

AE1M15PRE

# FACTS and HVDC systems in Power Engineering



# What is FACTS?

- **FACTS = Flexible AC Transmission Systems**
- **IEEE:**
  - FACTS: Alternating current transmission systems with static regulator integrated or based on high power electronic technology. Used for power flow control and transmission line capacity increasing.
  - FACTS controller: Unit with high power electronic or static, which allows controlling of one or several parameters of AC transmission system.

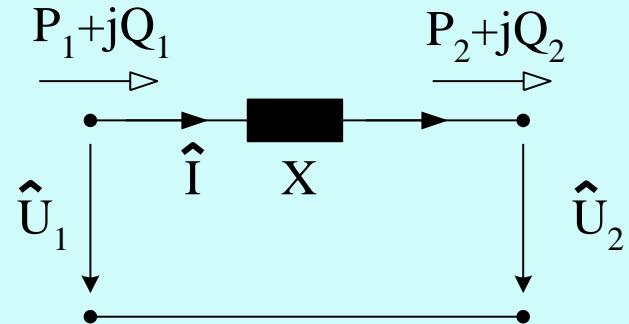
# Power transmission

- **Limits**

- thermal (current)
- dialectical (voltage)
- stability (static and dynamic)

- **Power flow control**

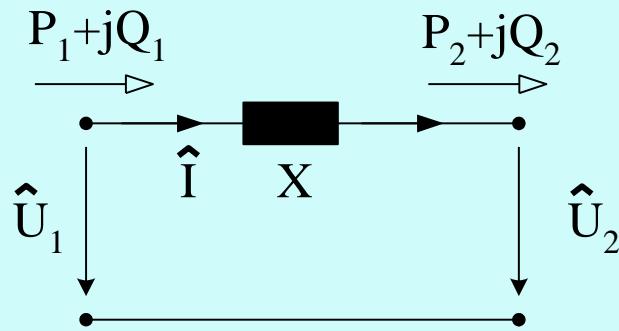
- Line impedance  $X$
- Load angle  $\delta$
- Voltage  $U$ ,  $\varphi$
- Injection of  $P, Q$



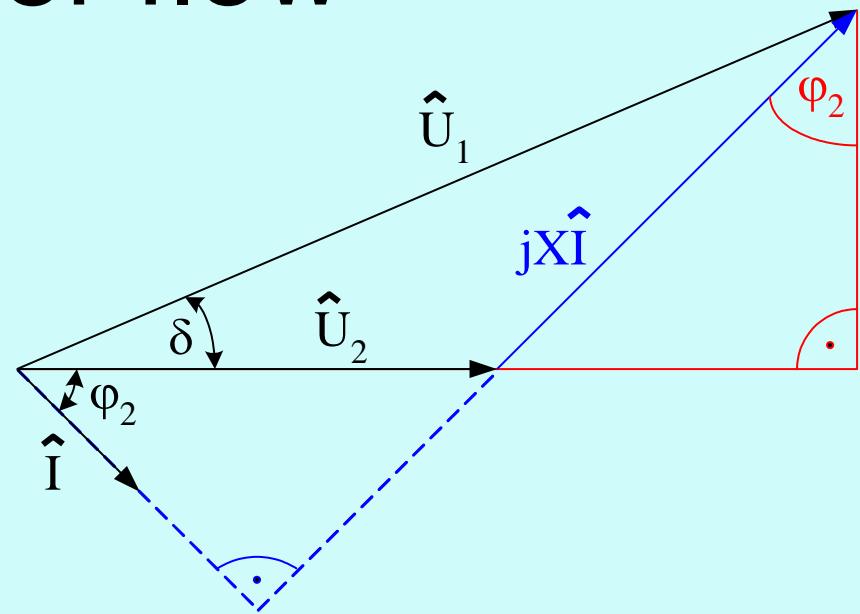
$$P_2 = \frac{U_1 U_2}{X} \sin \delta = P_1$$

$$Q_2 = \frac{U_1 U_2}{X} \cos \delta - \frac{U_2^2}{X}$$

# Power flow



$$P_2 = U_2 I \cos \varphi_2$$

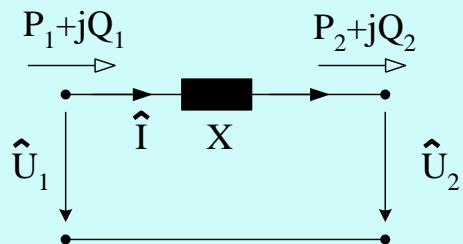


$$XI \cos \varphi_2 = U_1 \sin \delta$$

$$I \cos \varphi_2 = \frac{U_1}{X} \sin \delta$$

$$P_2 = \frac{U_1 U_2}{X} \sin \delta = P_1$$

# Power flow



$$Q_2 = U_2 I \sin \varphi_2$$

$$XI \sin \varphi_2 + U_2 = U_1 \cos \delta$$

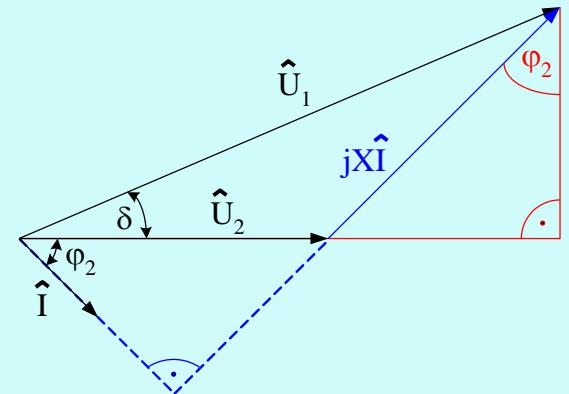
$$I \sin \varphi_2 = \frac{U_1}{X} \cos \delta - \frac{U_2}{X}$$

$$Q_2 = \frac{U_1 U_2}{X} \cos \delta - \frac{U_2^2}{X}$$

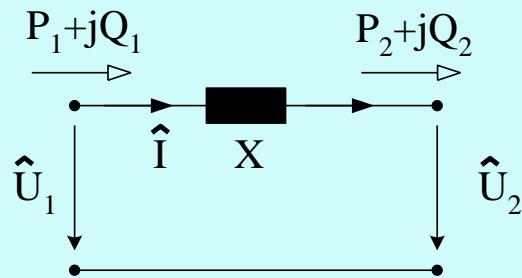
$$Q_1 = Q_2 + XI^2$$

$$\begin{aligned} Q_1 &= \frac{U_1 U_2}{X} \cos \delta - \frac{U_2^2}{X} \\ &\quad + \frac{1}{X} (U_1^2 + U_2^2 - 2U_1 U_2 \cos \delta) \end{aligned}$$

$$Q_1 = \frac{U_1^2}{X} - \frac{U_1 U_2}{X} \cos \delta$$



# P-Q transmission diagram

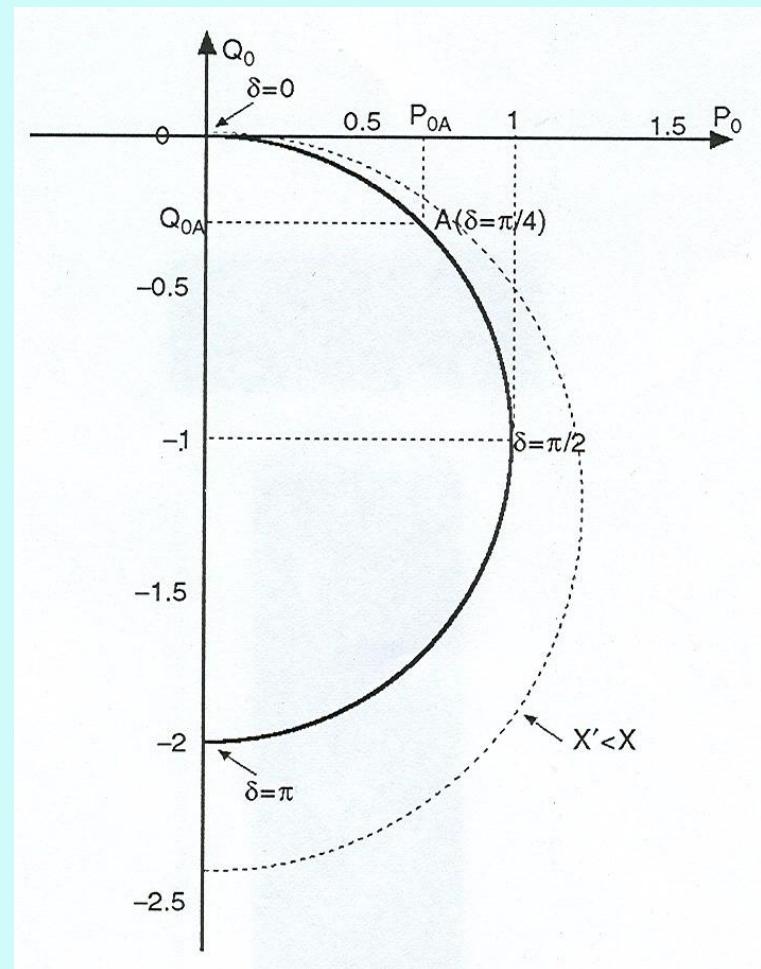


$$P_2 = \frac{U_1 U_2}{X} \sin \delta$$

$$Q_2 = \frac{U_1 U_2}{X} \cos \delta - \frac{U_2^2}{X}$$

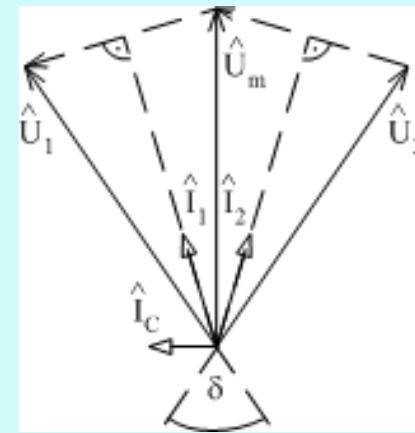
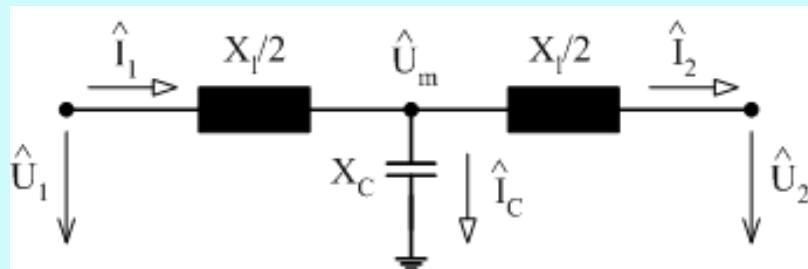
$$(P_2(\delta))^2 + \left(Q_2(\delta) + \frac{U_2^2}{X}\right)^2 = \left(\frac{U_1 U_2}{X}\right)^2$$

$$\text{circle } S \left[ 0, -\frac{U_2^2}{X} \right], \quad r = \frac{U_1 U_2}{X}$$

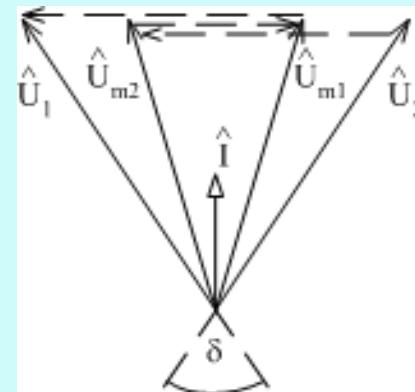
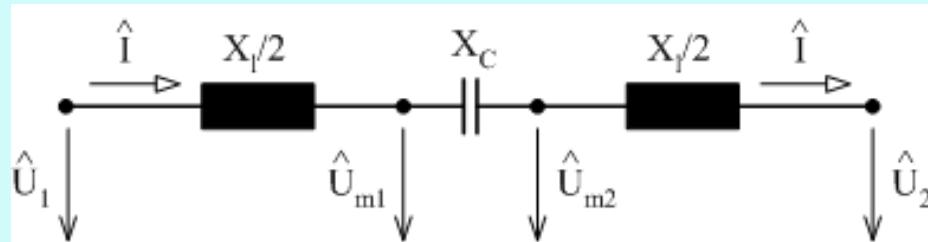


# Control principles - passive

- **Shunt**

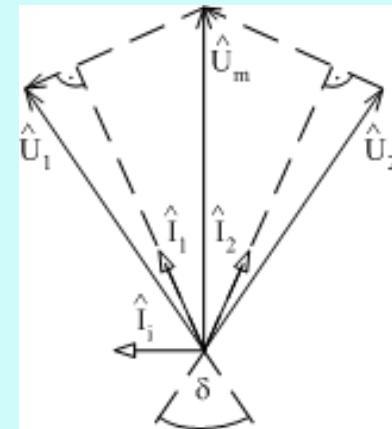
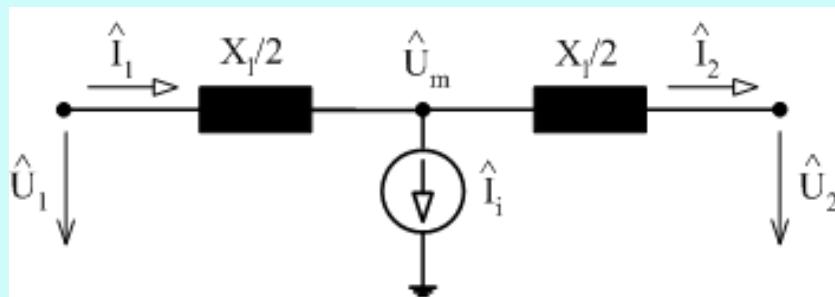


- **Series**

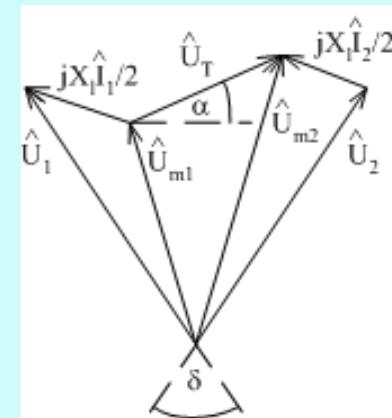
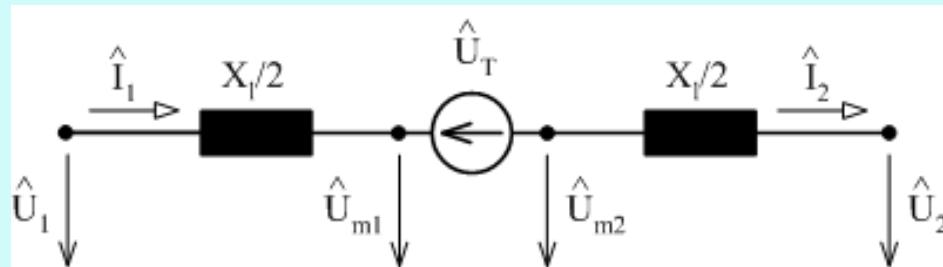


# Control principles - active

- **Shunt**

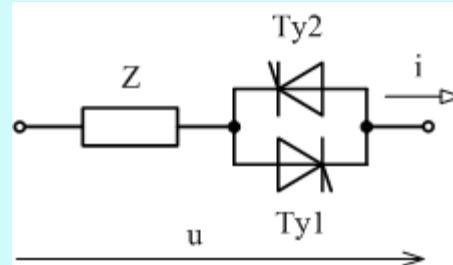


- **Series**

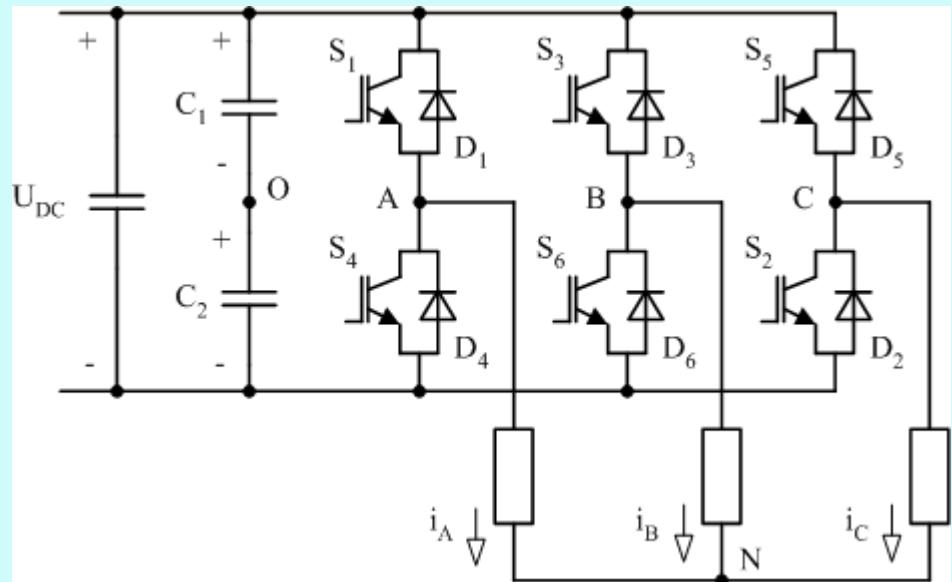


# Convertors

- Thyristor unit



- Three phase converters (VSC)

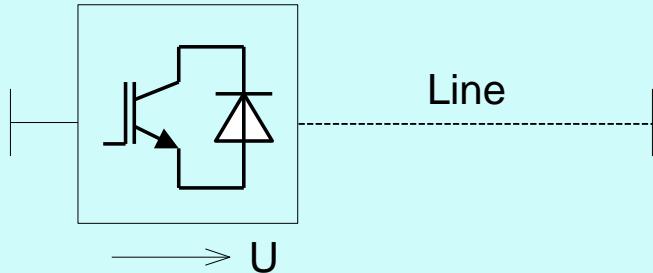


# Voltage Source Convertor(VSC)

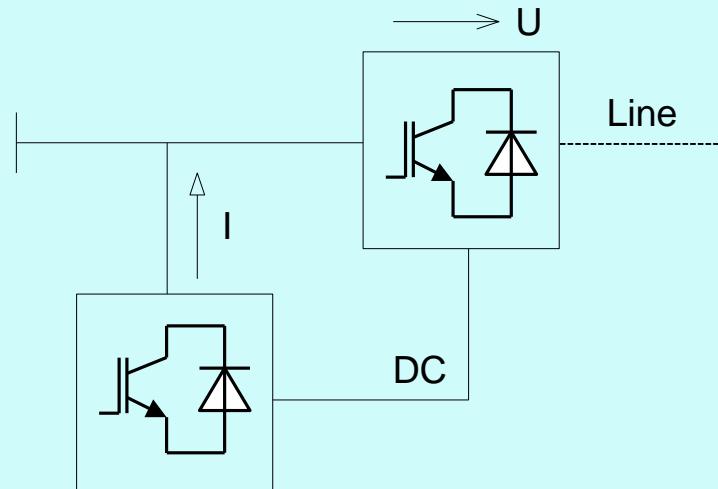
- **Switching element (GTO, IGBT, IGCT)**
- **Pulse Width Modulated (PWM) –  $U_{max}, \phi, 50$  Hz**
- **High harmonics → filters**
- **DC circuit – high capacity C or DC source**
  - C – I orthogonal to U → only Q control
  - source – any phase shift → P,Q control
- **Connected to the line through transformer**
  - shunt – ind., cap. current → U regulation
  - series – voltage injection → P,Q regulation

# FACTS

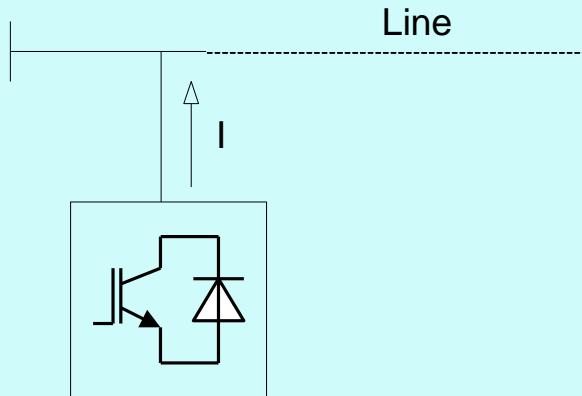
**1) series**



**3) combined (universal)**



**2) shunt**

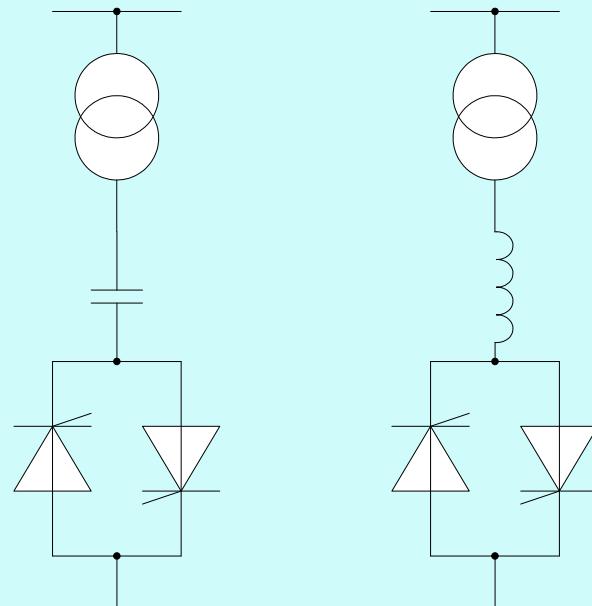


# FACTS

- **Shunt**

TSC – Thyristor Switched Capacitor

TCR – Thyristor Controlled Reactor

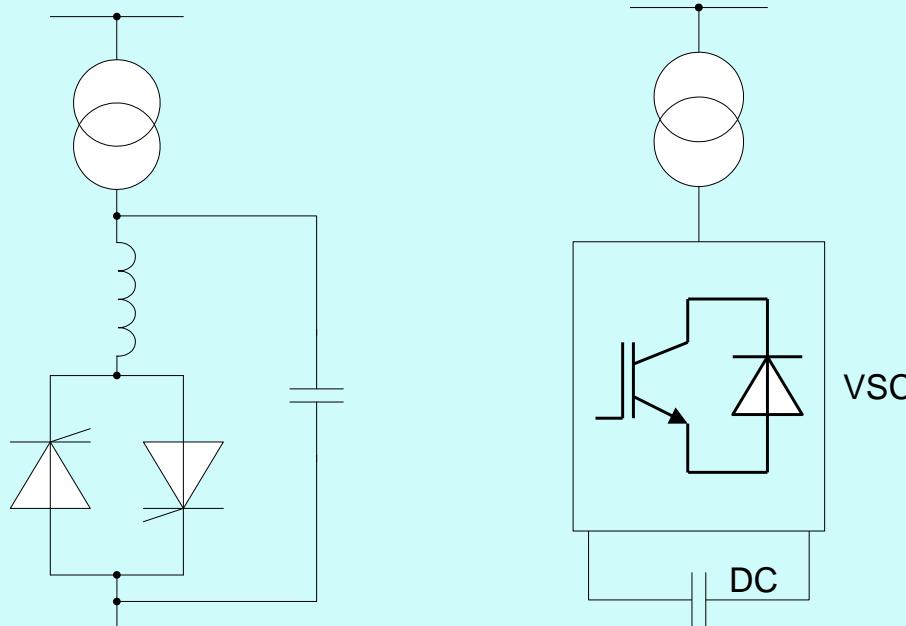


# FACTS

- **Shunt**

SVC – Static Var Compensator

STATCOM – Static Synchronous Compensator

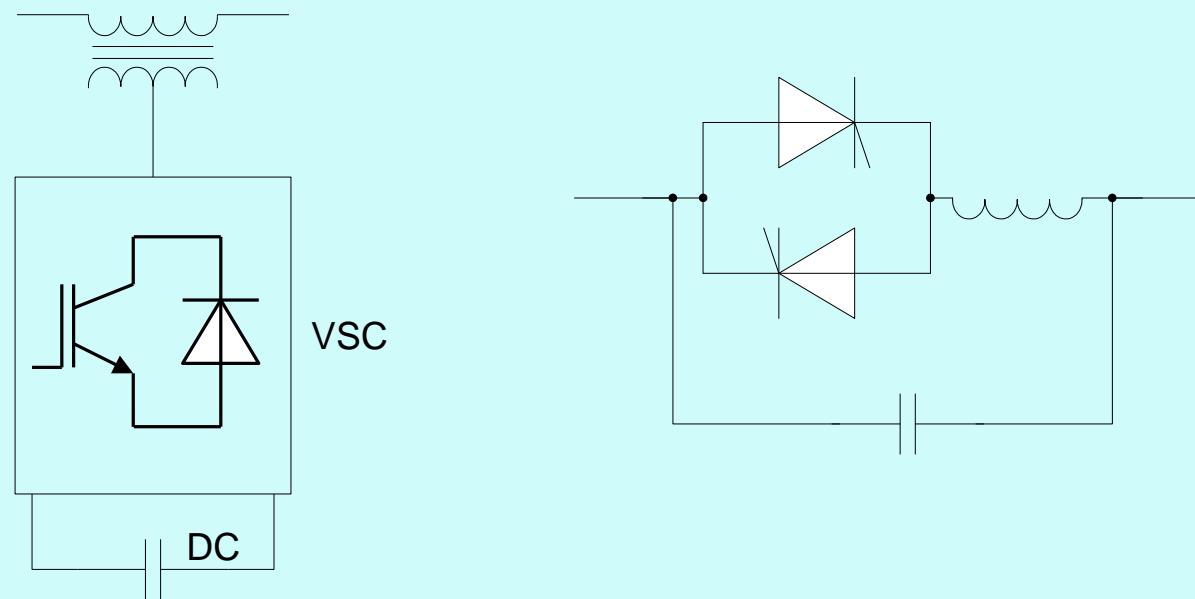


# FACTS

- **Series**

SSSC – Static Synchronous Series Compensator

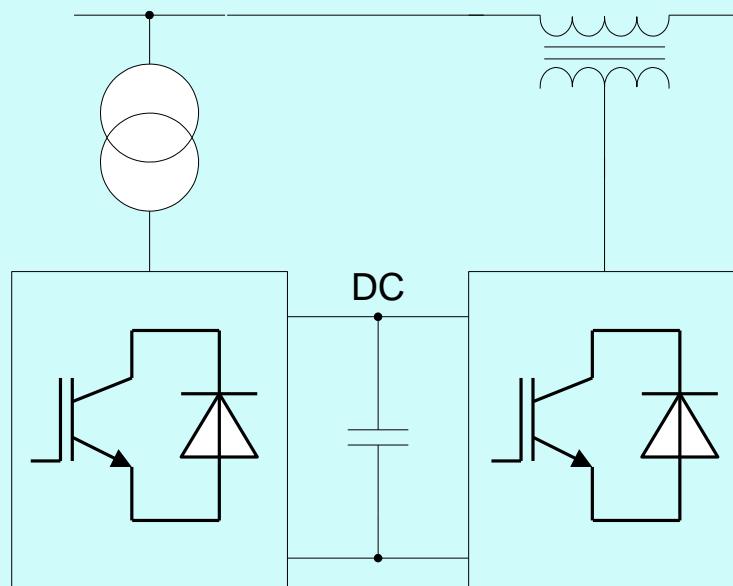
TCSC – Thyristor Controlled Series Capacitor



# FACTS

- **Universal**

UPFC – Unified Power Flow Controller



# Application

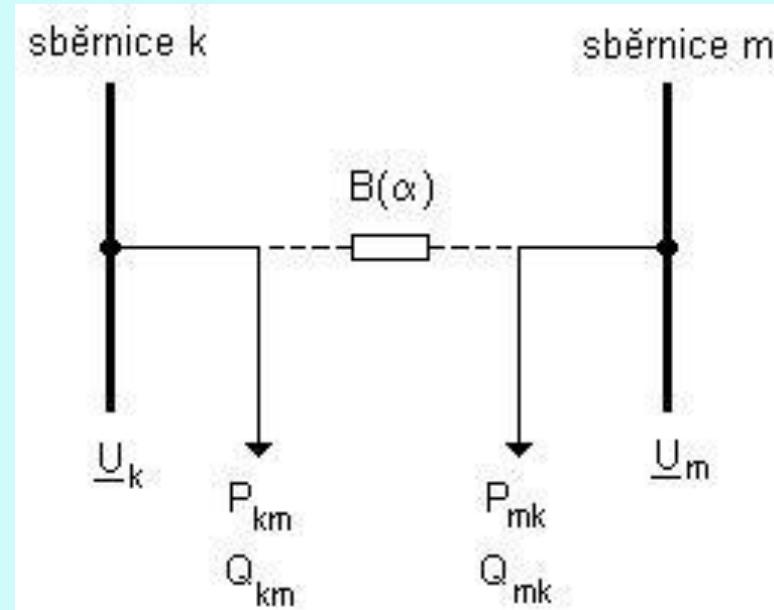
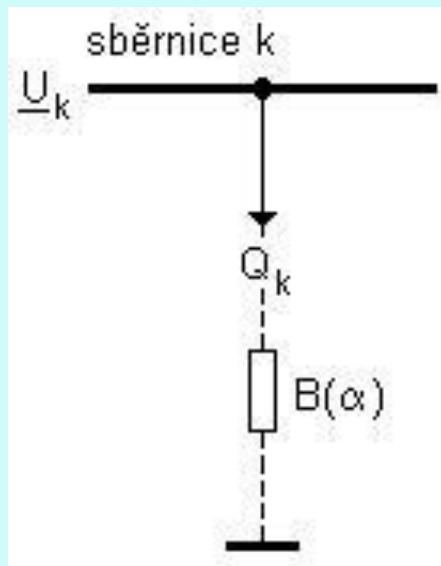
- **Power flow control (P,Q)**
- **Transmission lines capacity improvement (thermal limits)**
- **Safety rise (higher stability limits, short circuit currents and overload reduction, oscillation damping)**
- **Voltage control**
- *Controllable values ( $U, I, X, P, Q$  ) interconnected, some are dominant*

# Benefits

- **Fast response to the demand**
- **Frequent change in output**
- **Continuously adjustable output**

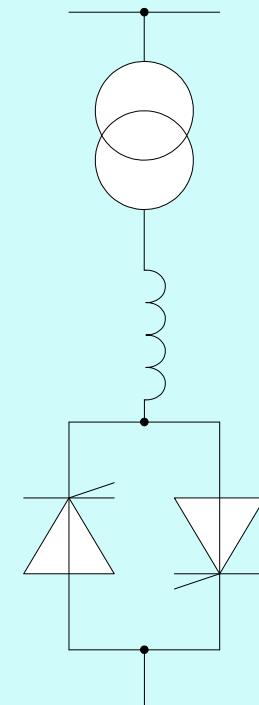
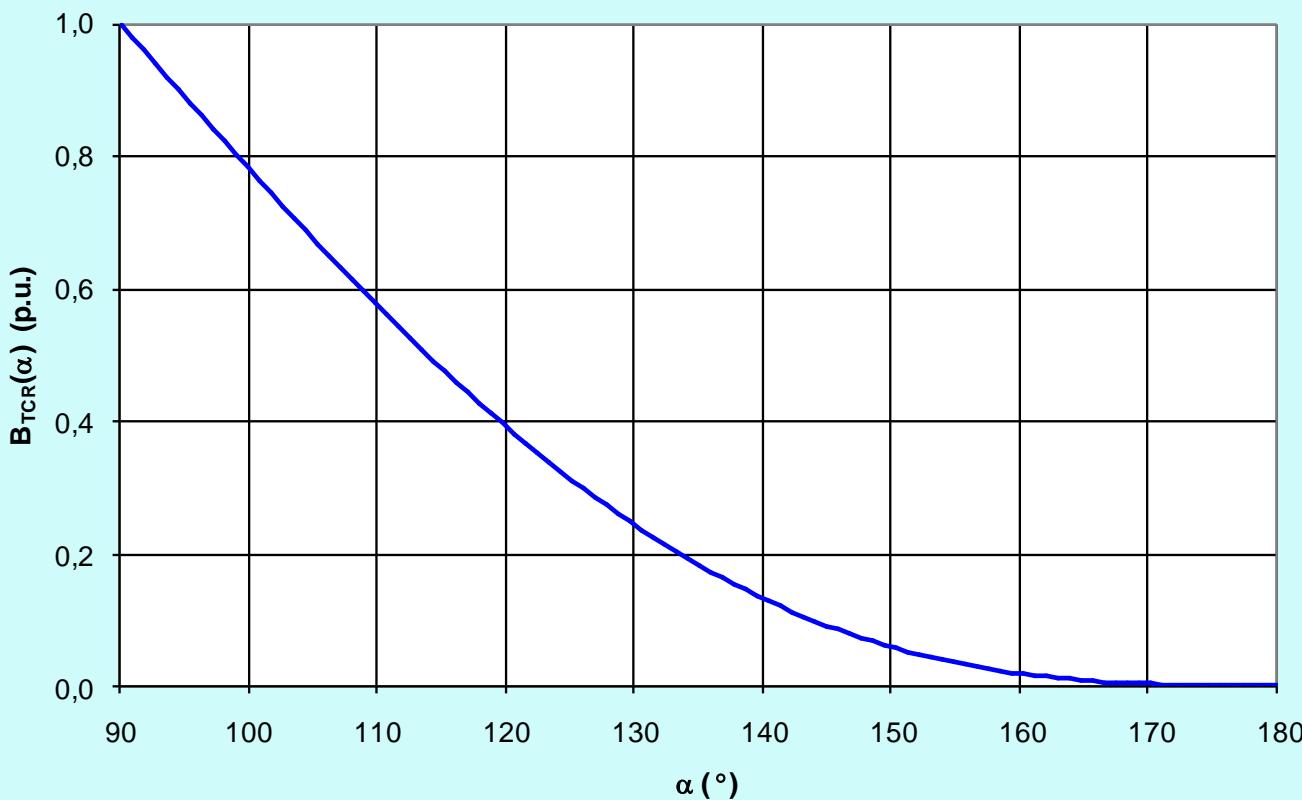
# Admittance model

- suitable for thyristor controlled converters



# Model TCR

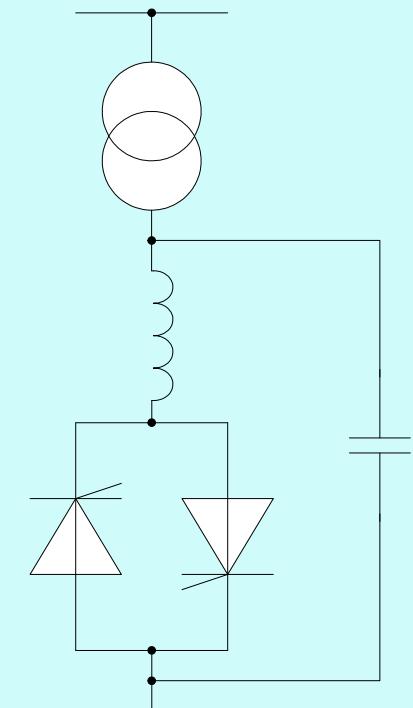
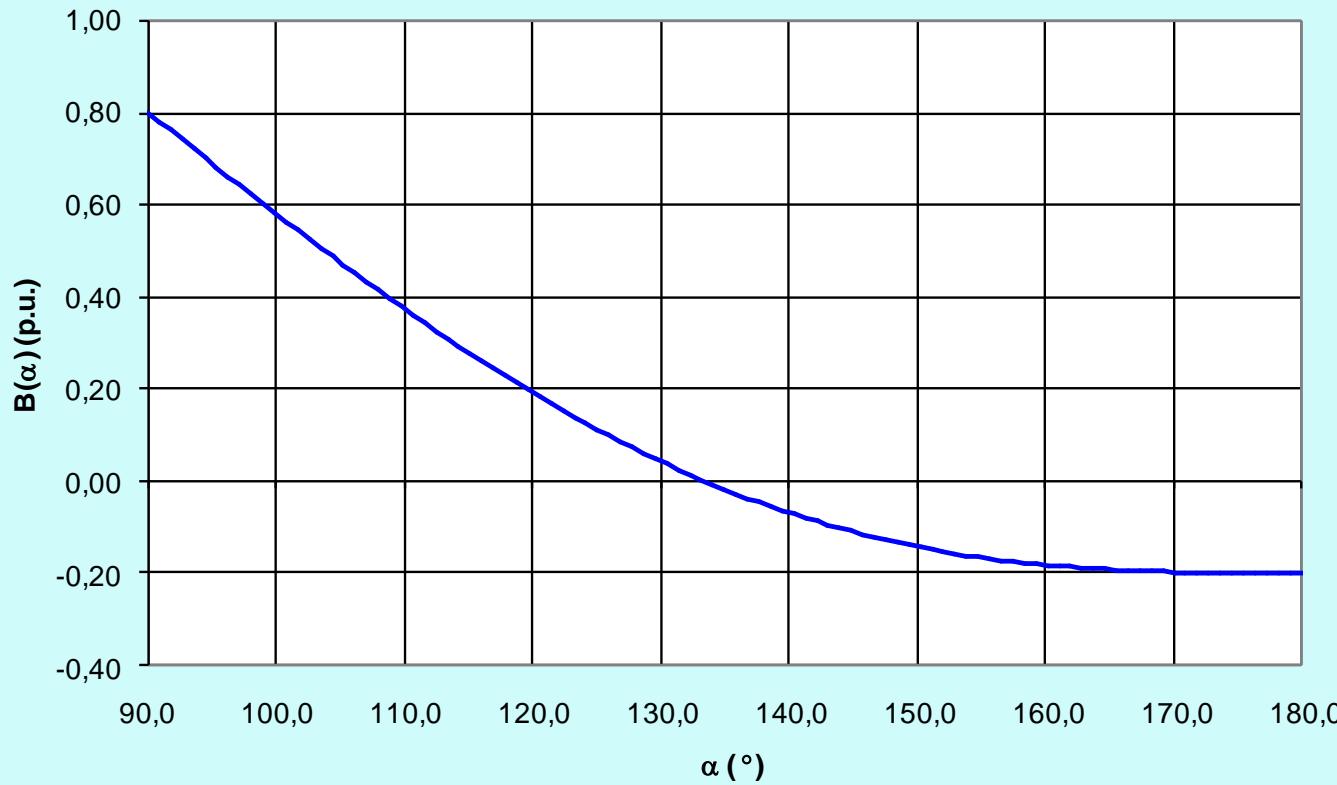
$$B_{TCR}(\alpha) = B_L \cdot \sqrt{\frac{\pi}{2[(\pi - \alpha)(2 + \cos 2\alpha) + 3 \cos \alpha \cdot \sin \alpha]}}$$



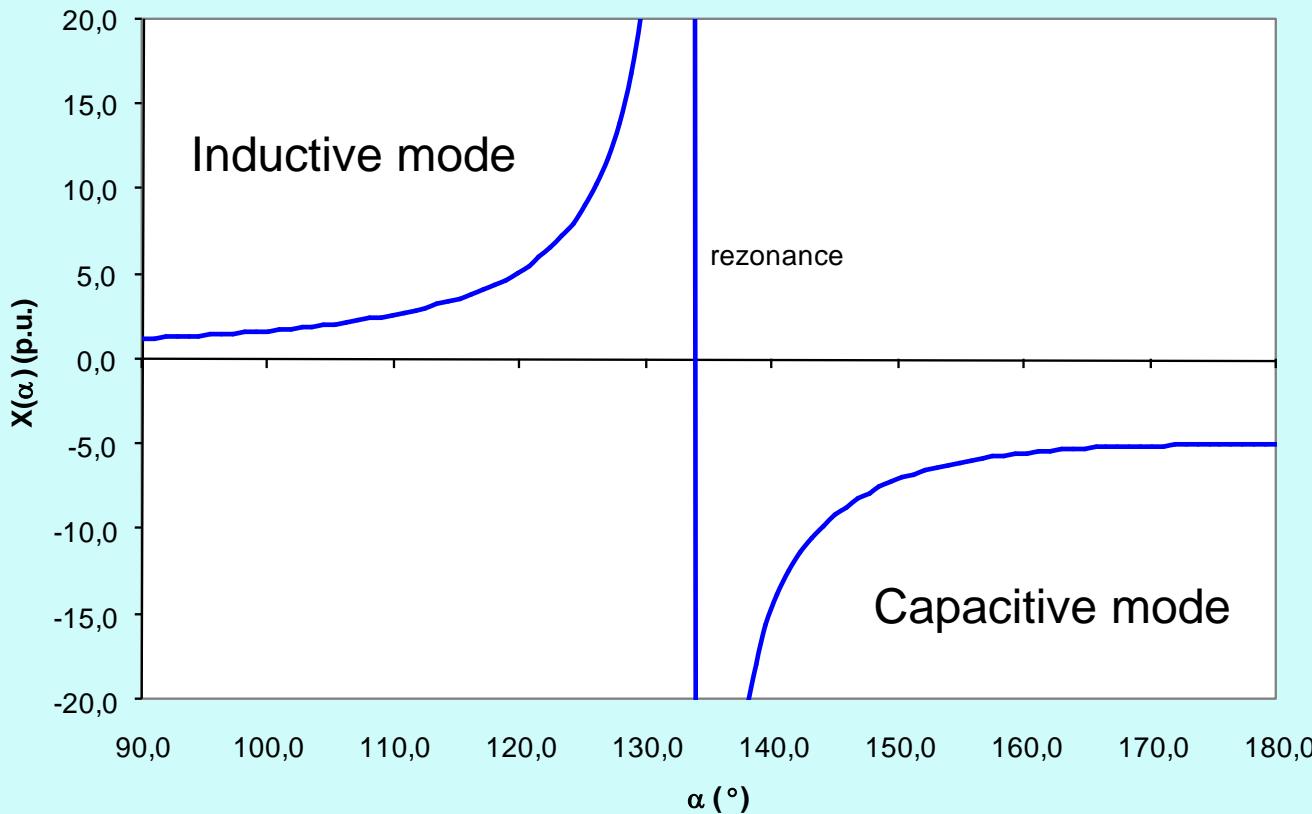
# Model SVC, TCSC

$$\omega \cdot L < \frac{1}{\omega \cdot C}$$

$$B_{TCR}(\alpha) = B_L \cdot \sqrt{\frac{\pi}{2[(\pi - \alpha)(2 + \cos 2\alpha) + 3 \cos \alpha \cdot \sin \alpha]}} + B_C$$

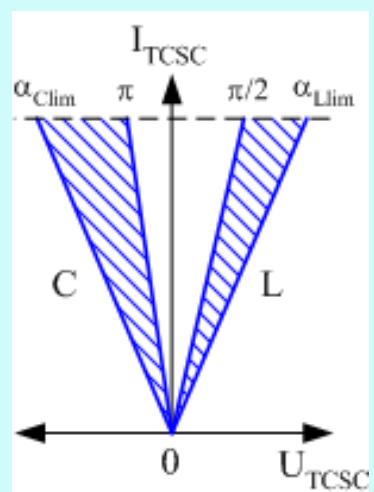
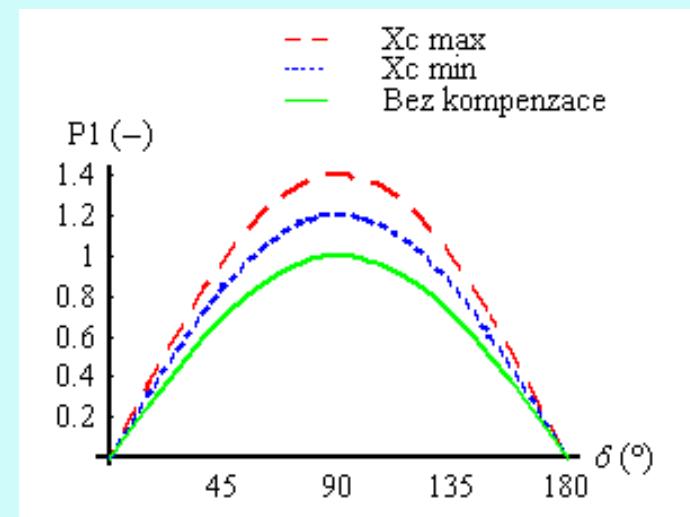
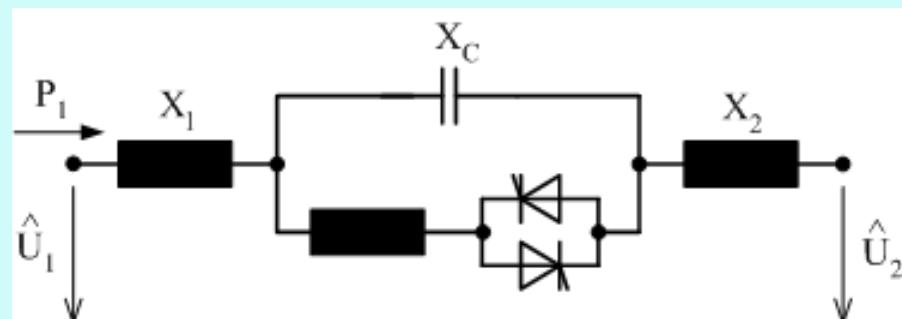


# Model SVC, TCSC

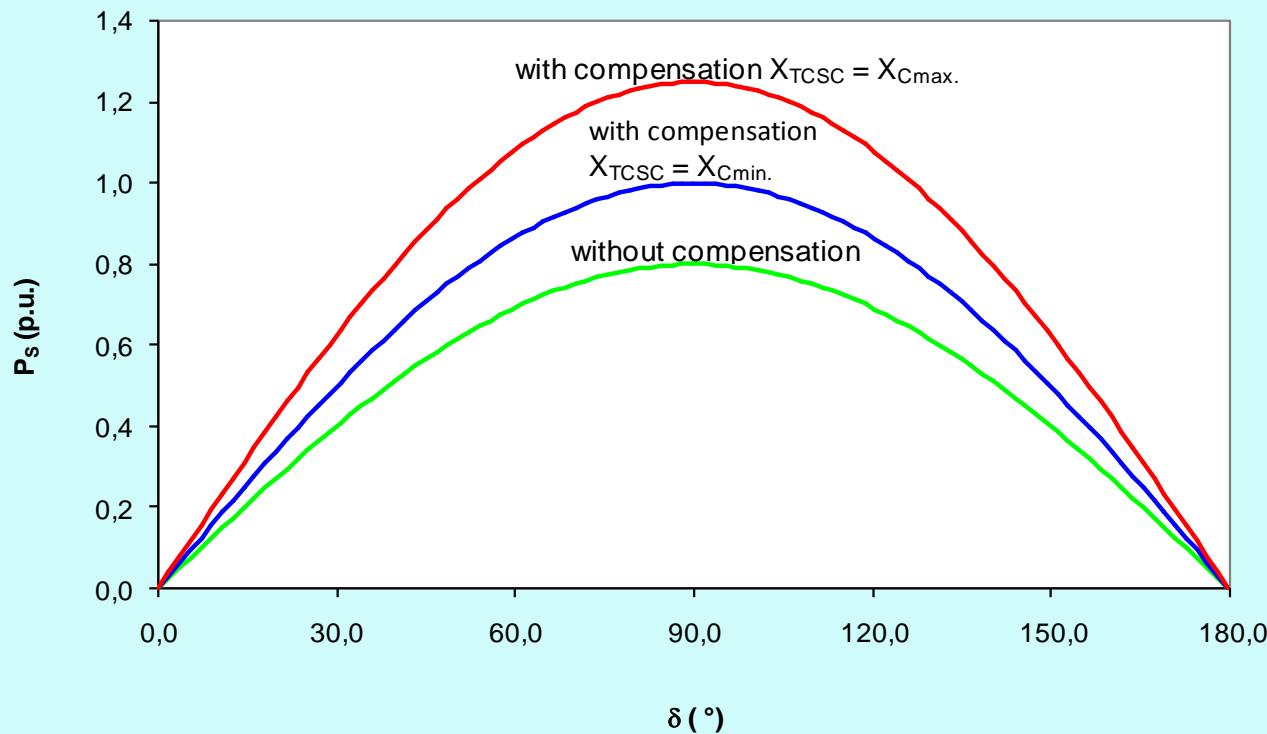
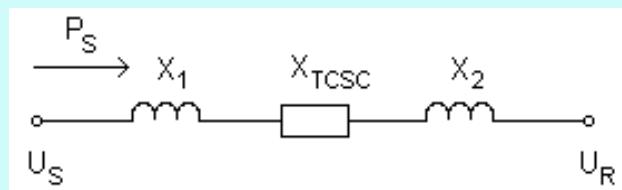


- **Resonance  $\Rightarrow \alpha_{\text{res}} - \Delta\alpha > \alpha > \alpha_{\text{res}} + \Delta\alpha$  (TCSC)**

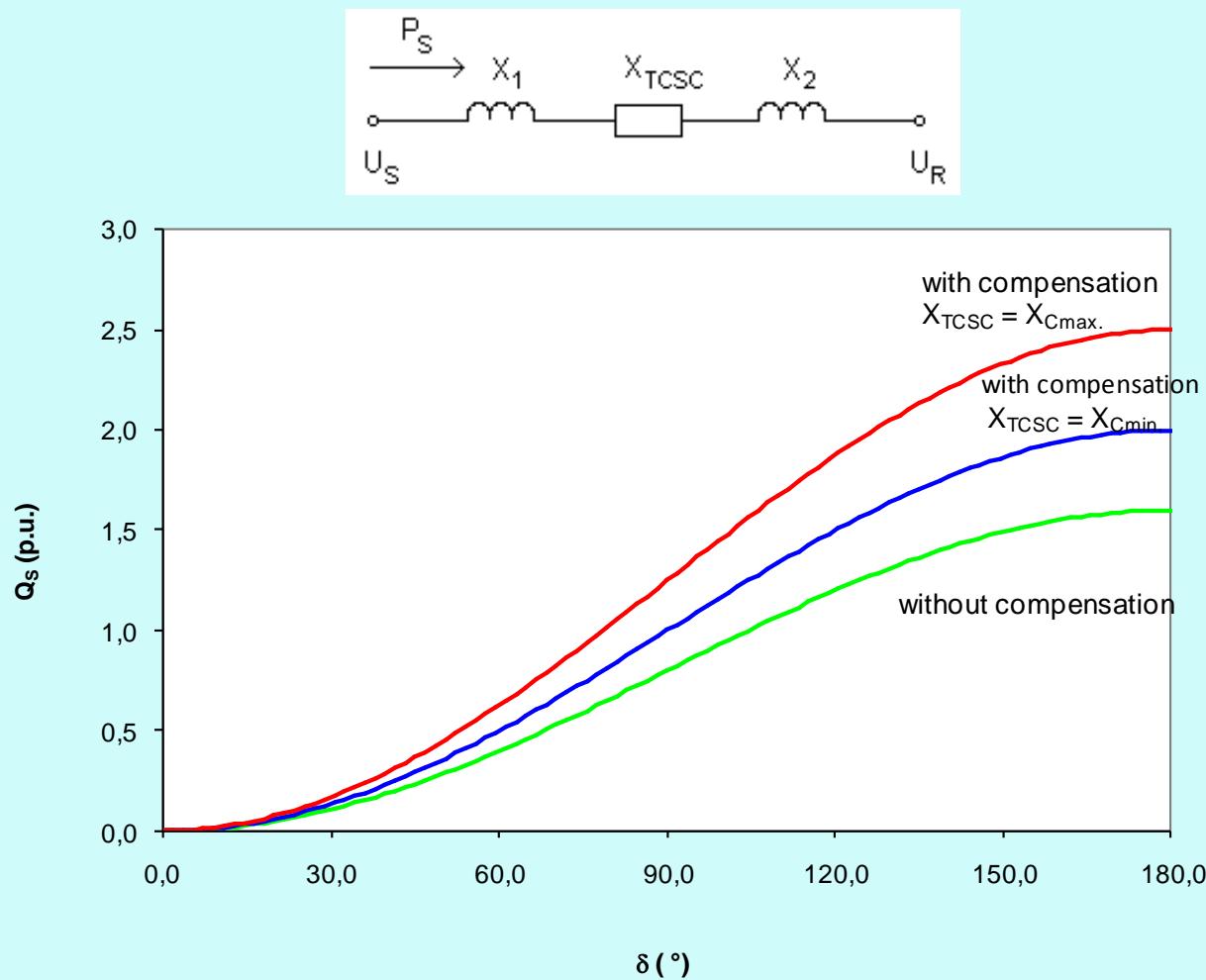
# TCSC



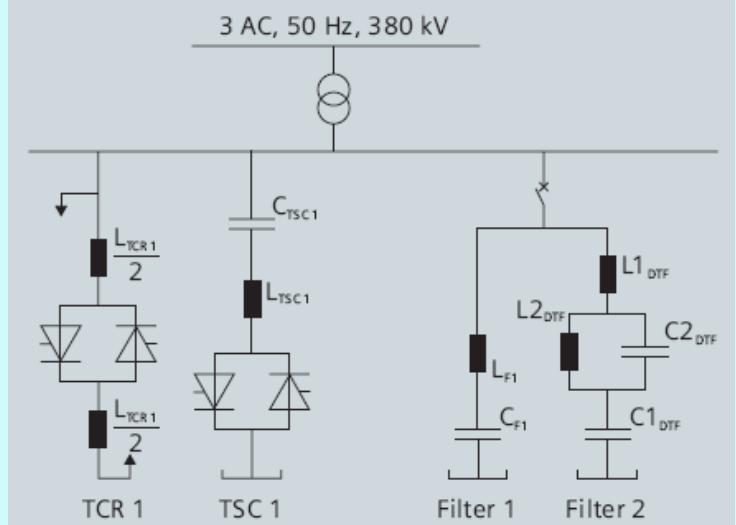
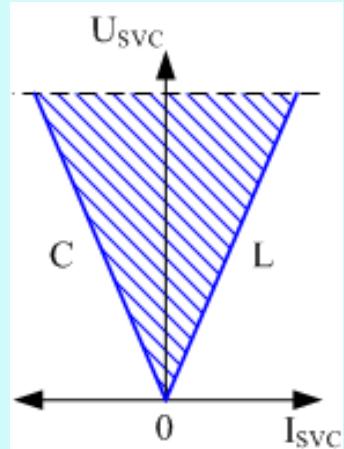
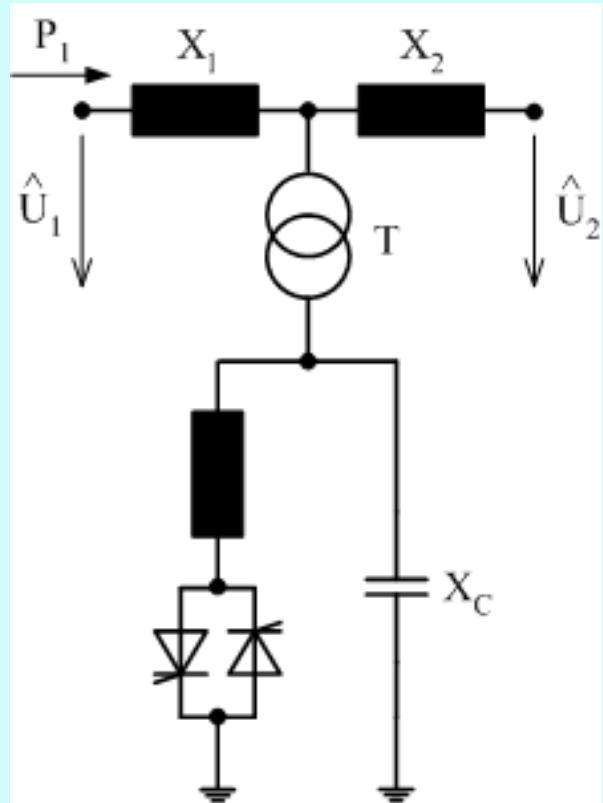
# Power characteristics - TCSC



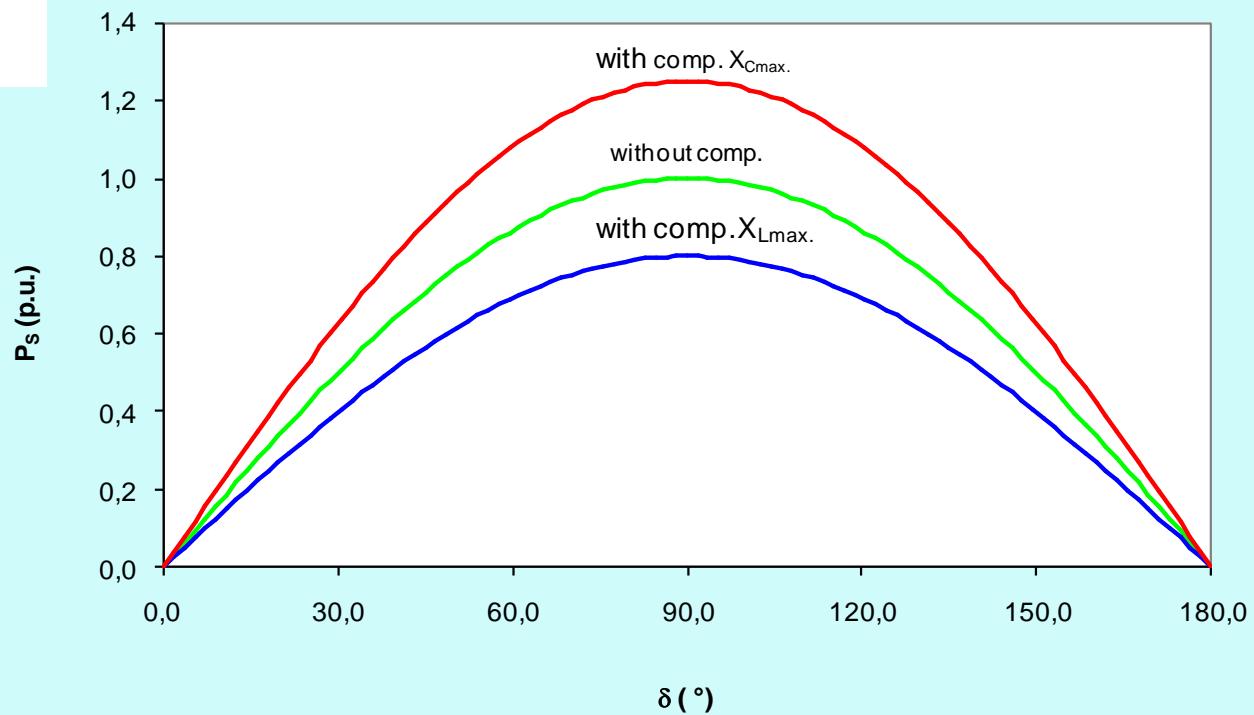
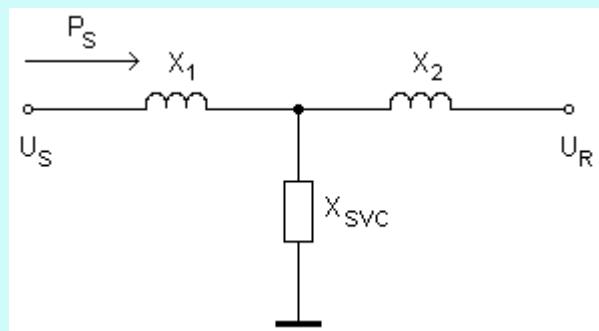
# Power characteristics - TCSC



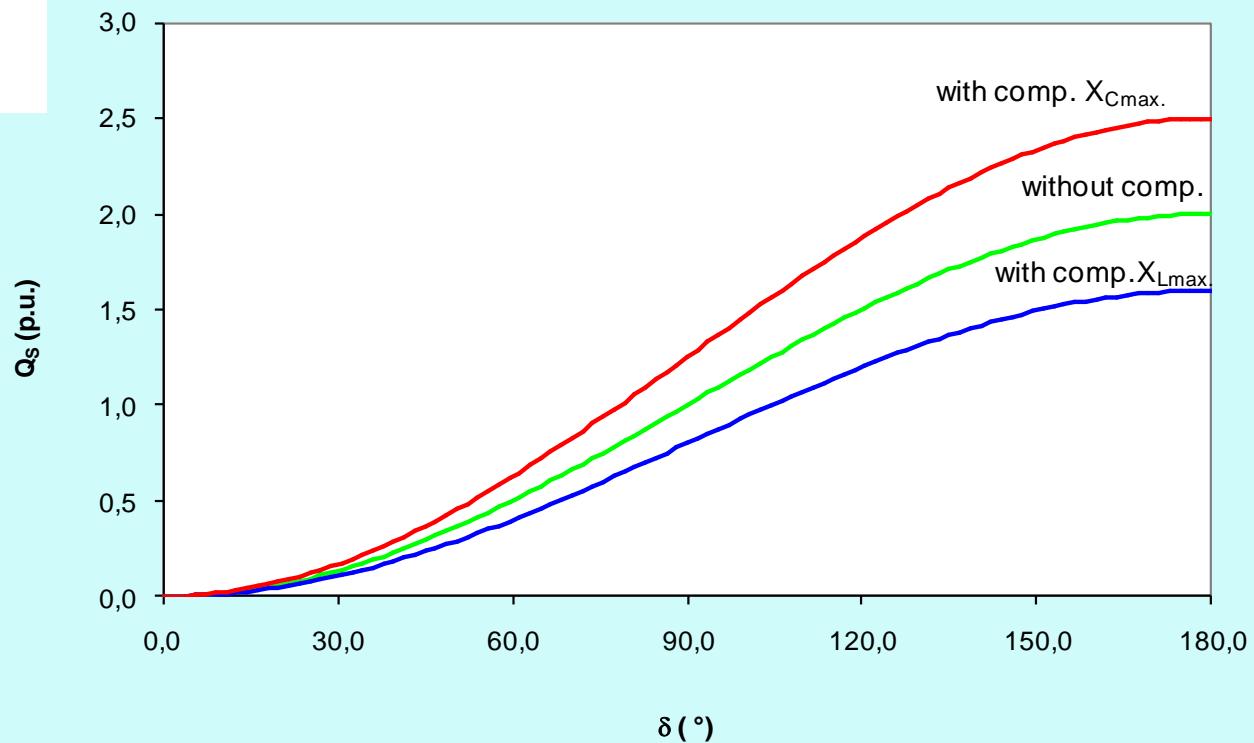
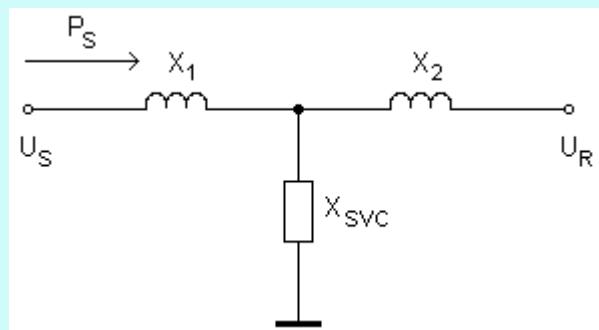
# SVC



# Power characteristics - SVC

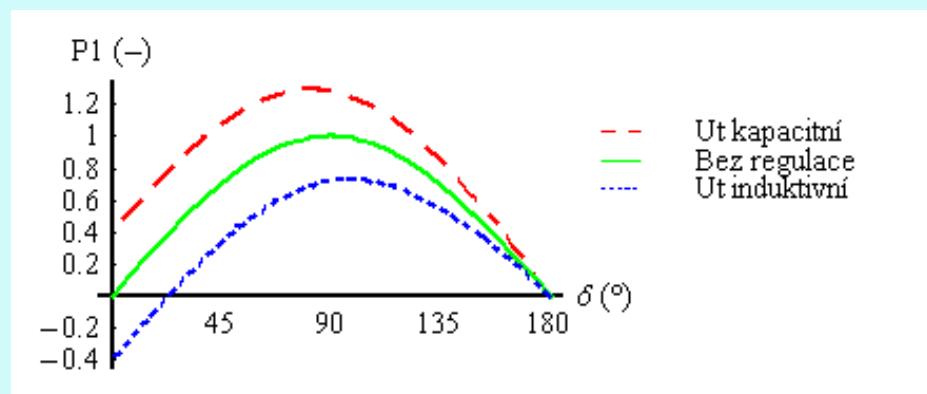
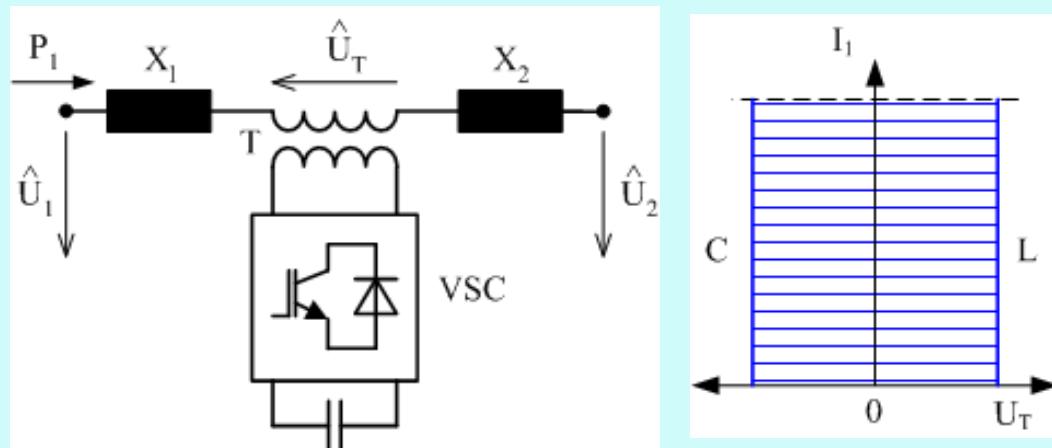


# Power characteristics - SVC



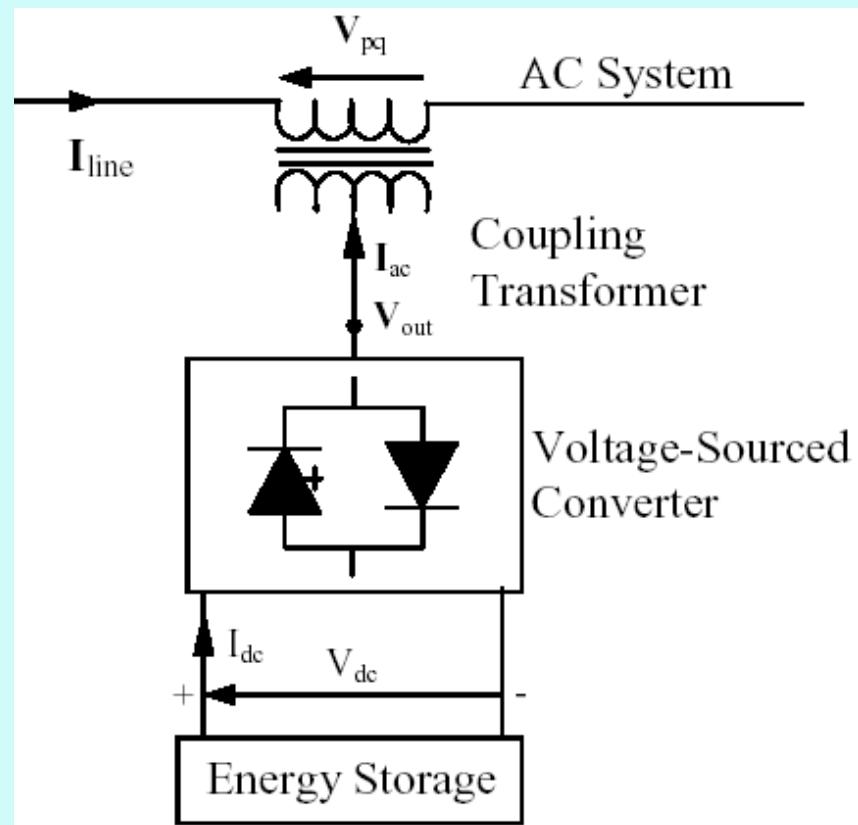
# SSSC

- Power flow control
- Oscillation damping
- Transmission stability improvement
- Voltage stability improvement



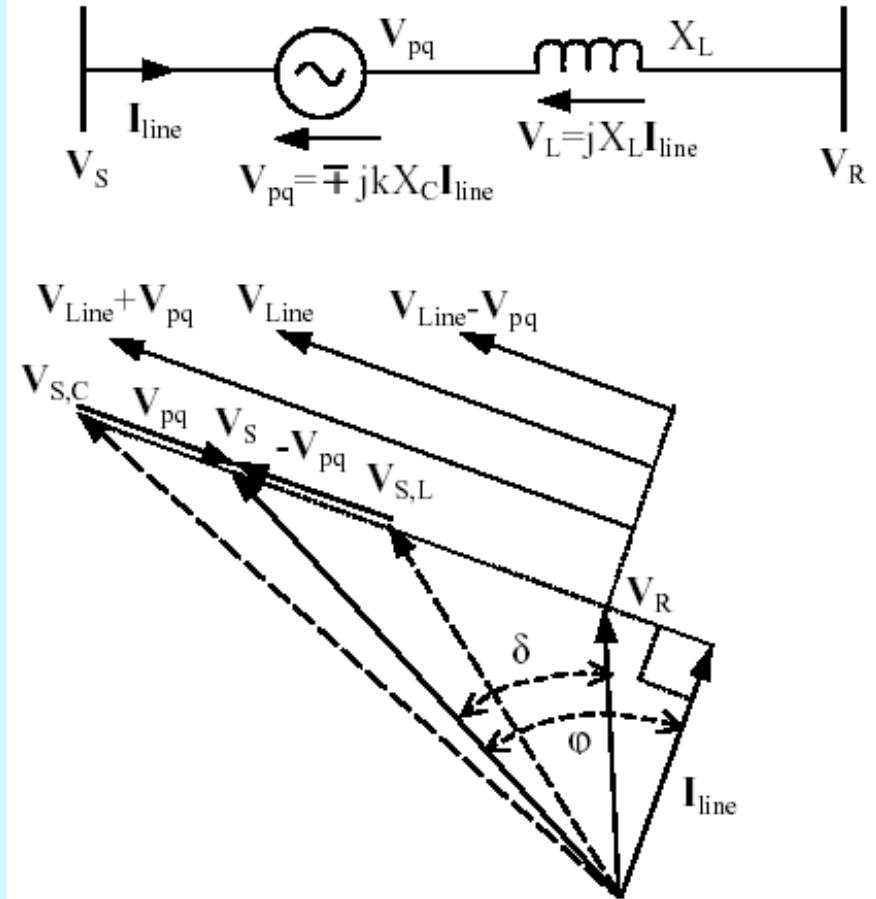
# SSSC

- **Power flow regulation  
(generation or absorption of Q),  
 $U_{pq} \perp I_{\text{Line}}$**
- **Injection of  $U_{pq} \rightarrow X_L$ ,  
 $X_C$  in series with line**
- **DC source**
  - P supply  $\rightarrow R_{\text{line}}$  compensation

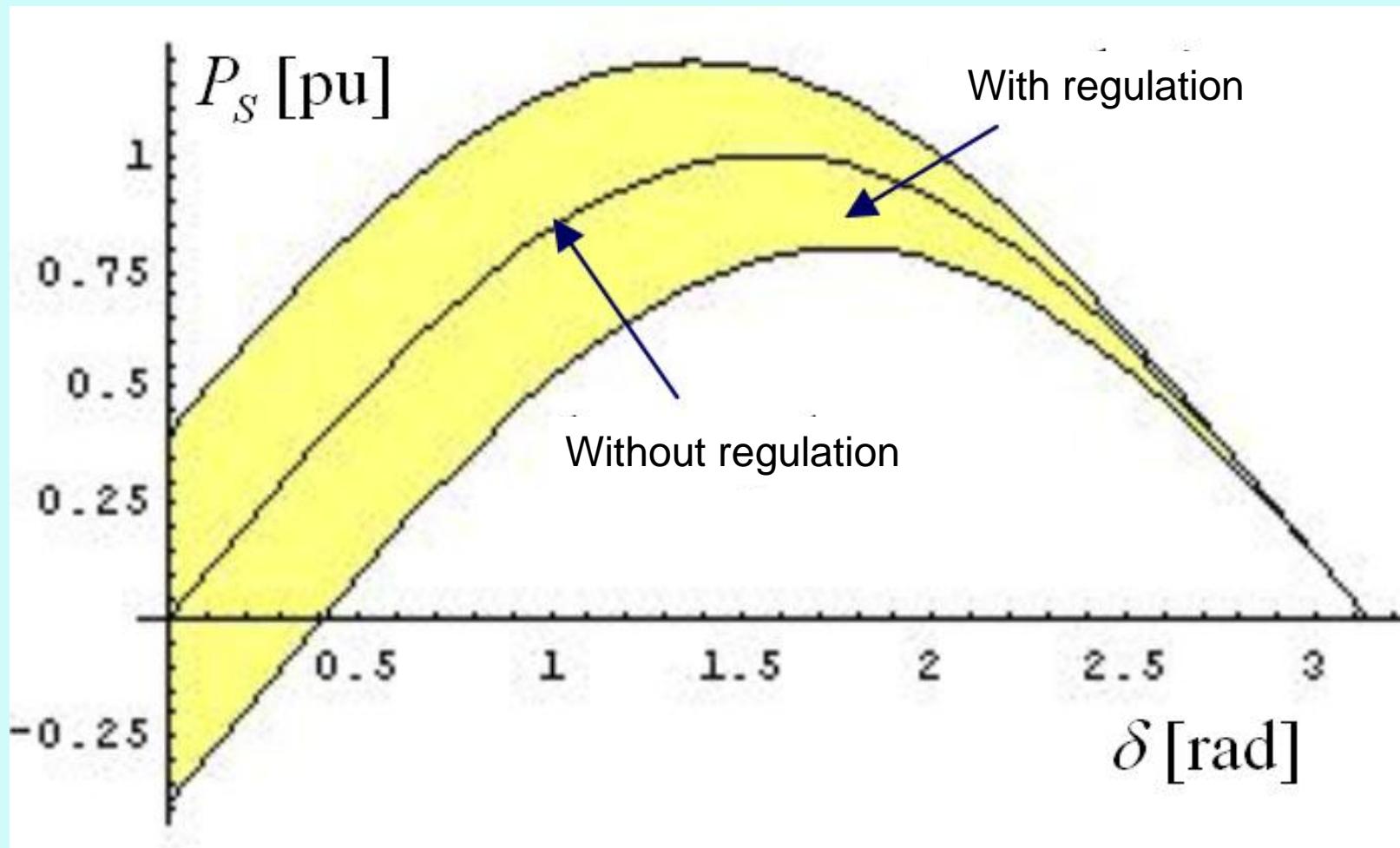


# SSSC

- **Inductive mode**
  - $U_{pq}$  in phase with drop  $\Delta U_L \rightarrow \uparrow X_L$
  - $U_{pq} < \Delta U_L \rightarrow$  else reverse power flow

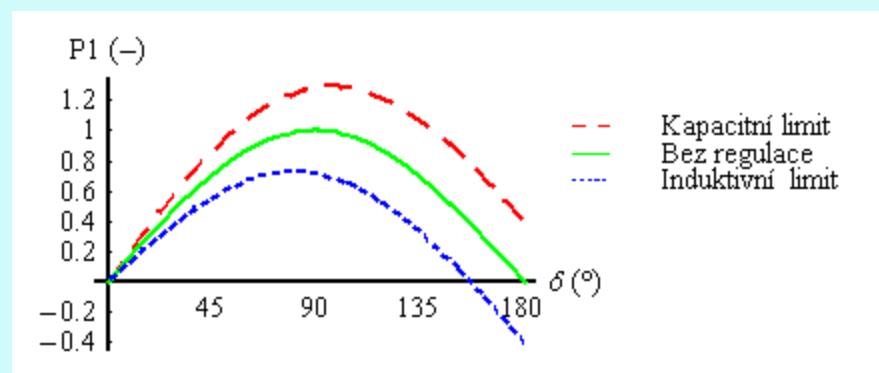
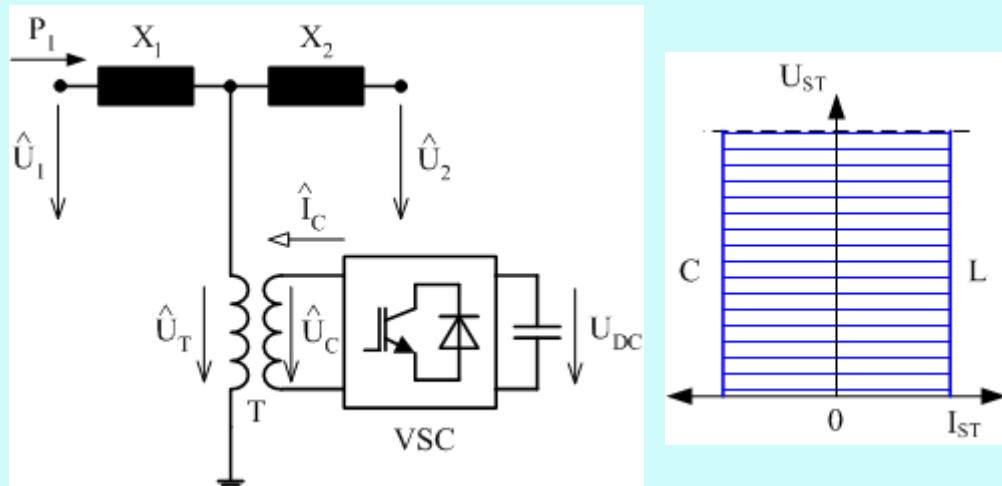


# SSSC



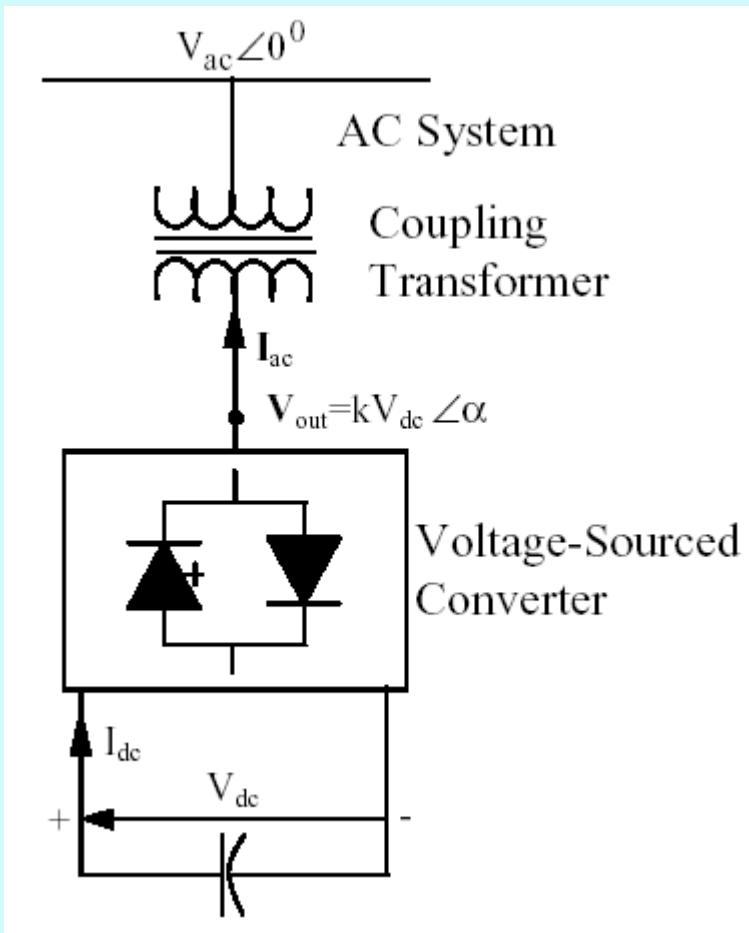
# STATCOM

- Voltage value and curve control
- Stability limits and line capacity improvement
- Oscillation damping
- Load symmetrisation
- Voltage stability and quality improvement
- Transmission, distribution and industrial application



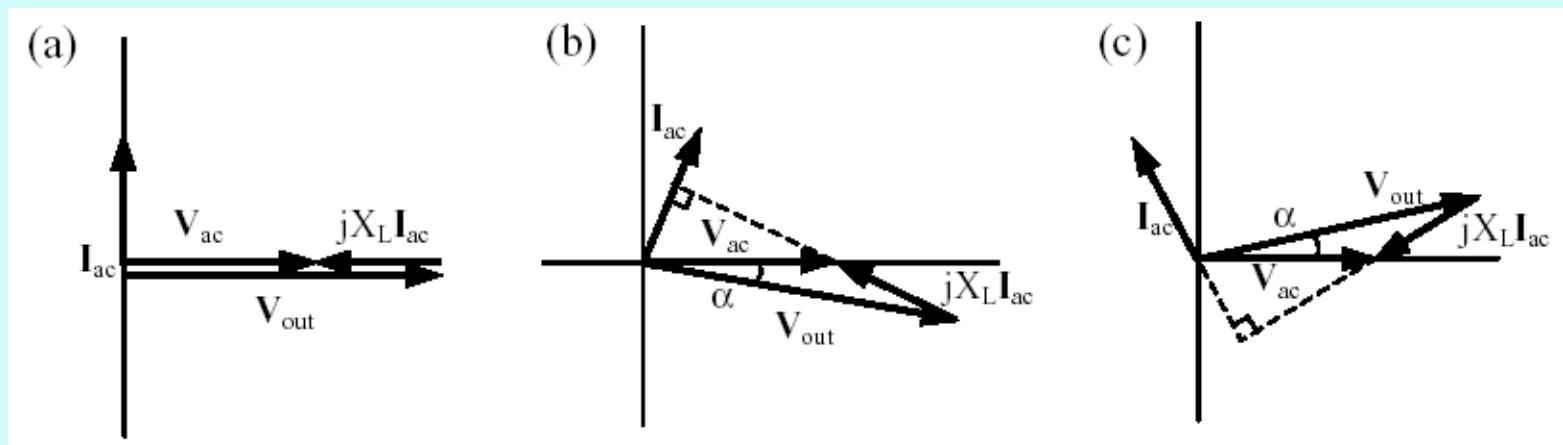
# STATCOM

- **Voltage regulation  
( $\downarrow$ load,  $\uparrow U$  ;  $\uparrow$ load,  $\downarrow U$ ),  
line capacity rise P,  
stability improvement**
- **Capacity C  $\rightarrow$  P  
consumed to cover  
losses in switches**
  - $\Delta P$  low  $\rightarrow$
  - $I_{AC} \pm 90^\circ$  from  $U_{AC}$

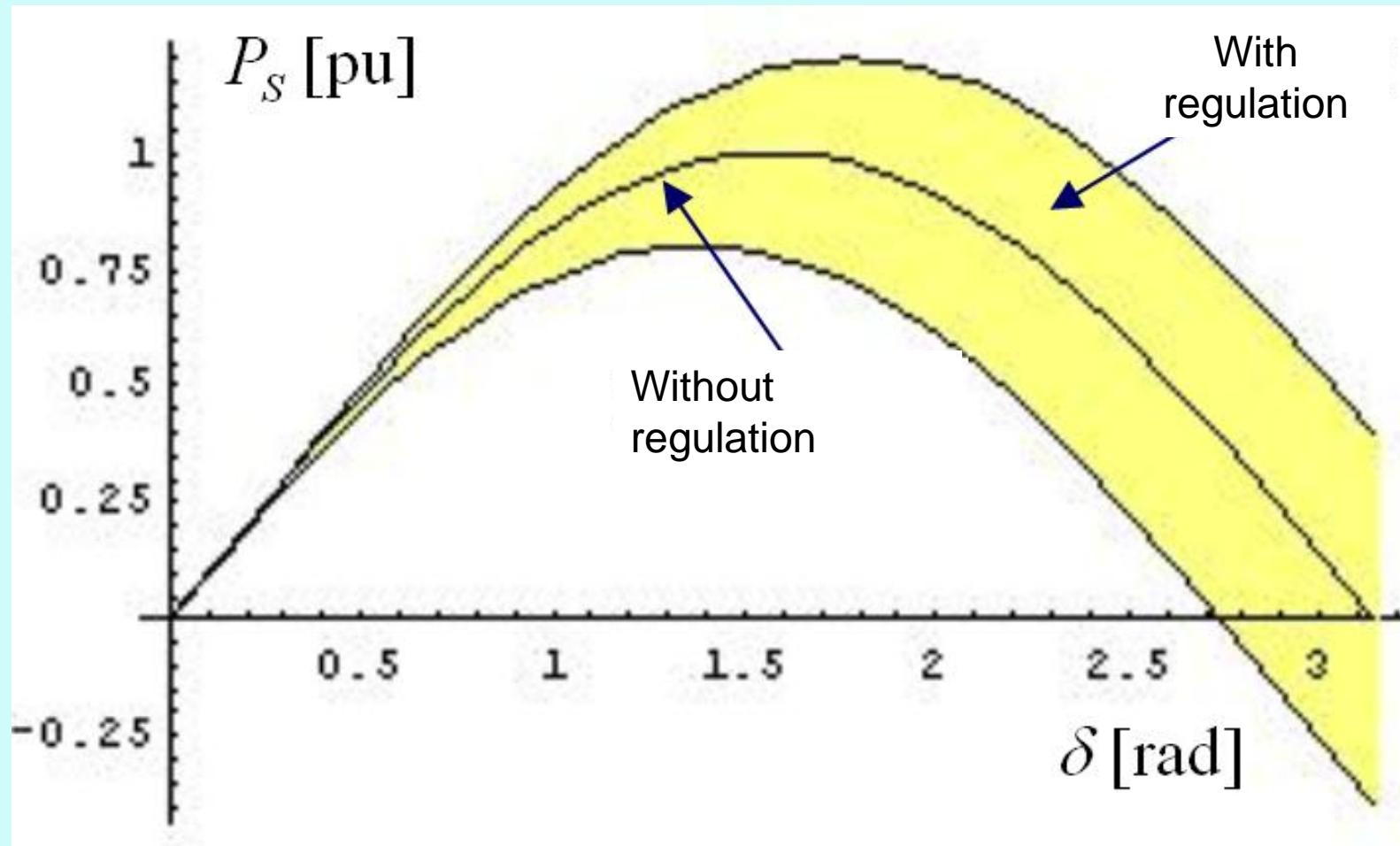


# STATCOM

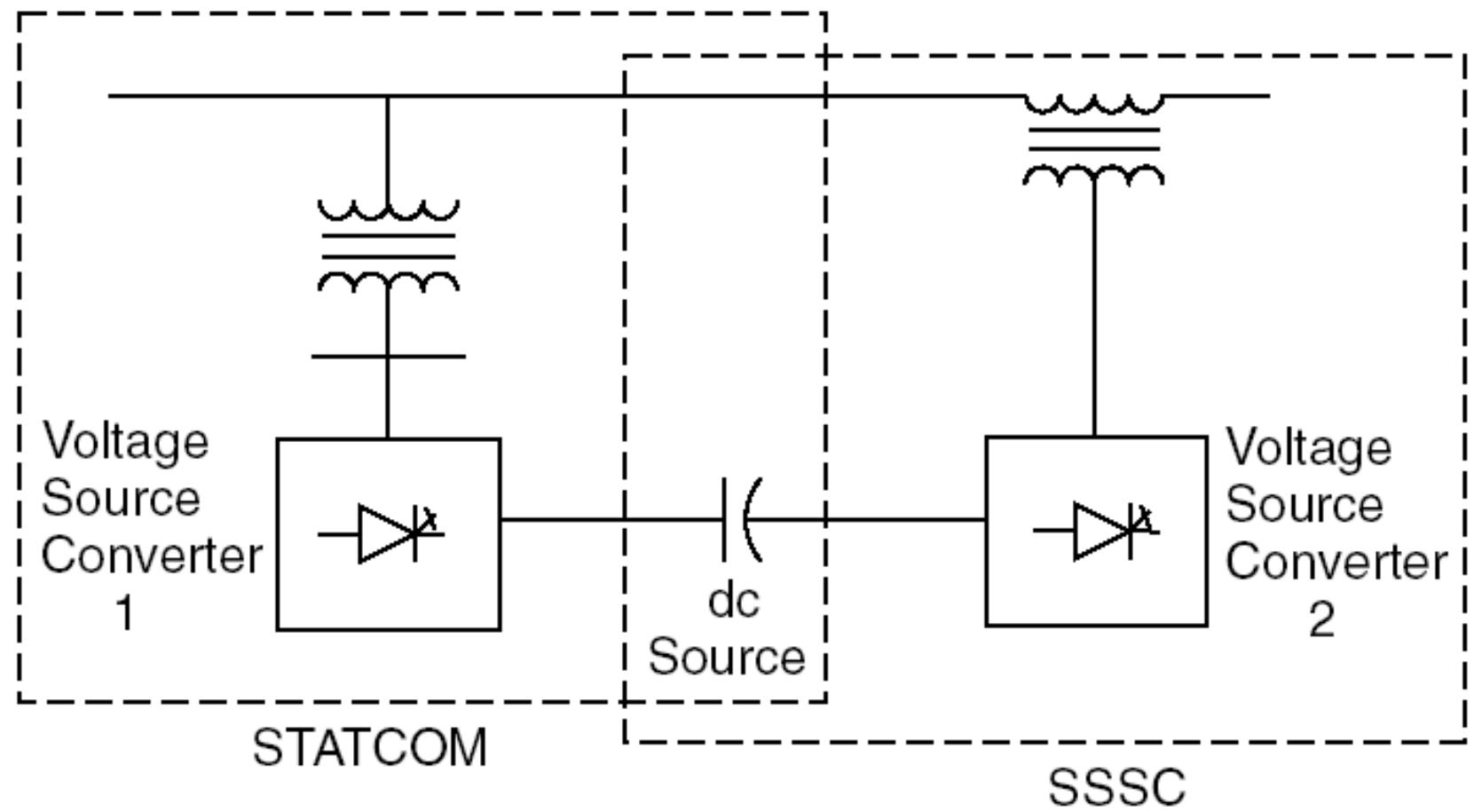
- **Q regulation – amplitude  $U_{out}$** 
  - $U_{out} > U_{AC}$  → injection Q to the system (C mode)
  - $U_{out} < U_{AC}$  → consumption Q (L mode)
- **P regulation – by angle between  $U_{out}$  and  $U_{AC}$** 
  - a)  $P = 0$
  - b) P from grid
  - c) P to grid



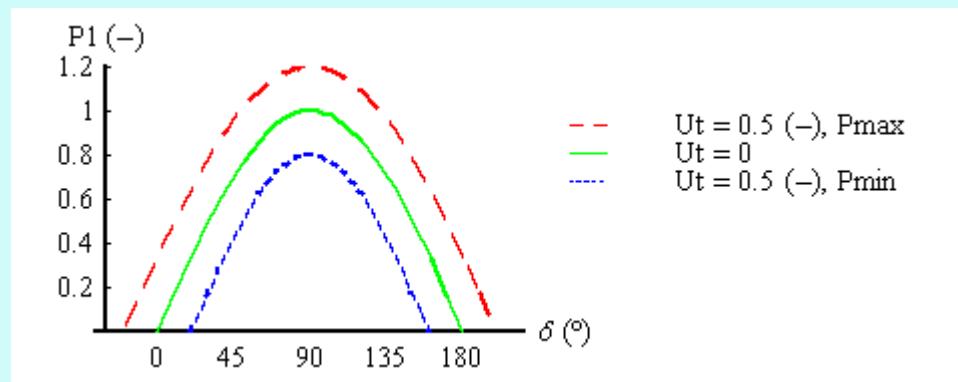
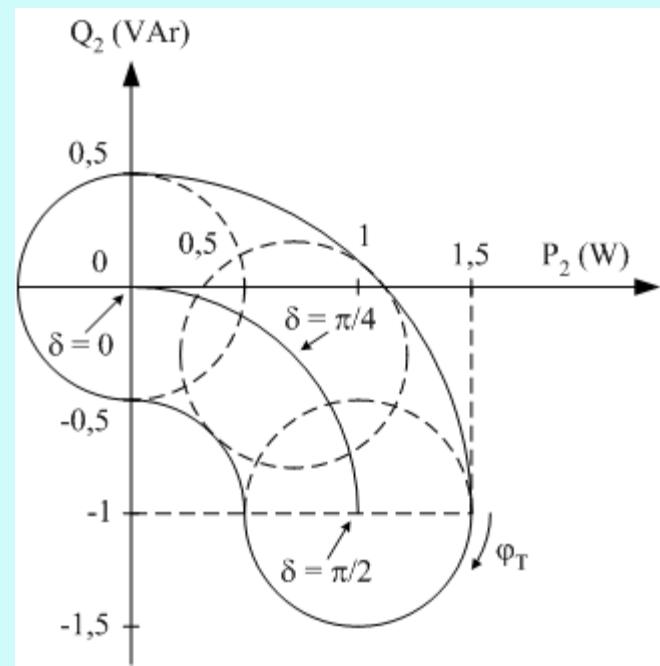
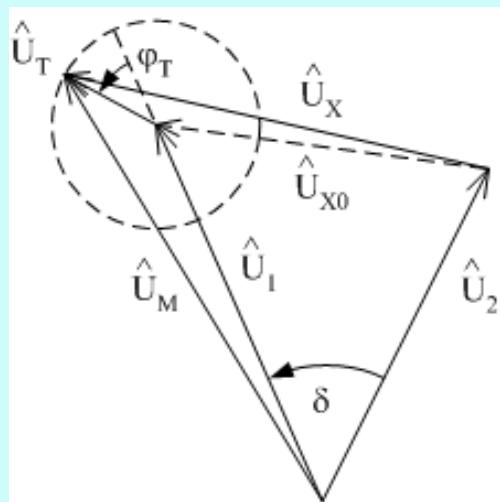
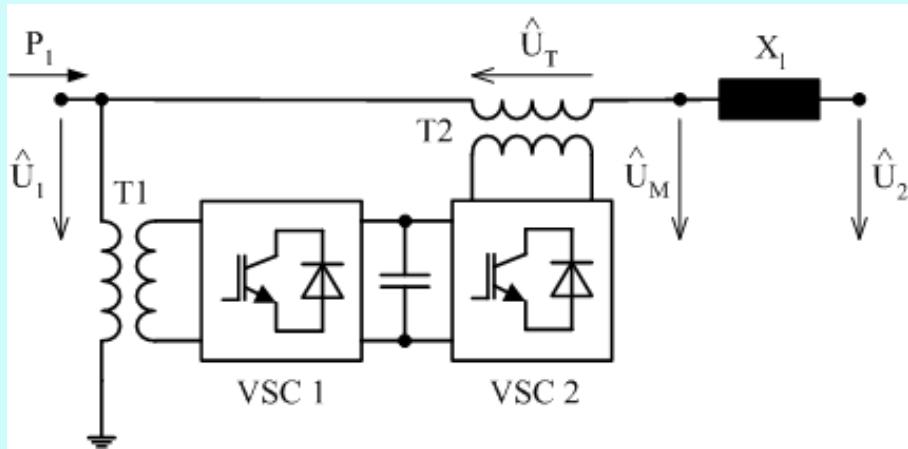
# STATCOM



# UPFC = STATCOM + SSSC



# UPFC

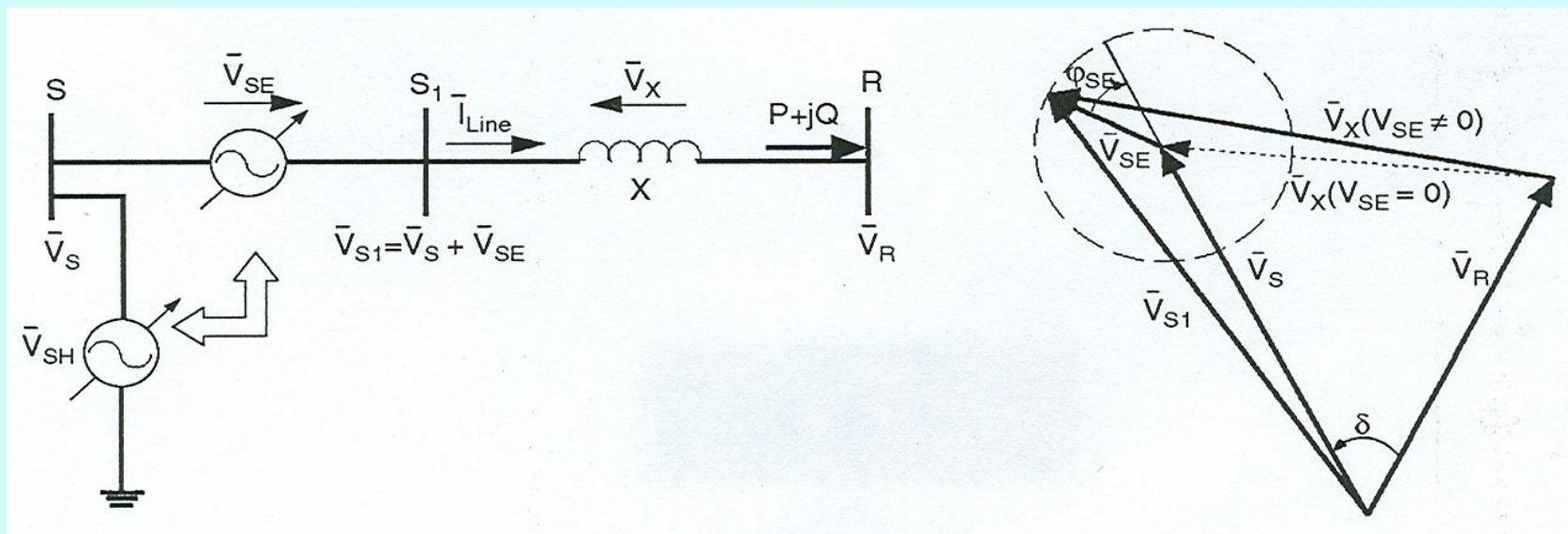


# UPFC

- **U, P, Q regulation**
  - $Q_{SH}$ ,  $Q_{SER}$  independent control
  - P flows from VSC1 to VSC2 (and other way)
    - performance area is circuit
  - Independent control  $U_1$ ,  $U_2$ ,  $X$ ,  $\delta$
- **VSC2**
  - $0 \leq U_{SE} \leq U_{SEmax}$ ,  $0 \leq \varphi_{SE} \leq 2\pi$ ,  $f = 50\text{Hz}$
  - P, Q both ways
- **VSC1**
  - P consumption for VSC2 + losses, Q both ways

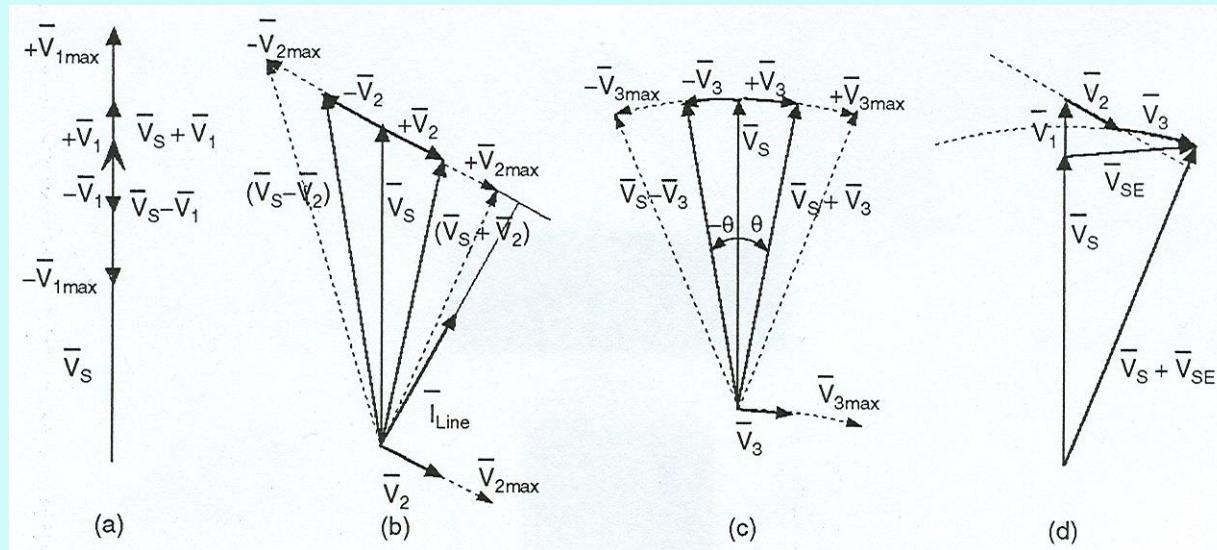
# UPFC in the grid

- At the beginning of transmission lain is placesed
  - Operates as 2 voltage sources with variable voltage amplitude and phase



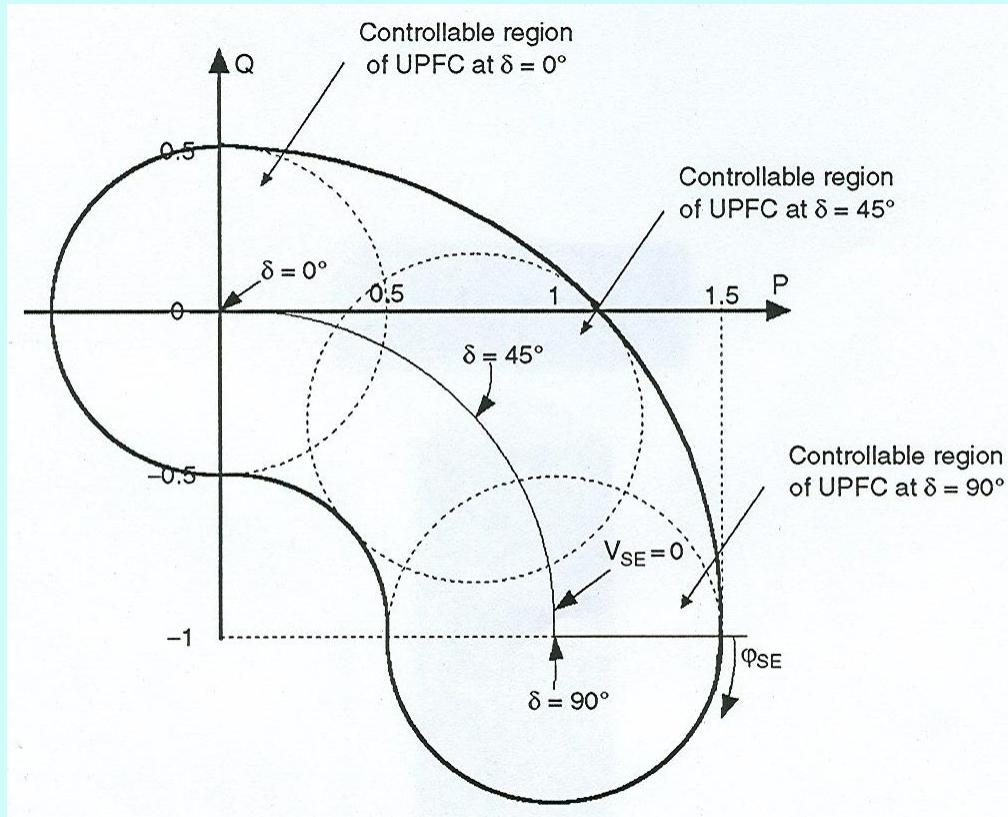
# UPFC – performance regimes

- **Regimes :**
  1. Voltage regulation
  2. Series compensation
  3. Voltage phase control
  4. Power flow control



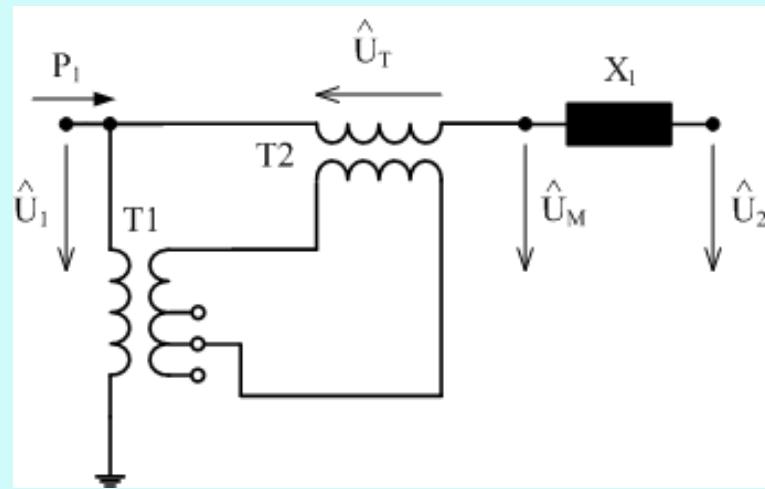
# UPFC – power flow control

$$(P_{SE}(\delta, \varphi_{SE}) - P_2(\delta))^2 + (Q_{SE}(\delta, \varphi_{SE}) - Q_2(\delta))^2 = \left( \frac{U_{SE} U_2}{X} \right)^2$$

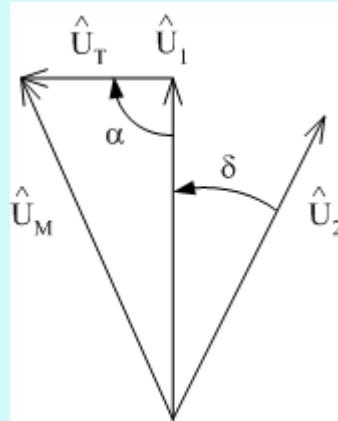


# PST

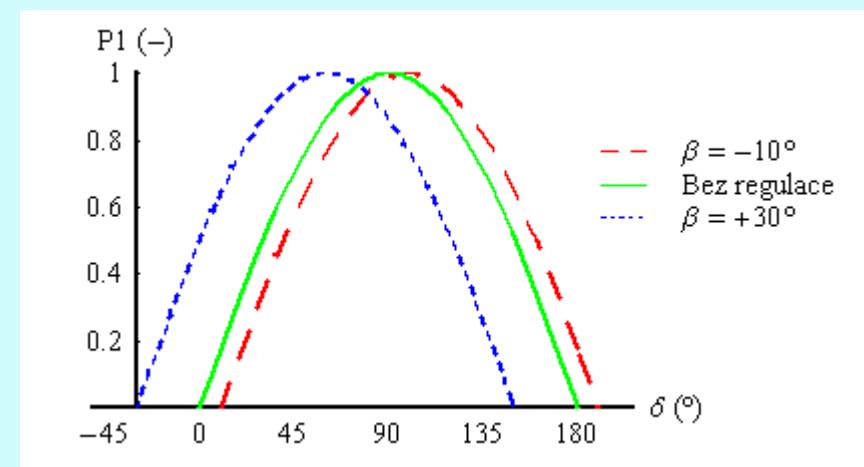
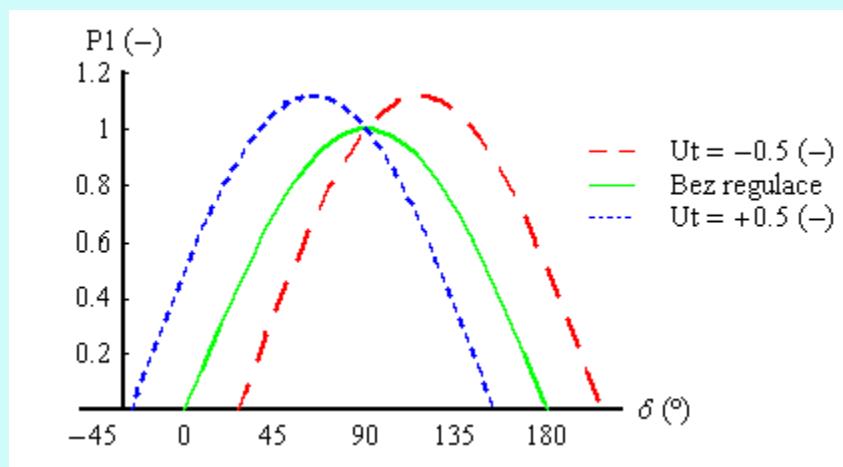
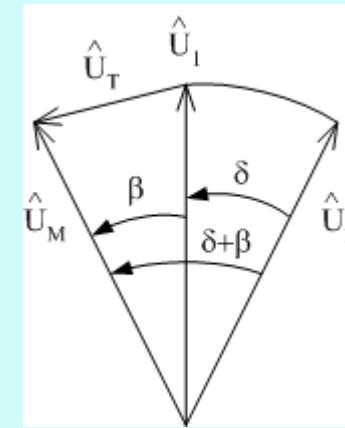
- Phase-shifting transformer
- Active power flow control



## quadrature-boosting transformers (QBT)

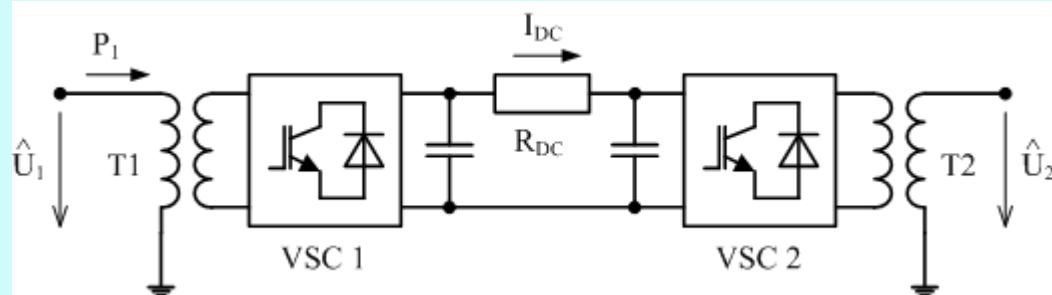


## PST phase-angle regulators (PAR)



# HVDC

- Long-distance transmission
- Interconnection of power systems
- Submarine cables
- Distant sources connection
- City and power islands supply
- thyristors x IGBT



# Conclusion

- **FACTS = high power electronic equipment for voltage and power control**
- **Lot of kinds with different properties and characteristics**
- **Improve stability and reliability of transmission system**
- **Numbers of applications x high price**