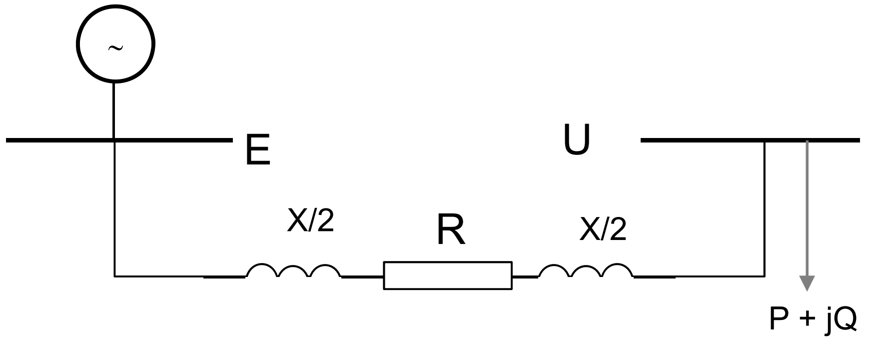
VAR management
Series/shunt compensation

Problems in long-range power transmission

The ability of the transmission system to transmit power becomes impaired by one or more of the following steady state and dynamic limitations:

- Thermal limit
- Voltage stability
- Transient stability
- Dynamic stability



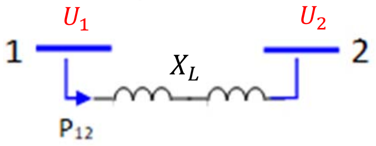
$$P_{loss} = R\,\frac{P^2 + Q^2}{U^2}$$

Voltage stability limit $$p_{max} = \frac{\cos\varphi}{2\,(1 + \sin\varphi)}$$

Steady-state stability limit $$P_{max} = \frac{E\,U}{X}$$

Example: Increasing stability margin

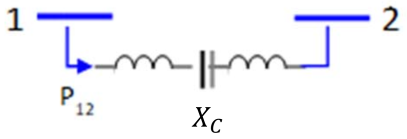
Without compensation



$$P_{12} = \frac{U_1U_2}{X_L}\sin\delta \qquad P_{max} = \frac{U_1U_2}{X_L}$$

$$\delta_{max} = \frac{\pi}{2}$$

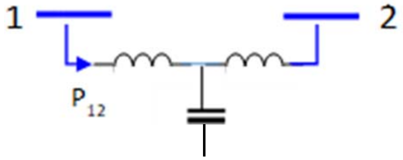
Series compensation



$$P_{12} = \frac{U_1U_2}{X_L - X_C}\sin\delta \qquad P_{max} = \frac{U_1U_2}{X_L - X_C} = \frac{U_1U_2}{X_L(1-k)}$$

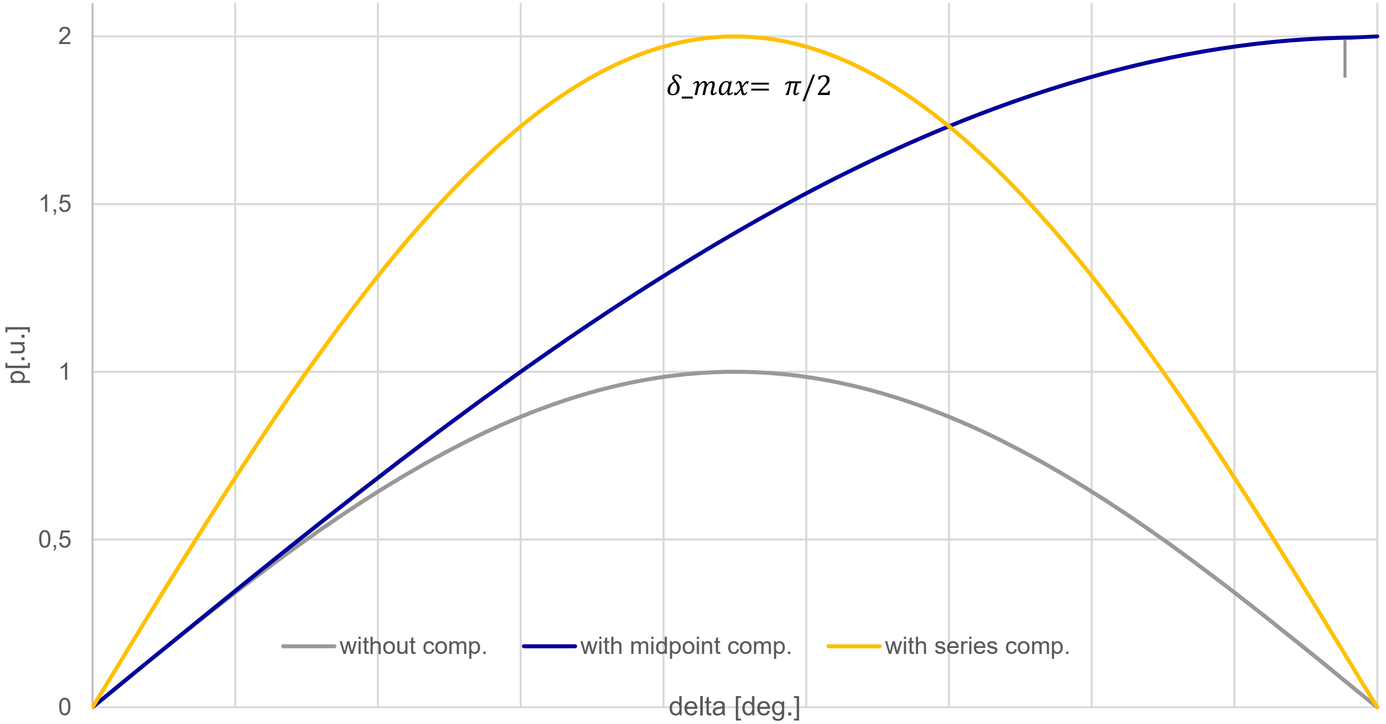
$$\delta\_max = \pi/2$$

Shunt midpoint compensation



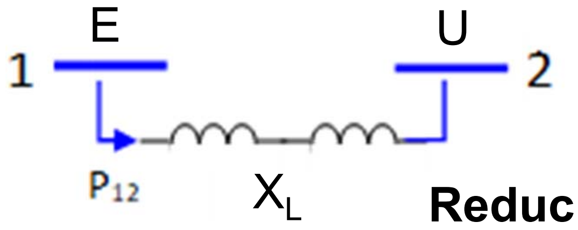
$$P_{12} = \frac{2\,U_1U_2}{X_L}\sin\delta$$

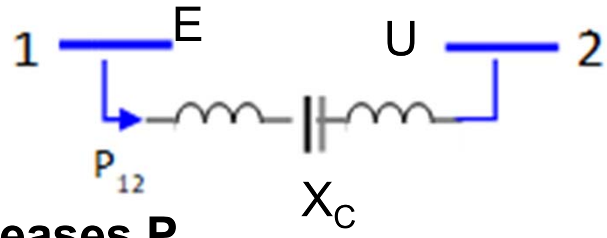
$$\delta_{max} = \pi$$



Series compensation

Since transmission lines are mostly inductive, adding series capacitance decreases the line’s total reactance





Reducing X_L increases P_{max}

$$\boxed{P = \frac{E\ U}{X_L} \sin\delta}$$

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

$$\boxed{P = \frac{E\ U}{X_L - X_C} \sin\delta = \frac{E\ U}{X_L(1-k)} \sin\delta}$$

Degree of compensation k : the percent of X_L offset by the series capacitor

Example: For $X_L = 1\ \Omega$, 30% compensation produces $X_L - X_C = 0.7\ \Omega$

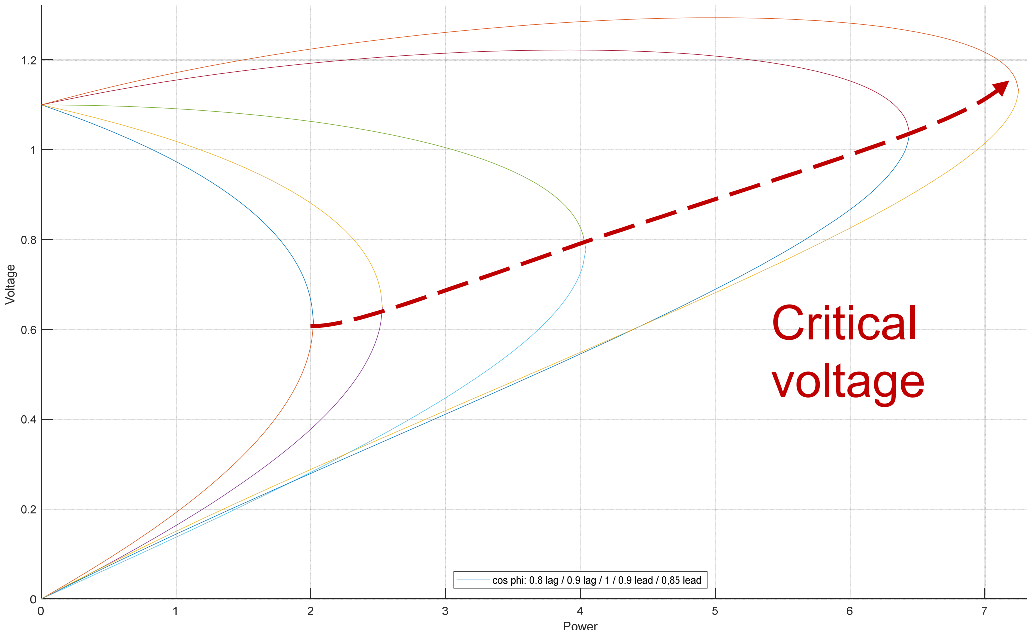
Series compensation increases Power Transfer Capability

Series compensation

Effect of Increasing Compensation Levels

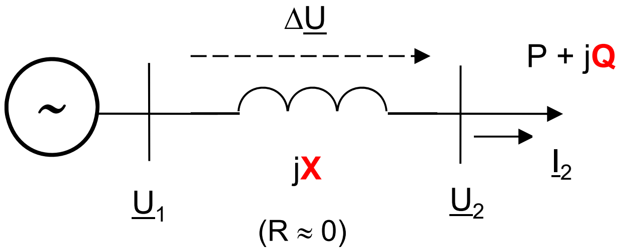
Series compensation:

- Compensates part of Q absorbed by line reactance
- Increases maximum power transfer capability of the line
- generator reactive power output made available for voltage control



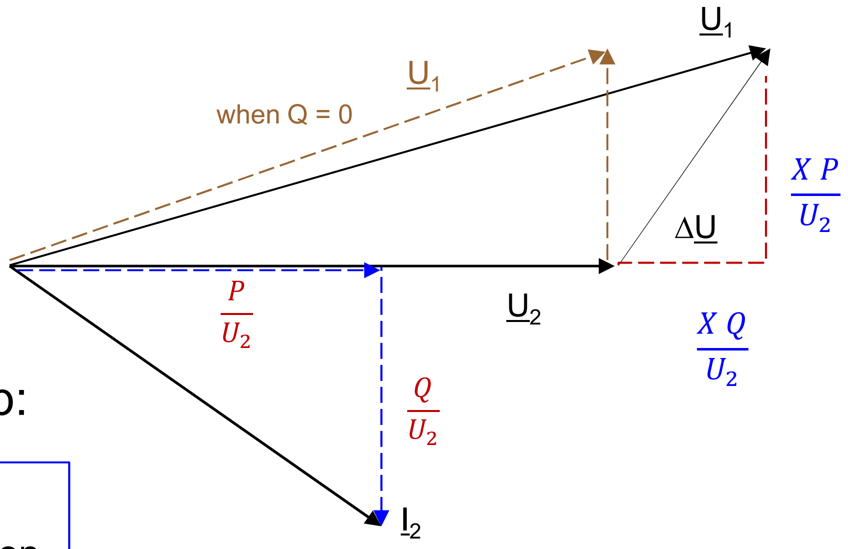
Improves Voltage Stability

Voltage drop on power transmission line



$$P + j\,Q = \underline{U}_2\,\underline{I}_2^* \rightarrow \underline{I}_2 = \frac{P}{U_2} - j\,\frac{Q}{U_2}$$

$$\Delta\underline{U} = jX\,\underline{I}_2 = \frac{XQ}{U_2} + j\,\frac{XP}{U_2}$$



Possibilities for reducing voltage drop:

Solution:

- ↓X → series compensation
- ↓Q transmission → shunt compensation

FACTS Controllers - basics

FACTS...?

- FACTS = Flexible Alternating Current Transmission Systems
- Concept: The incorporation of power electronic devices and methods into the high voltage network, to make the power network electronically controllable
- FACTS use high voltage and high current power electronics,
  - to increase power flow control capability in the network during steady state and transient conditions

FACTS...?

FACTS Controllers are broadly classified into two types:

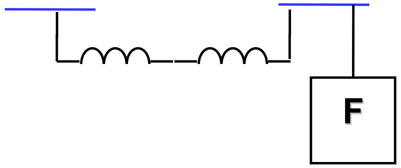
- Thyristor Based FACTS Controllers
  - Static Var Compensator (SVC)
  - Thyristor Controlled Series Compensator (TCSC)
  - Basic control element: thyristor controlled reactor (TCR)

- Voltage Source Converter (VSC) based Controllers
  - Static Synchronous Compensator (STATCOM)
  - Static Synchronous Series Compensator (SSSC)
  - Unified Power Flow Controller (UPFC)
  - Basic control element: voltage source converter (VSC)

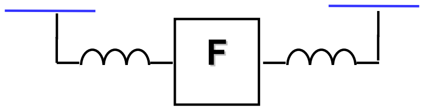
Classification of FACTS Controllers

FACTS controllers are classified as:

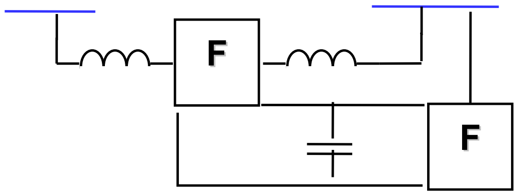
- Shunt Controllers



- Series Controllers



- Combination of Series-Shunt Controllers



Classification

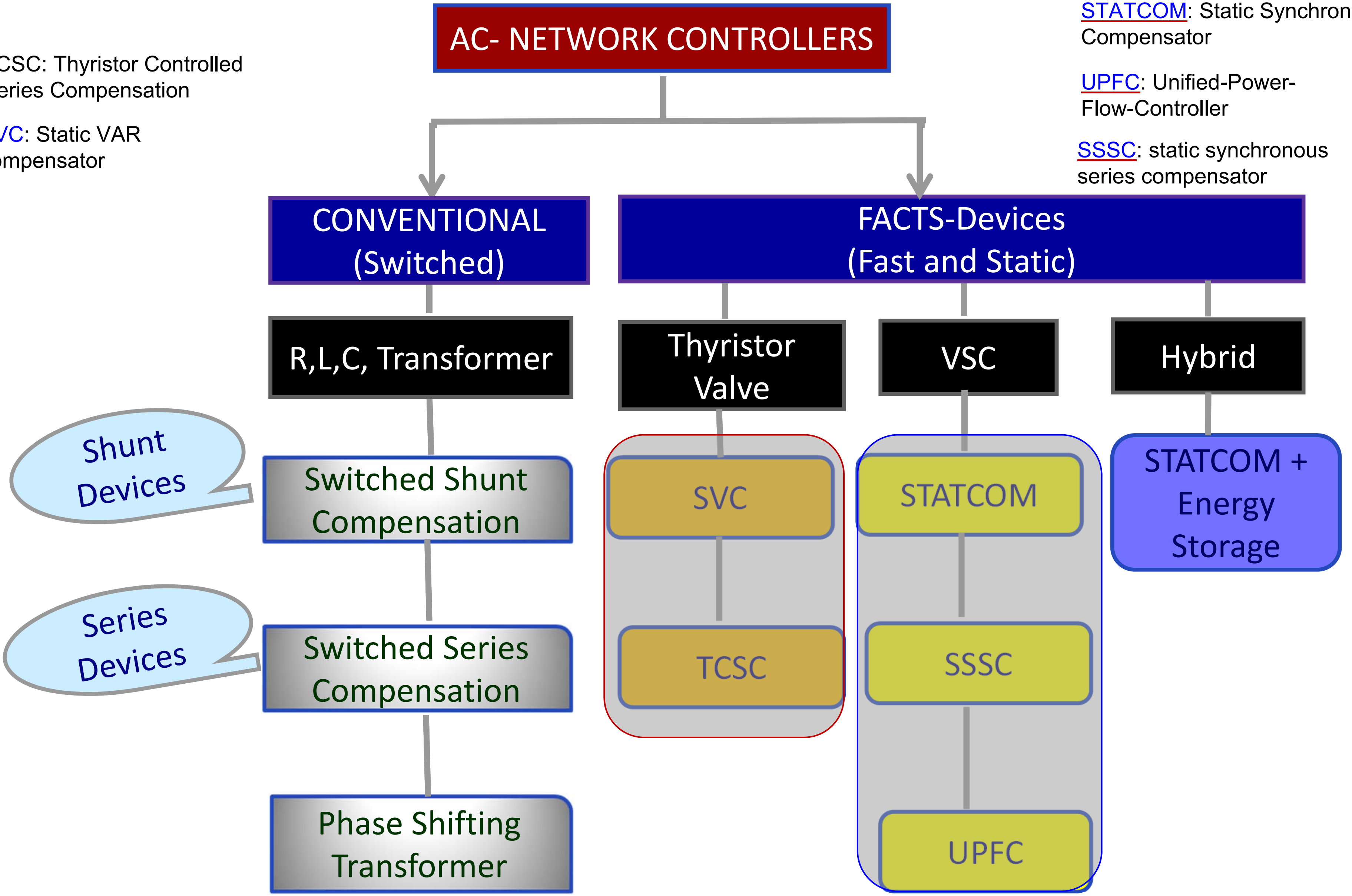
TCSC: Thyristor Controlled Series Compensation

SVC: Static VAR compensator

STATCOM: Static Synchronous Compensator

UPFC: Unified-Power-Flow-Controller

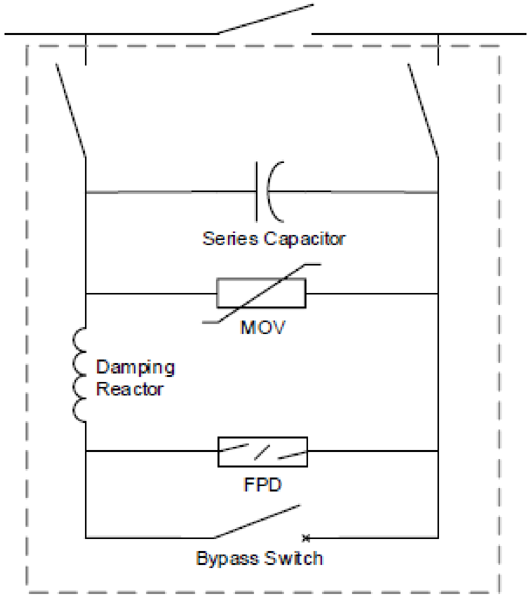
SSSC: static synchronous series compensator



Thyristor based FACTS Controllers

Fixed Series Compensation (FSC)

- Capacitor designed for line current rating
- Overvoltage protection
  - Zinc Oxide Varistor (MOV)
    - ✓ **Conducts when the voltage level across capacitor reaches protection voltage level**
  - Fast Protective Device (FPD)
    - ✓ **For example, an air gap conducts when energy absorbed by MOV exceeds rated values.**
- Bypass Breaker
- Damping Reactor

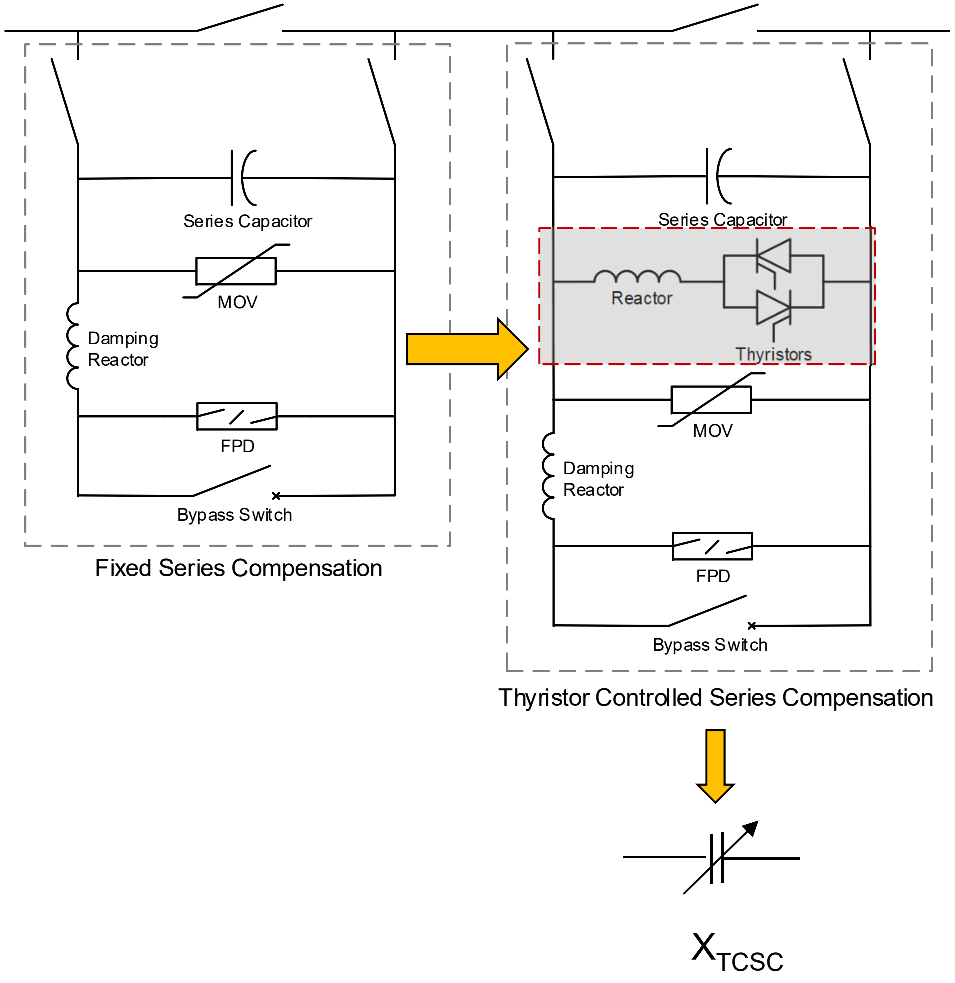


Fixed Series Compensation

Fixed Series Compensation (FSC)

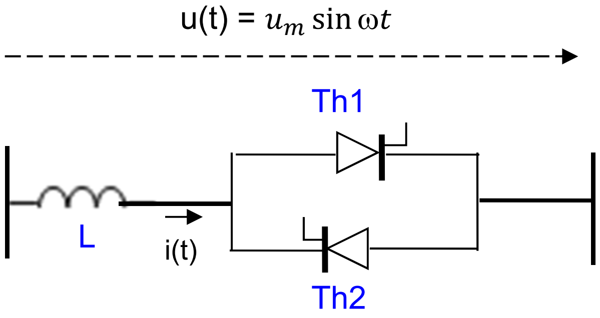
Thyristor controlled series compensation (TCSC)

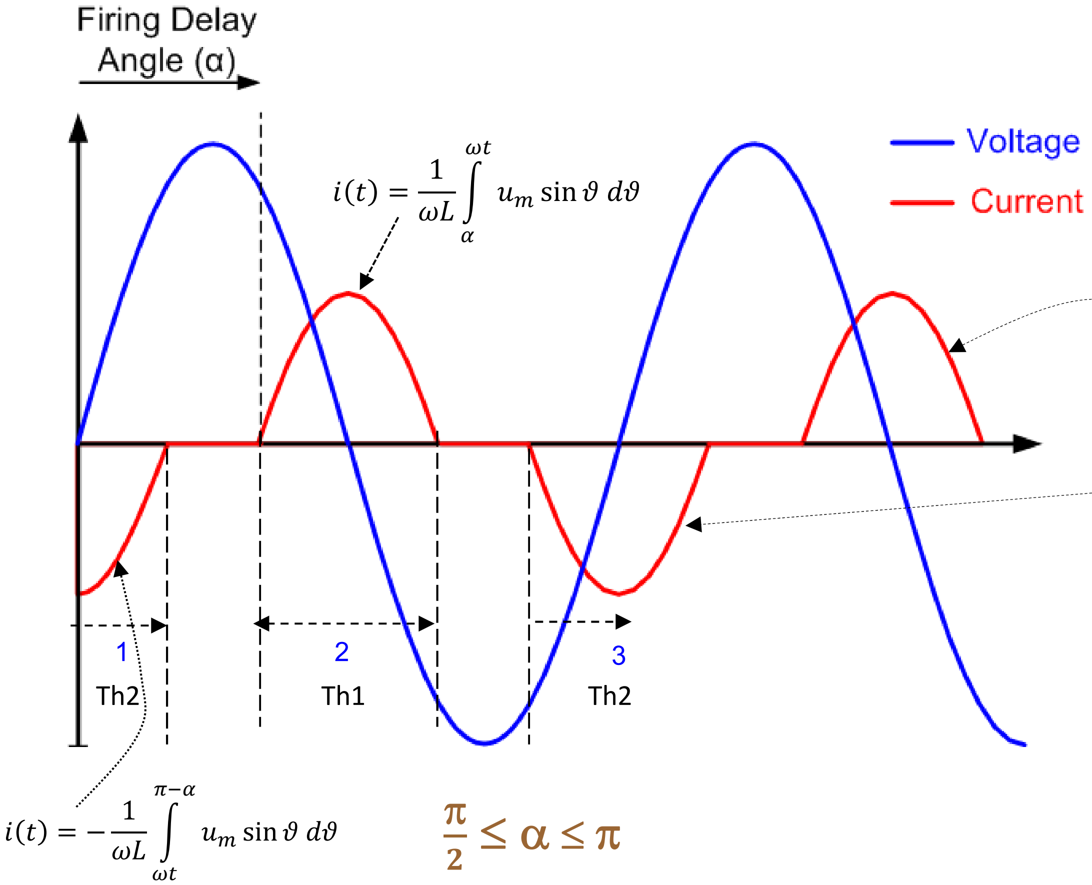
- Two Modules
  - FSC as previously described
  - Capacitor with thyristor controlled reactor to modulate line impedance
- Device
  - Offers dynamic power flow control
  - Reactance can be modulated to control compensation
    - Blocked Mode removes reactor from circuit
    - By-Passed Mode removes capacitor from circuit
    - Controlled Mode varies total reactance



Thyristor Controlled Series Compensation(TCSC)

Thyristor controlled reactor (TCR)





$$\frac{\pi}{2} \leq \alpha \leq \pi$$

1. (Th2 "conducting")

$\omega t < \pi - \alpha$

$$i(t) = -\frac{1}{L}\int_{\omega t}^{\pi-\alpha} u_m \sin\omega t\, dt$$

$$\vartheta = \omega t \to \frac{d\vartheta}{dt} = \omega \to dt = \frac{d\vartheta}{\omega}$$

$$i(t) = -\frac{1}{\omega L}\int_{\omega t}^{\pi-\alpha} u_m \sin\vartheta\, d\vartheta$$

$$= i_m(\cos(\pi-\alpha) - \cos\omega t)$$

$$with \quad i_m = \frac{u_m}{\omega L}$$

$$\boxed{i(t) = -i_m(\cos\alpha + \cos\omega t)}$$

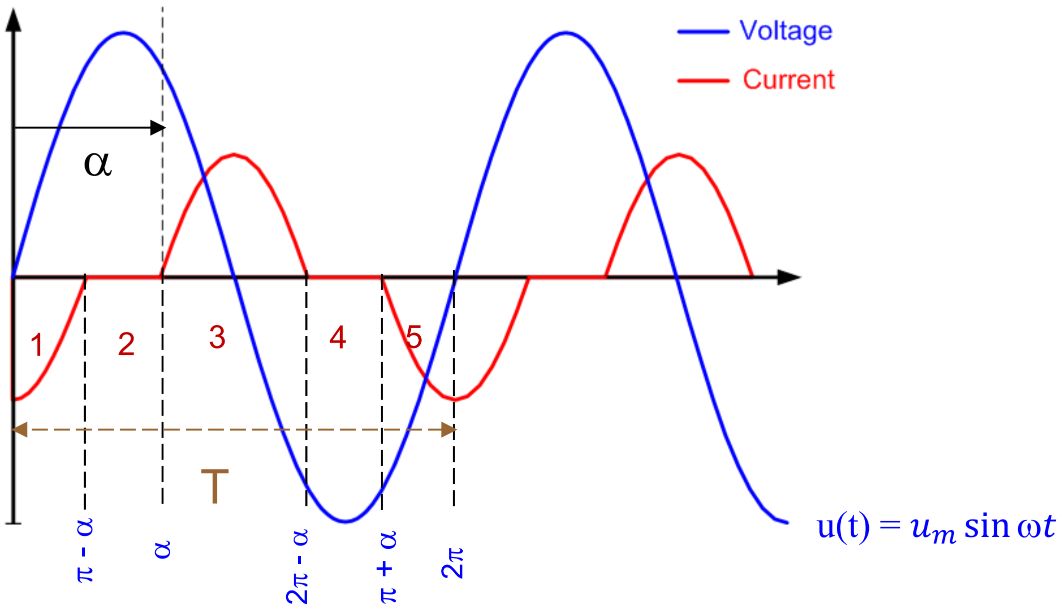
2. Th1 "conducting"

$\alpha < \omega t < 2\pi - \alpha$

$$\boxed{i(t) = i_m(\cos\alpha - \cos\omega t)}$$

Otherwise: $\boxed{i(t) = 0}$

Thyristor controlled reactor (TCR)



$$\frac{\pi}{2} < \alpha < \pi$$

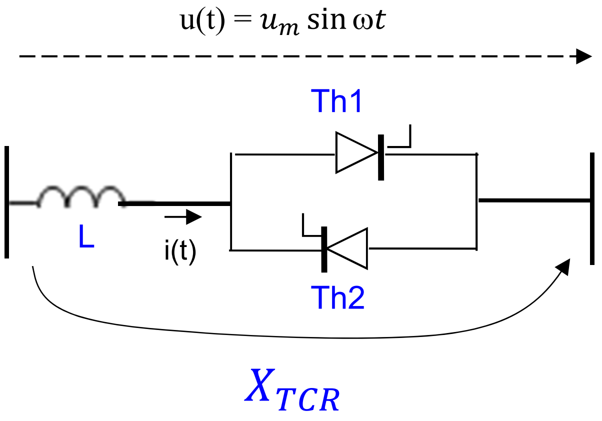
1	2, 4	3	5
0 <= ω t < π - α	π- α <= ω t < α 2π- α <= ω t < π+α	α <= ω t < 2π-α	π+α <= ω t < 2π
$\mathbf{i(t)} = -i_m(cos\alpha + \cos\omega t)$	$\mathbf{i(t)}$ =0	$\mathbf{i(t)} = i_m(cos\alpha - \cos\omega t)$	$\mathbf{i(t)} = -i_m(cos\alpha + \cos\omega t)$

Fundamental frequency component
(after Fourier transformation):

$$\boxed{i_1(t) = \frac{\sqrt{2}\,I}{\pi}\left(2\left(\pi - \alpha\right) + \sin 2\alpha\right) \sin\left(\omega t - \frac{\pi}{2}\right)}$$

$$I = \frac{\sqrt{2}\,u_m}{\omega L}$$

Thyristor controlled reactor (TCR)



$$i_1(t) = \overbrace{\frac{\sqrt{2}\,I}{\pi}\left(2\,(\pi-\alpha)+\sin 2\alpha\right)}^{I_1}\sin\left(\omega t-\frac{\pi}{2}\right)$$

$$i_1(t) = \sqrt{2}\,I_1\sin\left(\omega t-\frac{\pi}{2}\right) = -\sqrt{2}\,I_1\cos\omega t$$

$$I_1 = \frac{U(2\,(\pi-\alpha)+\sin 2\alpha)}{\pi\,\omega L}$$

$$\underline{I_1} = I_1\angle 180^0$$

$$I = \frac{\sqrt{2}\,u_m}{\omega L}$$

Assuming the voltage contains pure fundamental frequency component:

$$u_1(t) = u_m\sin\omega t = u_m\cos\left(\omega t-\frac{\pi}{2}\right) \rightarrow \quad \underline{U_1} = U_1\angle -90^0$$

$$\boxed{\frac{\underline{U_1}}{\underline{I_1}} = \frac{U_1\angle -90^0}{I_1\angle 180^0} = \mathrm{j}\omega L\,\frac{\pi}{2\,(\pi-\alpha)+\sin 2\alpha}}$$

$$\alpha = \frac{\pi}{2} \rightarrow X_{TCR} = \omega L$$

$$\alpha = \pi \rightarrow X_{TCR} = \infty$$

$$\boxed{X_{TCR} = \omega L\,\frac{\pi}{2\,(\pi-\alpha)+\sin 2\alpha}}$$

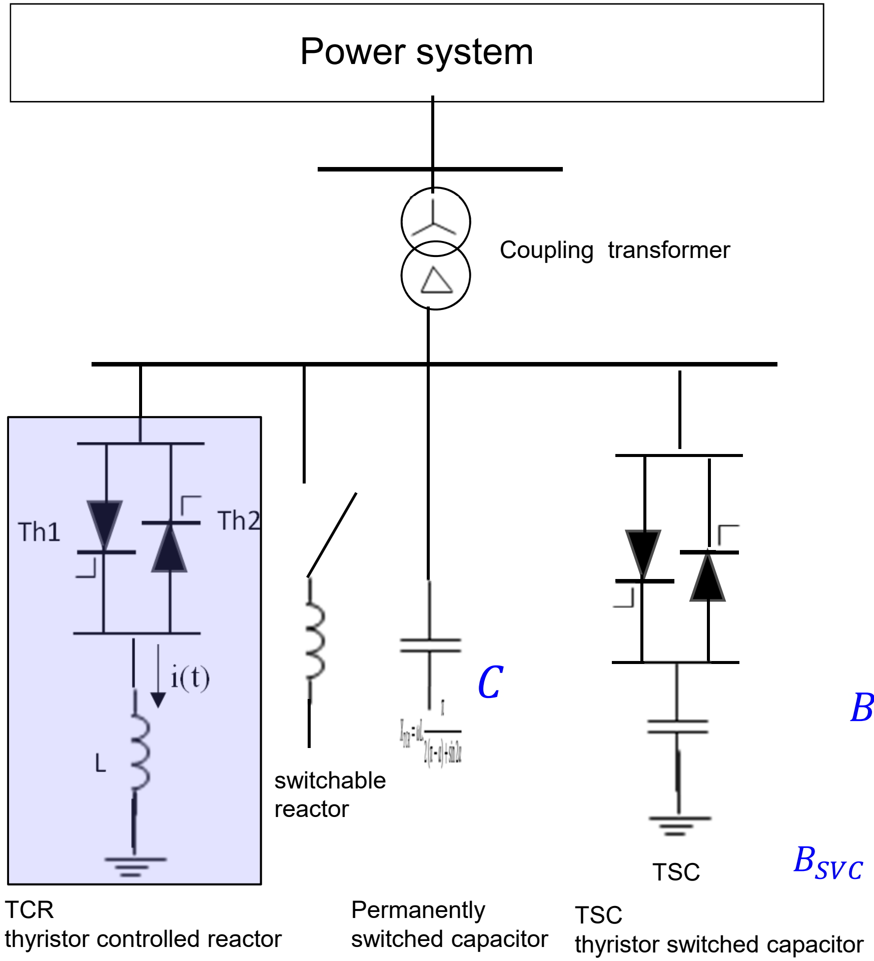
$$\omega L \le X_{TCR} < \infty$$

Static VAR Compensator (SVC)

Static VAR Compensator (SVC)

- The SVC is the most widely employed FACTS Controller.
- It is a shunt-connected static var generator / absorber
  - its output is adjusted to exchange capacitive / inductive current so as to control the bus voltage

SVC basic elements



- Basic elements:
  - –Thyristor-controlled reactor (TCR)
  - –Permanently switched capacitor
  - –Thyristor-switched capacitor (TSC)
  - –Switchable reactor (SR)

$$B_C = \omega_0 C$$

$$B_{TCR} = \frac{2\,(\pi - \alpha) + \sin 2\alpha}{\pi \omega_0 L}$$

$$B_{SVC} = -B_{TCR} + B_C = \omega C \left(1 - \frac{2\,(\pi-\alpha) + \sin 2\alpha}{\pi \omega_0 L \omega_0 C}\right)$$

$\pi/2 \le \alpha \le \pi$

$\pi \ldots 0$

$$B_{SVC} = B_C \left(1 - \frac{(2\,(\pi - \alpha) + \sin 2\alpha)}{\pi(\omega_0^2/\omega_R^2)}\right)$$

$$X_{TCR} = \omega L.\frac{\pi}{2\,(\pi - \alpha) + \sin 2\alpha}$$

$$L = \frac{1}{C}\frac{1}{\omega_R^2}$$

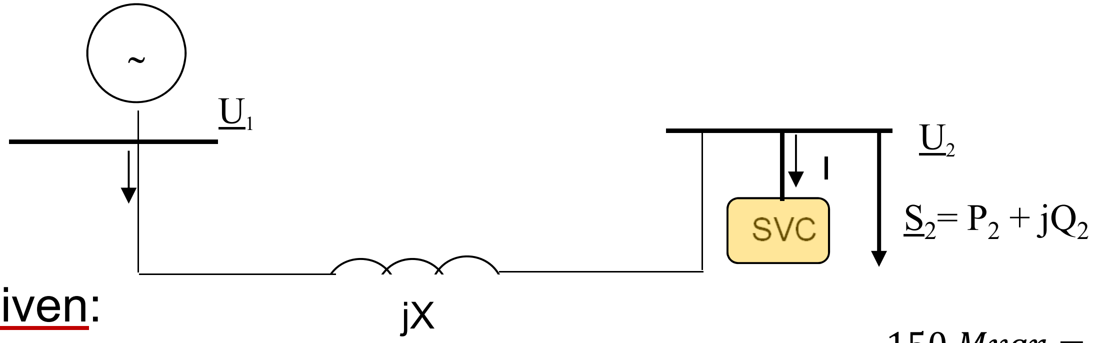
$$\omega_R = \frac{1}{\sqrt{LC}}$$

f_R = 50 Hz $B_{SVC} = B_C(1 \ldots 0)$

f_R = 55 Hz $B_{SVC} = B_C(1 \ldots -0.21)$

f_R = 60 Hz $B_{SVC} = B_C(1 \ldots -0.44)$

Example



$$B_{SVC} = B_C\left(1 - \frac{(2\,(\pi-\alpha) + \sin 2\alpha)}{\pi(\omega_0^2/\omega_R^2)}\right)$$

$$\alpha = \frac{\pi}{2} \ldots\ldots \pi$$

Given:

$X = 50\ \Omega$

Rated value:

$\underline{S}_2 = 500\ \text{MVA}\ \angle 36.9^0$

$$\underline{U}_2 = \frac{380}{\sqrt{3}}\ kV\ \angle 0^0$$

Output var of the fixed capacitor at rated voltage:

$Q_C = 150$ Mvar

$f_R = 61$ Hz

$$150\ Mvar = \omega C\ (380\ kV)^2 \rightarrow C = 3.3065\ \mu F$$

$$B_C = \omega C = 1.0387676\ mS$$

$$\omega_R = 2\pi\ 61\ Hz = 122\ \pi\ Hz$$

$$L = \frac{1}{C}\frac{1}{\omega_R^2} = 2.0588\ \text{H}$$

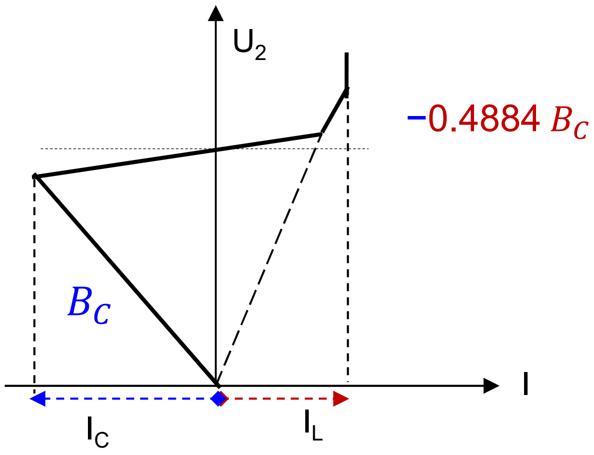
$$B_{SVC} = B_C(1\ \ldots\ -0.4884)$$

capacitive

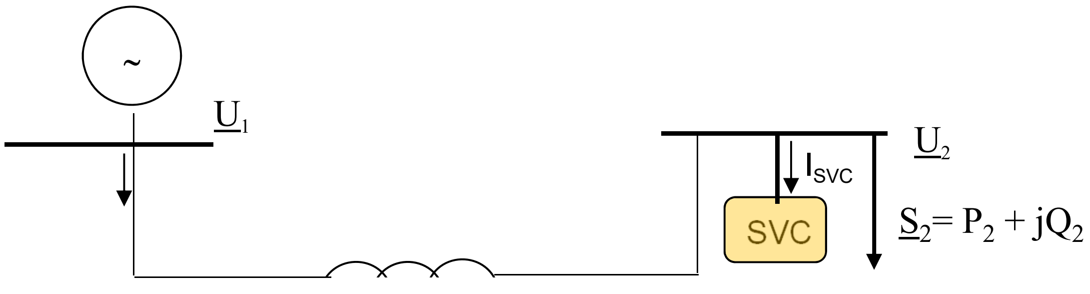
$\alpha = \pi$

inductive

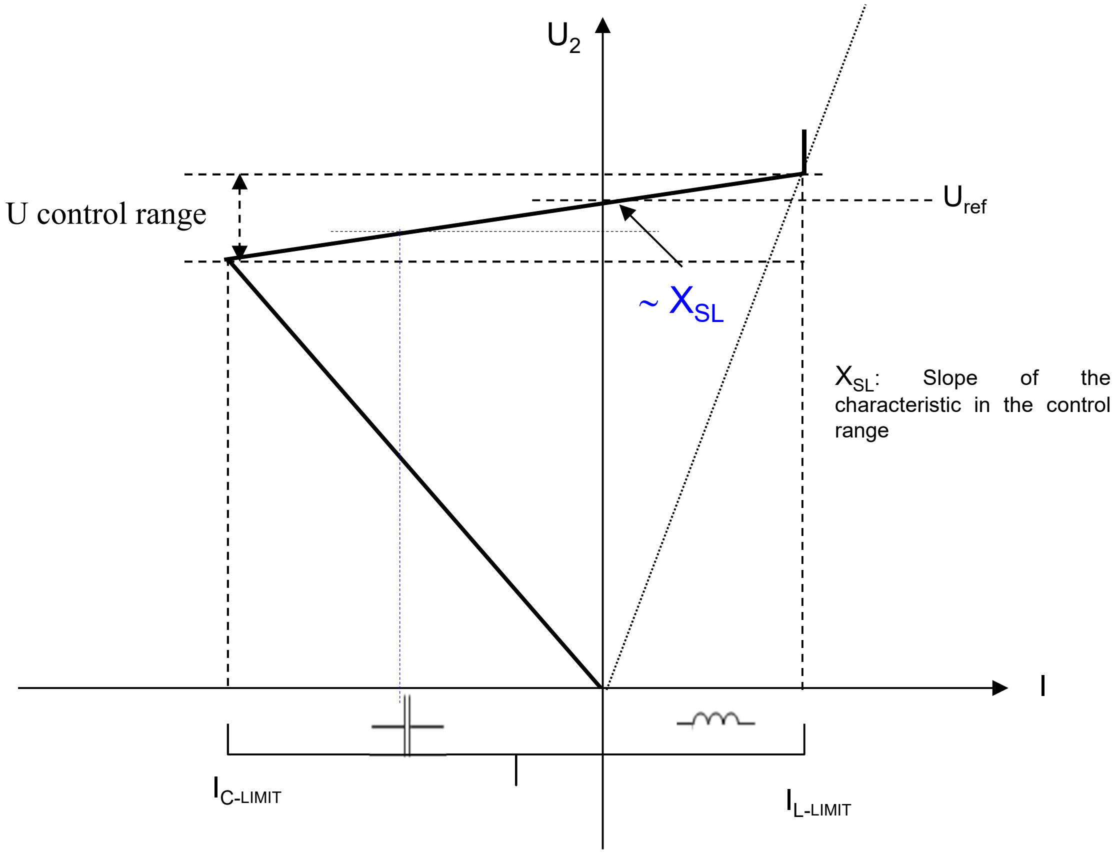
$\alpha = \frac{\pi}{2}$



SVC characteristic

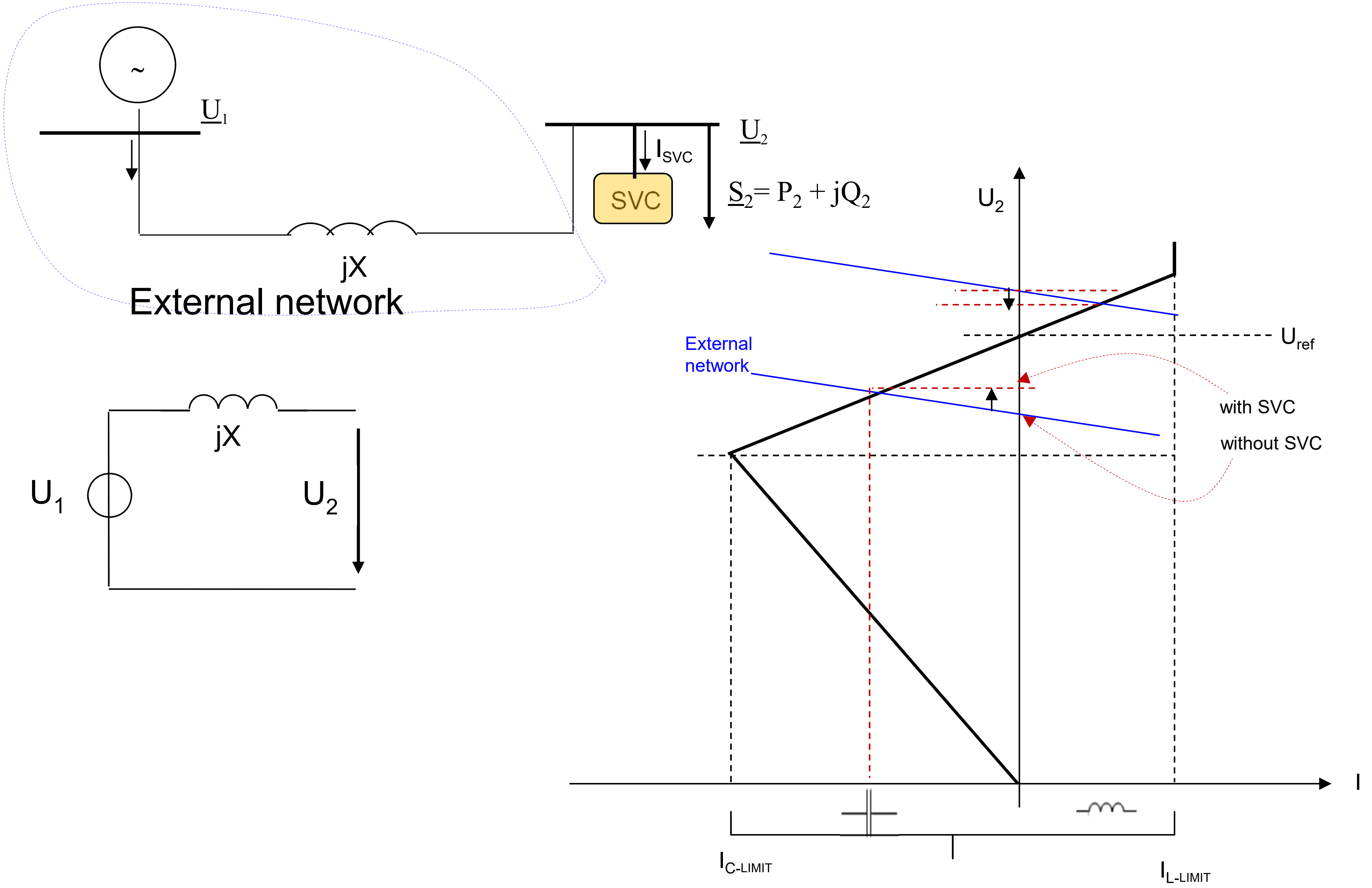


- The dynamic V-I characteristics of the SVC is described by its linear range, which varies over the entire capacitive to inductive range.
- Outside the linear controllable range on the inductive side, the SVC enters the overload zone.

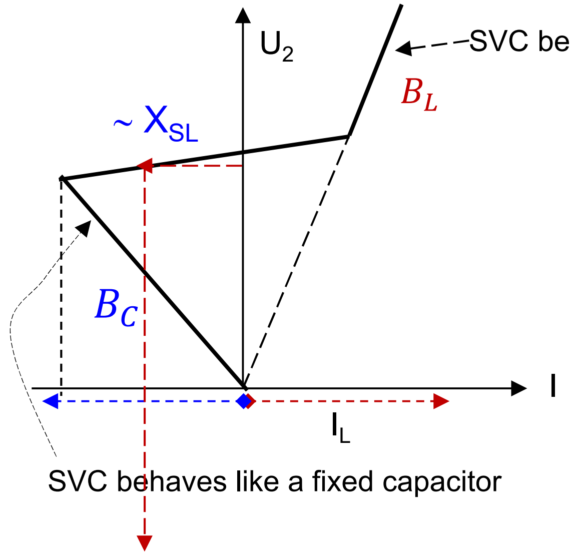


X_{SL}: Slope of the characteristic in the control range

SVC characteristic



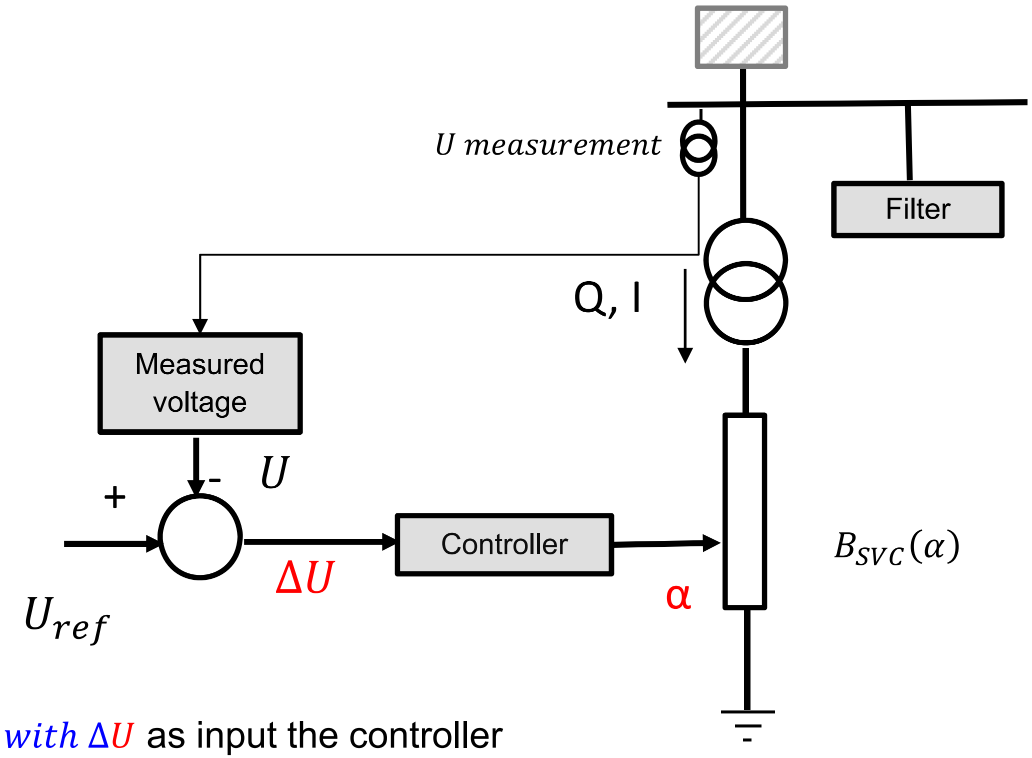
A typical SVC control system



SVC behaves like a fixed inductor

SVC behaves like a fixed capacitor

$$\Delta U \;\rightarrow\; \Delta I\, X_{SL} \;\rightarrow B_{SVC} = \frac{I}{U}$$

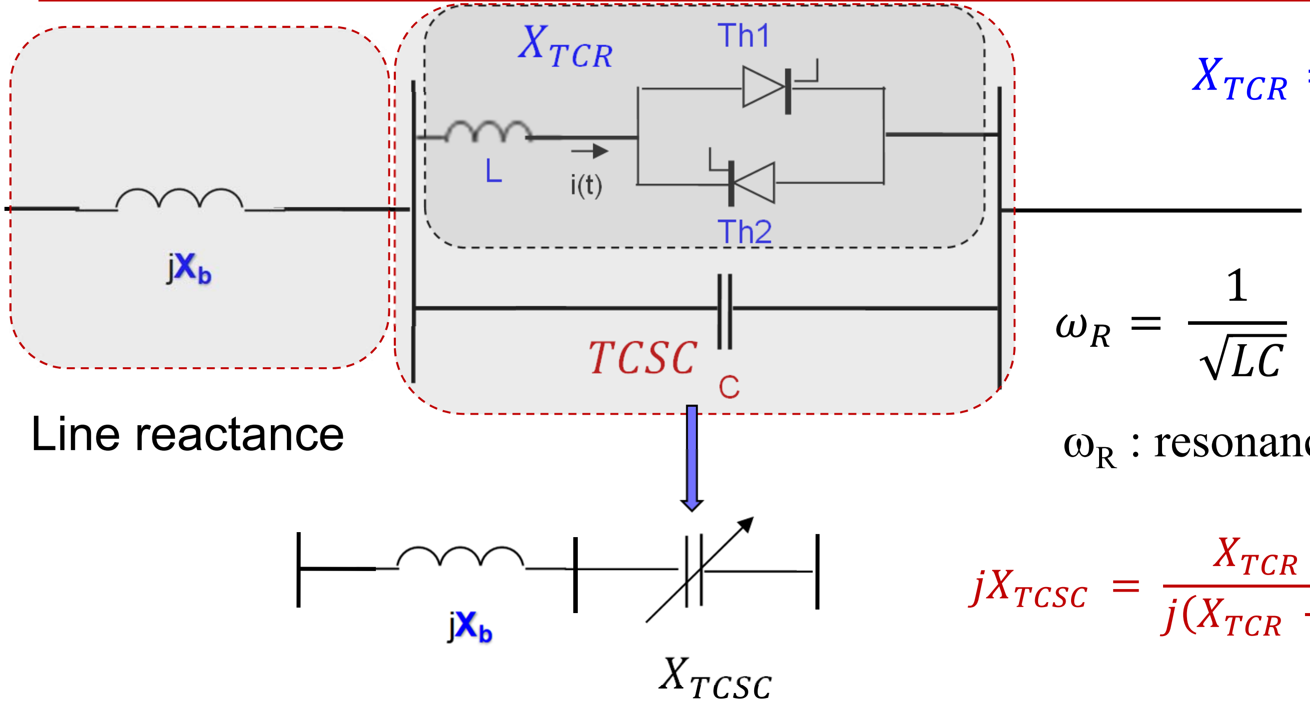


with ΔU as input the controller determines the required α

$$B_{SVC} = B_C\left(1 - \frac{(2\,(\pi-\alpha) + \sin 2\alpha)}{\pi(\omega_0^2/\omega_R^2)}\right) \rightarrow \alpha$$

Thyristor controlled series compensation (TCSC)

Thyristor controlled series compensation



$$X_{TCR} = \omega L \frac{\pi}{2\,(\pi - \alpha) + \sin 2\alpha}$$

$$\omega_R = \frac{1}{\sqrt{LC}}$$

$\omega_0 = 100\,\pi$

ω_R : resonance frequency

$$jX_{TCSC} = \frac{X_{TCR}\,X_C}{j(X_{TCR} - X_C)} = -jX_C \frac{1}{1 - X_C/X_{TCR}}$$

$$jX_{TCSC} = \frac{\frac{1}{\omega C}\,\omega_0 L \frac{\pi}{2\,(\pi-\alpha)+\sin 2\alpha}}{j\left(\omega_0 L \frac{\pi}{2\,(\pi-\alpha)+\sin 2\alpha} - \frac{1}{\omega_0 C}\right)} = -j\frac{1}{\omega C}\,\frac{1}{1 - \frac{(2\,(\pi-\alpha)+\sin 2\alpha)}{\pi}\left(\frac{\omega_R}{\omega_0}\right)^2}$$

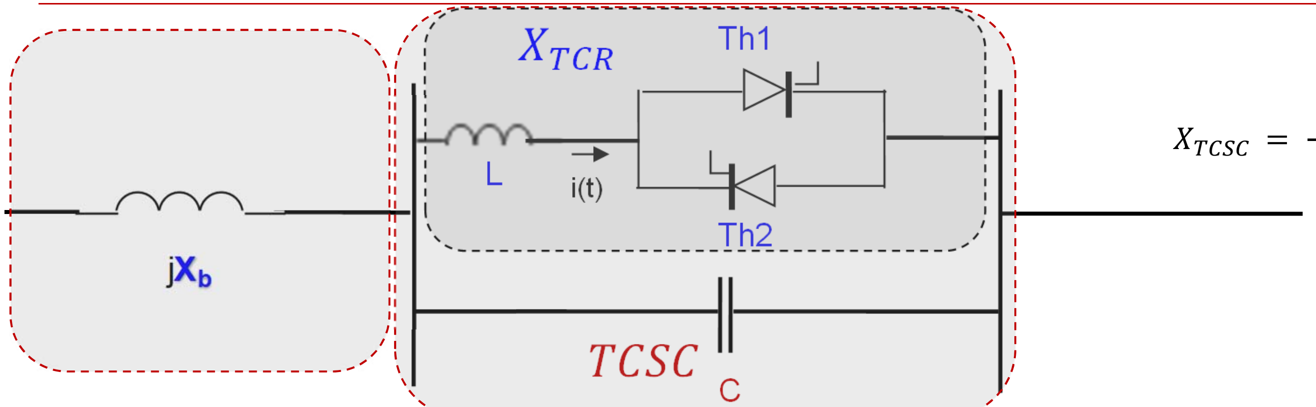
$$\frac{(2\,(\pi-\alpha)+\sin 2\alpha)}{\pi}\left(\frac{\omega_R}{\omega_0}\right)^2 < 1\text{: capacitive mode} \qquad \frac{(2\,(\pi-\alpha)+\sin 2\alpha)}{\pi}\left(\frac{\omega_R}{\omega_0}\right)^2 > 1\text{: inductive mode}$$

f_R : resonance frequency

f_R/Hz	100	120	130	160	170	180	190
$\alpha_c/^0$	129.3	135.6	138.2	143.9	145.5	146.8	148.0

$\alpha > \alpha_c$: capacitive mode

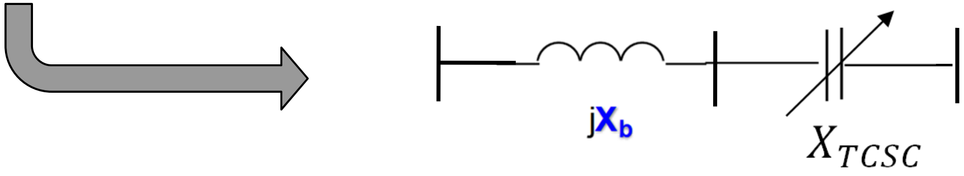
Example



Line reactance

$$X_{TCSC} = -j\frac{1}{\omega C}\frac{1}{1-\frac{(2\,(\pi-\alpha)+\sin 2\alpha)}{\pi}\left(\frac{\omega_R}{\omega_0}\right)^2}$$

$$\omega_R = \frac{1}{\sqrt{LC}}$$



$$X_{TOTAL} = X_b - X_C = X_b(1-k) \qquad k = \frac{X_C}{X_b}$$

Example:

380 kV, 300 km, X'_b = 0.25 Ω/km

Required compensation: K = 0.25 … 0.75

$$X_b = 0.25\ x\ 300 = 75\Omega$$

k = 0.25 → X_C = 0.25 X_b = 18.75 Ω

$X_C = \frac{1}{\omega\ C}$ =18.75 Ω → C = 170 μF

ω_R = 2π 100 Hz

$$X_{TCSC}= -j\frac{1}{\omega C}\overset{*}{\boxed{\frac{1}{1-\frac{(2\,(\pi-\alpha)+\sin 2\alpha)}{\pi}\left(\frac{\omega_R}{\omega_0}\right)^2}}}$$

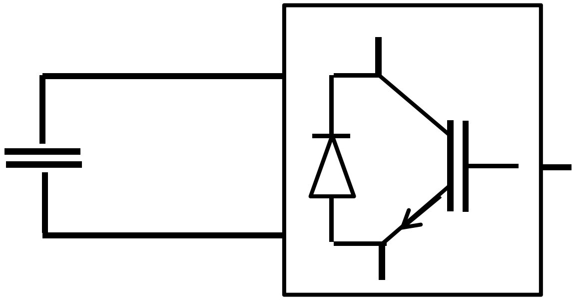
k = 0.75 → X_C = 0.25 X_b = 56.25 Ω

f_R = 100 Hz (chosen) → L = $\frac{1}{\omega_R^2\, C}$ =14.9 mH

α/°	π	0.83 π	0.78 π	0.77 π	0.76 π
$X_{TCSC} = \frac{1}{\omega C}\ {}^{*} \rightarrow$	1	1.3	2.1	2.5	3.16
k	0.25	0.325	0.525	0.625	0.769
X_{TCSC} [Ω]	18.75	24.38	39.38	46.88	59.25

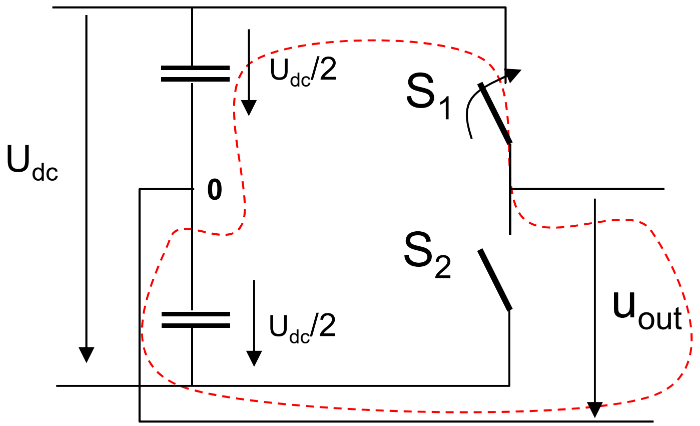
Voltage Source Converter (VSC) based Controllers

Basic element

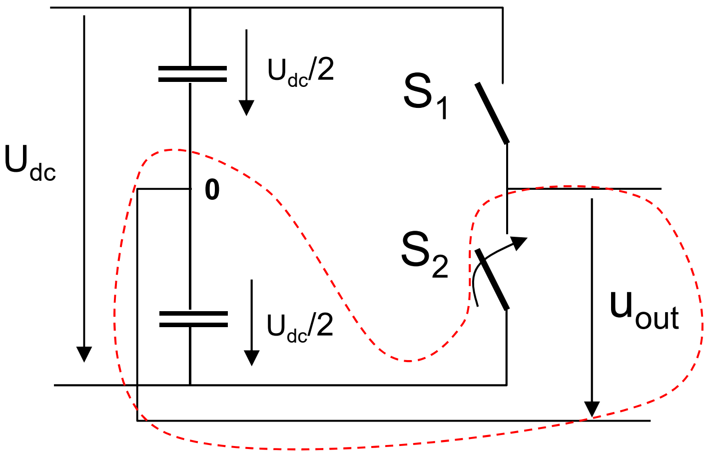


Switching device – Insulated Gate Bipolar Transistor IGBT

The concept of pulse width modulation (PWM)



S1: closed $-\frac{U_{dc}}{2} + u_{out} = 0 \rightarrow u_{out} = \frac{U_{dc}}{2}$



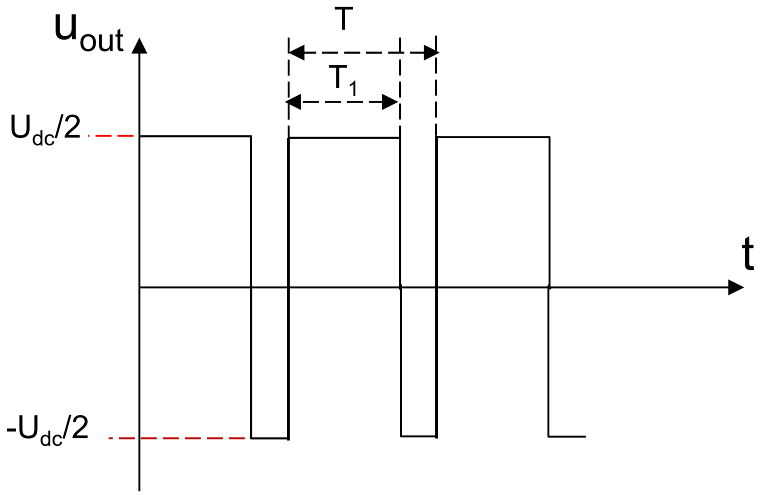
S2: closed $\frac{U_{dc}}{2} + u_{out} = 0 \rightarrow u_{out} = -\frac{U_{dc}}{2}$

Average over one cycle T:

$$U_{out} = \frac{U_{dc}}{2} \cdot \frac{1}{T} \cdot \left(T_1 - (T - T_1)\right)$$

$$U_{out} = U_{dc} \cdot \left(\frac{T_1}{T} - \frac{1}{2}\right)$$

$$\boxed{u_{out} = \frac{U_{out}}{U_{dc}} = \left(\frac{T_1}{T} - \frac{1}{2}\right)}$$



The output voltage is a function of the duty cycle.

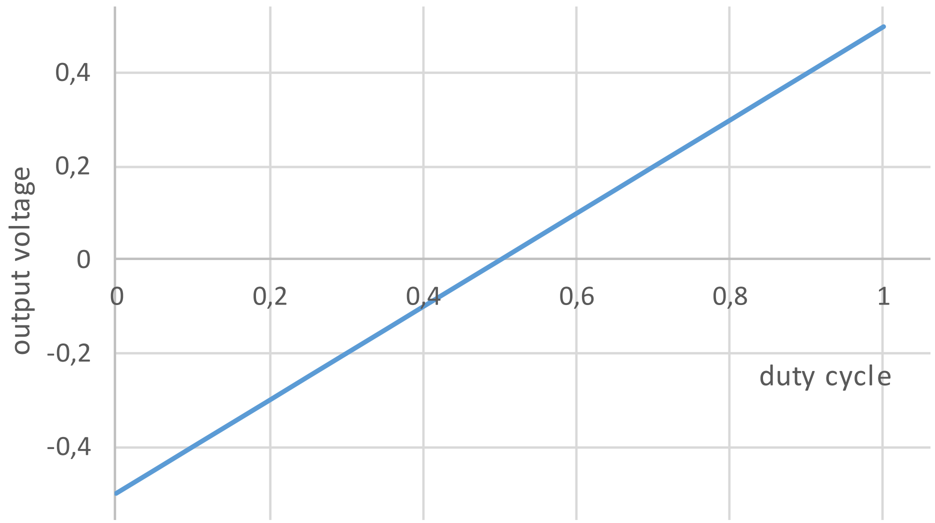
- By continuously changing the duty cycle, the output voltage can be changed continuously

$\frac{T_1}{T}$ = duty cycle = Tastverhältnis

The concept of pulse width modulation (PWM)

$$u_{out} = \frac{U_{out}}{U_{dc}} = \left(\frac{T_1}{T} - \frac{1}{2}\right)$$

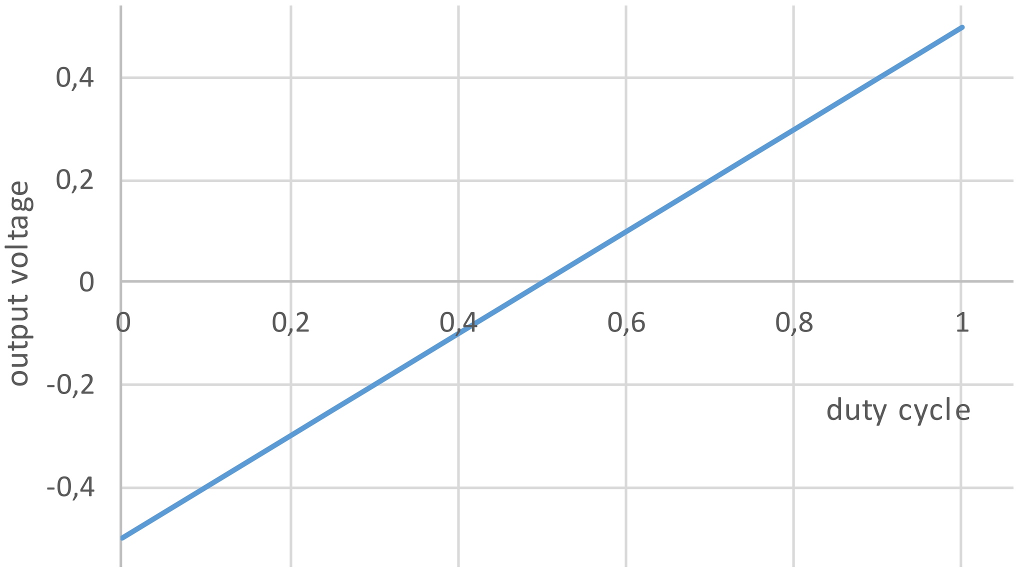
- constant duty cycle → constant voltage



Output voltage (u_{out}) as a function of $\frac{T_1}{T}$ (duty cycle)

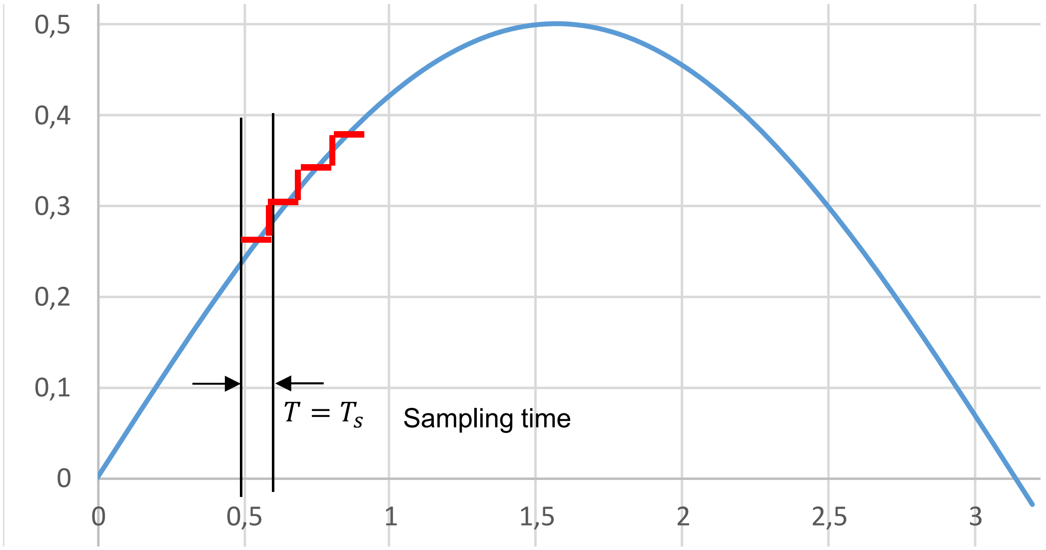
- If the duty cycle is changed sinusoidally,
  - ✓ a sinusoidal voltage will be generated at the output
- But how do we change the duty cycle so that the output conforms with a sinusoid?

Example – sinusoidal voltage



$$u_{out} = \frac{U_{out}}{U_{dc}} = \left(\frac{T_1}{T} - \frac{1}{2}\right)$$

$\frac{T_1}{T}$ = duty cycle = Einschaltdauer



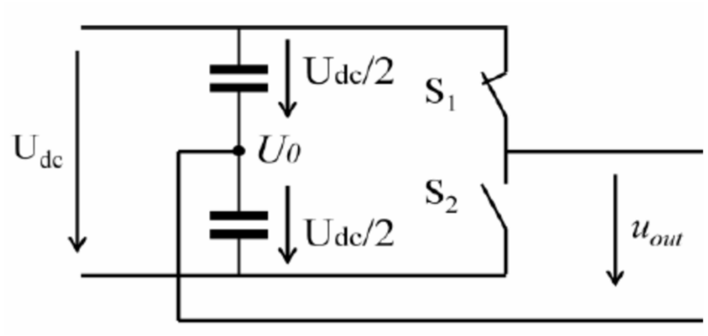
Modulation Types

- *Sinusoidal pulse width modulation (PWM)*
- *Space phasor modulation*

Sinusoidal pulse width modulation (SPWM)

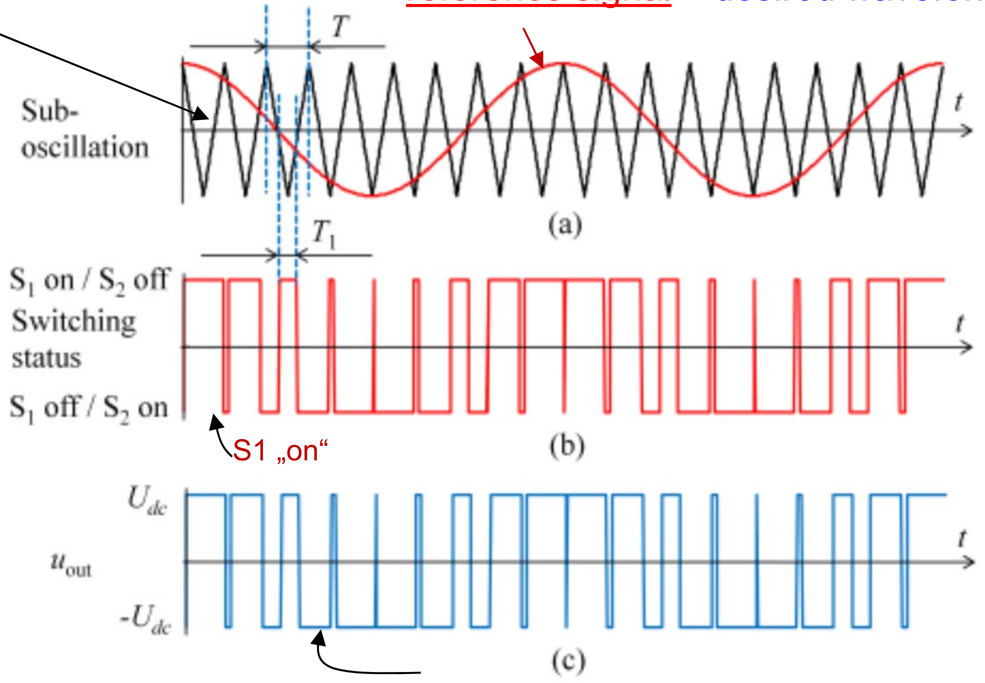
- With sinusoidal pulse width modulation, the widths of all pulses are increased or decreased by maintaining the sinusoidal proportionality.

Sinusoidal (Sub-Oscillation) PWM (SPWM)



Carrier signal : controls switching

reference signal = desired waveform



S1 „on“

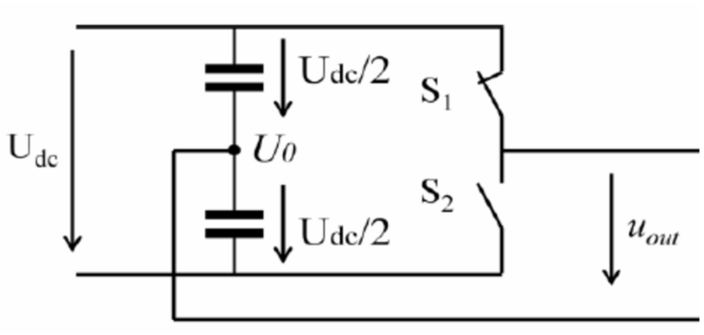
S2 „on“

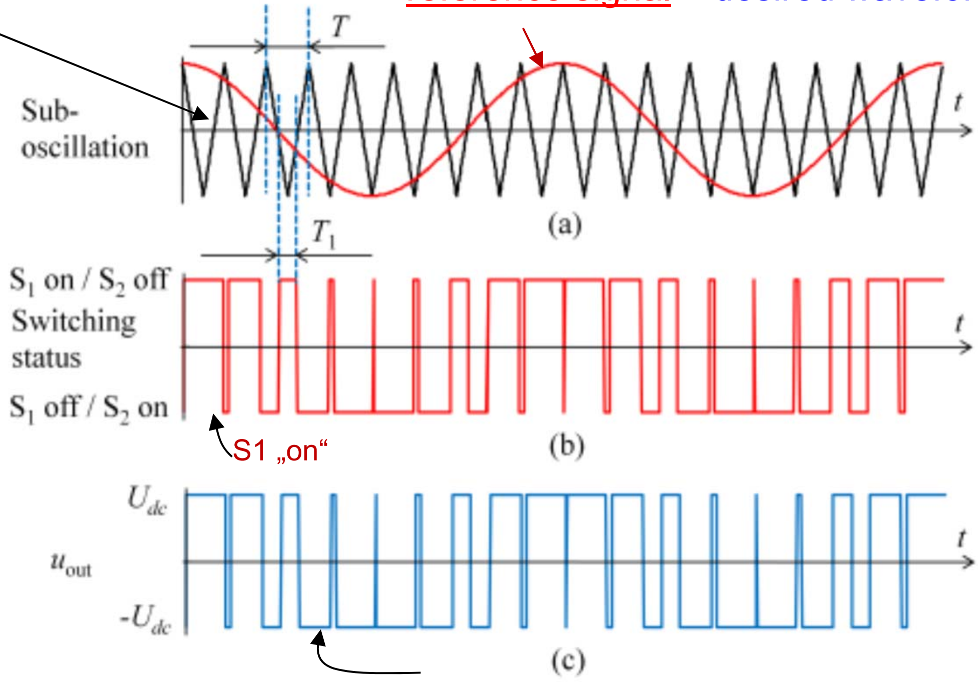
Output voltage

- The SPWM is realized by comparing a sine wave (the reference signal) with a high frequency triangular wave (the carrier signal)
- The interesection between carrier and reference signals is the switching instant
- These two signals are compared. At the time when the reference signal is larger than the triangle signal, the upper switch (S1) is turned on and the lower (S2) switch is off;
- Otherwise, the upper switch is off and the lower switch is on

- The amplitude of the reference signal adjusts the output voltage
- If the maximum value of the reference is equal to the maximum value of the triangle signal, the SPWM method will generate the highest available voltage.

Sinusoidal (Sub-Oscillation) PWM (SPWM)





Carrier signal : controls switching

reference signal = desired waveform

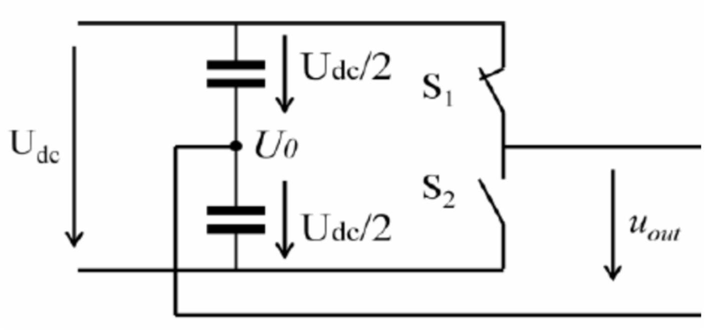
S1 „on“

S2 „on“

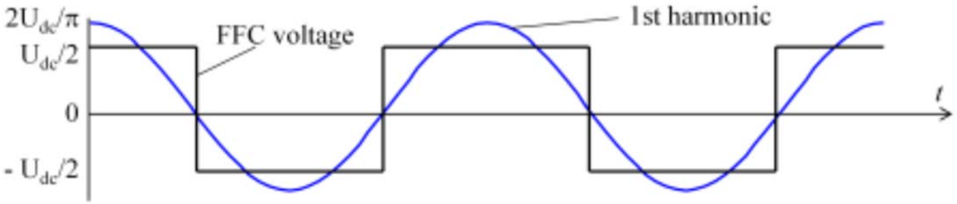
Output voltage

- In the above figure the generated voltage does not resemble the sinusoidal wave form.
- This is because of the low frequency of the triangular signal. If this signal is much faster than the reference signal, the low frequency components of the PWM output can be very close to the waveform of the reference signal.
- In practice, the PWM frequency is usually above 8 kHz

Sinusoidal (Sub-Oscillation) PWM (SPWM)



FFC: fundamental frequency clocking



- To measure the ability of a PWM method to deliver AC output voltage, the term Modulation Index (m) is defined:

$$m = \frac{\text{The maximum output voltage of SPWM method (Udc/2)}}{amplitude\ of\ 1st\ harmonic}$$

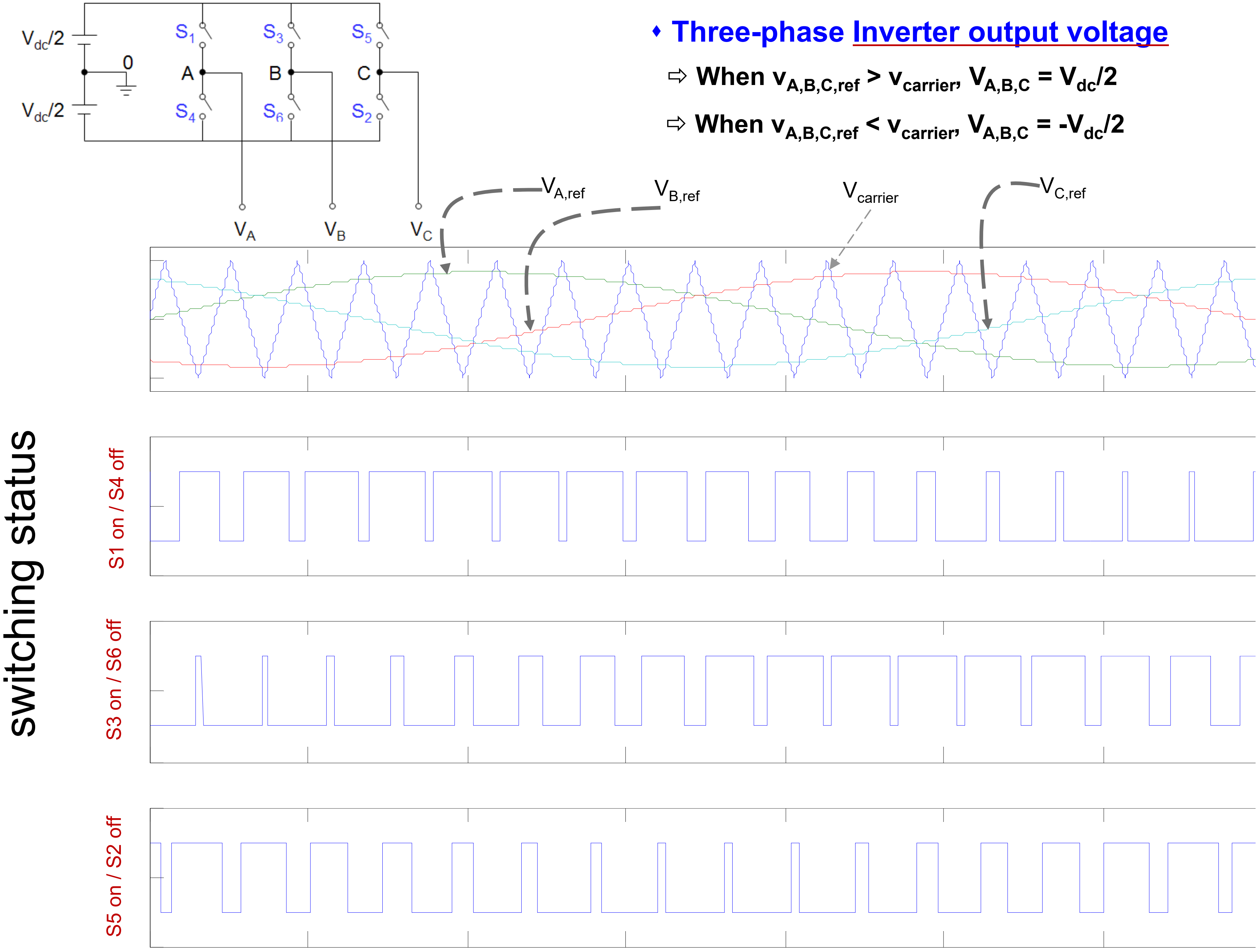
- According to the Fourier transformation, the maximum value of the first harmonic of a square wave is (4/π) times the maximum value of the square wave signal (Udc/2 in this case).
  - Thus the maximum value of its first harmonic is (2Udc/π).

$$m = \frac{U_{dc}/2}{\left(\frac{Udc}{2}\right)*\frac{4}{\pi}} = \frac{\pi}{4} = 0.7854$$

♦ Three-phase Inverter output voltage

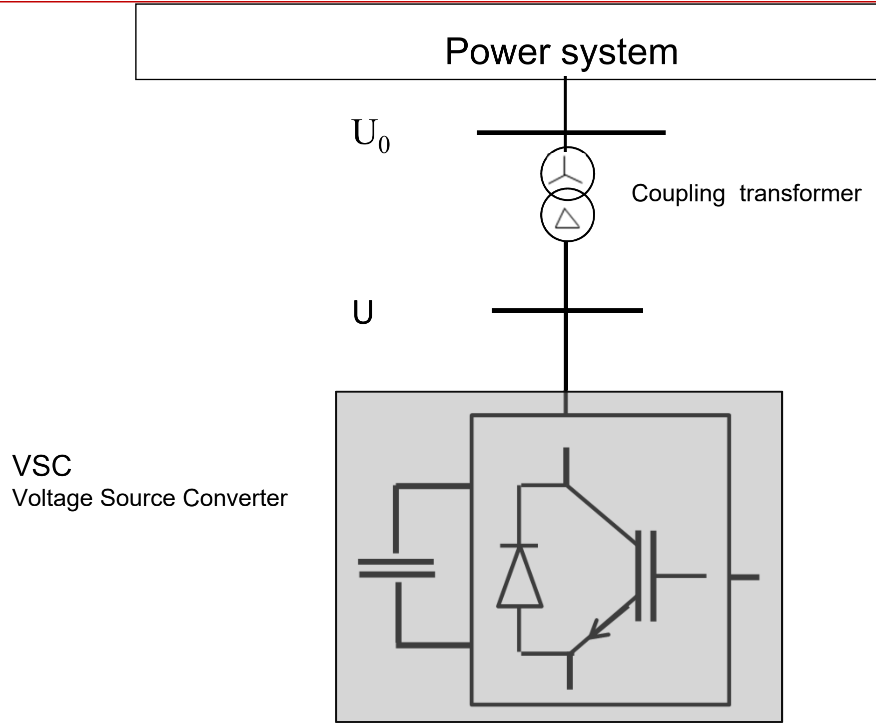
⇨ **When $v_{A,B,C,ref} > v_{carrier}$, $V_{A,B,C} = V_{dc}/2$**

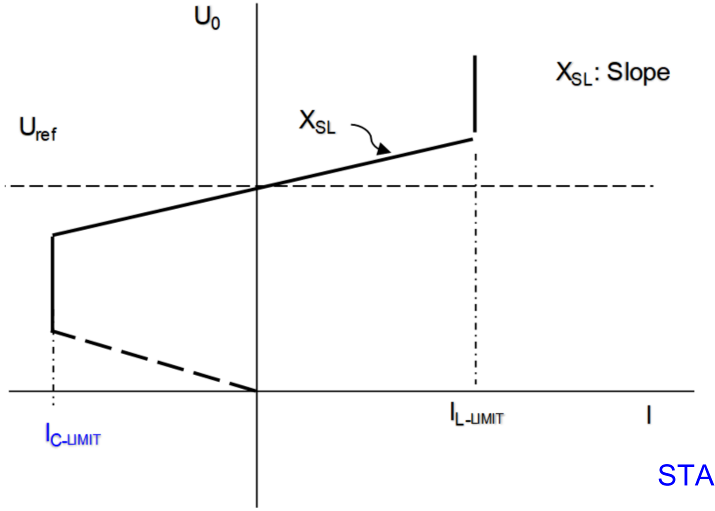
⇨ **When $v_{A,B,C,ref} < v_{carrier}$, $V_{A,B,C} = -V_{dc}/2$**



Static Synchronous Compensator (STATCOM)

STATCOM

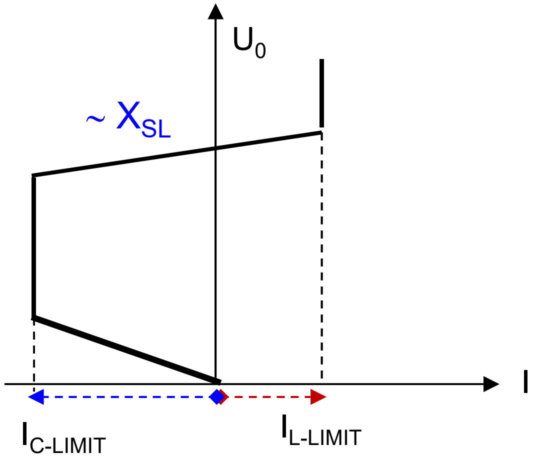




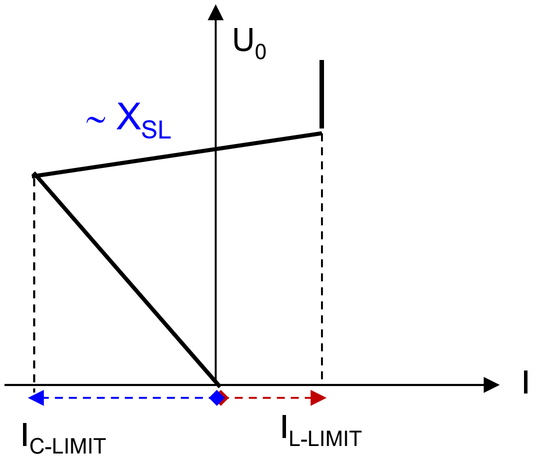
STATCOM V – I Characteristic

- STATCOM is a voltage source converter (VSC)-based device.
- As seen from the AC bus to which it is connected, STATCOM acts as a voltage source behind a reactance (in this case the reactance of the coupling transformer).
  - A STATCOM can be seen as an adjustable voltage source behind a reactance.
- The voltage source is created from a DC capacitor
- It provides desired reactive power generation as well as absorption purely by means of electronic processing of voltage and current waveforms in a voltage source converter (VSC)
- Capacitor banks and shunt reactors are not needed for generation and absorption of reactive power
  - compact design, a small footprint, as well as low noise and low magnetic impact.

COMPARISON
OF
STATCOM AND SVC
CHARACTERISTICS



STATCOM



SVC

STATCOM vs SVC

STATCOM has the following advantages over SVC:

- Faster response time (typical response time between 200 μs to 300 μs)
- Requires less space since STATCOM does not use bulky passive components (such as reactors); Inherently modular and relocatable
- It can be interfaced with active power sources such as battery, fuel cell or superconducting magnetic energy storage (SMES)
- A STATCOM has superior performance during low voltage condition as the reactive current can be maintained constant. It is even possible to increase the reactive current in a STATCOM under transient conditions if the devices are rated for the transient overload.
  - Can be operated over its full output current range even at very low (typically 0.2 pu) system voltage levels
- Requires fewer harmonic filters and capacitors than an SVC, and no reactors
  - significantly more compact

STATCOM vs SVC

- The power loss on STATCOM is higher than the loss for the SVC.
  - This is because presently available power semiconductor devices with internal turn-off capability have higher conduction losses than conventional thyristors.

Operation on unbalanced AC System

- **SVC** controls establishes three identical shunt admittances, one for each phase. Consequently, with unbalanced system voltages the compensating currents in each phase would become different.

  It is theoretically possible to control the three compensating admittances individually by adjusting delay angle of the TCRs so as to make the three compensating currents identical, but impractical.
- In this case triple-n harmonic content would be different in each phase and their normal cancellation through delta connection would not take place.
  - This operation mode thus would generally require the installation of the normally unneeded third harmonic filters.

Operation with unbalanced AC System

- The operation of the **STATCOM** under unbalanced system conditions is different from that of the SVC, but the consequences of the such operation are similar.
- The STATCOM operation is governed by fundamental physical law requiring that the net instantaneous power at the ac and dc terminals of the voltage-sourced converters employed must always be equal.
  - This is because the converter has no internal energy storage and thus the net instantaneous power at the ac and dc terminals must be equal.