High Voltage DC Transmission Systems

POWER SYSTEM MODELLING AND CONTROL (EEEN40550)

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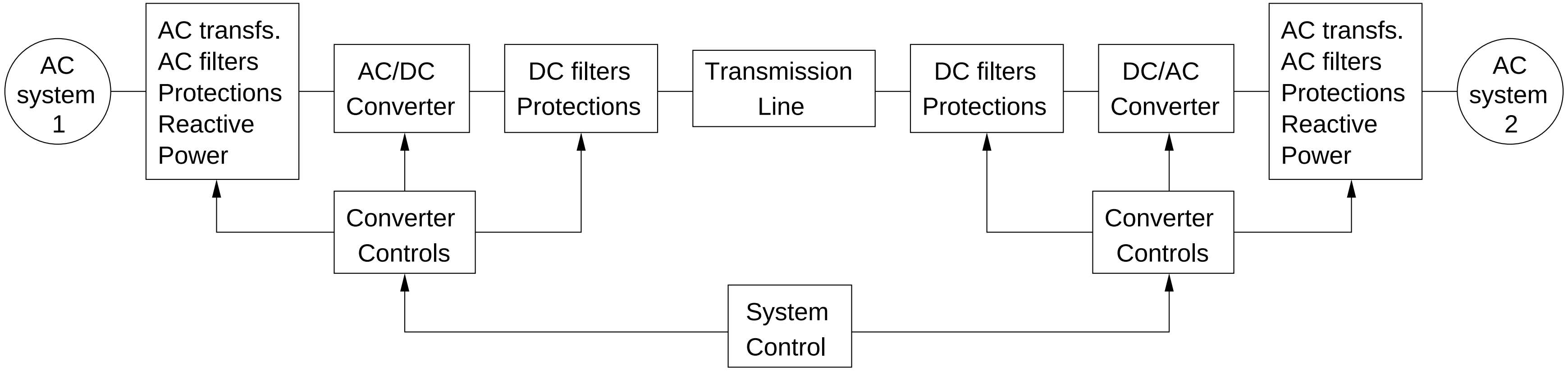
Outlines

- Basic structure and operation.
- Commutation.
- Harmonics.
- Typical DC links.
- Controls.
- Fundamental frequency, reduced model.
- Steady state model.

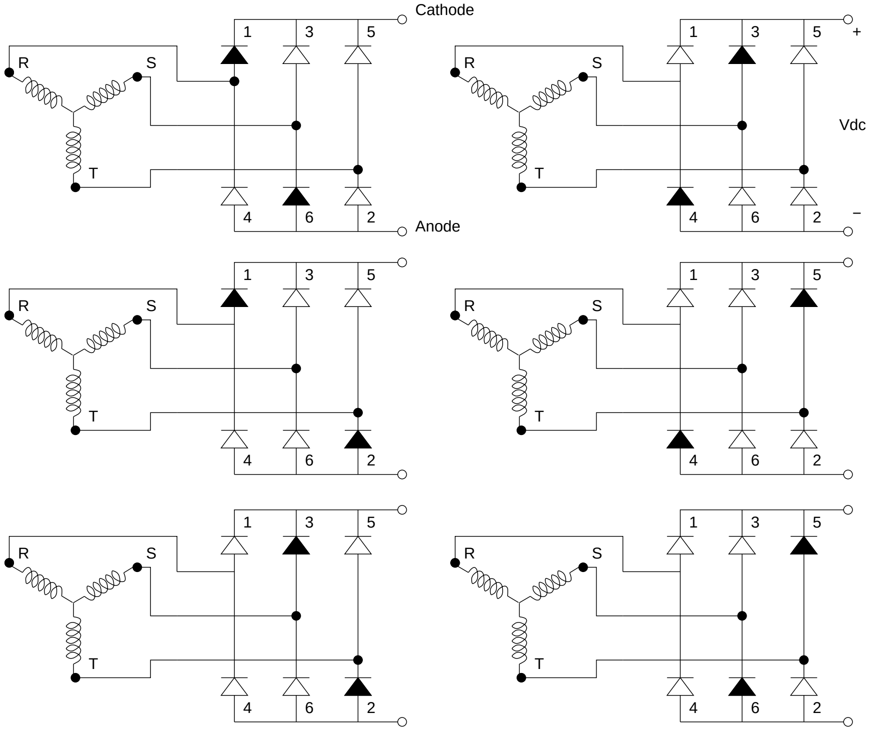
Basic Structure and Operation (I)

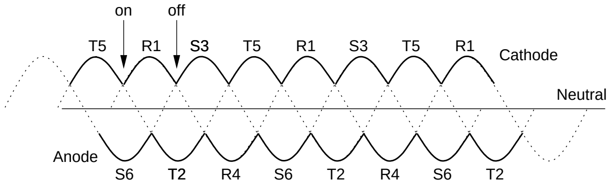
- AC voltages are first converted into dc, the power is then transmitted on a high voltage dc line, and finally converted again into ac at the other side of the HVDC link.



Basic Structure and Operation (II)

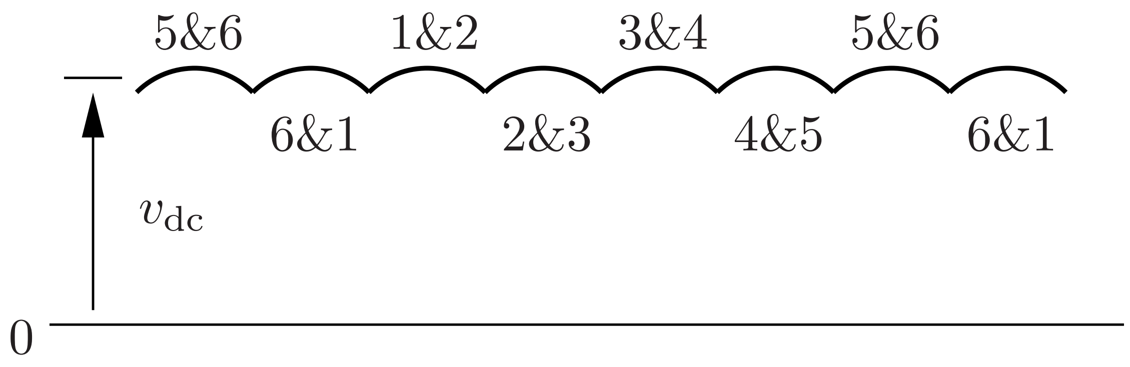
- AC/DC 6-pulse converter.





Basic Structure and Operation (III)

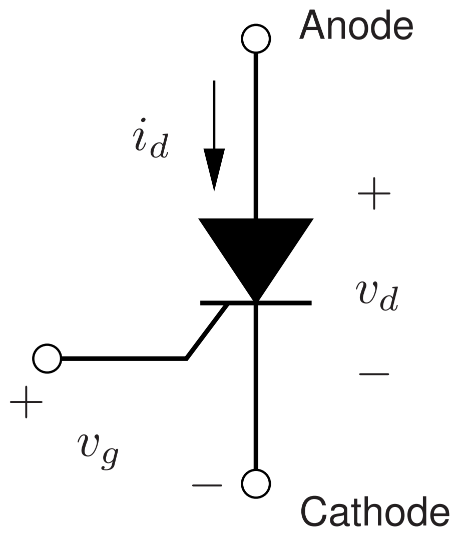
- This results on V_{dc} voltage:



- Each “valve” is on for $120°$.

Basic Structure and Operation (IV)

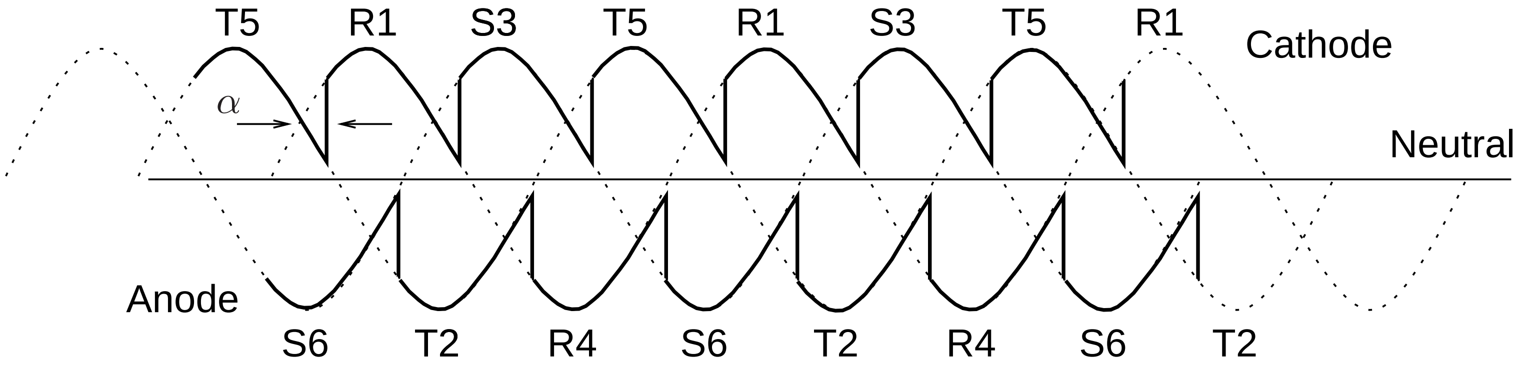
- Using thyristor valves in the converter:

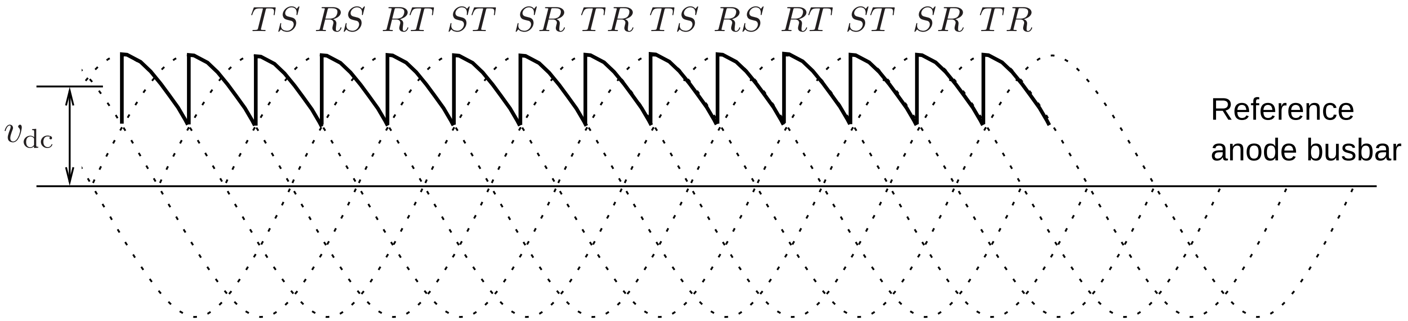


- on ⇒ $v_d > 0 \quad \& \quad v_g > 0$
- off ⇒ $i_d < 0$

Basic Structure and Operation (V)

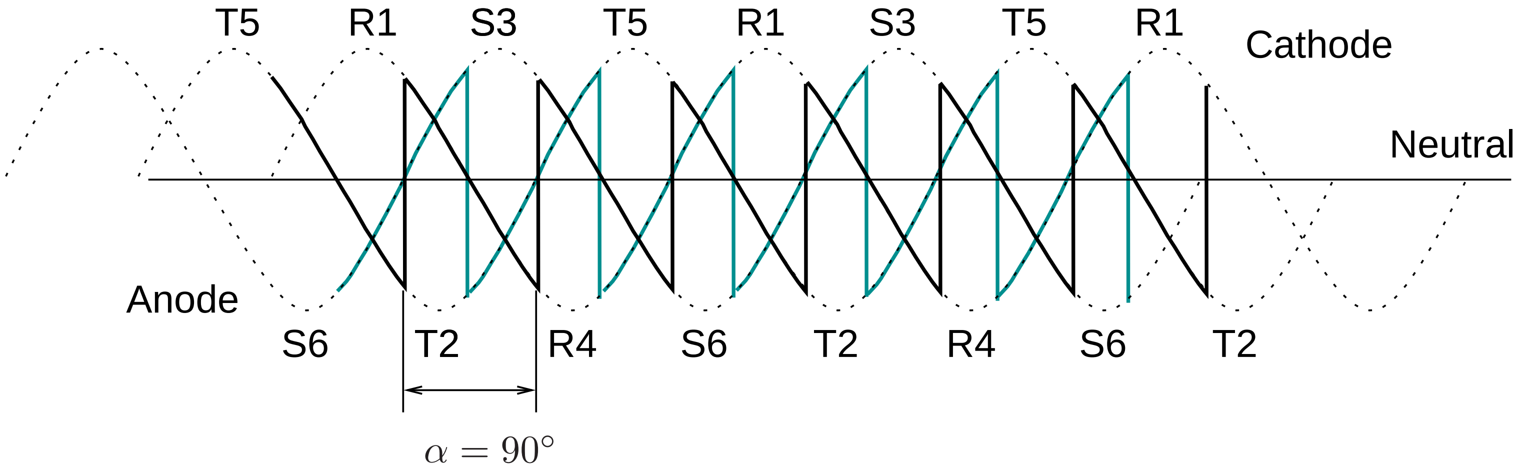
- For firing delay angle $0 < \alpha < 90^\circ$ (rectifier, i.e., $v_{\mathrm{dc}} > 0$):

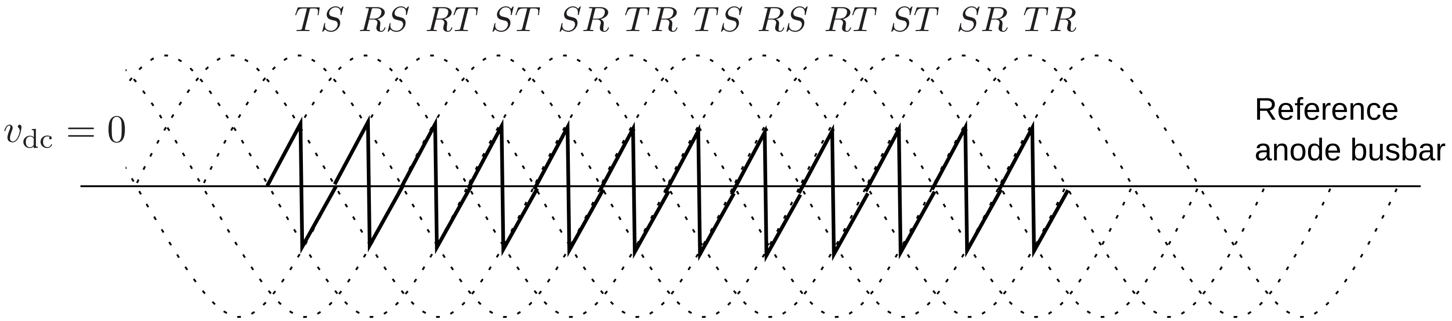




Basic Structure and Operation (VI)

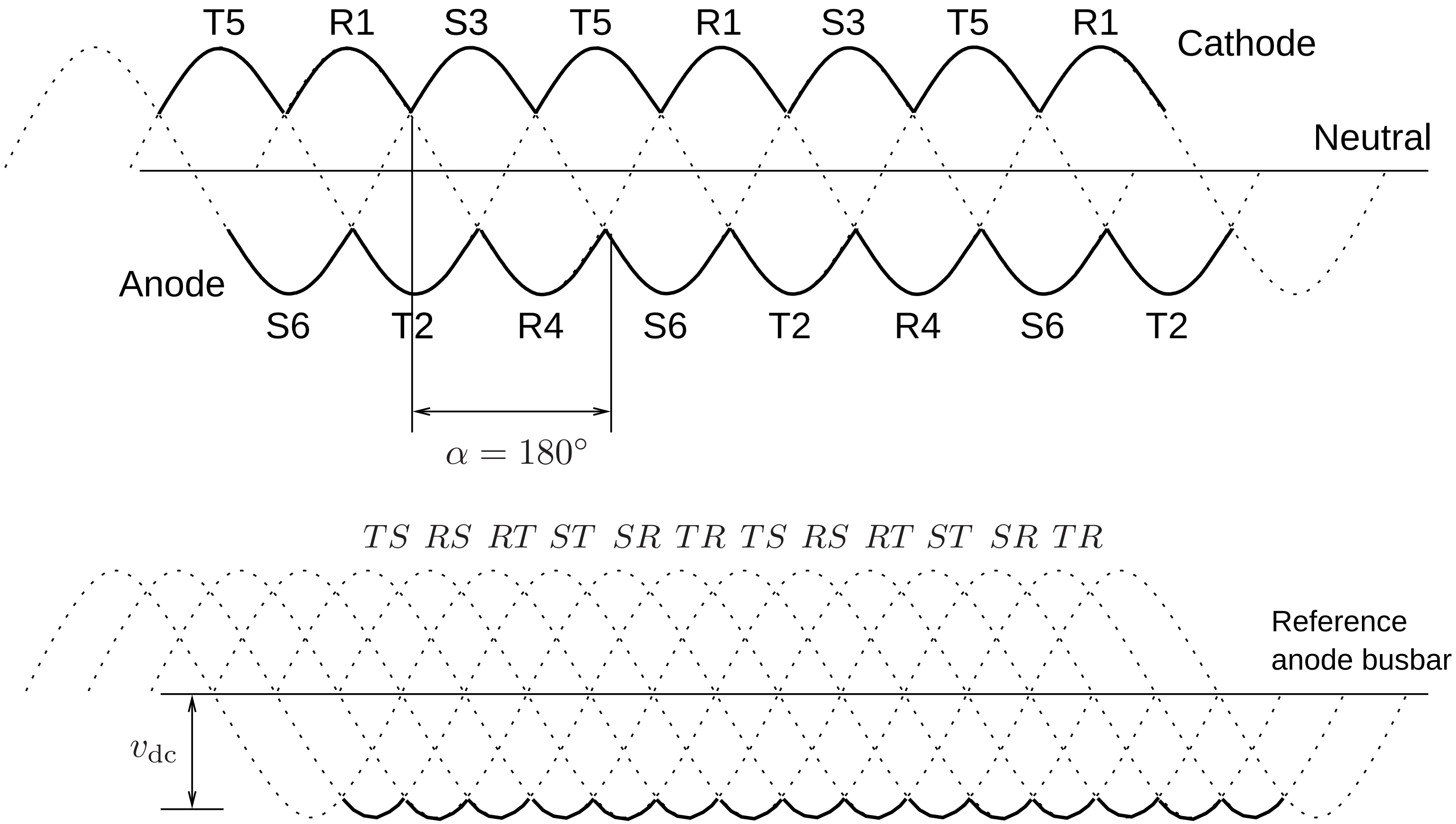
- For firing delay angle $\alpha = 90°$, $v_{\mathrm{dc}} = 0$:





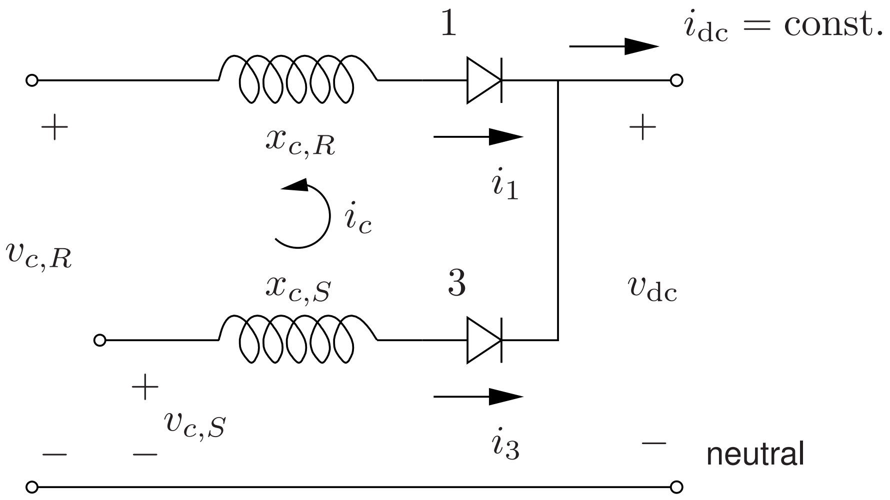
Basic Structure and Operation (VII)

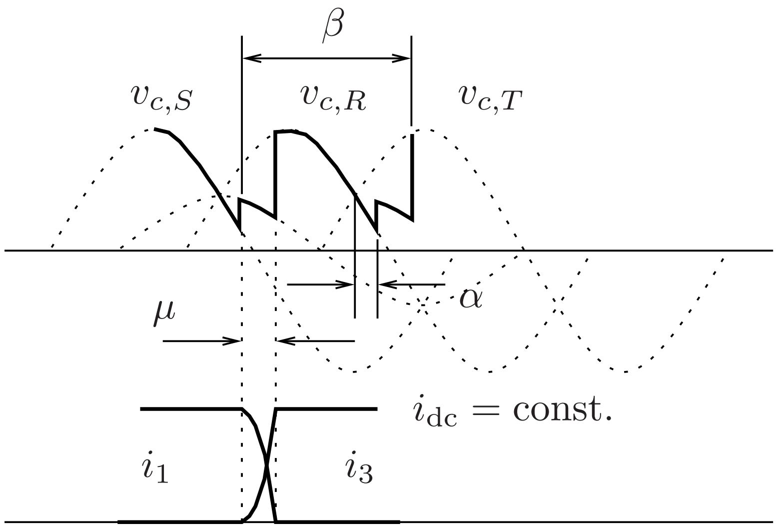
- For firing delay angle $\alpha = 180^\circ$, (inverter, i.e., $v_{\text{dc}} < 0$):



Commutation (I)

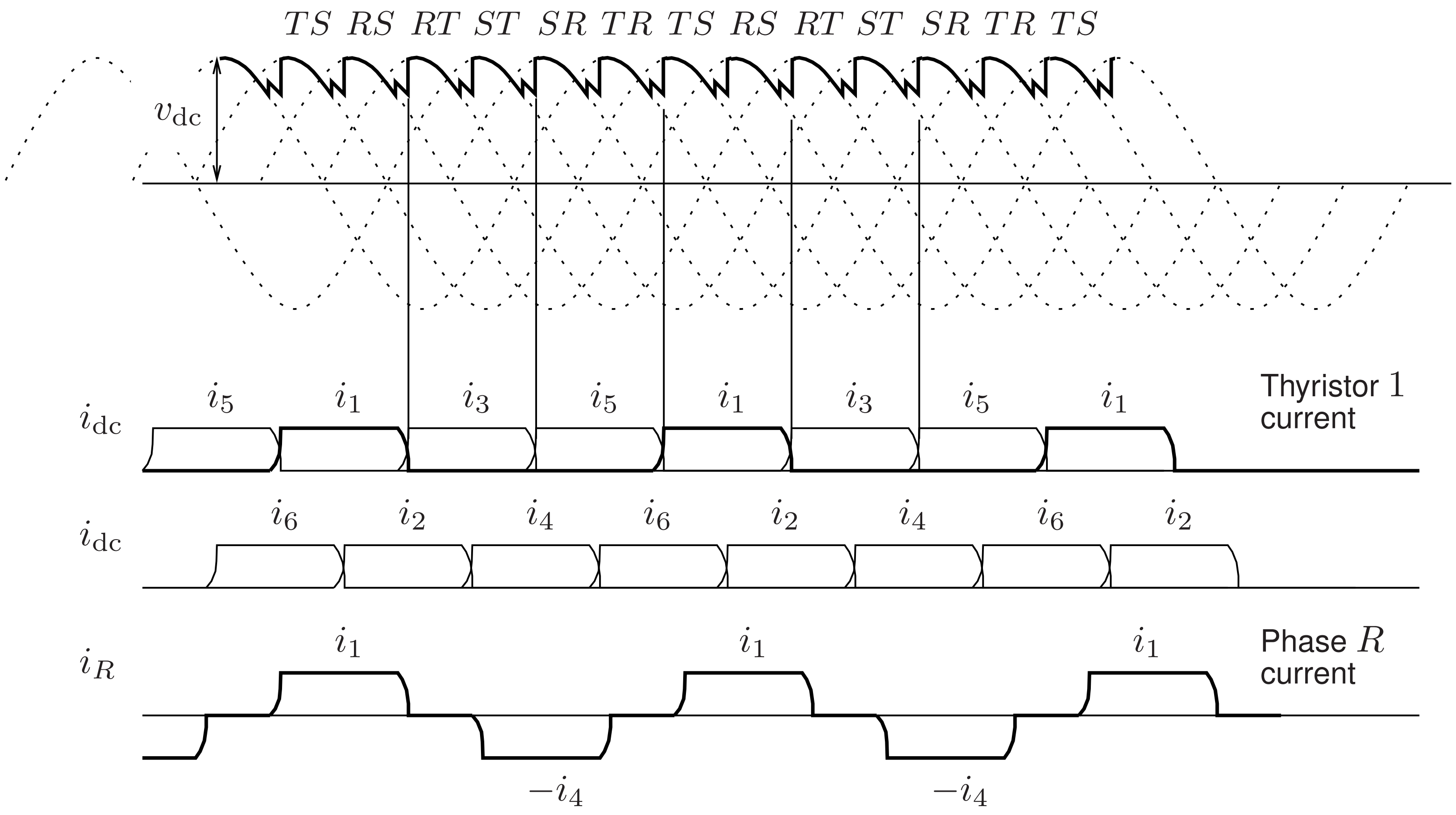
- The transformer reactance x_c and the constant current lead to commutation problems:





Commutation (II)

- Effect of commutation on voltages and currents.



Commutation (III)

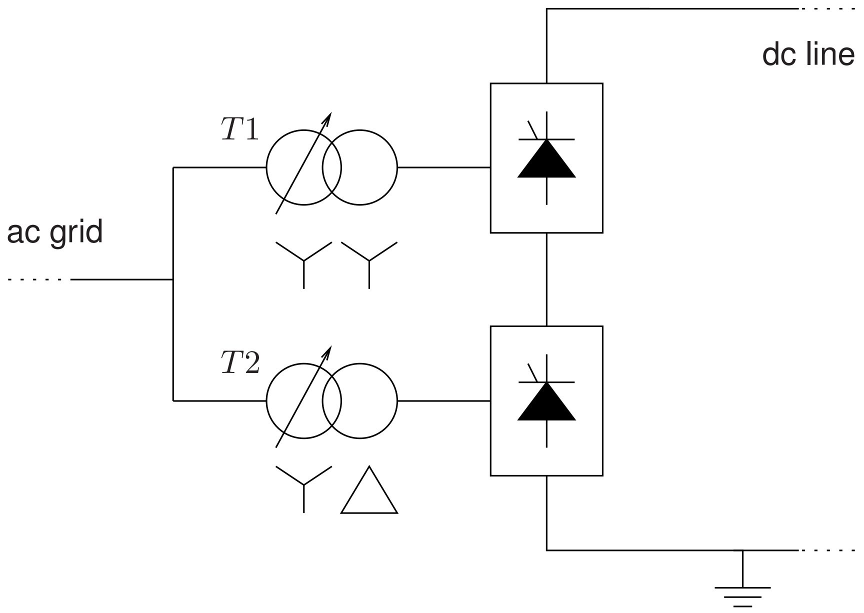
- Definitions:
    - α Firing angle
    - μ Overlap angle
    - β *On* angle
    - γ Extinction angle:

$$\gamma = 180^\circ - \alpha - \mu$$

- The value of angle γ is associated with the valve *extinction* angle , i.e. the time these valves have to turn off.
- Commutation problems or “failures” may occur in inverters when the value of α is large, i.e., γ is small, as there is not enough time for the valves to turn off.
- Hence, inverter controls are designed to keep $\gamma > \gamma_{\min} \approx 10^\circ$.

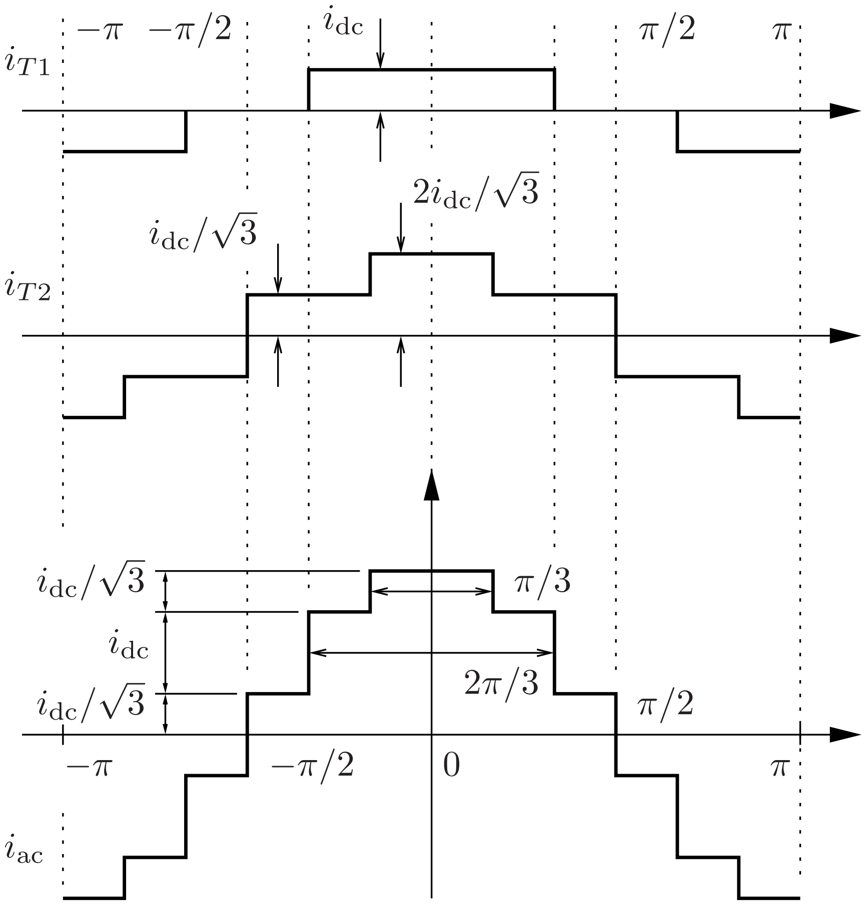
Harmonics (I)

- As I_{dc} is constant, the ac current has large harmonic content, as previously shown.
- This can be reduced by connecting in series two phase-shifter 6-pulse converters:



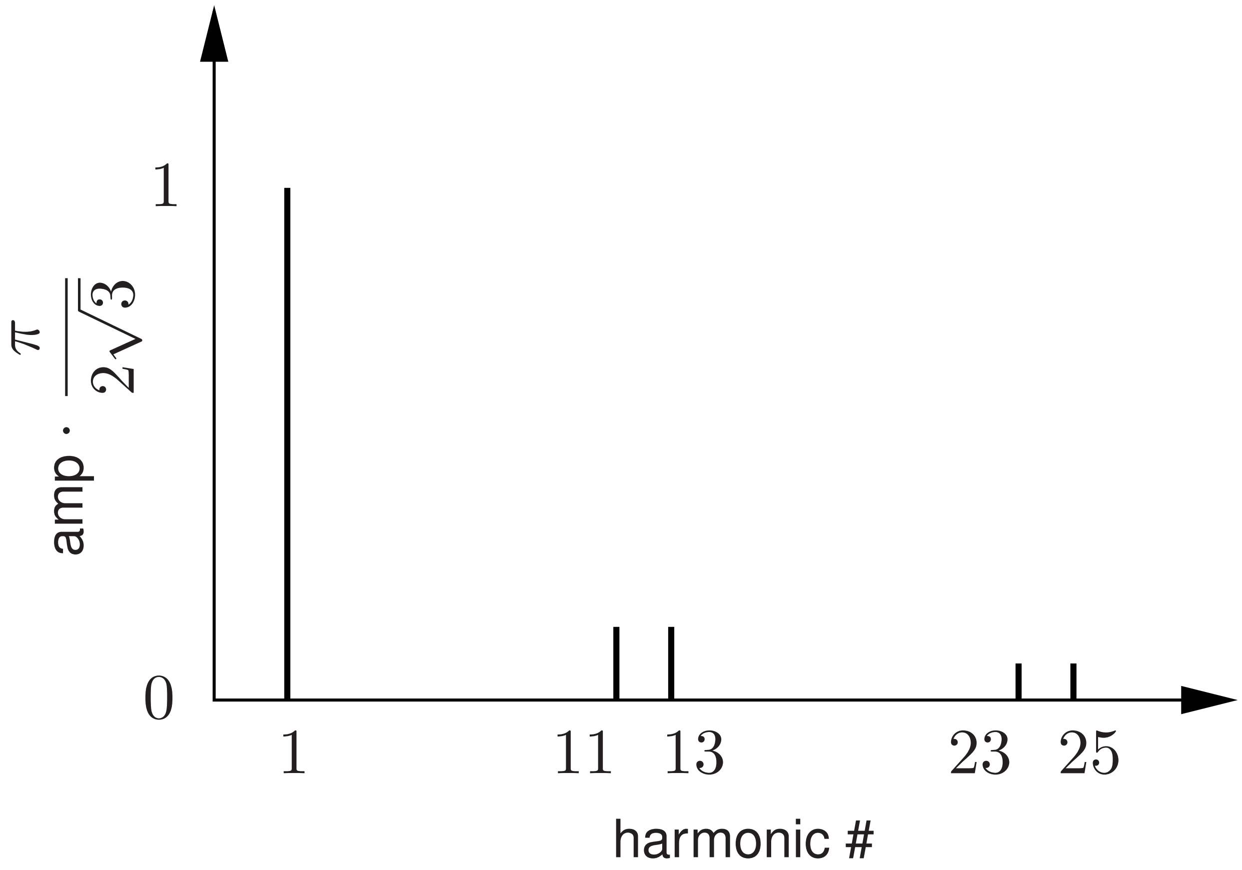
Harmonics (II)

- $i_{\mathrm{ac}} = i_{T1} + i_{T2}$



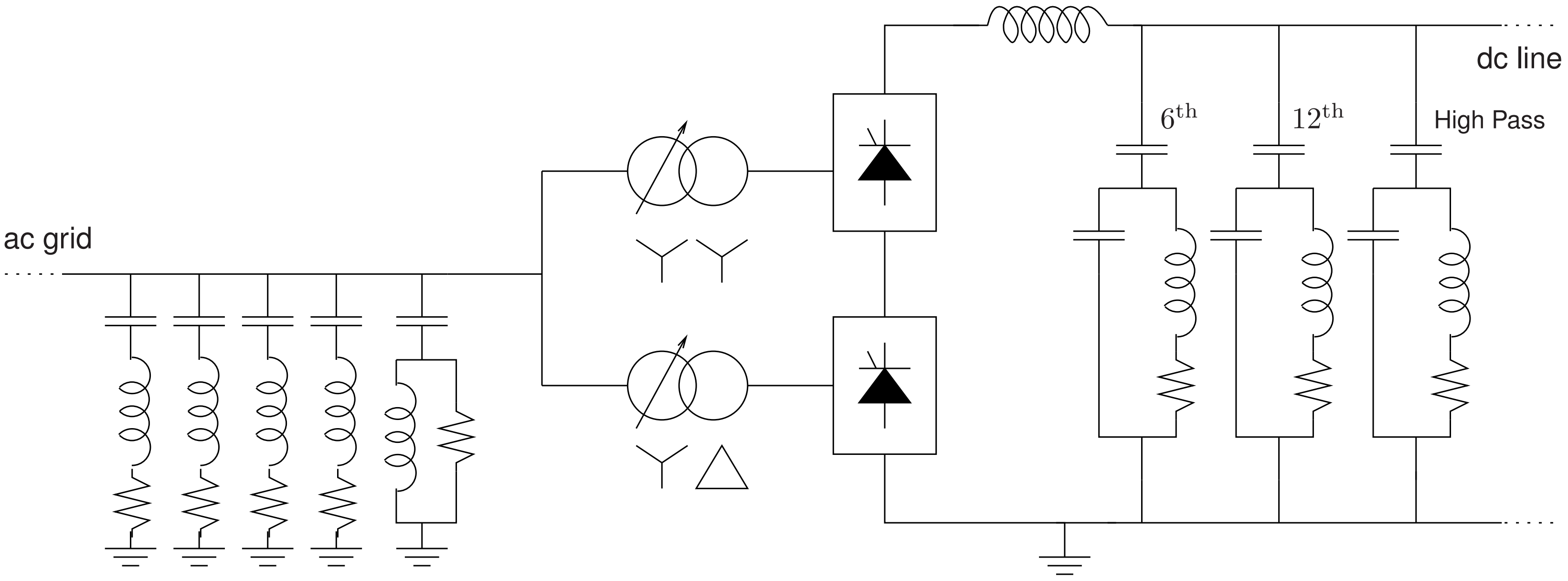
Harmonics (III)

- The harmonic content in this signal is reduced by eliminating the 5^{th} and 7^{th} harmonics:



Harmonics (IV)

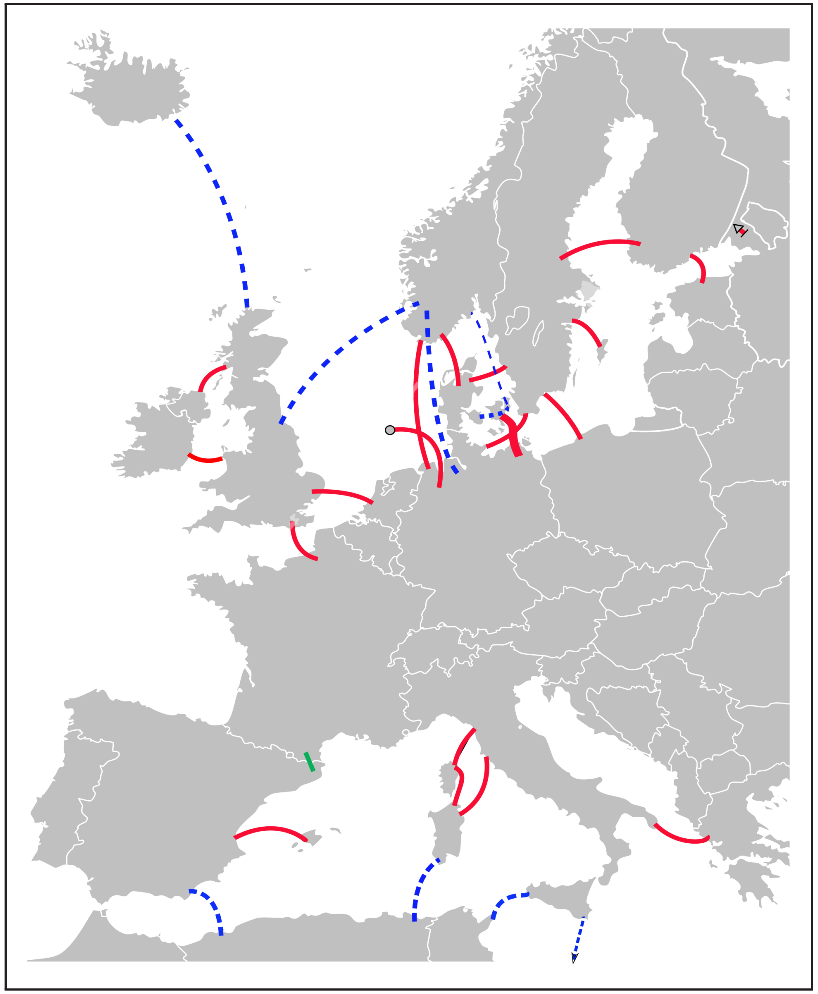
- Harmonics in the ac and dc side are reduced by introducing filters:



DC Links

- Bipolar (e.g. Nelson River, Manitoba, Bipole 1, ±450 kV, 1620 MW, 1972 & 1977; Bipole 2, ±500 kV, 1800 MW, 1978 & 1985):
- More terminals can be added leading to Multi-terminal HVDC links (e.g. Quebec-New England, ±450 kV, 2000 MW, at least 3 terminals, 1990).
- Monopolar underwater connections (e.g. Moyle, link between Auchencrosh, South Ayrshire in Scotland and Ballycronan More, County Antrim in Northern Ireland, Italy, 275 kV, 500 MW, 2001). Bipolar connections are preferred nowadays for technical and environmental reasons.
- Multiterminal monopolar connections (e.g. SACOI, Sardinia-Corsica-Italy, 200 kV, 200 MW, 2012).
- Back-to-back (e.g. connection between Finnish and Russian high voltage systems, Vyborg, 12-pulse, ±85 kV, 1420 MW, 1980-2001).

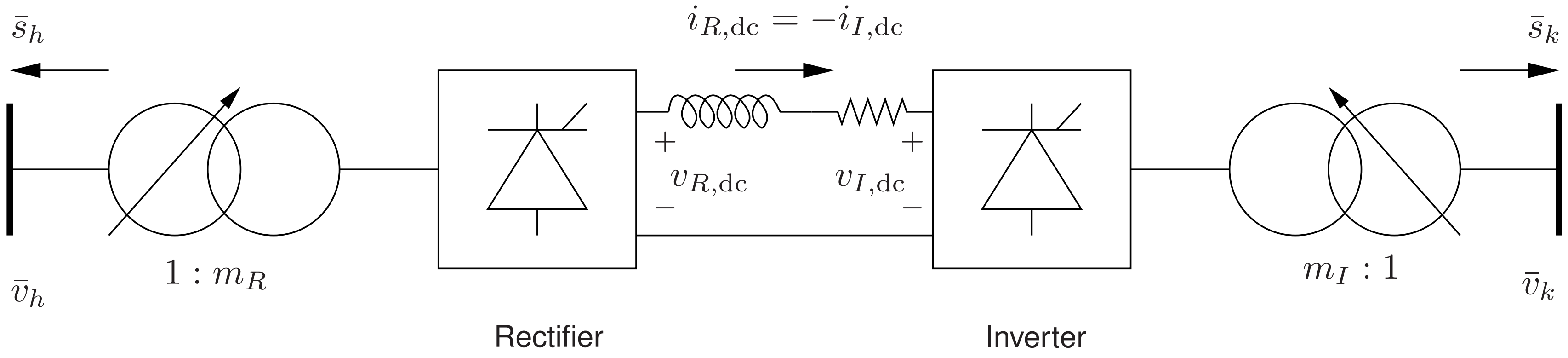
DC Links in Europe



Source: `http://en.wikipedia.org/wiki/File:HVDC_Europe.svg`

Model of a Standard 6-pulse HVDC Link

- Let consider the following scheme:



- Large inductors are used to make the dc current constant.

Bases and Per Unit System (I)

- Ac/dc devices not only separates the ac grid side from the dc one.
- They also fully separate the ac quantities and bases from dc ones.
- In the following, dc bases are considered fully decoupled from ac ones and base conversions are taken into account in the equations of ac/dc devices.
- All ac quantities are in pu with respect to ac bases, i.e., $V^{\mathrm{ac}}_{\text{base}}$ and $S^{\mathrm{ac}}_{\text{base}}$, and all dc quantities are in pu with respect to dc bases, i.e., $V^{\mathrm{dc}}_{\text{base}}$ and $I^{\mathrm{dc}}_{\text{base}}$.

Bases and Per Unit System (II)

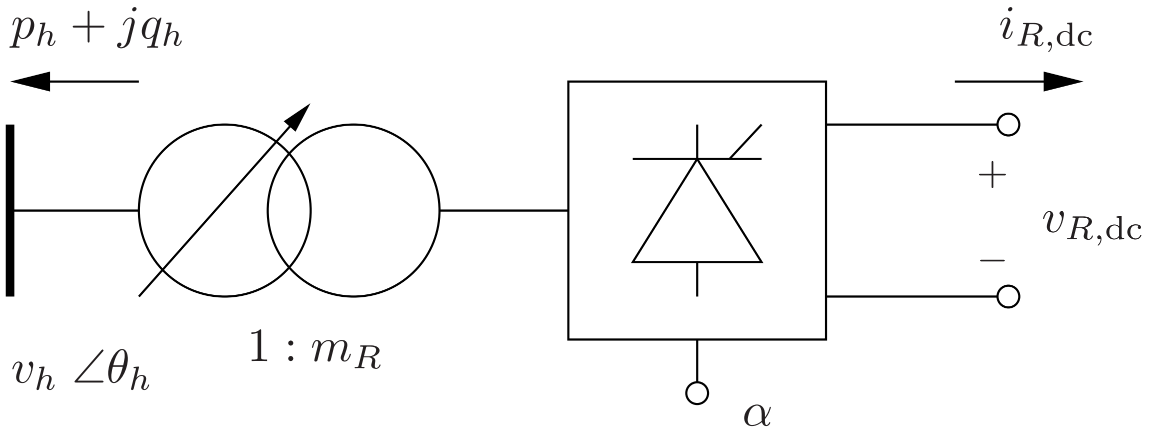
- The following bases define the dc per unit quantities:

$$\begin{aligned} V_{\text{base}}^{\text{dc}} &= \frac{3\sqrt{2}}{\pi} V_{\text{base}}^{\text{ac}} \\ I_{\text{base}}^{\text{dc}} &= I_{\text{rate}}^{\text{dc}} = I_n^{\text{dc}} \\ S_{\text{base}}^{\text{dc}} &= V_{\text{base}}^{\text{dc}} I_{\text{base}}^{\text{dc}} \\ R_{\text{base}}^{\text{dc}} &= V_{\text{base}}^{\text{dc}} / I_{\text{base}}^{\text{dc}} \end{aligned}$$

- Furthermore, $S_{\text{base}}^{\text{ac}} = S_n \approx V_n^{\text{dc}} I_n^{\text{dc}} = S_{\text{base}}^{\text{dc}}$ holds to avoid inconsistencies.

Rectifier Model (I)

- The rectifier scheme with current and voltage sign notation is shown below.



Rectifier Model (II)

- The active and reactive power injections at the ac-side are:

$$
\begin{aligned}
p_h &= -\hat{k}_s \, v_{R,\mathrm{dc}} \, i_{R,\mathrm{dc}} && (1) \\
q_h &= -\hat{k}_s \, \hat{k}_v \, m_R \, v_h \, i_{R,\mathrm{dc}} \, \sin\phi_h
\end{aligned}
$$

- Where ϕ_h is the angle between the average ac voltage and the ac current of the rectifier, m_R is the transformer tap ratio, and:

$$
\begin{aligned}
\hat{k}_s &= \frac{S^{\mathrm{dc}}_{\text{base}}}{S^{\mathrm{ac}}_{\text{base}}} && (2) \\
\hat{k}_v &= 0.9995 \cdot 3 \, \frac{\sqrt{2}}{\pi} \, \frac{V^{\mathrm{ac}}_{\text{base}}}{V^{\mathrm{dc}}_{\text{base}}} && (3)
\end{aligned}
$$

Rectifier Model (III)

- The link between the ac and the dc sides is given by:

$$\begin{aligned} 0 &= \hat{k}_v\, m_R\, v_h\, \cos\alpha - \hat{k}_\omega\, x_{R,c}\, i_{R,\mathrm{dc}} - v_{R,\mathrm{dc}} \\ 0 &= \hat{k}_v\, m_R\, v_h \cos\phi_h - v_{R,\mathrm{dc}} \end{aligned} \tag{4}$$

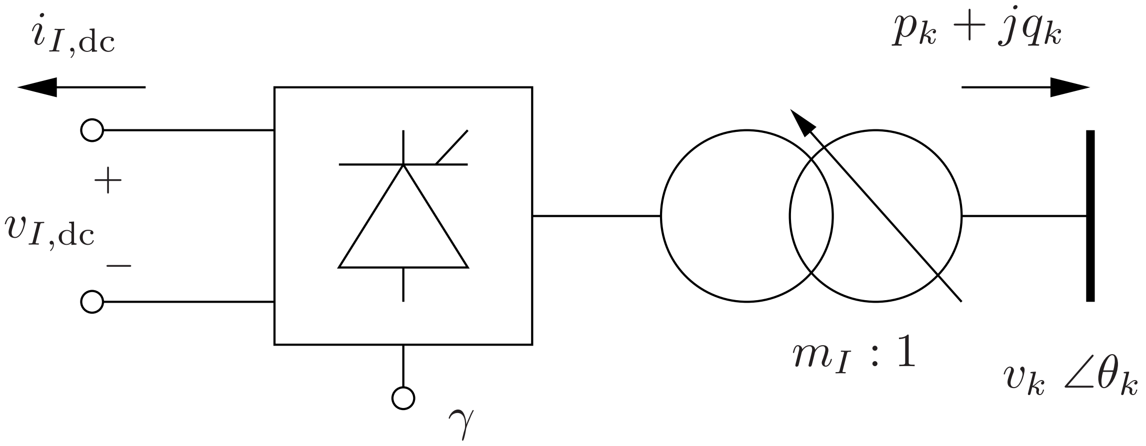
where α is the *firing angle* of the rectifier and

$$\hat{k}_\omega = \frac{3}{\pi}\,\frac{Z^{\mathrm{ac}}_{\text{base}}}{R^{\mathrm{dc}}_{\text{base}}} \tag{5}$$

- Two additional equations are required to complete the converter model. These equations model the controllers of the transformer tap ratio m_R and the firing angle α

Inverter Model (I)

- The inverter scheme with current and voltage sign notation is shown below.



Inverter Model (II)

- Equations (1) and (4) have to be rewritten to take into account the *extinction angle* or *commutation margin* γ and the sign of the dc current on the inverter dc side.
- For the two-terminal scheme above: $i_{I,\mathrm{dc}} = -i_{R,\mathrm{dc}}$, hence one has:

$$
\begin{aligned}
p_k &= -\hat{k}_s \, v_{I,\mathrm{dc}} \, i_{I,\mathrm{dc}} \\
q_k &= \hat{k}_s \, \hat{k}_v \, m_I \, v_k \, i_{I,\mathrm{dc}} \, \sin \phi_k \\
0 &= \hat{k}_v \, m_I \, v_k \cos(\pi - \gamma) - \hat{k}_\omega \, x_{I,c} \, i_{I,\mathrm{dc}} + v_{I,\mathrm{dc}} \\
0 &= \hat{k}_v \, m_I \, v_k \, \cos \phi_k - v_{I,\mathrm{dc}}
\end{aligned}
\tag{6}
$$

where ϕ_k is the angle between the ac voltage and the ac current of the inverter.

Inverter Model (III)

- Since $i_{I,\mathrm{dc}} < 0$, the inverter injects active power and consumes reactive power at the ac bus k.
- Observe that the ac power and voltage bases (as well as the system frequency) have not to be necessarily the same as those used for recitifier ac-side quantities.
- As for the rectifier, two equations are required to complete the model. These equations model the controllers of the transformer tap ratio m_I and the extinction angle γ.

HVDC Control

- HVDC controllers have to coordinate the operations of the rectifier and the inverter devices.
- The controlling variables are the transformer tap ratio and the firing angle on the rectifier side and the transformer tap ratio and the extinction angle on the inverter side.
- Tap ratio controls are necessarily slower than those of firing/extinction angles.
- The firing and extinction angles, which are characterized by fast dynamics, are considered algebraic variables, while the tap ratio, whose dynamic is relatively slow, are considered state variables.

Rectifier Current Control Mode (RCCM)

- Rectifier-side regulators control the dc current $i_{\rm dc}$ through a PI controller that varies the firing angle α, and the ac voltage v_h through the off-nominal tap ratio m_R.
- Inverter-side regulators maintain constant the extinction angle $\gamma = \gamma^{\rm ref} \geq \gamma^{\rm min}$ and control the dc voltage $v_{I,{\rm dc}}$ through the tap ratio m_I.
- The DAE system is as follows:

$$
\begin{aligned}
\dot{m}_R &= (v_h - v_{\rm ac}^{\rm ref})/T_R \\
\dot{m}_I &= (v_{\rm dc}^{\rm ref} - v_{I,{\rm dc}})/T_I \\
\dot{x}_{R,\alpha} &= K_i(i_{\rm dc}^{\rm ref} - i_{\rm dc}) \\
0 &= x_{R,\alpha} + K_p(i_{\rm dc}^{\rm ref} - i_{\rm dc}) - \alpha \\
0 &= \gamma^{\rm ref} - \gamma
\end{aligned}
\tag{7}
$$

- The PI control undergoes an anti-windup limiter in order to maintain the firing angle within its limits.

Inverter Current Control Mode (ICCM)

- Inverter-side regulators control the dc current i_{dc} through the extinction angle γ and the ac voltage v_k through the tap ratio m_I.
- Rectifier-side regulators maintain constant the firing angle $\alpha = \alpha^{\mathrm{min}}$ and control the dc voltage $v_{R,\mathrm{dc}}$ through the tap ratio m_R.
- The DAE system is as follows:

$$
\begin{aligned}
\dot{m}_R &= (v_{\mathrm{dc}}^{\mathrm{ref}} - v_{R,\mathrm{dc}})/T_R \\
\dot{m}_I &= (v_k - v_{ac}^{\mathrm{ref}})/T_I \\
0 &= \alpha^{\mathrm{min}} - \alpha \\
\dot{x}_{I,\gamma} &= K_i(i_{\mathrm{dc}}^{\mathrm{ref}} + i_{\mathrm{dc}} - i_{\mathrm{dc}}^{m}) \\
0 &= x_{I,\gamma} + K_p(i_{\mathrm{dc}}^{\mathrm{ref}} + i_{\mathrm{dc}} - i_{\mathrm{dc}}^{m}) - \gamma
\end{aligned}
\tag{8}
$$

where the *current margin* i_{dc}^{m} avoids that the RCCM and ICCM controls overlap.

Power Control

- If a power/frequency control is required, the reference current $i_{\rm dc}^{\rm ref}$ can be the output of a power (or *master*) control, as follows:

$$i_{\rm dc}^{\rm ref} = \min\{i_{\rm dc}^{\rm des}, i_{\rm dc}^{\rm lim}\} \tag{9}$$

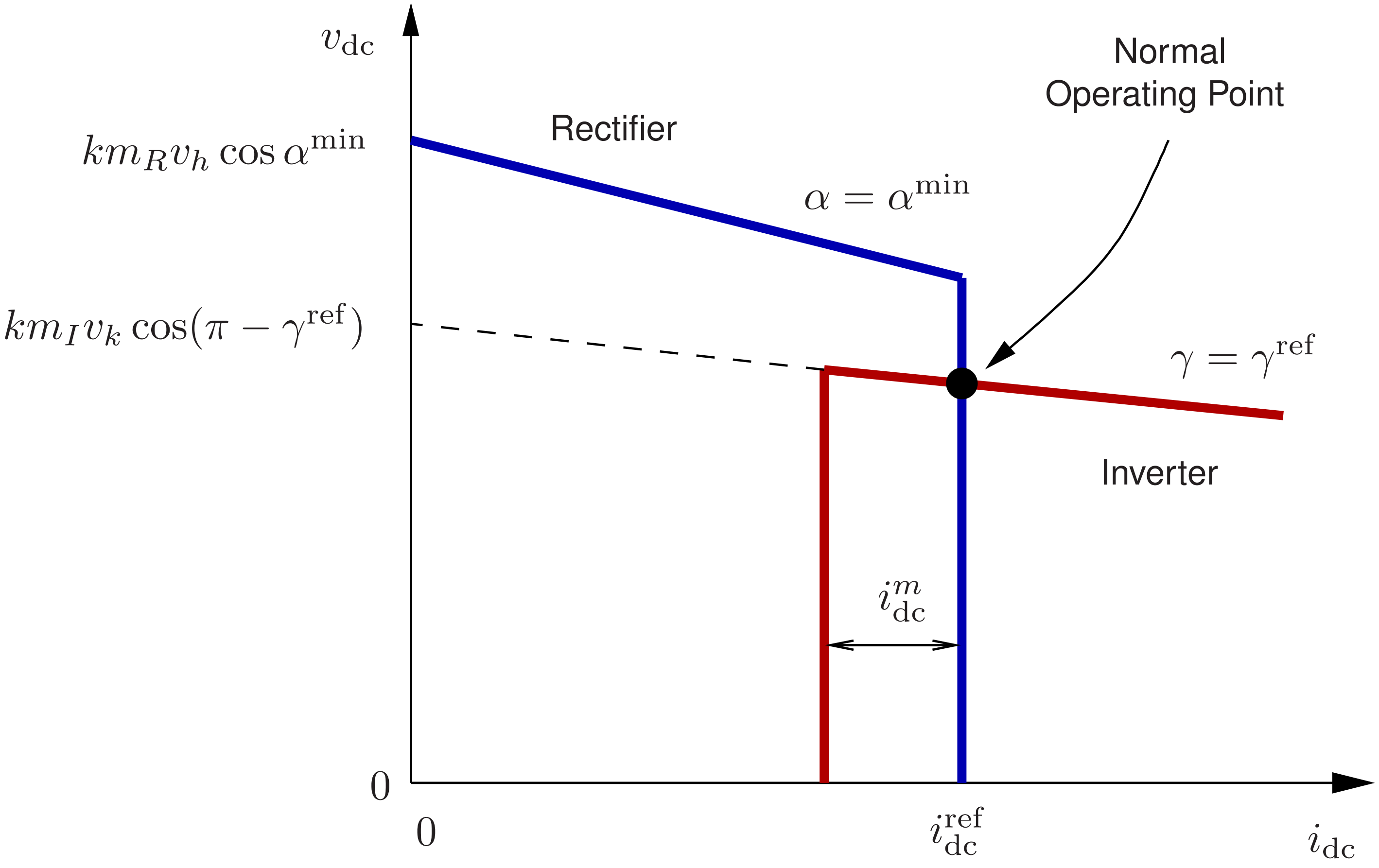
where $i_{\rm dc}^{\rm des} = p^{\rm ref}/v_{\rm dc}$ is the current that provides the desired reference power $p^{\rm ref}$ and $v_{\rm dc}$ is the dc voltage at one of the two converter terminals, and $i_{\rm dc}^{\rm lim}$ is defined based on the dc voltage value, as follows:

$$i_{\rm dc}^{\rm lim} = \begin{cases} i_{\rm dc}^{\rm min}, & \text{if } v_{\rm dc} < v_{\rm dc}^{\rm min} \\ i_{\rm dc}^{\rm min} + c(v_{\rm dc} - v_{\rm dc}^{\rm min}), & \text{if } v_{\rm dc}^{\rm min} \leq v_{\rm dc} \leq v_{\rm dc}^{\rm max} \\ i_{\rm dc}^{\rm min} + c(v_{\rm dc}^{\rm max} - v_{\rm dc}^{\rm min}), & \text{if } v_{\rm dc} > v_{\rm dc}^{\rm max} \end{cases} \tag{10}$$

where, typically, $c = 1$ pu/pu.

HVDC Steady-state RCCM

- The figure below summarizes the steady-state characteristic of the HVDC control for the RCCM.



Current Margin Control (I)

- In RCCM, to obtain an operating point, the inverter can operate only in the constant extinction angle γ control mode of operation.
- However, if the AC voltage at the rectifier bus drops, the α^{min} characteristics will fall below the constant extinction angle γ characteristics.
- In this case, the inverter-side dc voltage is too high for the rectifier to be able to force a current through the dc circuit.
- However, if the inverter is provided with a current control mode, there exists a new operating point.
- This basic control mode for HVDC has been called the **current margin control**.
- in practice, $i_{\mathrm{dc}}^{m} \approx 10\%$.

Current Margin Control (II)

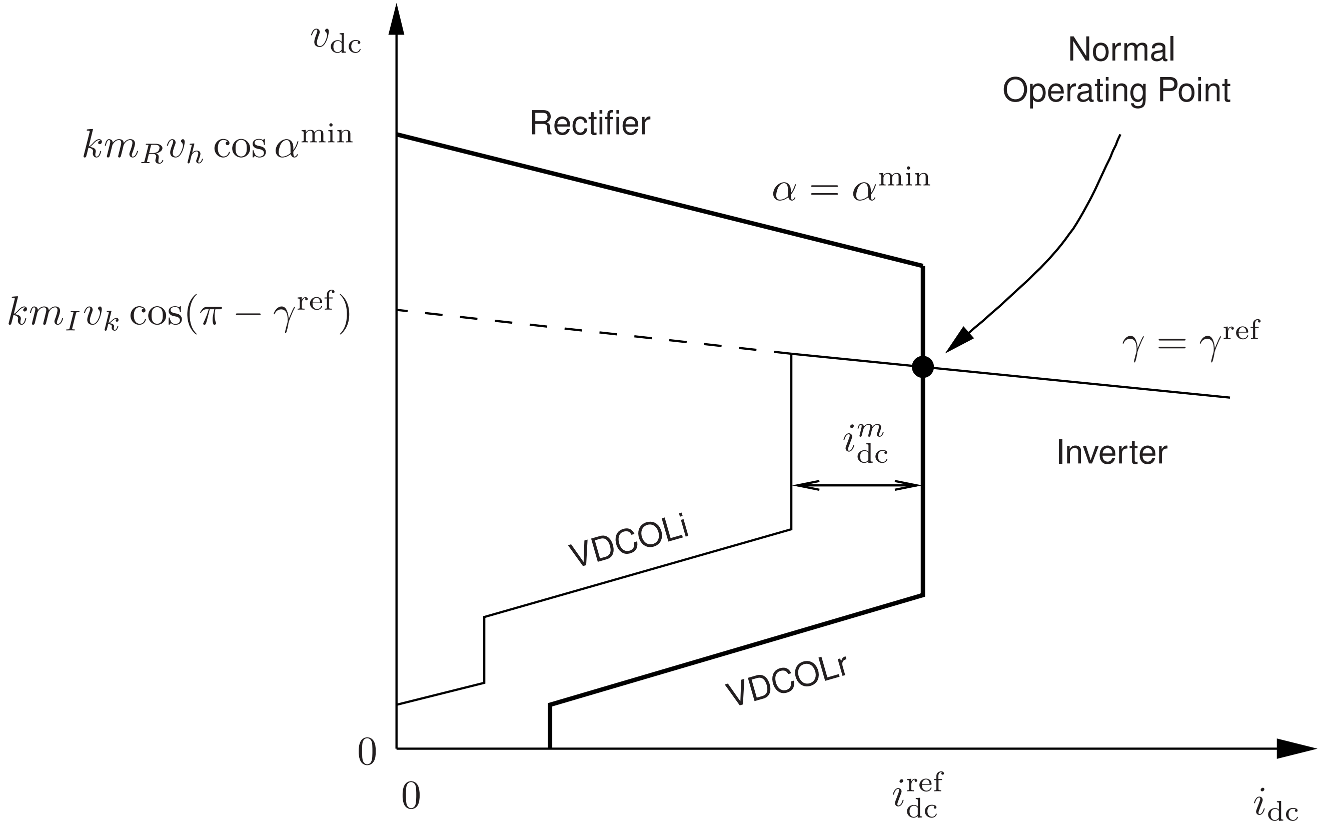
- We conclude from the discussion above that with the use of the current margin control:
  - The station with the highest maximum voltage will control the current.
  - The station with the lowest will determine the voltage.

Voltage Dependent Current Order Limiter VDCOL (I)

- The VDCOL is a control mode that reduces the reactive power demand of the converter when ac voltages are too low, and thus decreases the risk of a commutation failure.
- If v_{dc} is too low, the VDCOL reduces i_{dc}, which lead to a in a reduction in p, and as a result in a q reduction as well.

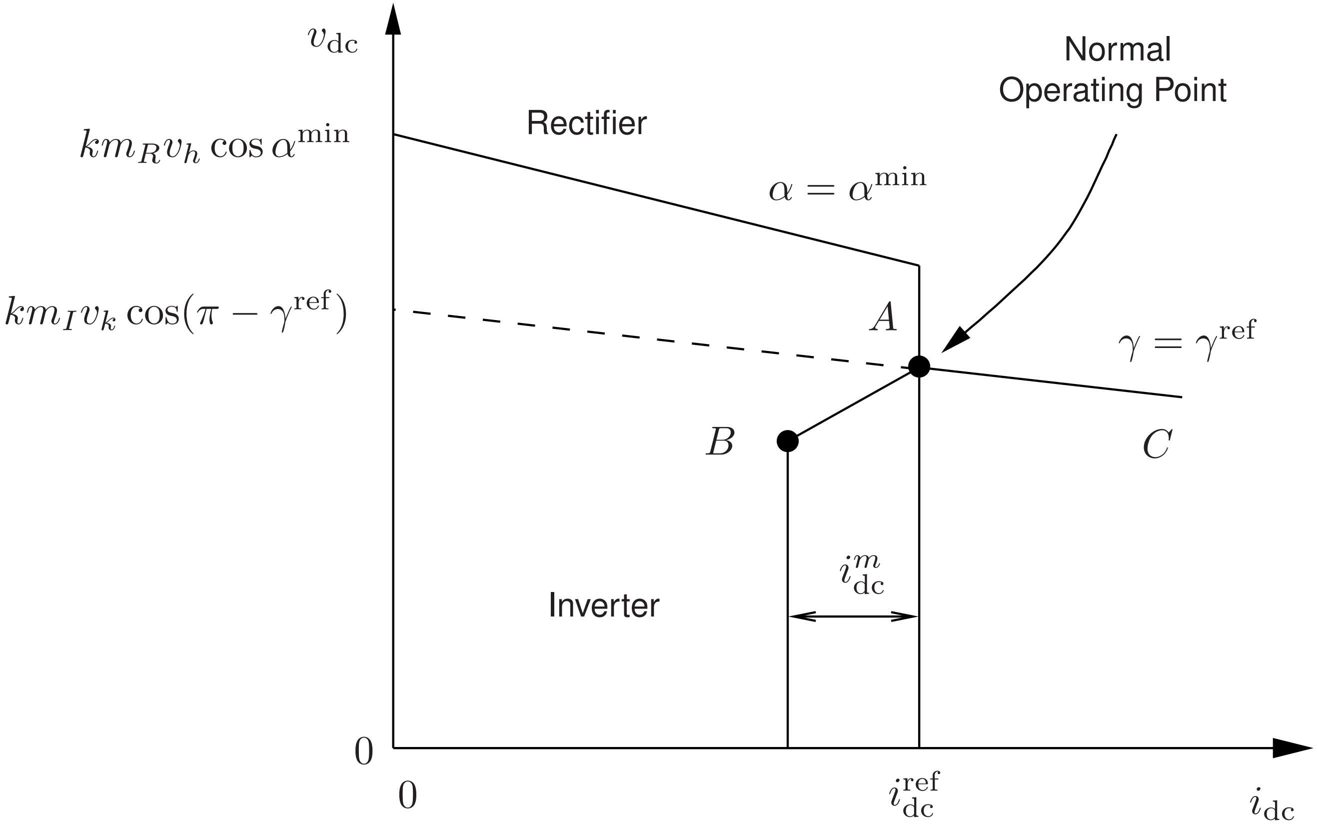
Voltage Dependent Current Order Limiter VDCOL (II)

- The steady-state characteristic of the VDCOL is illustrated below.



Positive Slope Section (I)

- The positive slope section between points B and A, was originally introduced to avoid that the characteristics of the converters, $\alpha^{\min}$ for the rectifier and the minimum extinction angle $\gamma^{\min}$ for the inverter were nearly parallel.



Positive Slope Section (II)

- The positive slope is important for the stability of the current control system.
- When the inverter is operating in the constant γ mode, the rectifier sees the inverter as a negative impedance.
- For lower frequencies in the dc current fluctuations the characteristics A-C in the previous figure has a negative slope.
- This means that the voltage across the inverter decreases with an increasing current.

AC/DC System Interaction (I)

- Reference for the remainder of the lecture:

  J. Arrillaga, Y. H. Liu, N. R. Watson, “Flexible Power Transmission - The Hvdc Options”, Wiley, 2007.

- The exclusive use of the basic controls often gives rise to unwanted interaction between the AC and DC systems, which is manifested in a variety of voltage, harmonic and power instabilities.
- When full advantage is taken of the fast and adaptable converter controllability a more useful interaction can be achieved which manifests itself in stable AC and DC system operation.
- AC/DC system interactions are concerned with voltage stability, overvoltages, resonances and recovery from disturbances.

AC/DC System Interaction (II)

- Voltage stability criteria are used to determine the type of voltage control and of reactive power supply.
- The level of temporary overvoltage (TOV) influences station design, including thyristor valve and surge arrester ratings. The TOV levels will increase with decreasing values of the short-circuit ratio (SCR), the ratio of the AC system MVA fault at the converter terminals to the nominal DC power.
- Shunt capacitors are used in converter stations as part of the AC filters and VAR compensation. The larger the ratio of shunt capacitor MVAR to AC system short-circuit MVA, the lower will be the resonant frequency.
- Recoveries from AC and DC faults are slower with weak systems (i.e. high-impedance source), although modern controls are less affected by the system impedance than those used in earlier schemes.

Voltage Interaction

- The rectifier and the inverter consume reactive power, which can be typically 60% of the power transmitted at full load.
- If the presence of local generators (i.e. close to a rectifier) can be guaranteed, it is always more economical to supply most reactive power from these, with minimum size filters to reduce harmonics.
- In general, however, it is necessary to provide full reactive power compensation to the converter and, sometimes, extra compensation for the AC system loads as well.

Dynamic Voltage Regulation

- During HVDC link disturbances, voltage control requirements depend on the nature and location of the disturbance.
- The reactive power consumption is partially or totally eliminated following the disturbance, with the result of considerable dynamic overvoltage regulation.
- Following a voltage drop in the AC network, the initial effect is a fall in power.
- The power controller of the DC link then increases the current reference to try and restore the ordered power; the extra current increases the reactive demand and tends to reduce the AC system voltage further.
- With very weak AC systems this could lead to voltage collapse; however, power controllers always have limits built in to avoid excessive action.
- Dynamic compensation equipment is used to reduce the dynamic voltage regulation (e.g., shunt FACTS devices).

Dynamic Stabilisation of AC Systems

- An example of dynamic instability [15] is the northern and southern parts of the Western US power system, which are connected by the parallel Pacific AC and DC Interties with ratings of 2500 and 1400 MW, respectively.
- The AC Intertie has a long history of negatively damped 1/3 Hz oscillations resulting from interactions between generators with automatic voltage regulators and system loads.
- As a result of these oscillations, and because the oscillatory tendency imposed a constraint on the amount of surplus northwest hydro power which could be transmitted to the southwest, a control system to modulate the Pacific DC Intertie was developed.
- Damping in the Pacific Intertie was produced by small signal modulation of the DC power in proportion to the frequency difference across the AC Intertie.

Controlled Damping of DC Interconnected Systems

- With an AC tie line, if one of the interconnected systems is in difficulty following a disturbance, the line is normally tripped to prevent the disturbance affecting the other system, and thus the system in difficulty loses an essential infeed.
- An HVDC link, on the other hand, even with the basic controls, shields one system from disturbances on the other.
- Although the specified power flow can continue, the option is available to vary the power setting to help the system in difficulty to the extent which the healthy system can allow, without putting itself in difficulty, and subject to the rating on the link.
- With appropriate control, a disturbance originating in either system can be shared in a predetermined manner, and the resulting system oscillations can be damped simultaneously.

Damping of Subsynchronous Resonance

- The torsional modes of vibration of the turbine/generator shaft are normally stable when connected to an AC transmission system.
- With the addition of series capacitor compensation in the AC network, however, the negative damping contribution of the AC system is dramatically increased when the electrical and mechanical resonant frequencies are close.
- Under these conditions the torsional modes of vibration can become unstable, a phenomenon which is commonly referred to as sub-synchronous resonance (SSR).
- The potential destabilisation of torsional oscillations due to HVDC systems is similar to that caused by series-compensated AC transmission lines.
- However, the interaction with DC systems can be solved relatively simply by providing power modulation control to cancel the negative damping impact of the basic constant power control loop.

Other Interactions

- *Active and Reactive Power Coordination*: Coordination between the active and reactive power modulation can be achieved by DC system voltage modulation. An increase in DC voltage will increase the DC power transfer as well as the power factor at both terminals, and hence decrease the reactive consumption as a percentage of active power transmitted.
- *Transient Stabilisation of AC Systems*: If the loss of synchronism is irrelevant, as in the case of an HVDC link connecting generation to load areas, it is advantageous to increase the sending end DC link power in the post-fault period in response to the increase of generator speed. This action will remove energy from the generator, reduce its speed, and thus reduce the angular displacement between the generator and the AC receiving system.