CHAPTER 7

HIGH VOLTAGE DC (HVDC) TRANSMISSION SYSTEMS

HVDC

HVDC (High Voltage Direct Current) transmission systems connect two separate high voltage AC Systems via a DC link.

The basic principle of operation of an HVDC system is based on the conversion of AC to DC and vice-versa by means of converter valves comprising power thyristors, which are the heart of a converter station.

Why HVDC

They are a useful supplement or in some cases the only alternative for traditional High Voltage Alternating Current (HVAC) systems.

Advantages

- Economically transmit electrical energy long distances via overhead lines or cable,
- Connect asynchronous grids with different voltages or frequencies,
- Connecting a remote generating plant to the distribution grid,
- Reducing line cost. HVDC needs fewer conductors as there is no need to support multiple phases. Also, thinner conductors can be used since HVDC does not suffer from the skin effect,

It is particularly suited to harnessing wind power generated offshore onto onshore grids, and for connecting offshore oil platforms to mainland grids??

Symbols and Capabilities of Power Semiconductor Devices

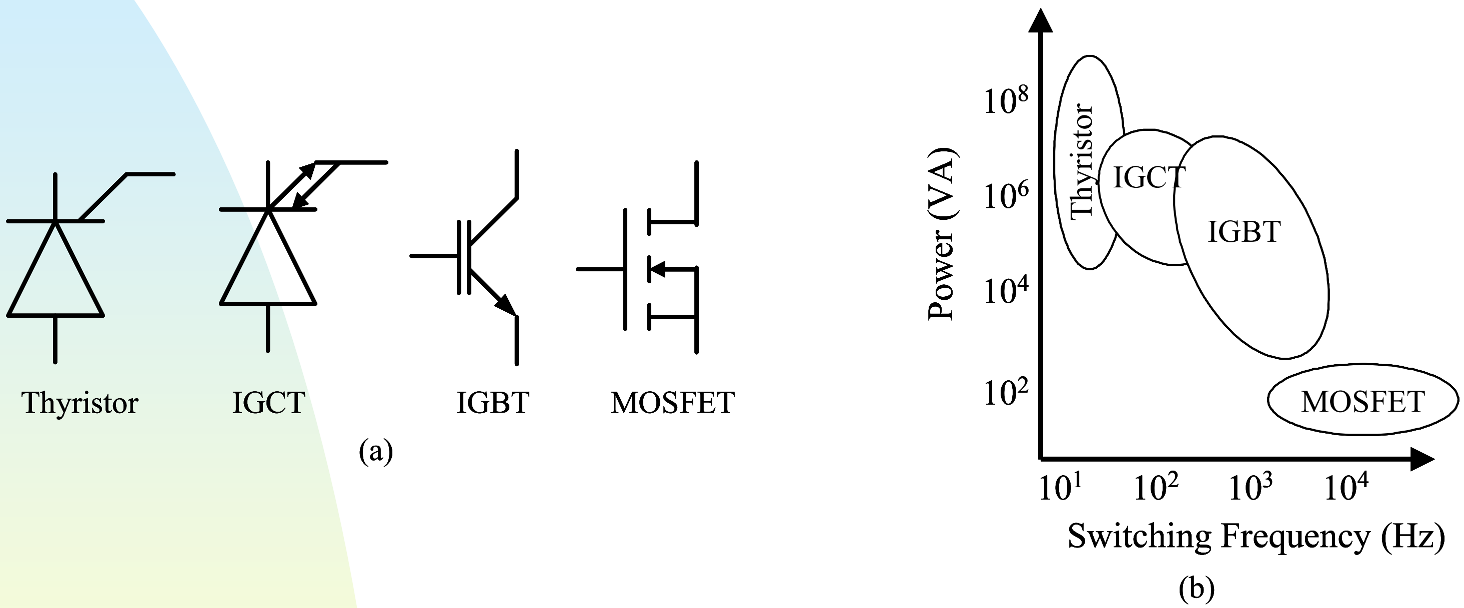
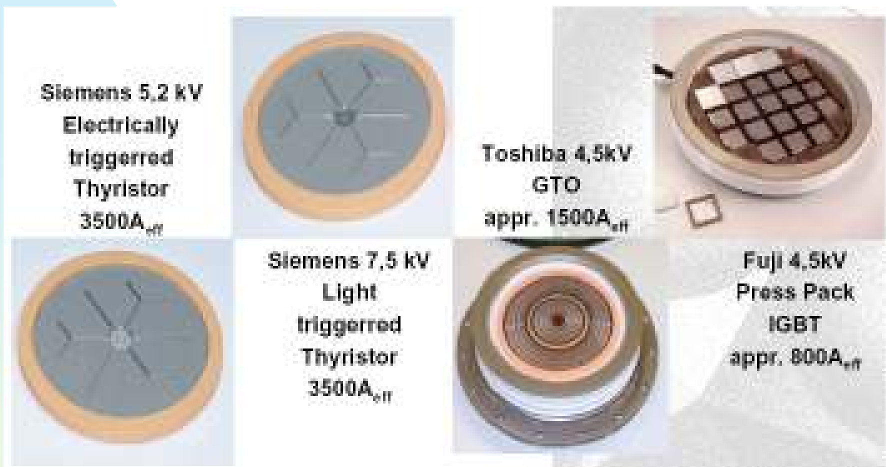


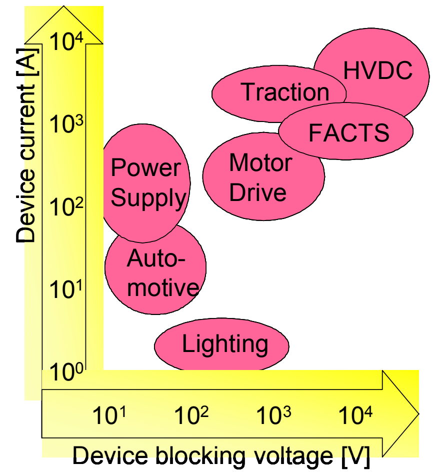
Fig. 7-1 Power semiconductor devices.

http://www.energy.siemens.com/cms/us/US_Products/Portfolio/HVSystemsupto800kV/HighVoltageDCTransmissionSystems/Pages/BasicsofHVDCTransmissions.aspx

Power Semiconductor Devices and Applications



(*a*)



(*b*)

Figure 7-2 Power semiconductor devices: (a) ratings (source: Siemens), (b) various applications (source: ABB).

HVDC System

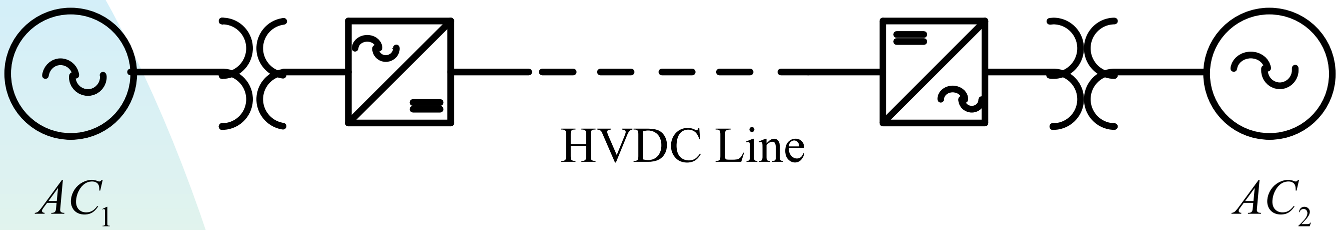


Fig. 7-3 HVDC system – one-line diagram.

Direction of the power flow can be reversed

HVDC Systems:

Current-Link System using thyristors

Voltage-Link uses switches such as IGBT

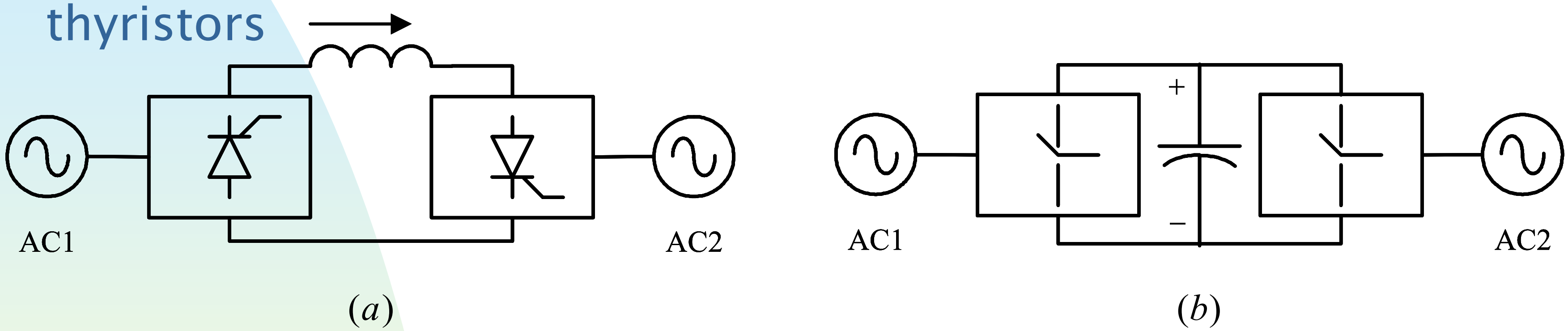


Fig. 7-4 HVDC systems: (a) Current-Link, and (b) Voltage-Link.

Both systems are discussed in this chapter

HVDC Projects in North America

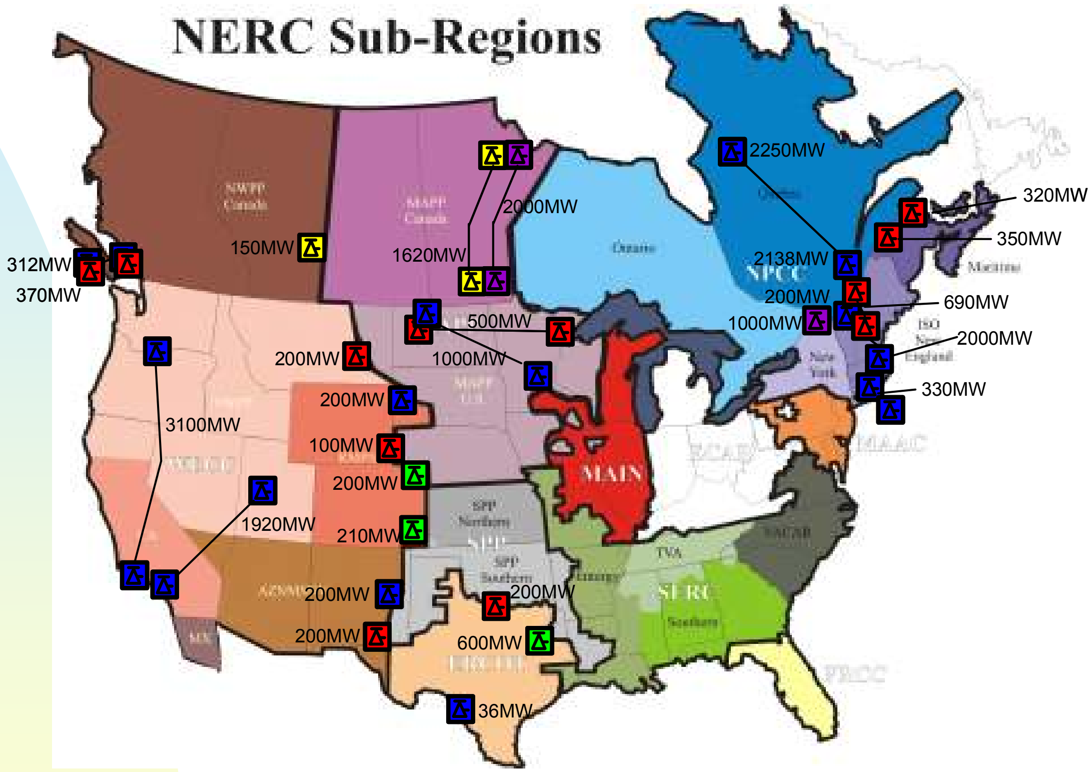


Fig. 7-5 HVDC projects, mostly current-link systems, in North America [source: ABB]

Current-Link HVDC System

Mono pole or Bipolar?

Monopole:
One HV line for DC current transmission.
Return path optionally via ground or LV conductor Rating up to 1500 MW

Bipolar:
Two DC lines with +/- DC voltage level for transmission
Rating up to 3000 MW

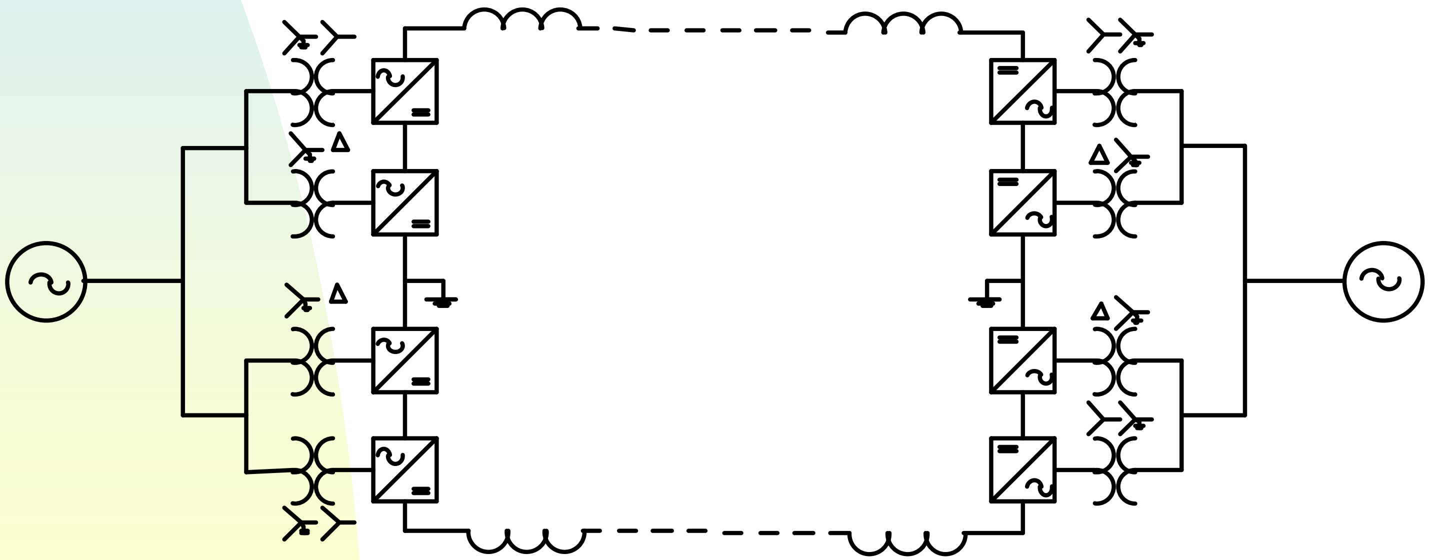


Fig. 7-6 Block diagram of a current-link HVDC system.

Thyristors

A thyristor (or SCR) is like a transistor. When a small current flows into the *GATE* (G), this allows a larger current to flow from the *ANODE* (A) to the CATHODE (K). Even when the current into the gate stops the thyristor continues to allow current to flow from anode to cathode. It latches on.

Like diodes, they conduct current in forward direction.

But unlike diodes thyristors can also block the flow of the current in forward biased situation

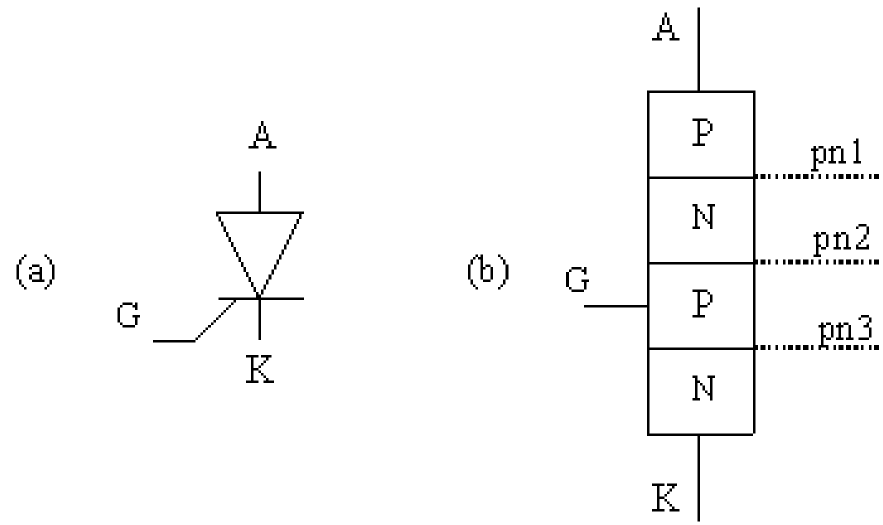


Fig. 7-7 Thyristors.

http://www.technologystudent.com/elec1/thyris1.htm

Primitive Thyristor Circuit to convert ac into dc

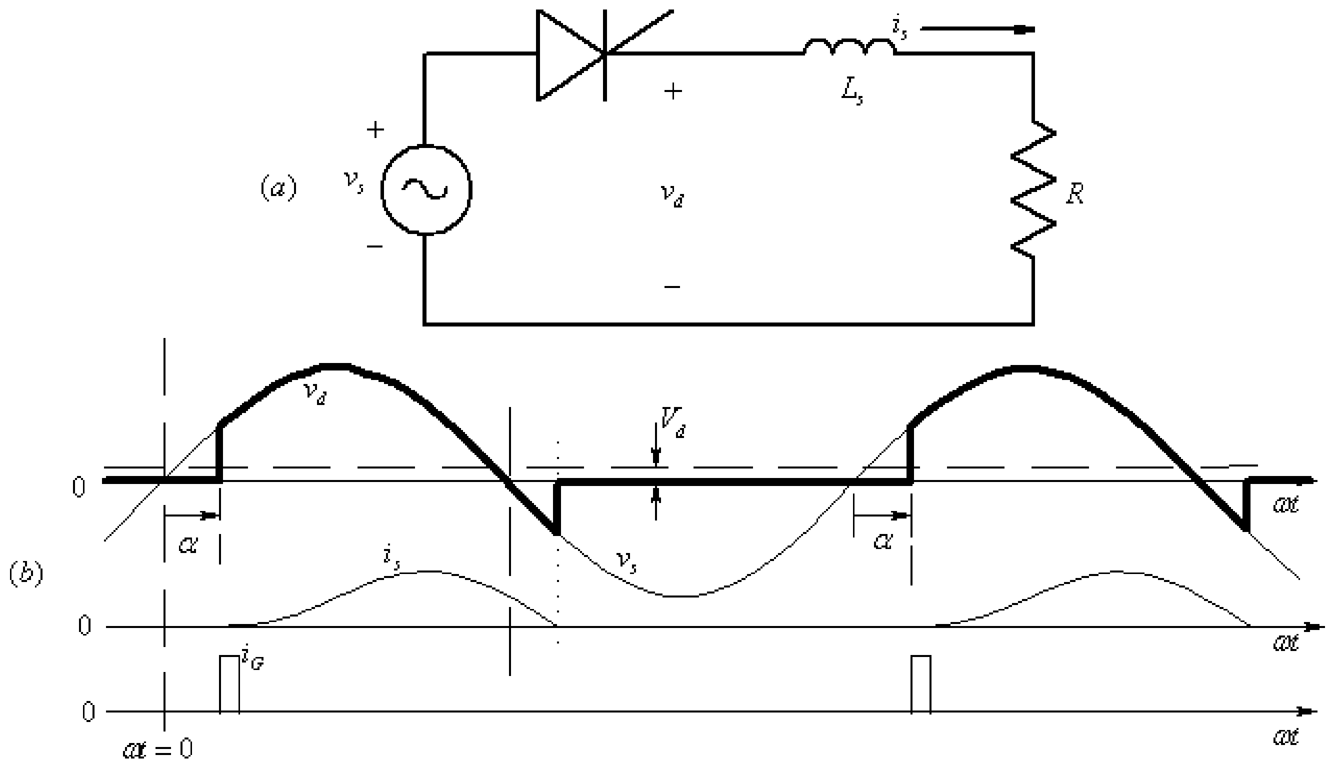


Fig. 7-8 Thyristor circuit with a resistive load and a series inductance.

http://www.google.com/#hl=en&q=three+phase+full+bridge+thyristor+converter&aq=f&oq=&aqi=&fp=KxYPMM6r3XA

Three-Phase Thyristor Converter

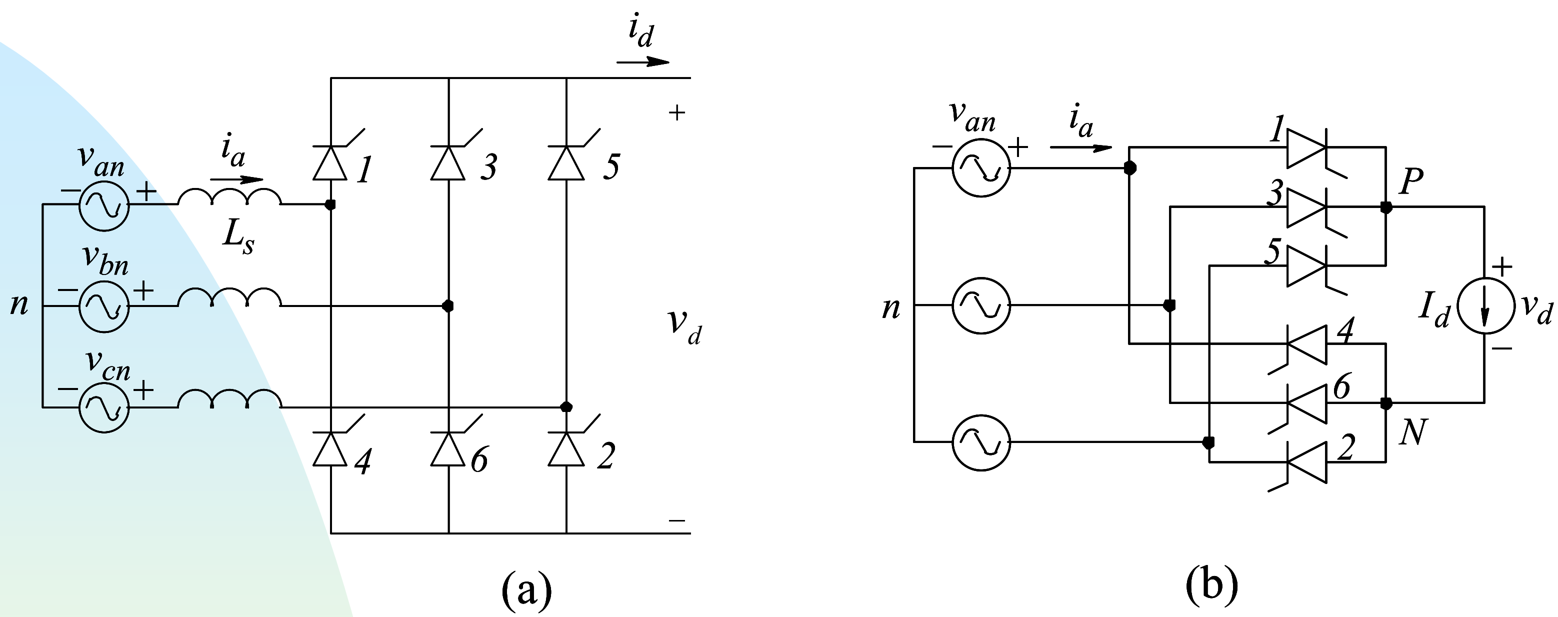


Fig. 7-9 Three-phase Full-Bridge thyristor converter.

- Current flows through one diode from the top group and one from the bottom
- Diode with highest anode potential from the top and diode with lowest cathode potential from the bottom will conduct

Three-Phase Diode Rectifier Waveforms (Ls=0, α=0)

Each waveform is on for 120°, off for 60, and on again (on the negative cycle) for 120°

$v_d = v_{Pn} - v_{Nn}$ is the line to line voltage within each 60° interval as shown in (b)

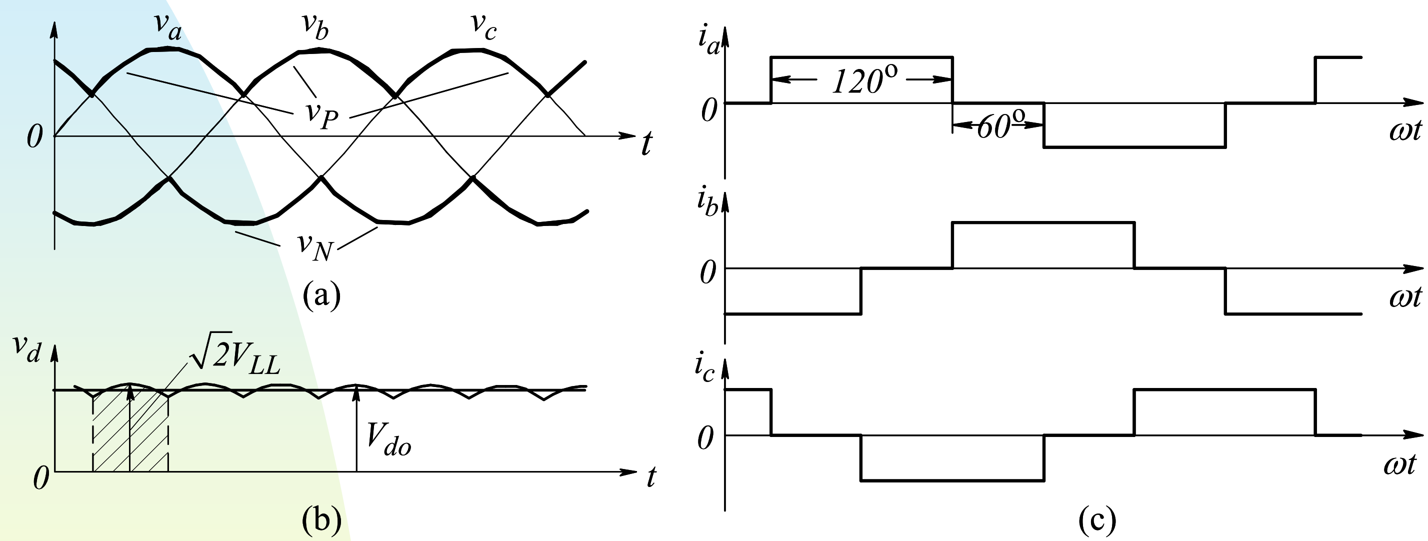


Fig. 7-10 Waveforms in a three-phase rectifier with $L_s = 0$ and $\alpha = 0$.

$$V_{d0} = \frac{1}{\pi/3} \int_{-\pi/6}^{\pi/6} \sqrt{2} V_{LL} \cos(\omega t).d(\omega t) = \frac{3\sqrt{2}}{\pi} V_{LL}$$

Three-Phase Thyristor Converter Waveforms with zero AC-Side Inductance **(Ls=0, α≠0º)**

In some applications (battery charger, some ac/dc drives), the dc voltage has to be controllable

Thyristor converters provide controlled conversion of ac into dc

Primarily used in three-phase, high power application

The drop in the dc voltage is:

$$\Delta V_\alpha = \frac{1}{\pi/3}\int_0^\alpha \underbrace{\sqrt{2}V_{LL}\sin\omega t . d(\omega t)}_{A_\alpha}$$

$$= \frac{3\sqrt{2}}{\pi}V_{LL}(1-\cos\alpha)$$

$$V_{d\alpha} = V_{d0} - \Delta V_\alpha = \frac{3\sqrt{2}}{\pi}V_{LL}\cos\alpha$$

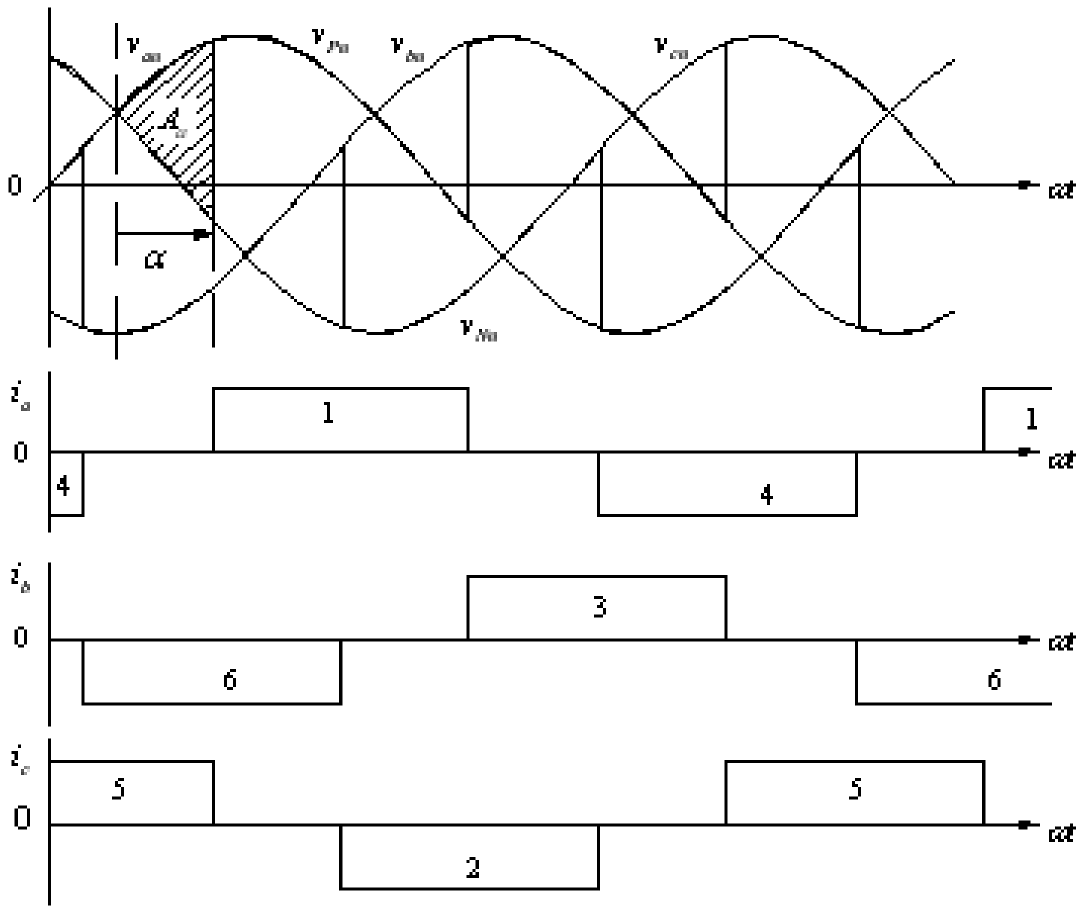


Fig. 7-11 Waveforms with $L_s = 0$.

for $0 \le \alpha \le 90$ V_{da} is positive - rectifier

for $\alpha \ge 90$ V_{da} is positive - inverter

Three-Phase Inverter Waveforms (α=150º)

This example shows the inverter mode of operation

On the dc side, v_{Nn} is positive and v_{Pn} is negative

$\therefore v_{Pn}\ (= v_{Pn} - v_{Np})$ is negative

Therefore the dc-side average voltage will be negative

Therefore the flow of the power is from ac side to dc side

On the ac-side, the phase-current waveforms are shifted (lagging) by α=150º

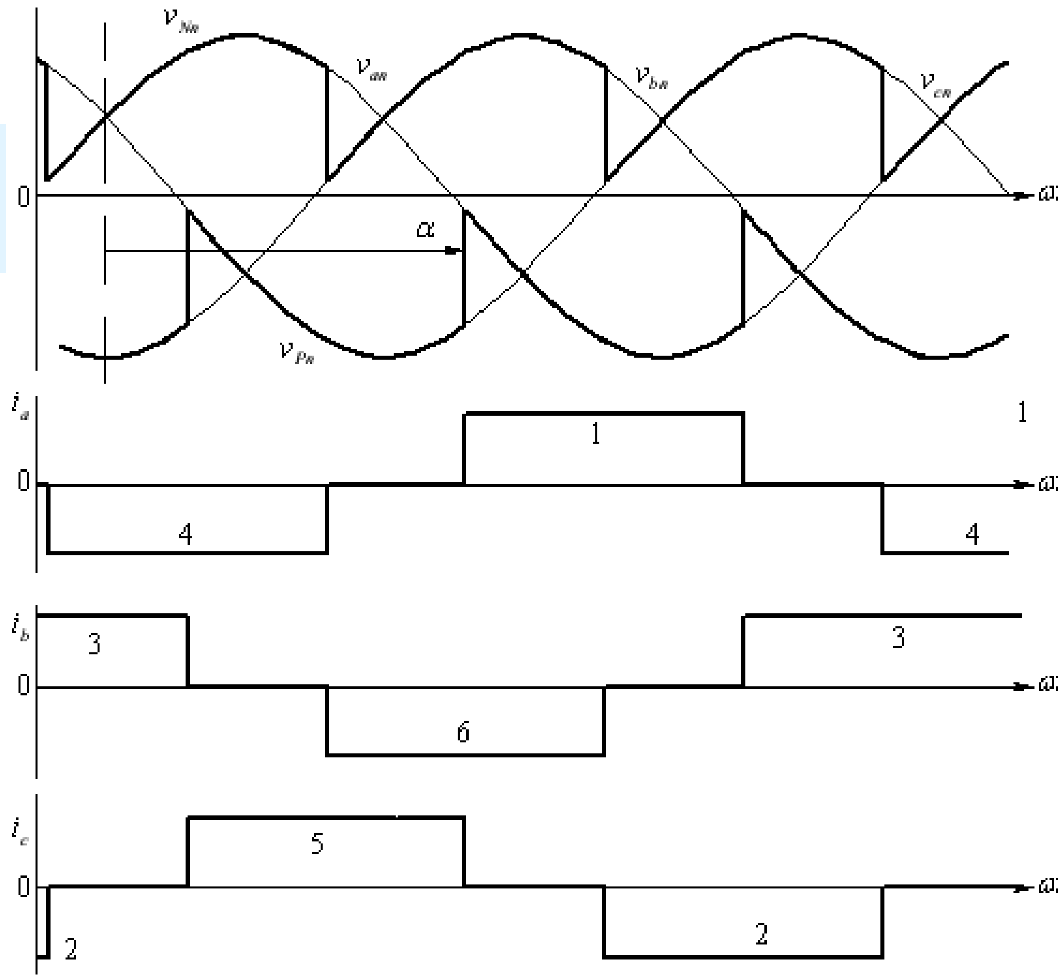


Fig. 7-12 Waveforms in the inverter mode.

DC-Side Voltage as a Function of Delay Angle

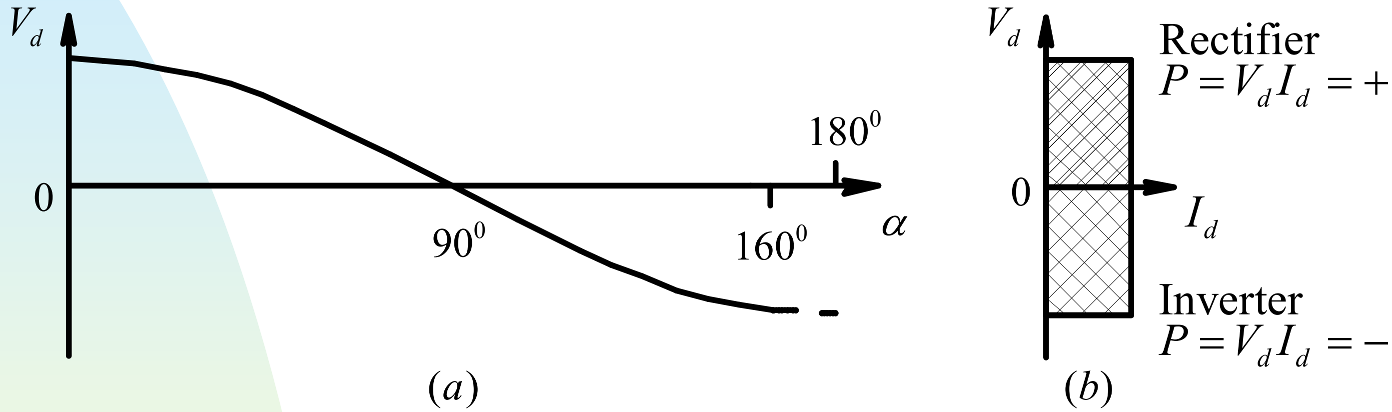


Fig. 7-13 Average dc-side voltage as a function of α .

Thyristor Converter Waveforms in the Presence of AC-Side Inductance **Ls≠0, α≠0º**

L_s=0 meant that ac-side currents commutates instantly from one thyristor to another

For L_s≠0, it takes an interval u for current to commutate from one thyristors to another

The average dc voltage will be reduced by an additional area A_u for every π/3 radians.

On the ac-side, the phase-current waveforms are shifted by α=150º

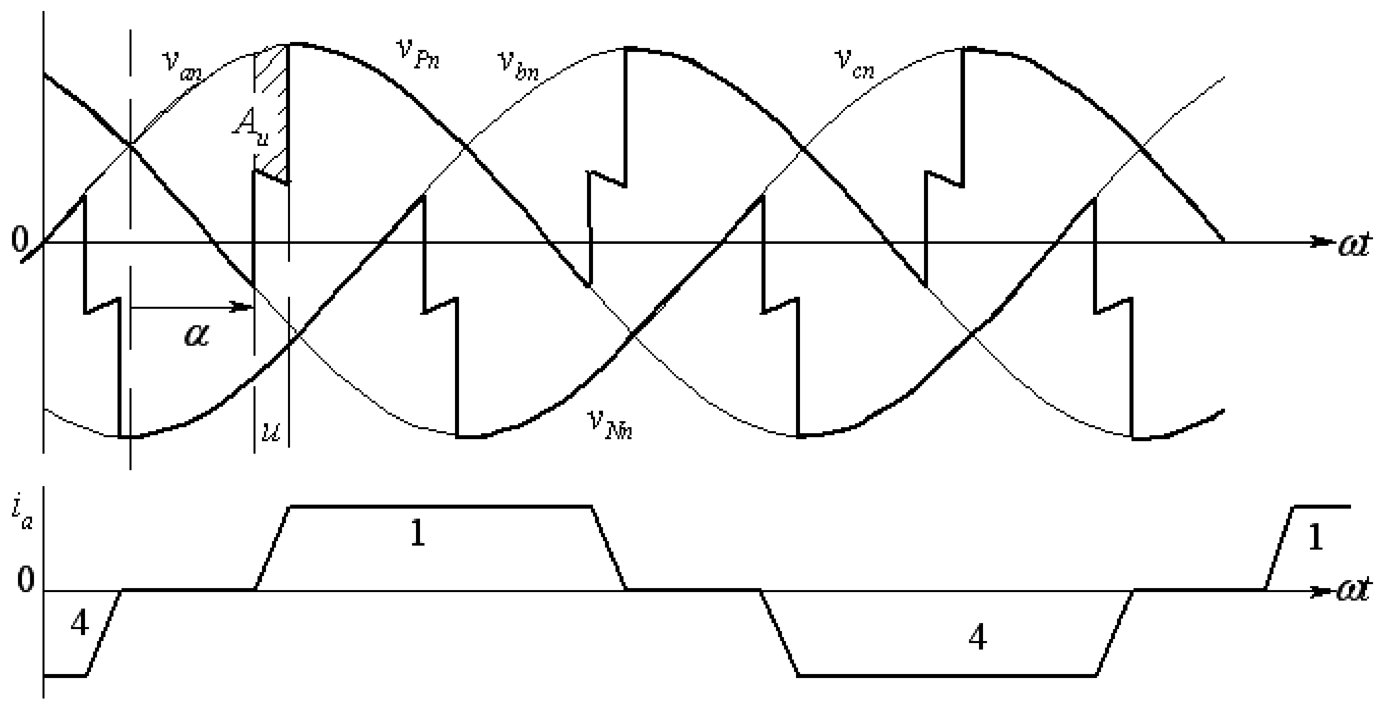


Fig. 7-14 Waveforms with L_s .

The current on the ac-side of the converter follows a trapezoid shape

Area by which the dc voltage is reduced is:

$$A_u = \int_{\alpha}^{\alpha+u} v_L \, d(\omega t) = \omega L_s \int_{0}^{I_d} di_s = \omega L_s I_d$$

The additional voltage drop due to L_s is then $\Delta V_u = \frac{A_u}{\pi/3} = \frac{3}{\pi}\omega L_s I_d$

The dc-side voltage is: $V_d = V_{d\alpha} - \Delta V_u = \frac{3\sqrt{2}}{\pi} V_{LL}\cos\alpha - \frac{3}{\pi}\omega L_s I_d$

$$V_d = \frac{3\sqrt{2}}{\pi} V_{LL}\cos(\alpha+u) + \frac{3}{\pi}\omega L_s I_d \qquad ??? \qquad (7-9)$$

Power Factor Angle in Rectifier and Inverter Modes

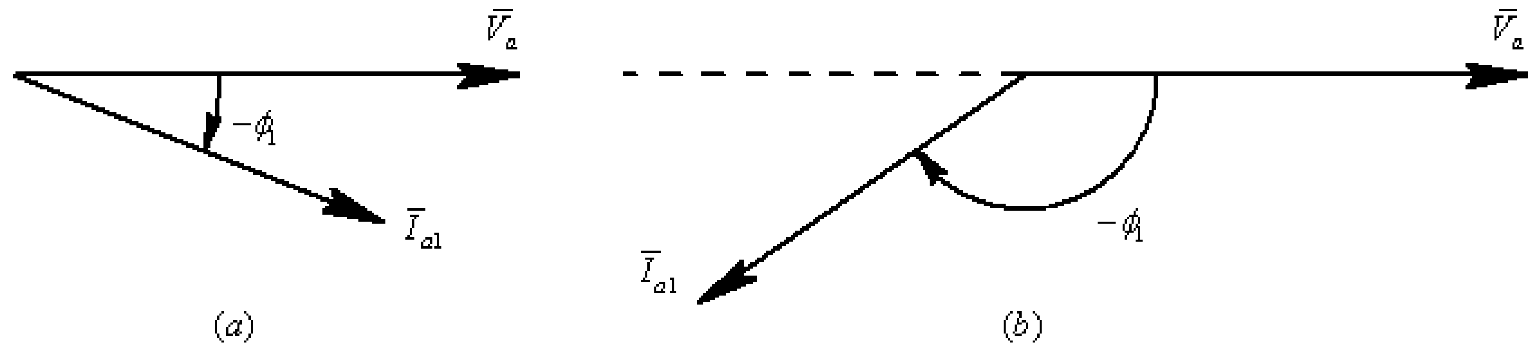


Fig. 7-15 Power-factor angle.

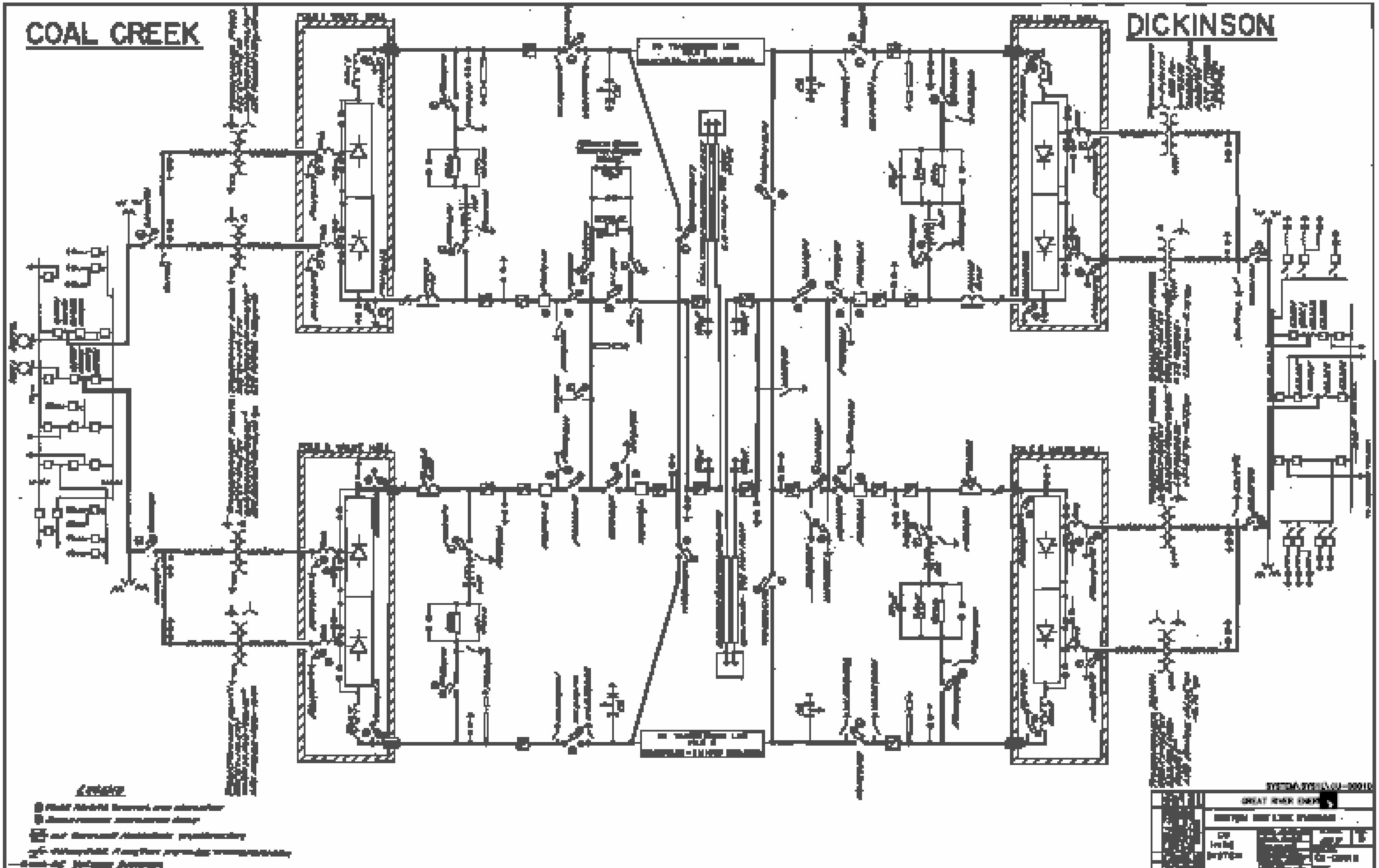
In the rectifier mode, the fundamental component i_{a1} lags the phase voltage by $\Phi_1=\alpha+u/2$

In the inverter mode, $\Phi_1=\alpha+u/2+180^o$

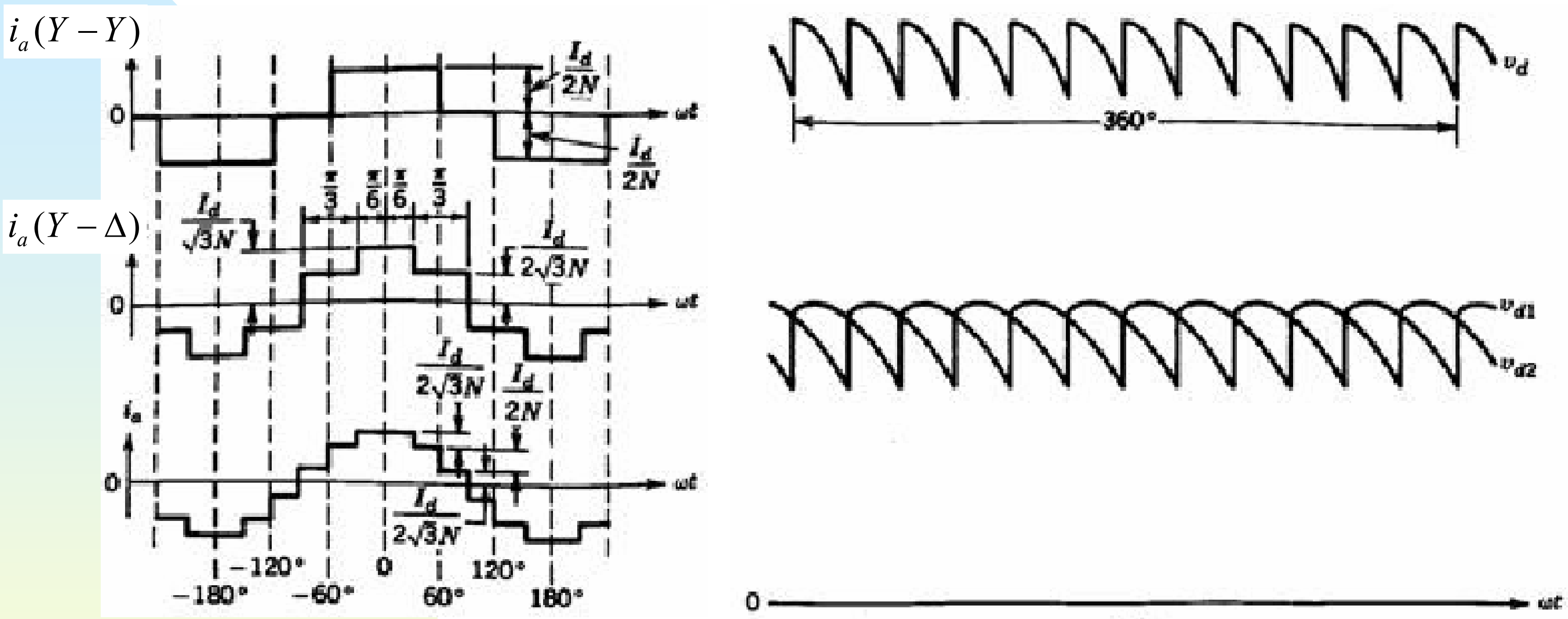
The power factor (PF)=$\cos(\alpha+u/2)$ lagging

the 3-phase reactive power consumed by the converter is:
$Q_{3\varphi} = 3V_a I_a \sin(\alpha + u/2)$

HVDC CU project - One-line Diagram



12-Pulse Waveforms



(a) (b)

Fig. 7-17 Six-pulse and 12-pulse current and voltage waveforms [2].

HVDC System Representation for Control

One of the two poles (the positive pole) is shown

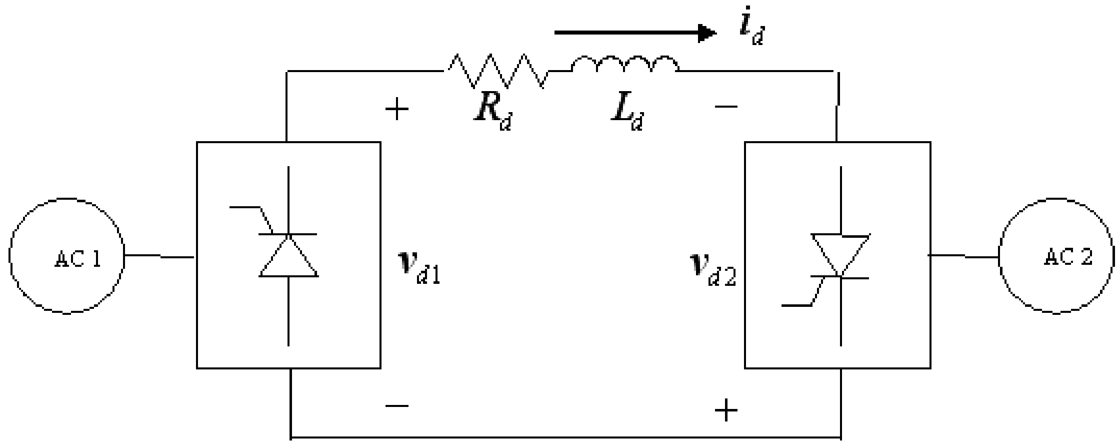


Fig. 7-18 A pole of an HVDC system.

Since each terminal consists of two six-pulse thysistors, then:

$$V_{d1} = 2 \times \left[\frac{3\sqrt{2}}{\pi} V_{LL1} \cos \alpha_1 - \frac{3}{\pi} \omega L_{s1} I_d \right]$$

$$V_{d2} = 2 \times \left[\frac{3\sqrt{2}}{\pi} V_{LL2} \cos \alpha_2 - \frac{3}{\pi} \omega L_{s2} I_d \right]$$

By controlling the delay angles α_1 α_2 , v_{av} and i_{av} and p_{av} can be controlled

HVDC System Representation for Control

current through the dc link is: $I_d = \dfrac{V_{d1} + V_{d2}}{R_d}$

For power to flow from system 1 to system 2, V_{d2} has to be made negative

Which is done by choosing α_2 to make it operate as inverter and set the voltage of the dc link

α_1 is chosen such that it controls the flow of he current in the dc-link