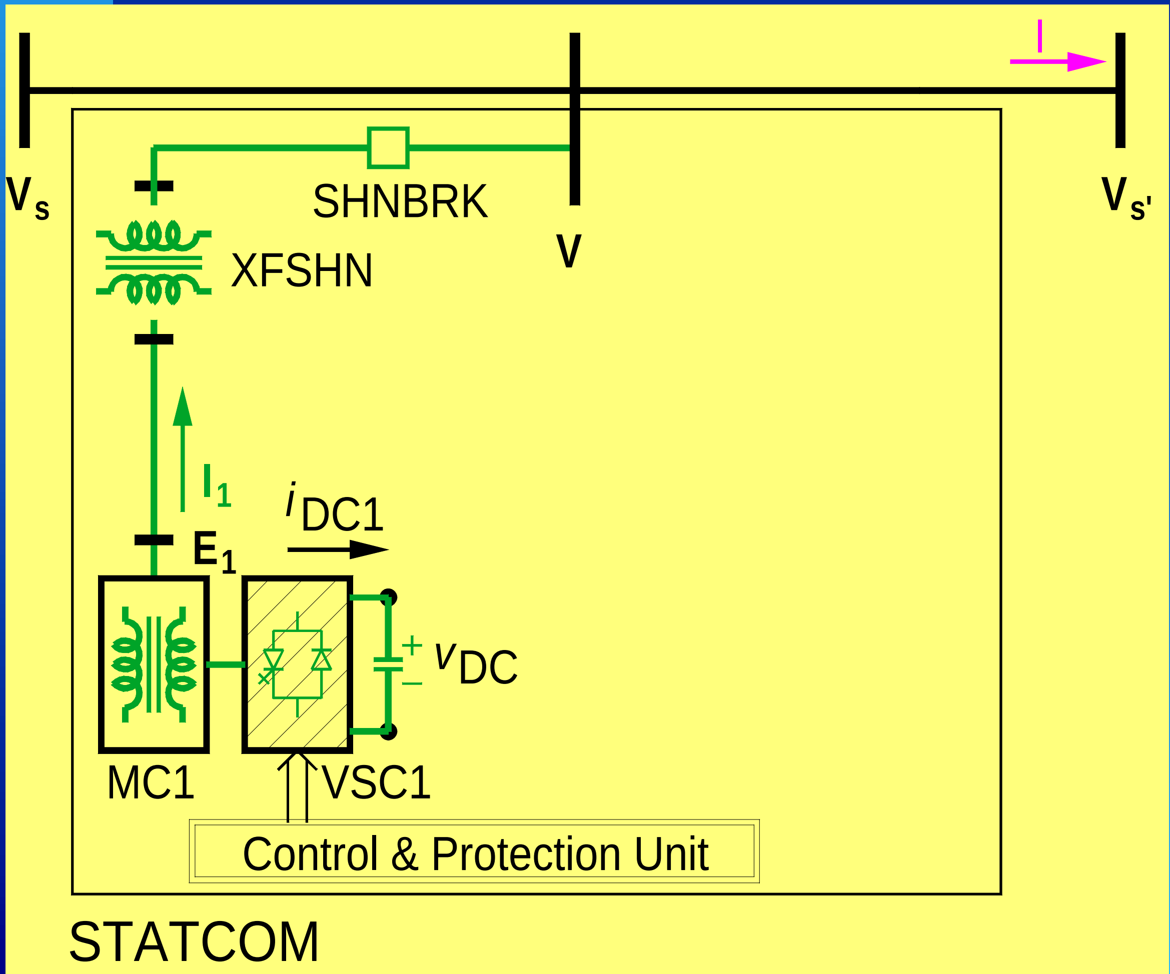

- Regulates the line voltage by connecting an inductor or a capacitor in parallel with the transmission line.

# Voltage and Current of a Thyristor-Controlled Reactor



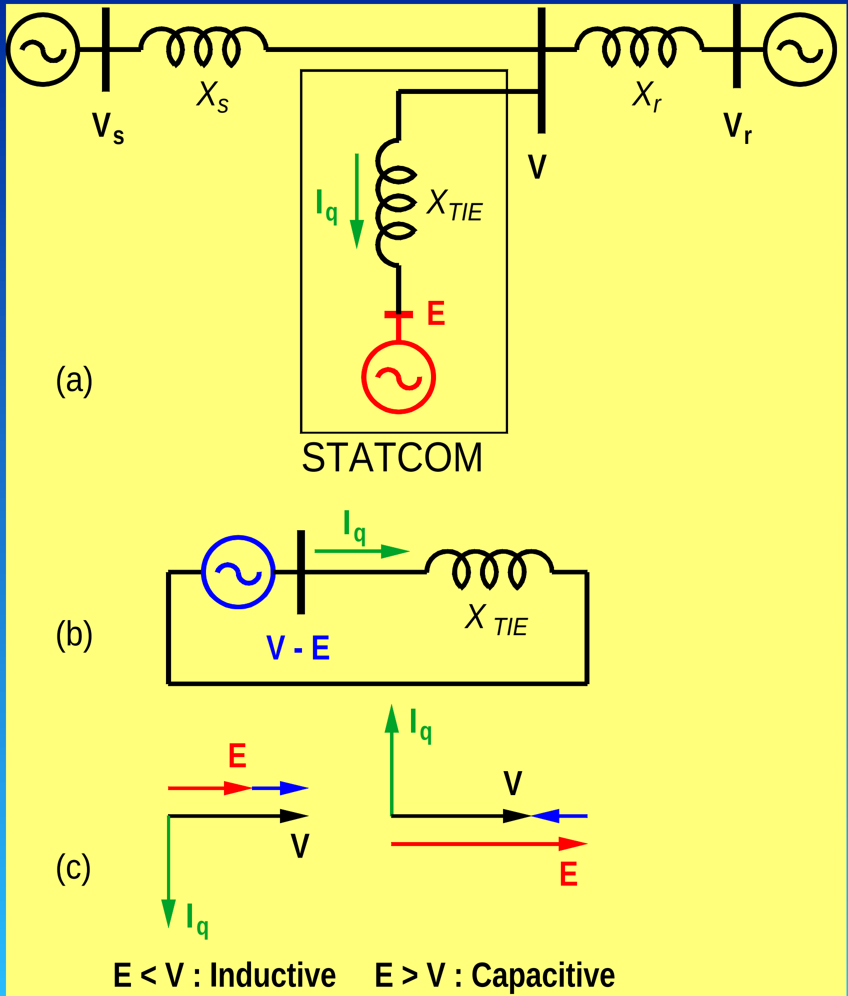

TCR current
Bus voltage

# STATic synchronous COMpensator-STATCOM



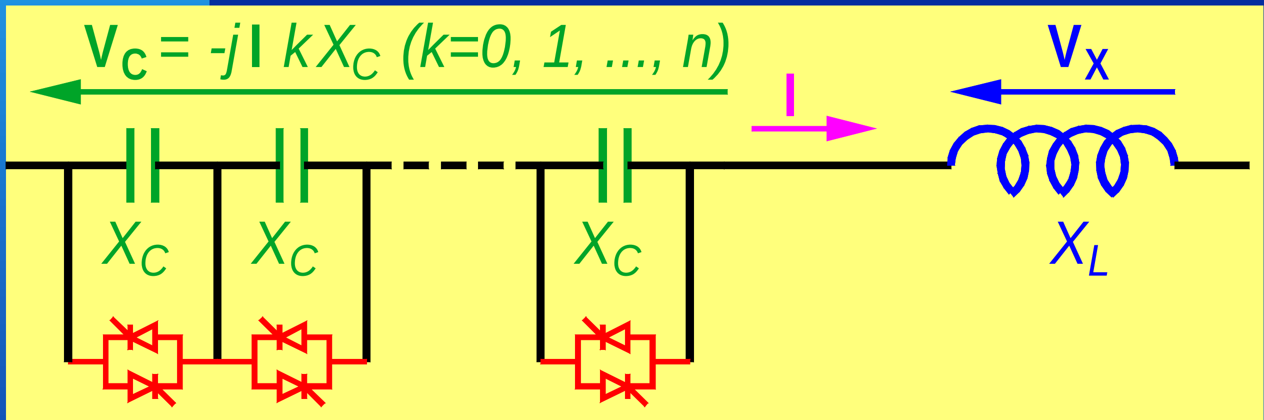

- Regulates the line voltage by injecting a shunt reactive current into the transmission line.

# A STATCOM Operating in Inductive and Capacitive Modes



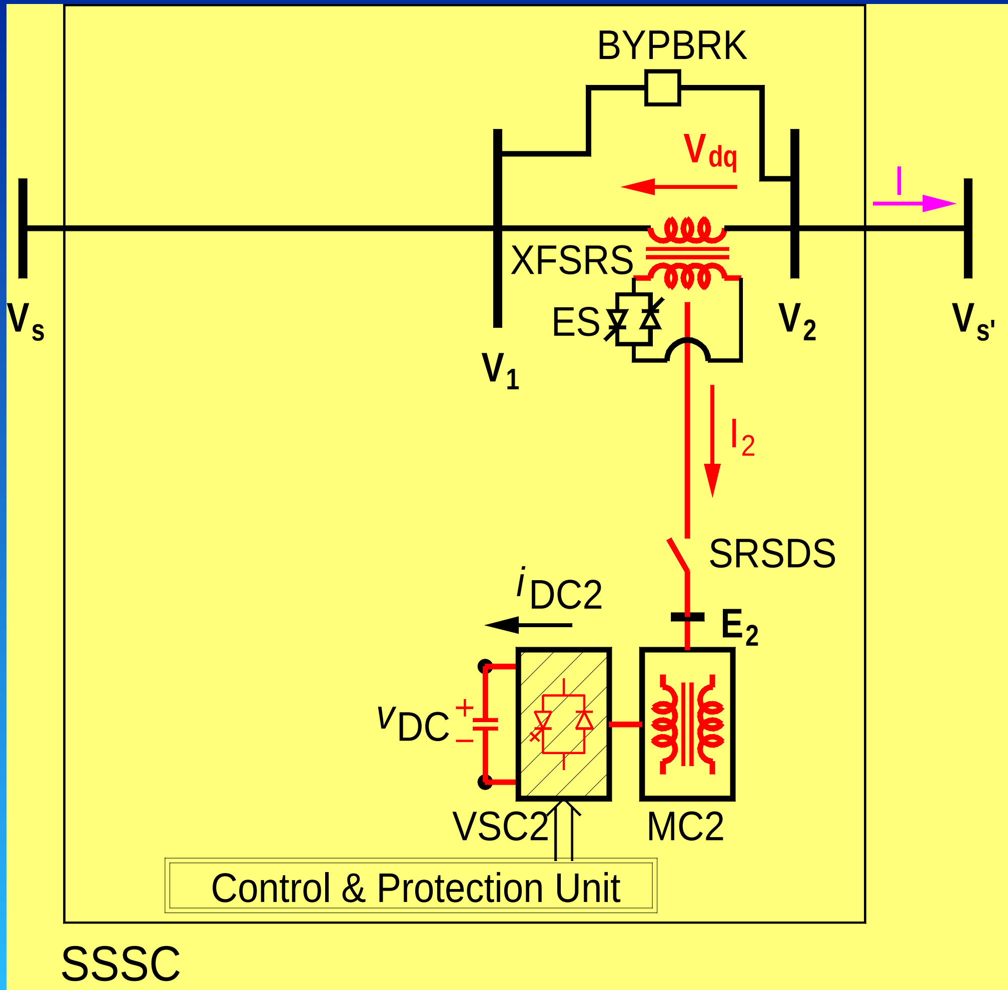

- Inductive operation means E<V.
- Capacitive operation means E>V.

# Thyristor-Switched Series Capacitor (TSSC)



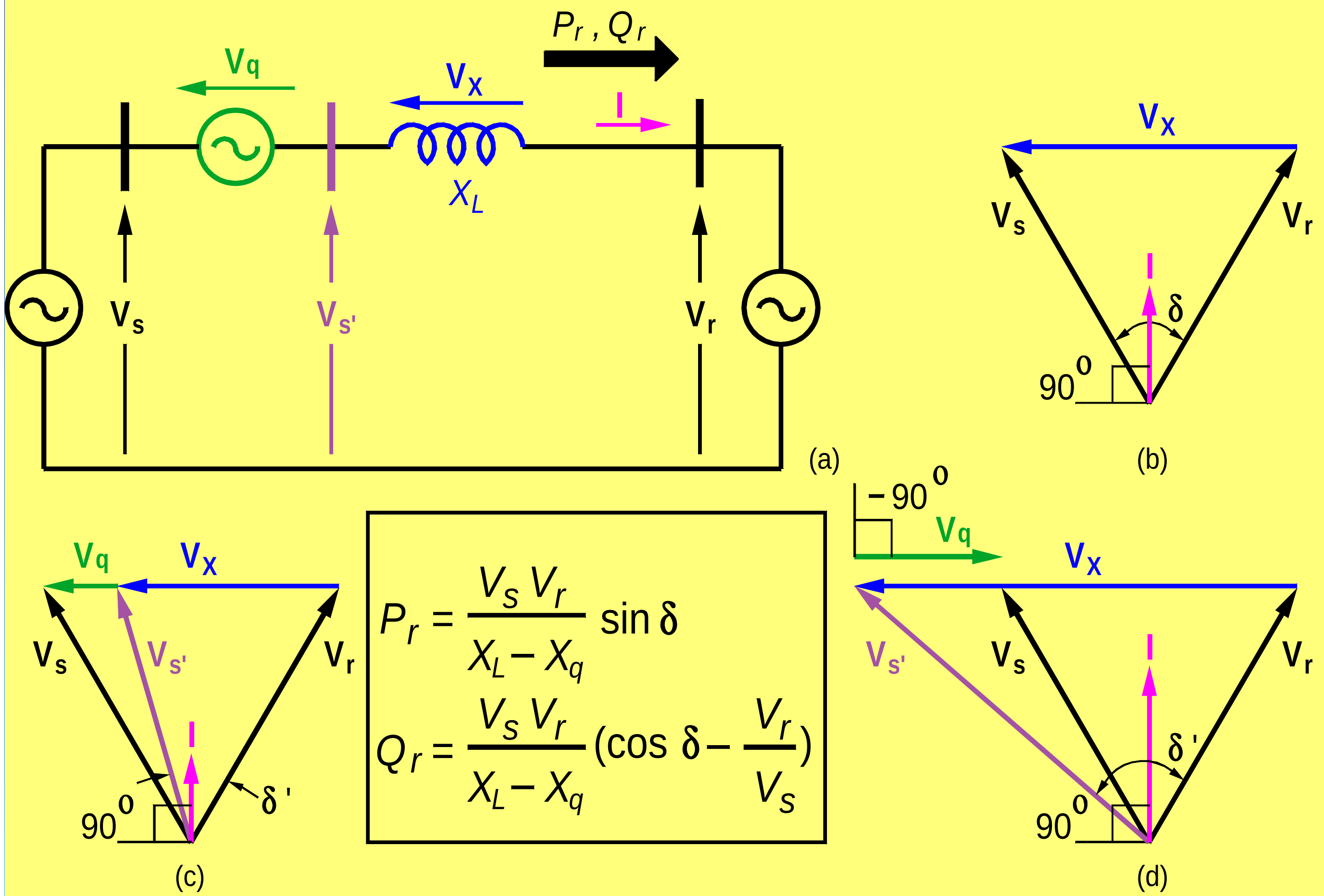

- Regulates the transmission line’s effective reactance by connecting a capacitor, parallel with a bypass switch, in series with the transmission line.

# Static Synchronous Series Compensator-SSSC




- Regulates the transmission line's effective reactance by connecting a compensatng voltage in series with the line and in quadrature with the prevailing line curretnt.

# An SSSC Operating in Inductive and Capacitive Modes

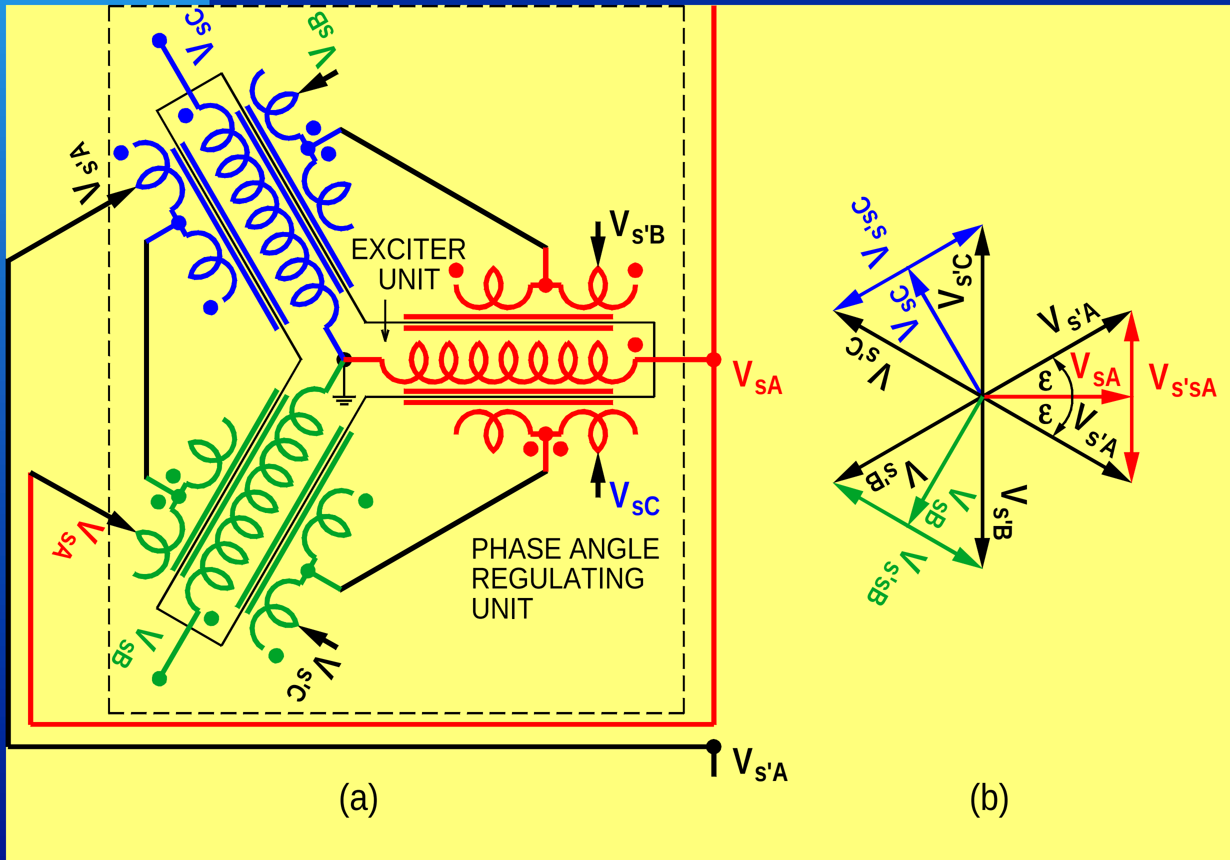



$$P_r = \frac{V_s V_r}{X_L - X_q} \sin\delta$$

$$Q_r = \frac{V_s V_r}{X_L - X_q} (\cos\delta - \frac{V_r}{V_s})$$

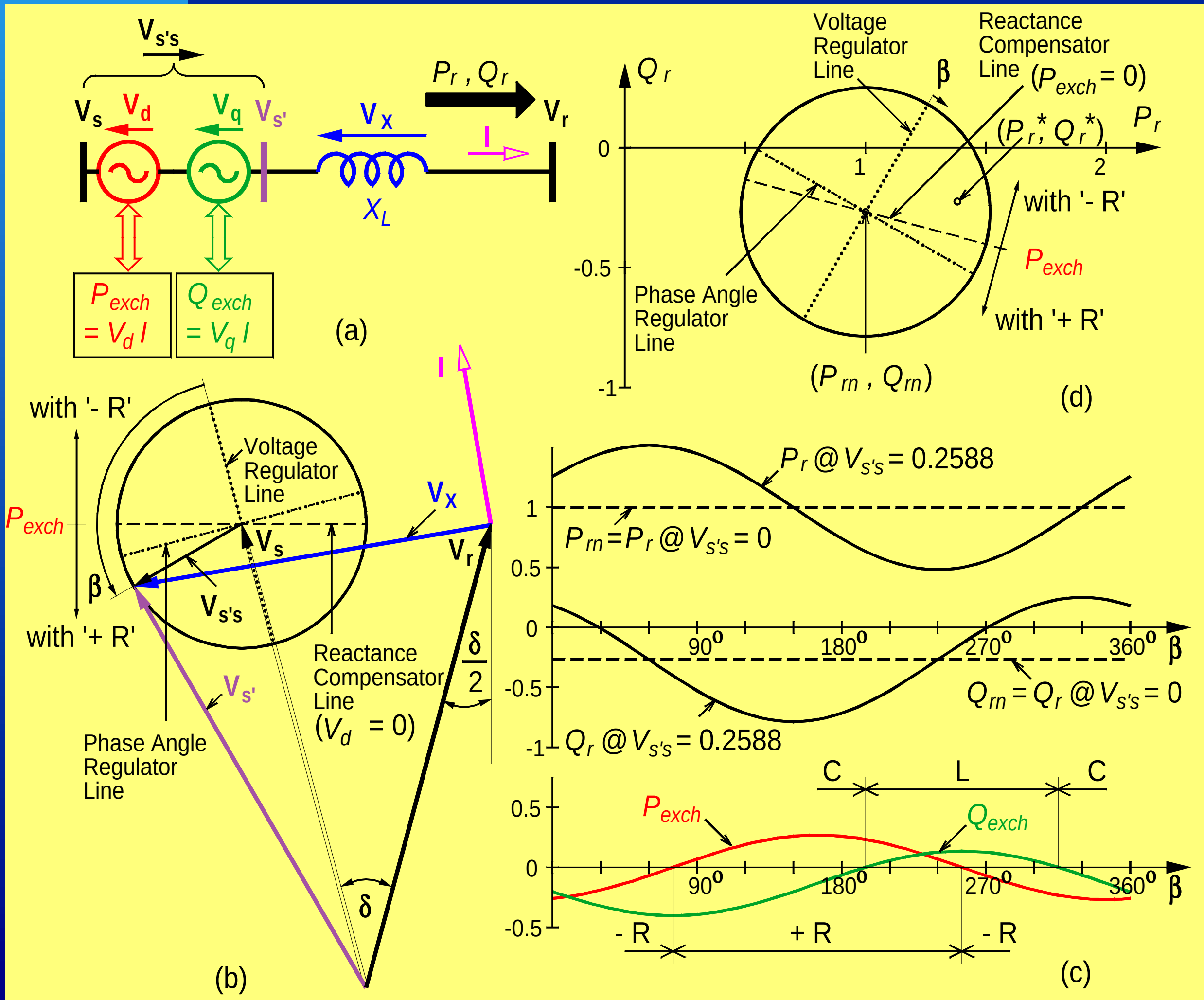
- A series-injected voltage while
  - leading the prevailing line current, provides an inductive compensation
  - lagging the prevailing line current, provides a capacitive compensation

# A Phase Angle Regulator




- Regulates the phase angle of the line voltage by a series-connected compensating voltage that is in quadrature with respect to the line voltage.

# The Effect of a Series-Injected Voltage on Power Flow in a Transmission Line

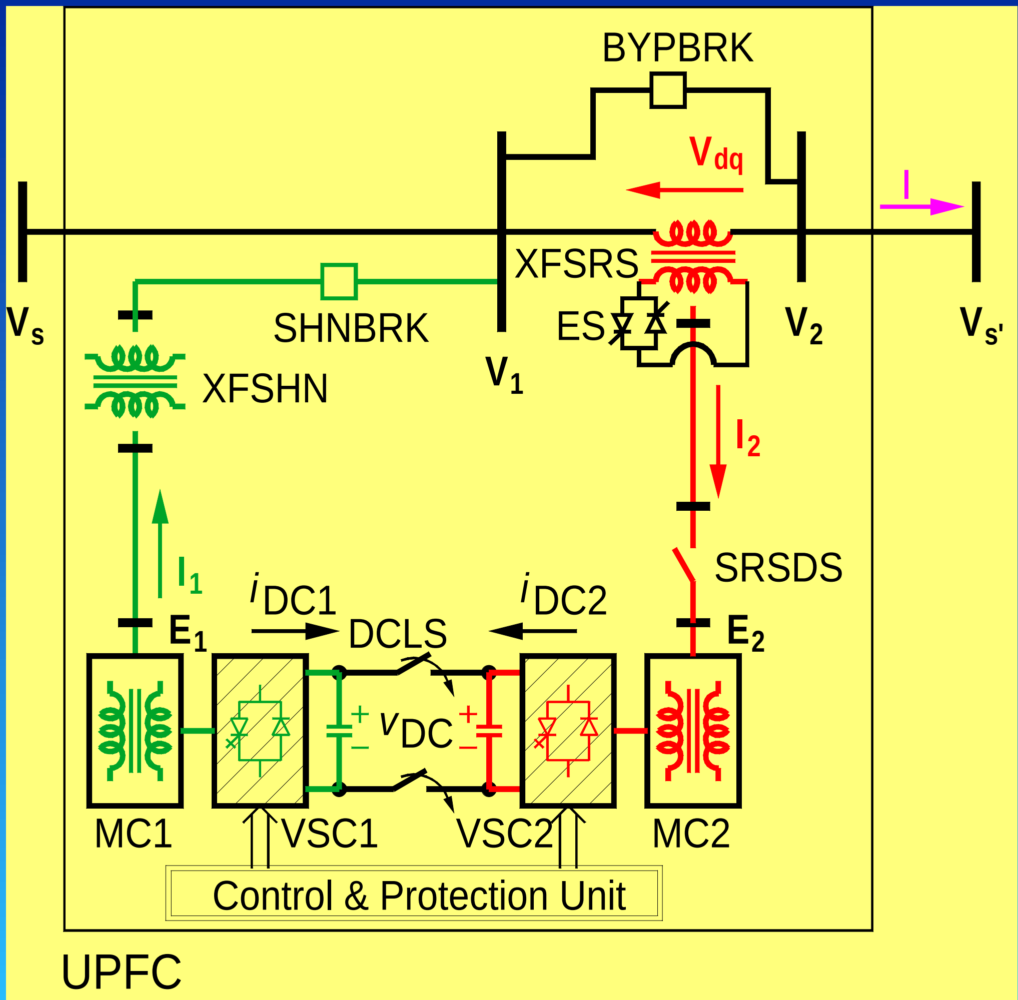



- Active and reactive power flow in the line is regulated independently.
- Exchanged power by the series unit is active and reactive.

# Characteristics of Power Flow Controllers

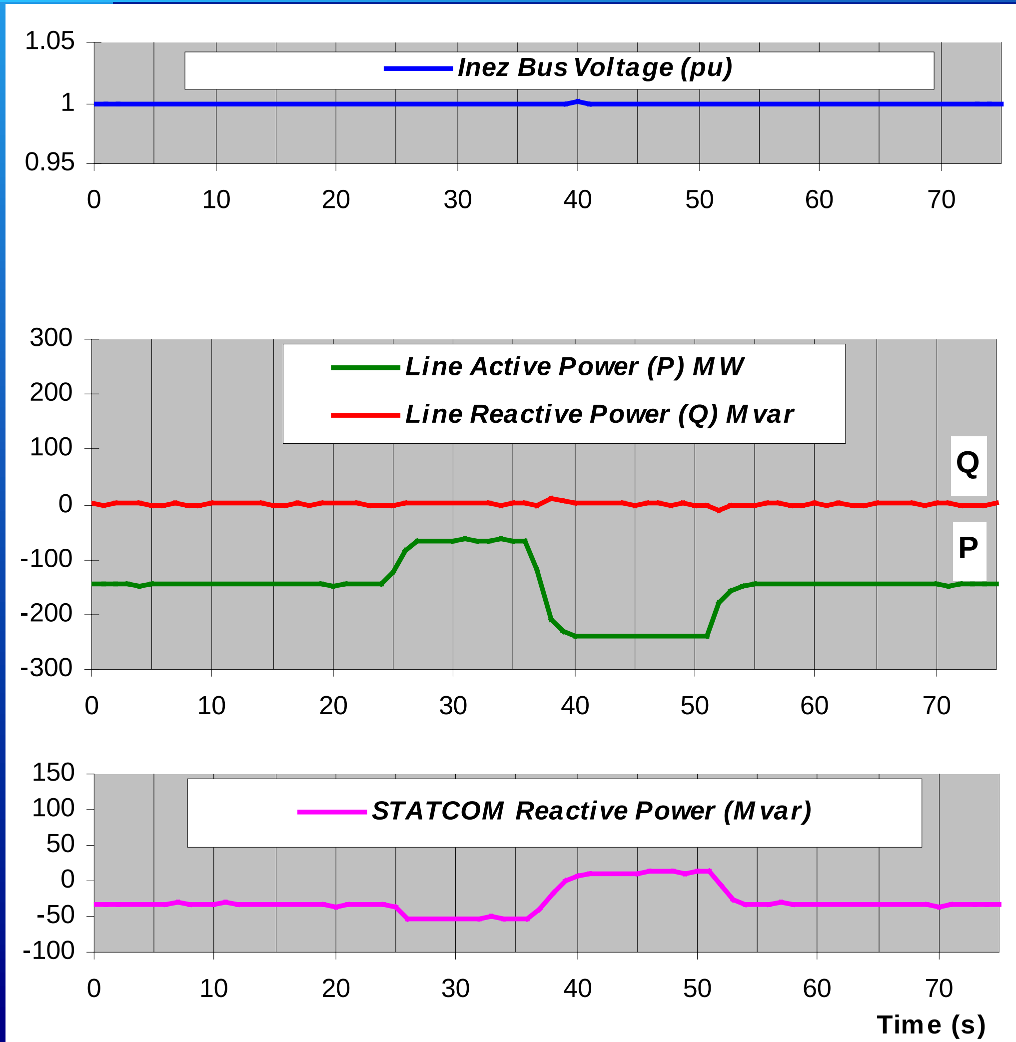
- Traditional power flow controllers
  - each controls only one of the three parameters (voltage, reactance or angle).
- Single Voltage-Sourced Converter-based power flow controllers
  - each controls one of the transmission line parameters.
  - can have fast dynamic response.
- Dual Voltage-Sourced Converter-based power flow controllers
  - can exchange real power with the line and generate or absorb reactive power.

# Unified Power Flow Controller-UPFC




- Regulates the active and the reactive power flow in the line independently.
- Regulates the line voltage by injecting a shunt reactive current into the transmission line.

# AEP UPFC Test Results




- Holding unity power factor while changing line active power.
- Sub-cycle performance of a UPFC is not required in a utility application.

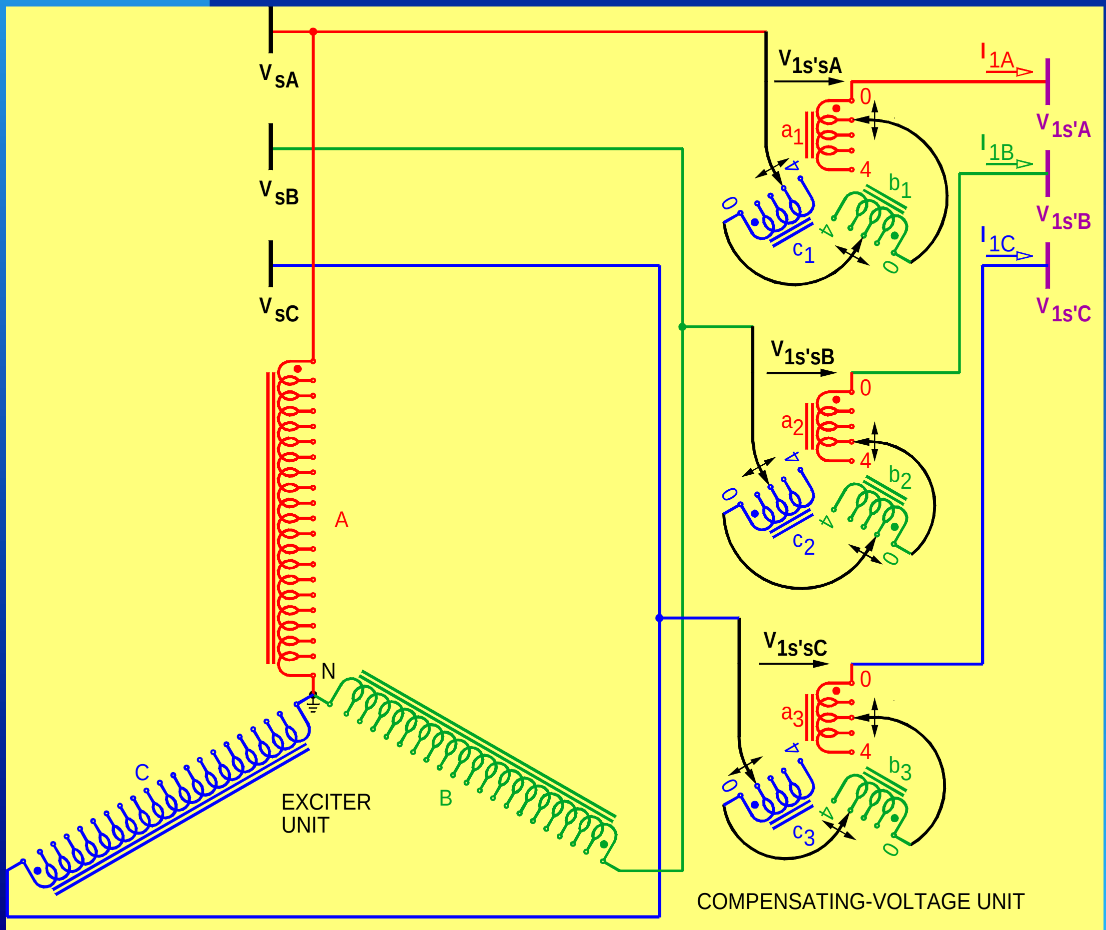
# What Are We Looking For in a Utility Application?

- A power flow controller that is
  - reliable
  - independent regulator of active (*P*) and reactive (*Q*) power flow
  - fast enough for a utility application
  - inexpensive

# ‘Sen’ Transformer Concept

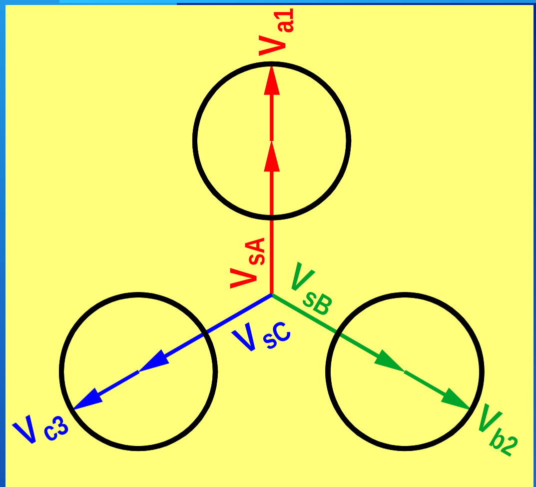
- Combines power flow control parameters, using a single-core three-phase transformer with load tap changers,
  - voltage
  - phase angle
  - reactance
- Regulates active and reactive power flow selectively,
- Regulates line voltage.

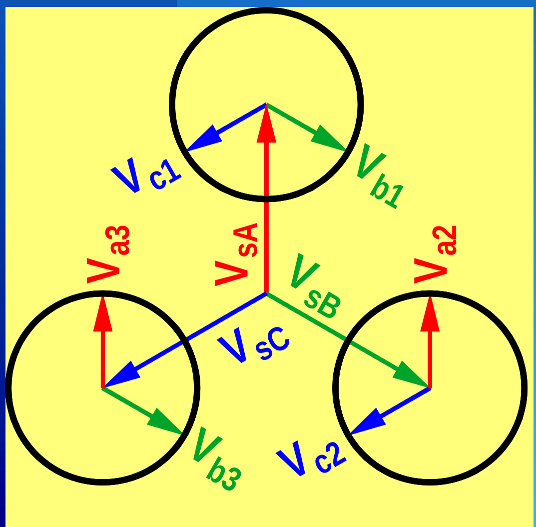
# ‘Sen’ Transformer

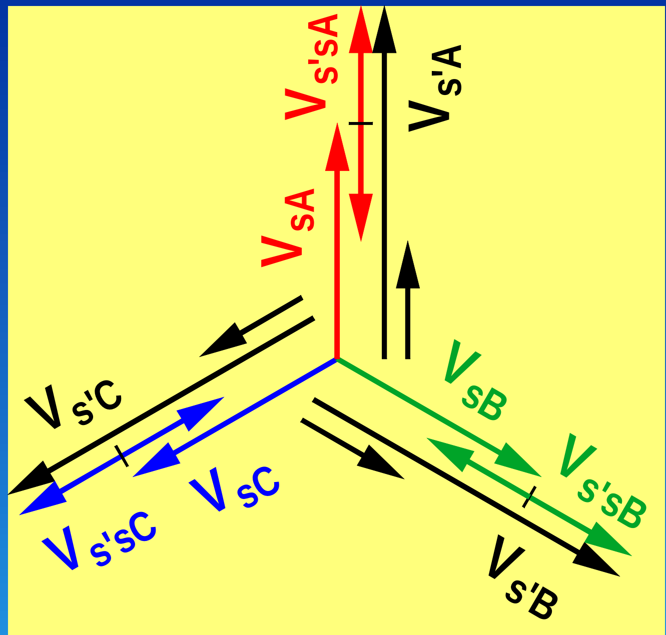


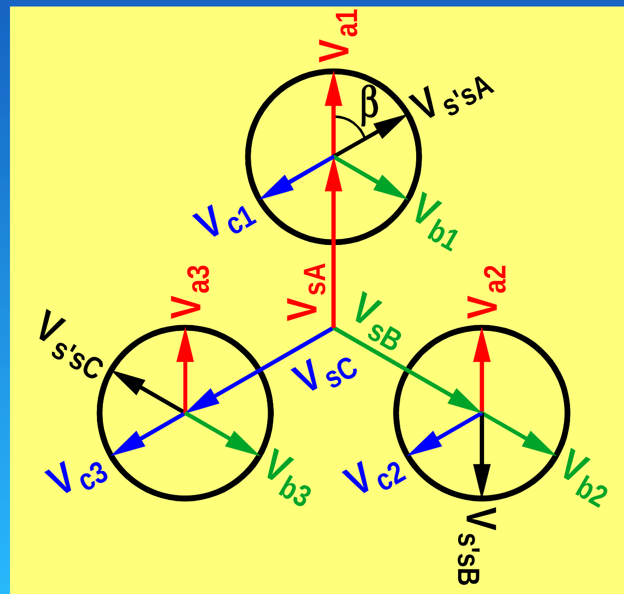

- Regulates line votage like an autotransformer.
- Controls active and reactive power flow in the line by a series-connected compensating voltage that is at any angle with respect to the line voltage.

# ‘Sen’ Transformer Operation

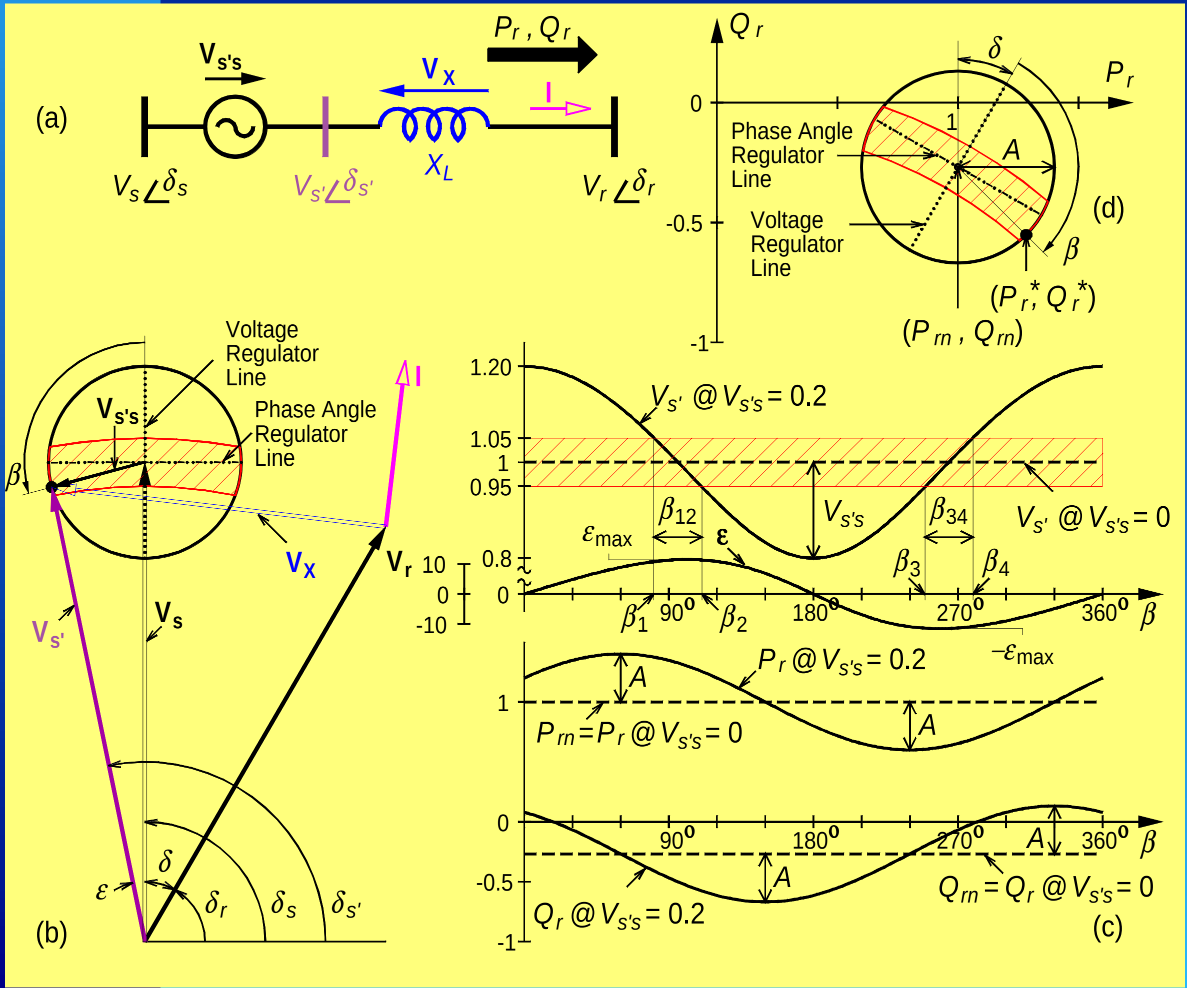


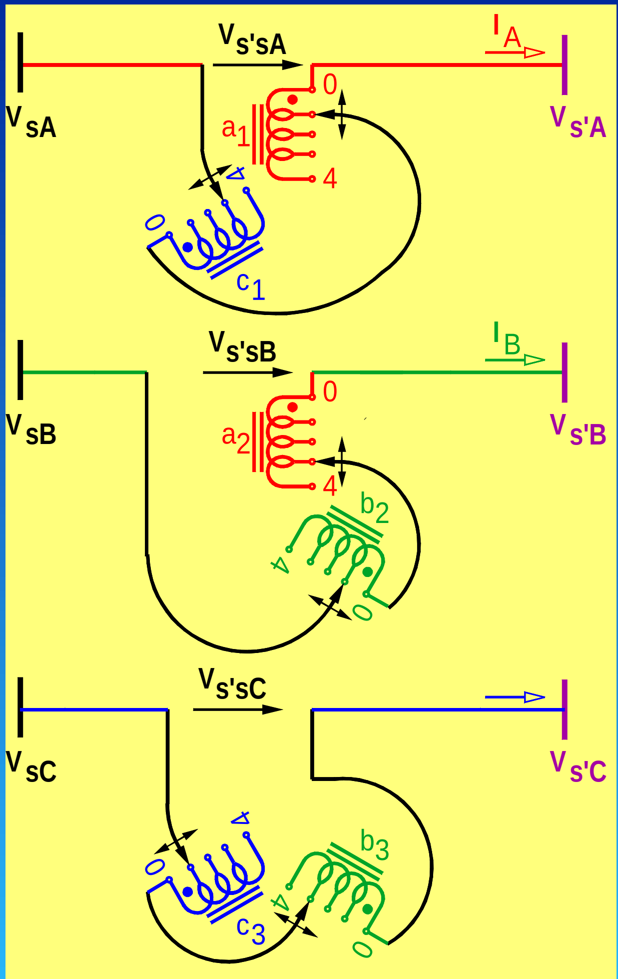



# Practical Compensator's Operating Range



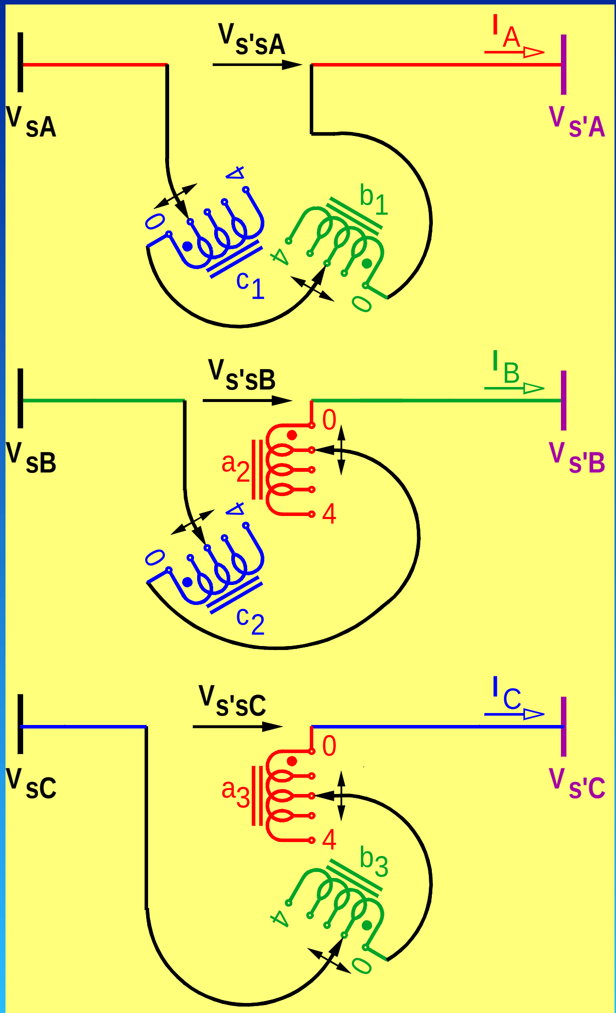

- Line voltage is bounded by ±5% over nominal voltage.
- Full range of voltage injection is not permitted.
- Full capability of a UPFC is not utilized.
- ST can be modified to fit customers' needs.

# Limited Angle Operation of a 'Sen' Transformer



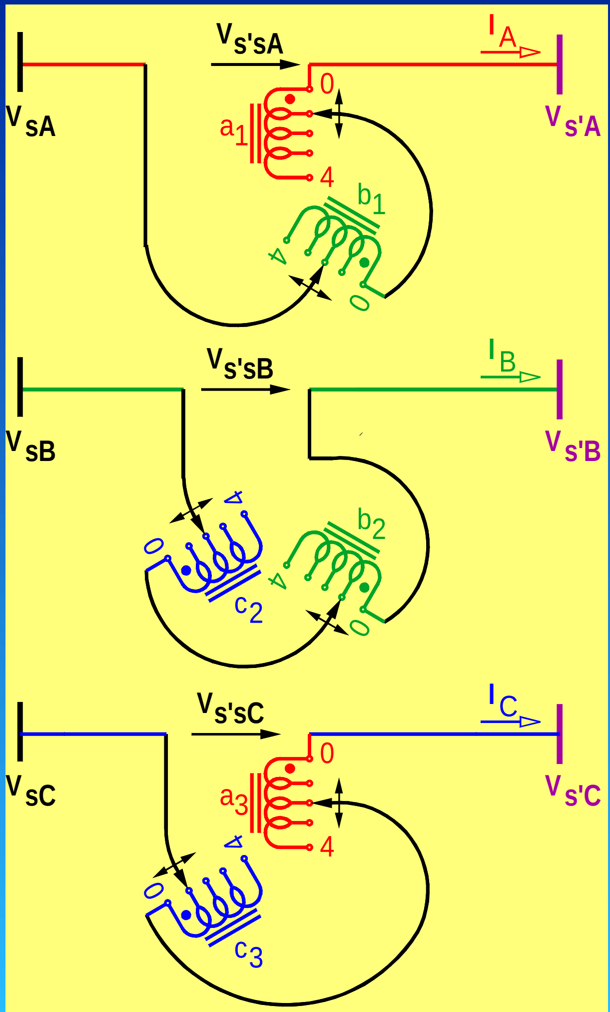

- Injects voltage from $0^{o}$ to $120^{o}$.

# Limited Angle Operation of a 'Sen' Transformer



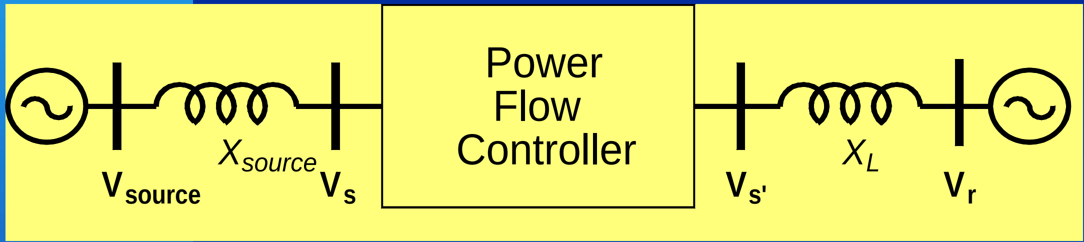

- Injects voltage from 120° to 240°.

# Limited Angle Operation of a ‘Sen’ Transformer




- Injects voltage from 240° to 360°.

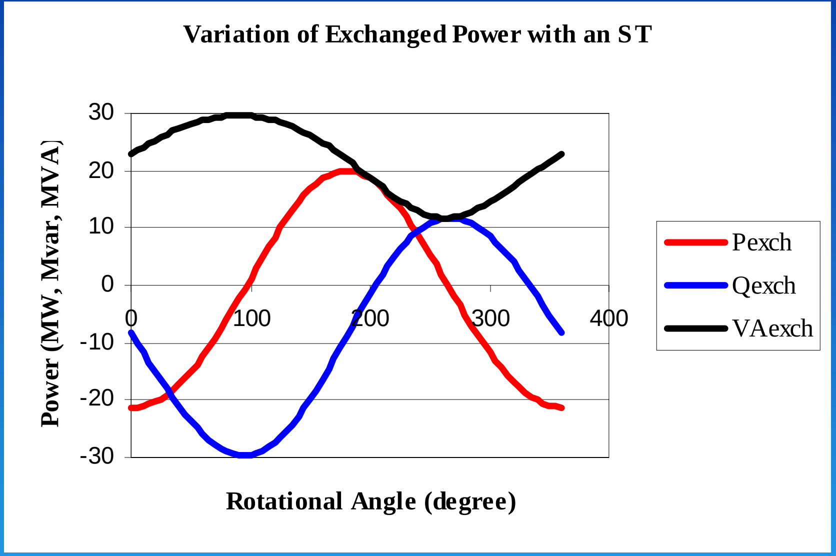
# A Power Flow Controller in a 2-Bus Network

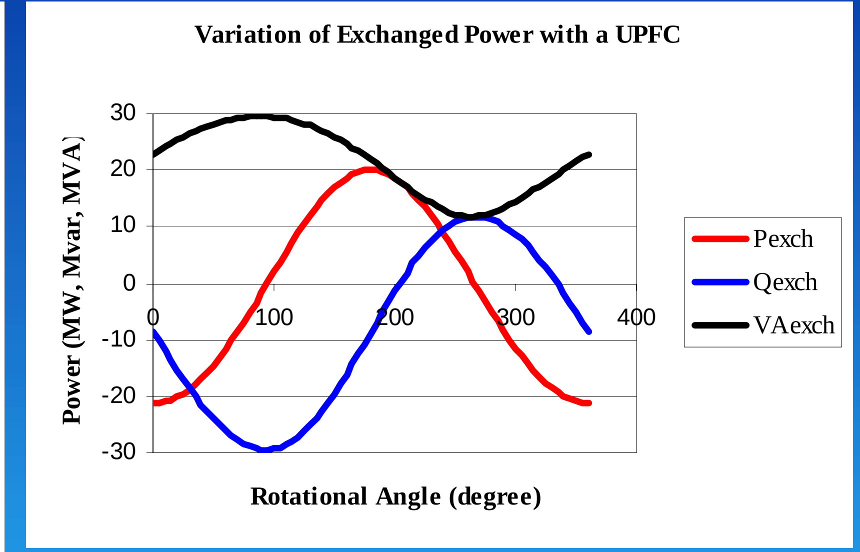



- Controls the active and the reactive power flow in the line by a series-injected voltage that is at any angle with respect to the line voltage.

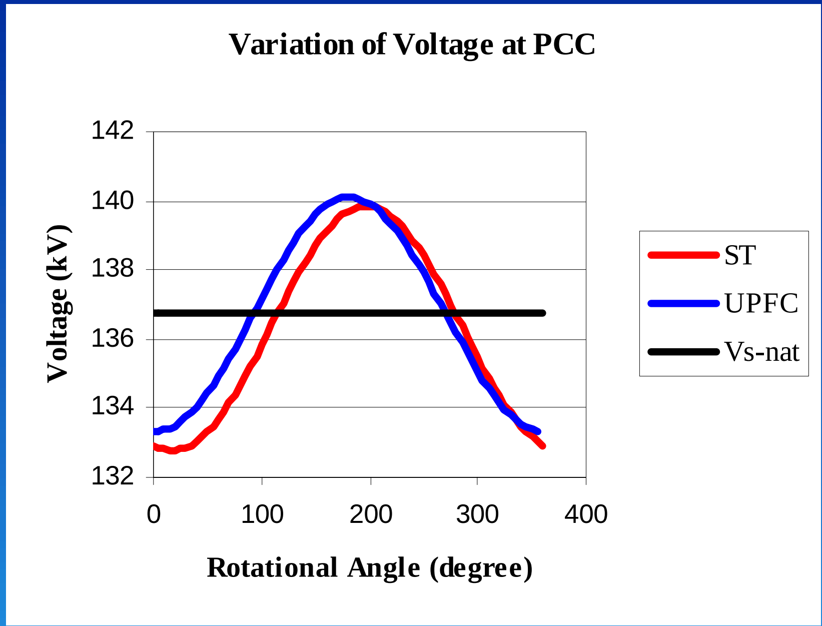
# Simulation of ST and UPFC ($V_{s's}$ = 0.15 pu)

- The exchanged power by the series unit of an ST and a UPFC are identical.



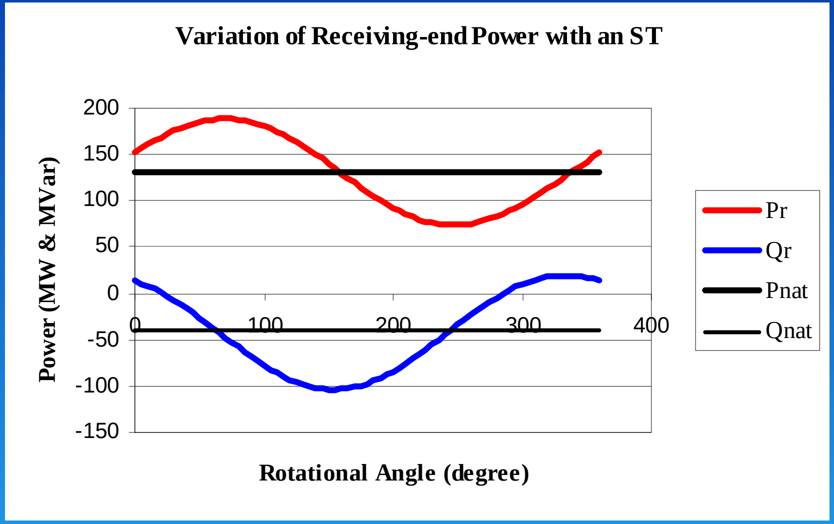
# Simulation of ST and UPFC ($V_{s's}$ = 0.15 pu)

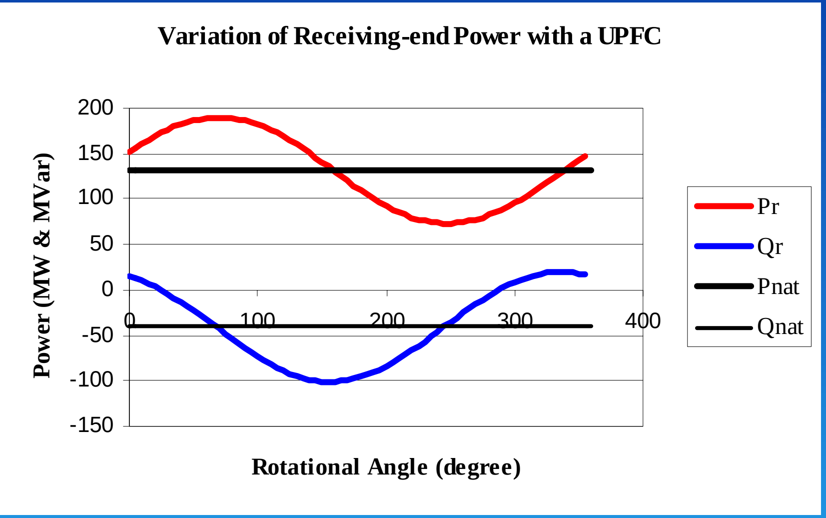



- From 205° to 335°, an ST maintains a higher line voltage than a UPFC.
- From 0° to 205° and 205° to 335°, a UPFC maintains a higher line voltage than an ST.

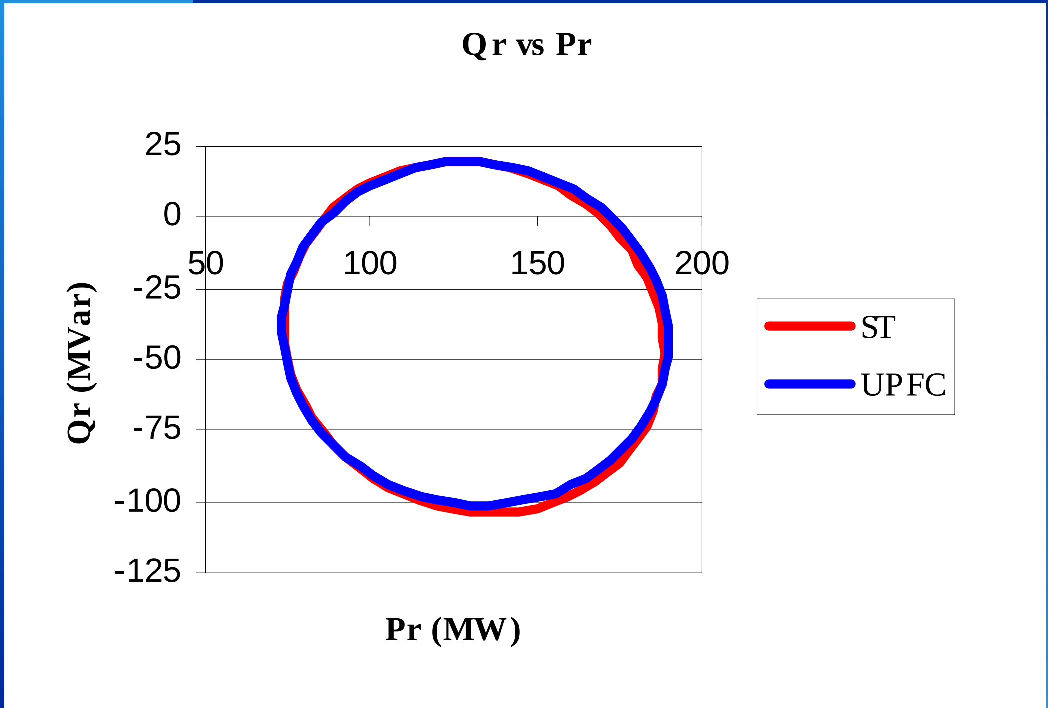
# Simulation of ST and UPFC ($V_{s's}$ = 0.15 pu)

- The variation of power flow, at the receiving-end of the transmission line, by an ST and a UPFC are identical.



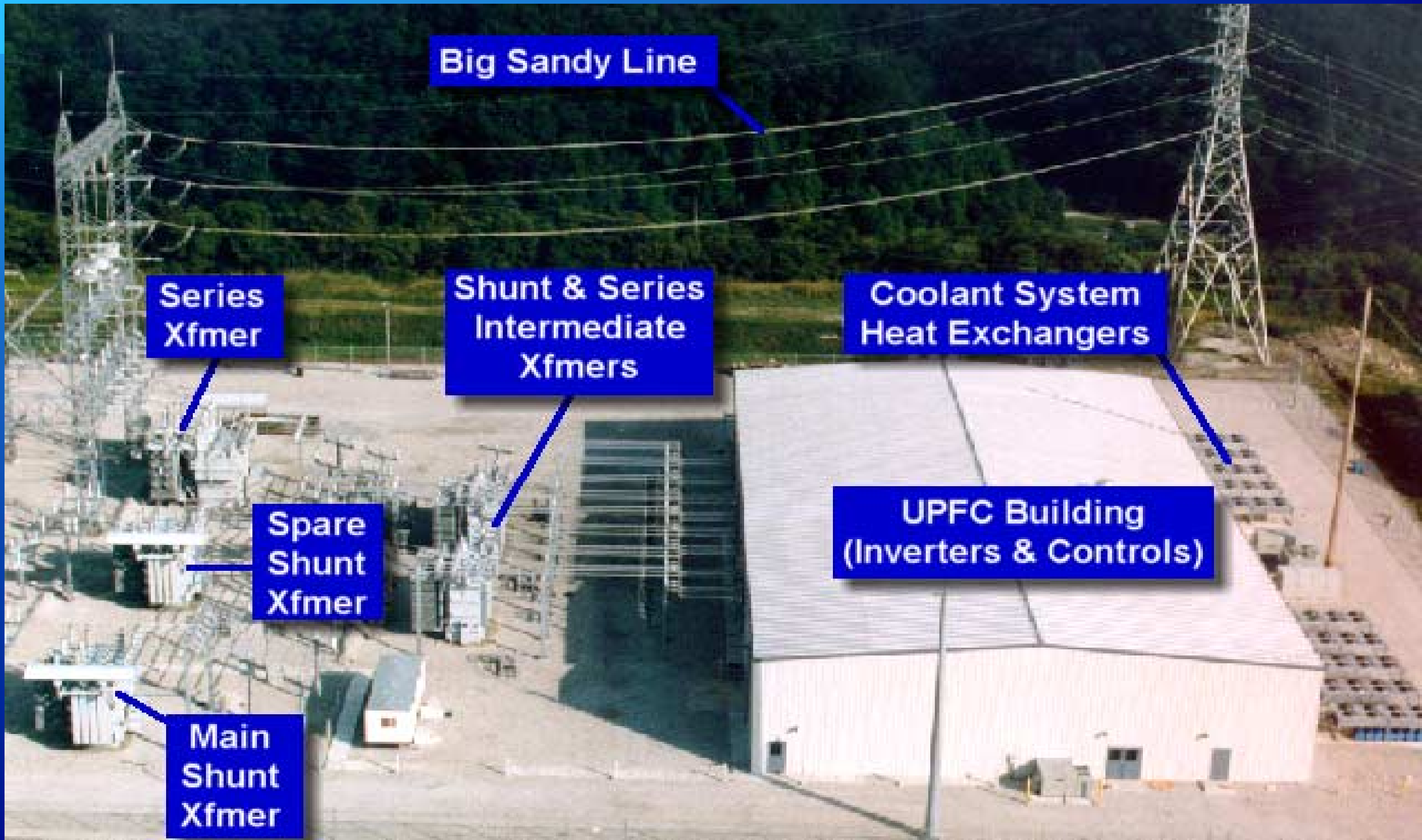



# Simulation of ST and UPFC ($V_{s's}$ = 0.15 pu)




- Area of controllability in the *P*-*Q* plane for an ST and a UPFC are almost identical.

# Aerial View of AEP UPFC at Inez Substation



# Advantages and Shortcoming of an ST

- Advantages
  - voltage regulation
  - independent control of active and reactive power (*P and Q*) flow
  - established transformer and load tap changer-based technology
  - limited angle operation with reduced amount of hardware
  - reliable and less expensive power flow controller
  - low operating cost
  - injection of line frequency voltage into the power system network
  - high enough response for most utility applications
- Shortcoming
  - coarse voltage injection, which is acceptable for a utility application.

# Main Differences Between Power Flow Controllers

| | ST | PAR | VRT | UPFC |
|---|---|---|---|---|
| Voltage Regulation | X | | X | X |
| Independent Line Active and Reactive Power Control | X | | | X |
| Low installation and operating costs | X | X | X | |
| Reliability and high availability | X | X | X | |
| Injection of line frequency voltage | X | X | X | |
| Low leakage reactance in the coupling Transformer | X | X | X | |
| Fast bypass switch not needed | X | X | X | |
| Fast response for utility applications | X | X | X | X |
| Coarse voltage injection | X | X | X | |
| Capability of independent reactive power generation and absorption | | | | X |

# Main Differences Between Power Flow Controllers

| | ST | PAR | VRT | UPFC |
|---|---|---|---|---|
| Losses | <1% | <1% | <1% | 3%-8% |
| Cost ($/kVA) | 15-20 | 15-20 | 10-15 | 75-100 |

# Conclusion

- A new power flow controlling transformer is presented.
- ‘Sen’ Transformer
  - uses traditional technology of transformer and tap changers.
  - uses proven technology that is reliable.
  - provides four quadrant control of active power (*P*) and reactive power (*Q*) for an optimum system operation.
  - provides more features than a PAR at the same cost.
  - displaces UPFC for most utility applications.
- An emerging power flow controller market can be exploited with the right technology.