Electronics and
Computer Science

ELEC2208 Power Electronics and Drives

Rectifier (2)

- Three Phase Rectifier -

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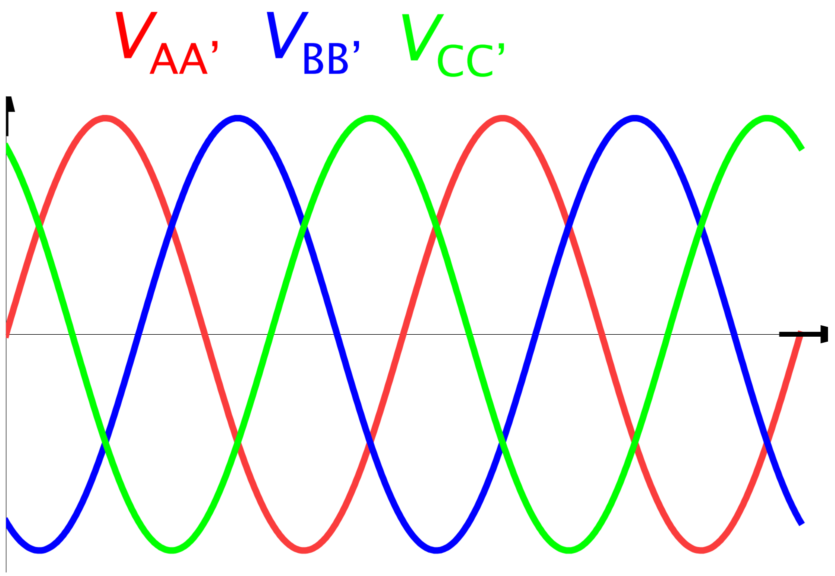
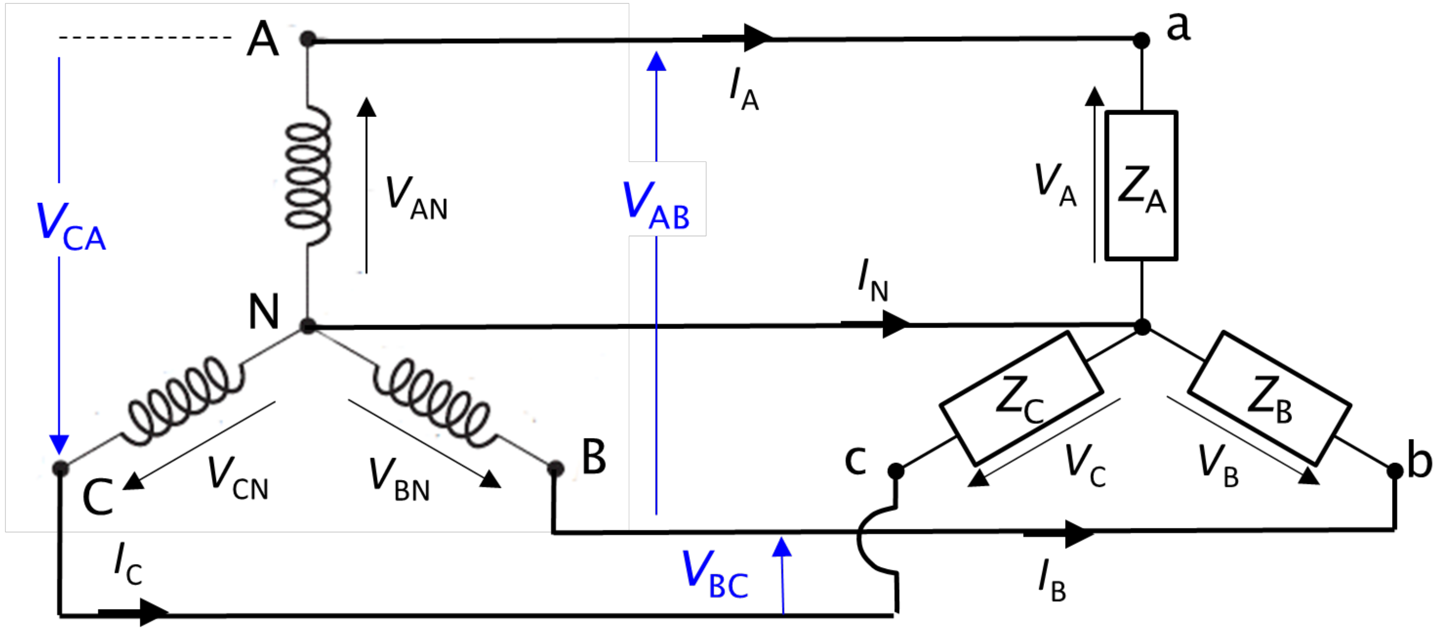
Three phase - Revision

Star-Star system





(1) Which are the phase voltages (source)? V_{AN}, V_{BN}, V_{CN}

(2) Which are the line-to-line voltages? V_{AB}, V_{BC}, V_{CA}

V_P: Peak phase voltage, V_L: Peak line-to-line voltage

(3) How V_P is expressed with V_L?

$$V_P = \frac{V_L}{\sqrt{3}}$$

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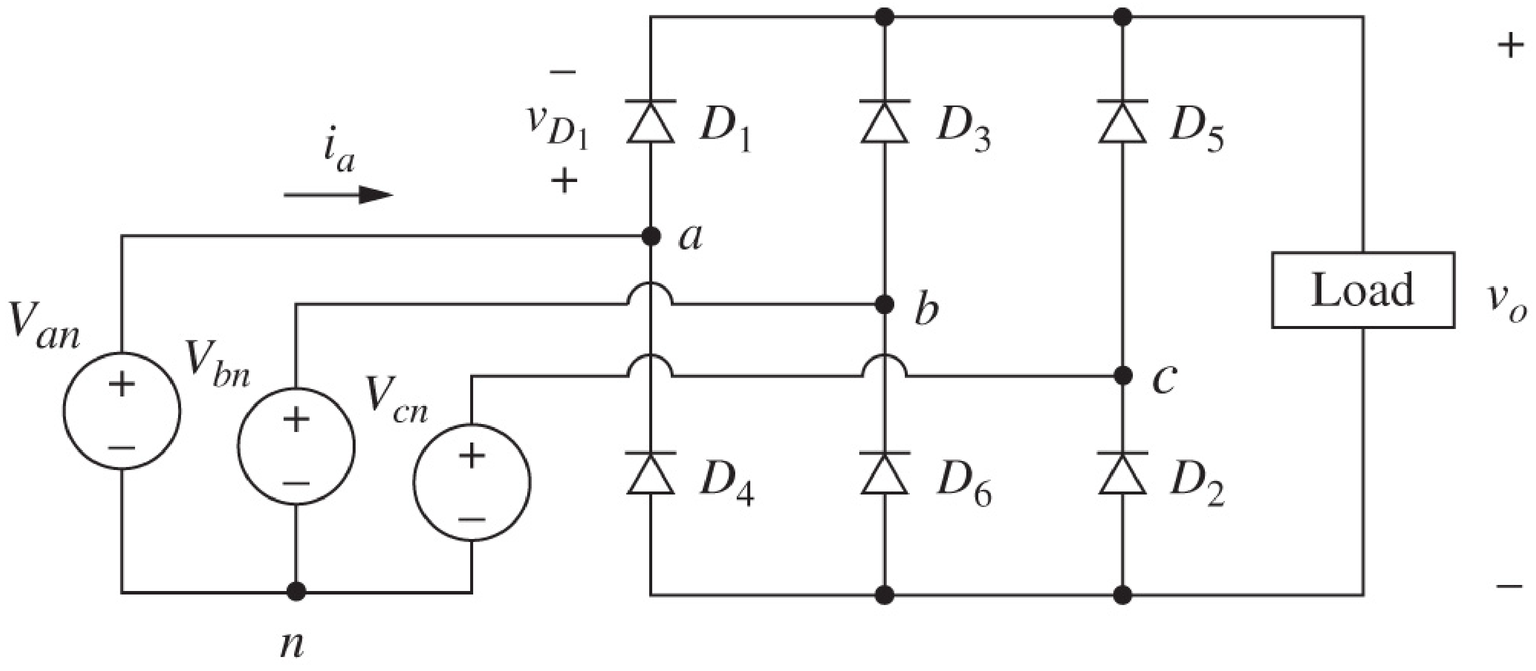
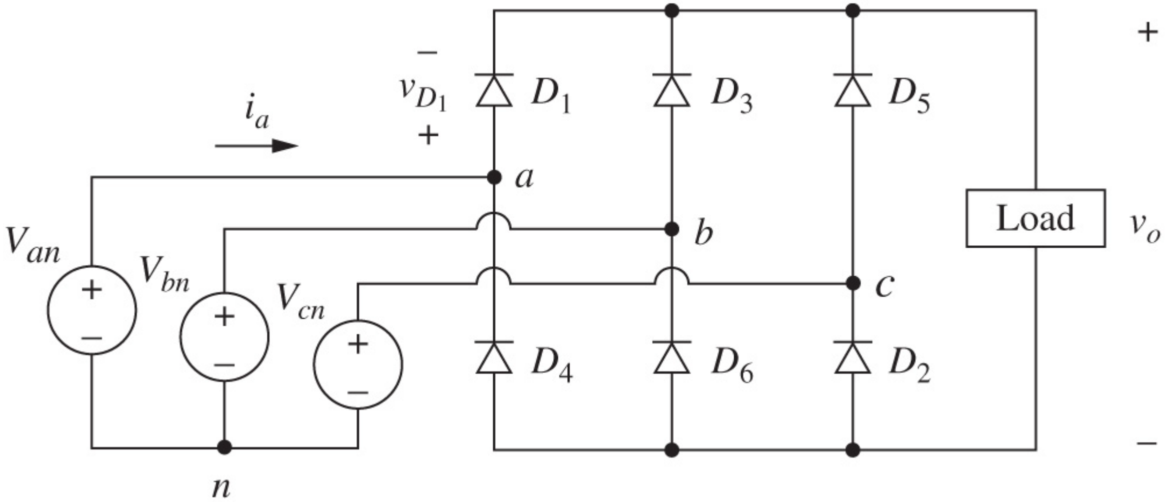
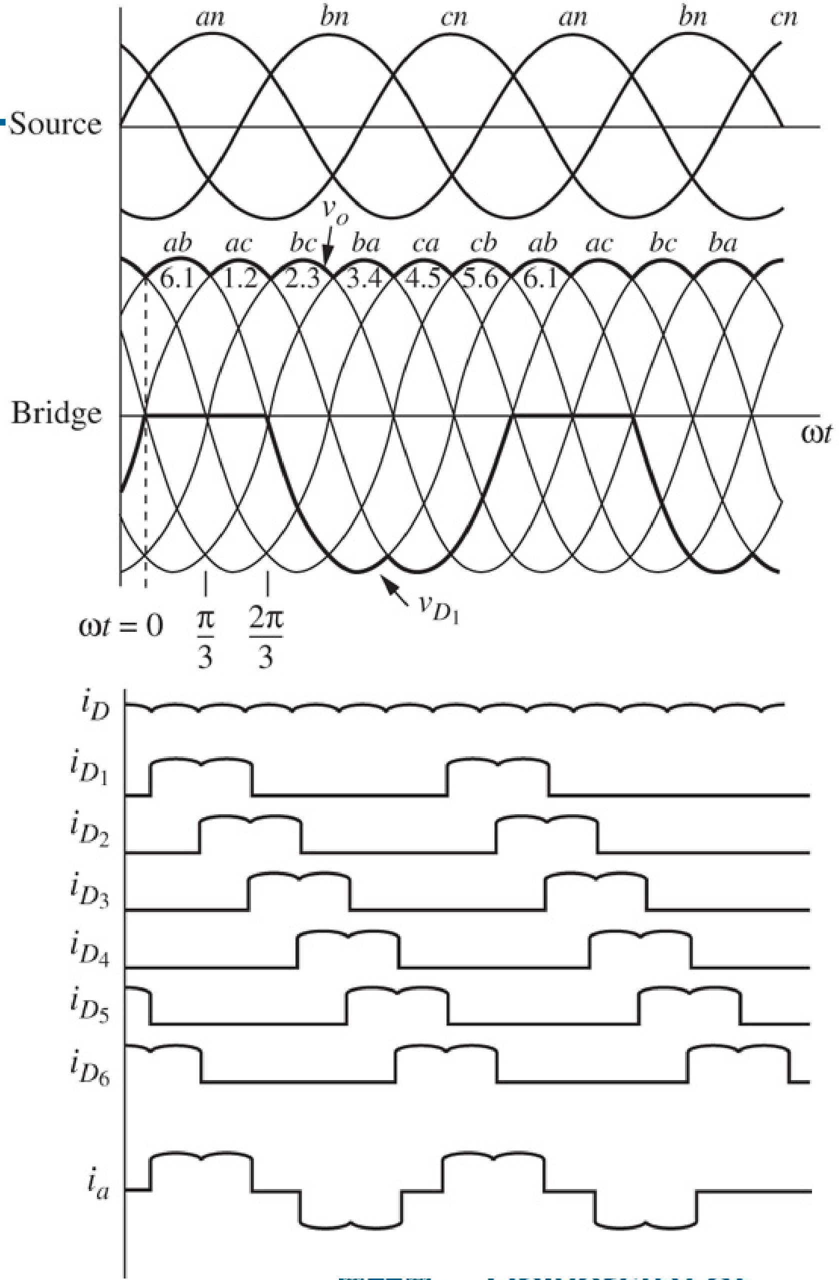
Three Phase Uncontrolled Rectifier



- Three phase rectifiers are commonly used in industry to produce a dc voltage and current for large loads.
- 6-pulse rectifier.

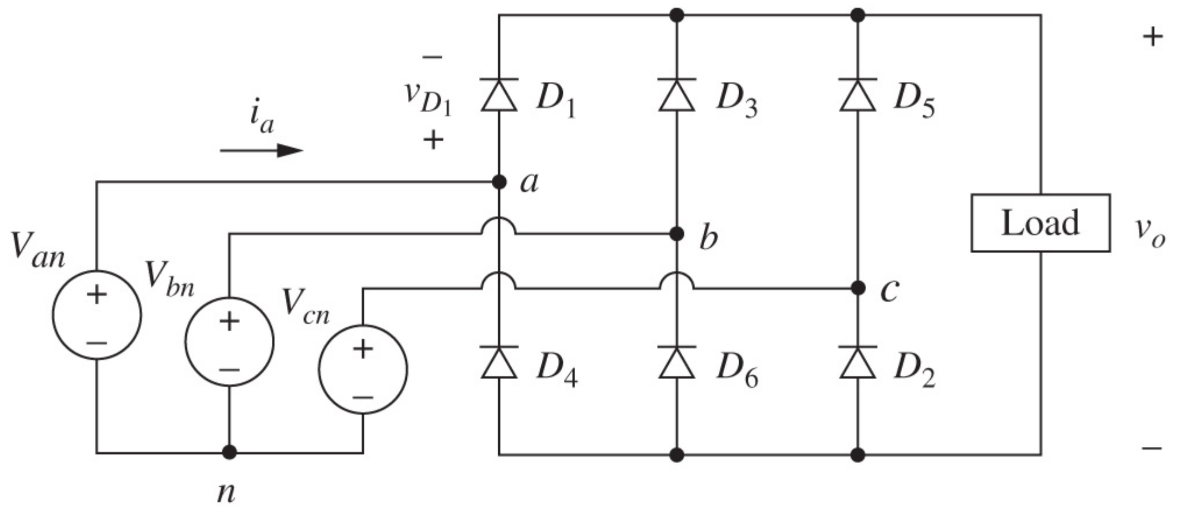
Waveform

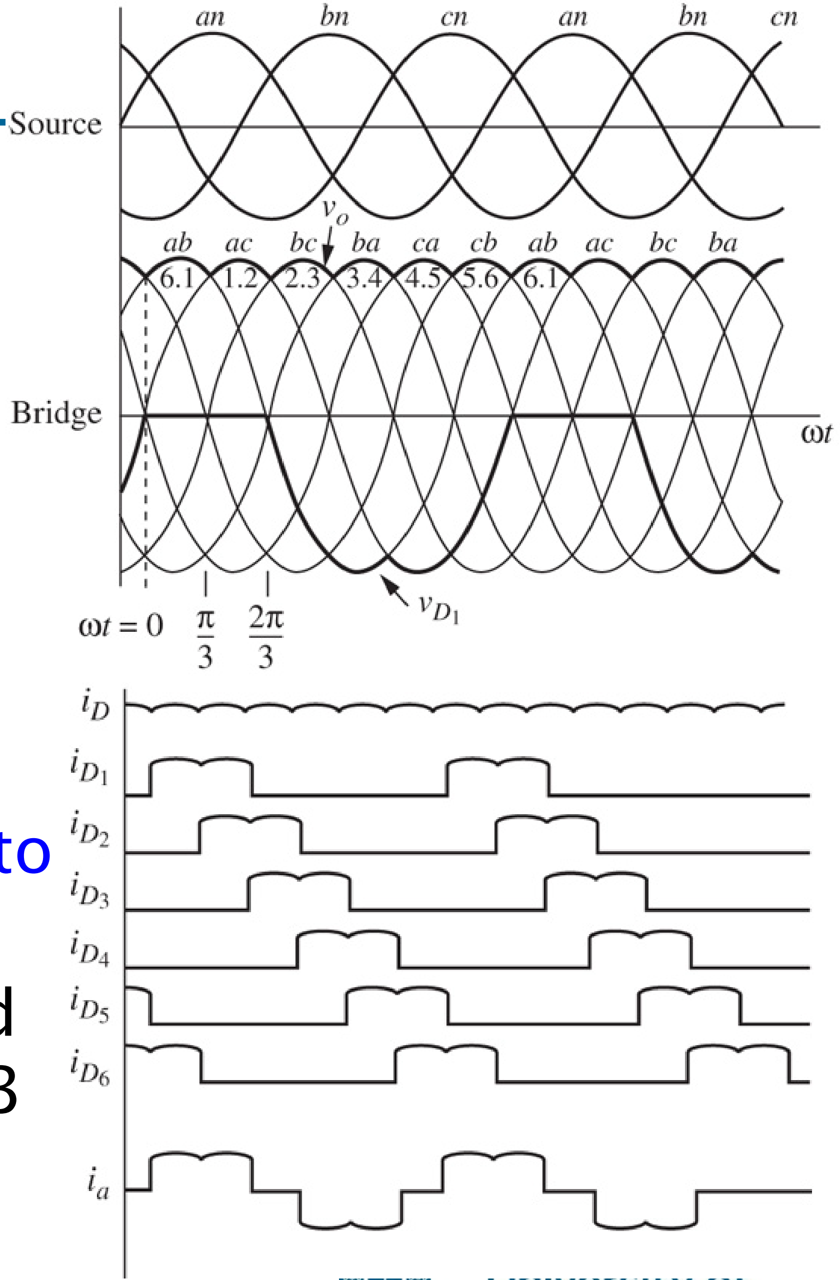




- Output voltage consists of 6 combinations (6 pulses of 60 degree) of line-to-line voltages.
- KVL around any path shows that only one diode in the top half may conduct at one time (D1, D3, or D5). The conducting diode will have its anode connected to the phase voltage that is highest at that instant.

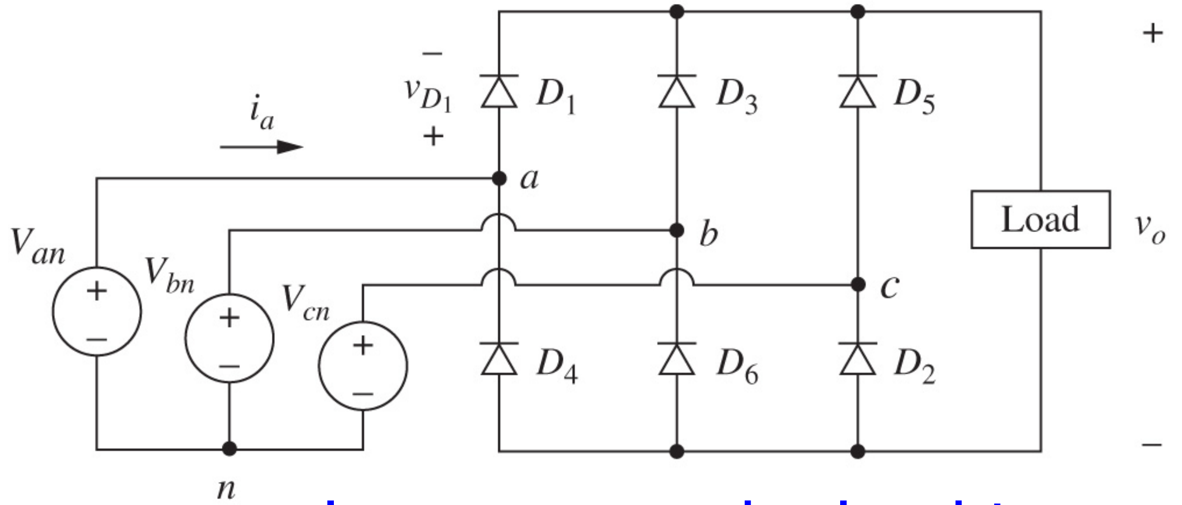
Waveform

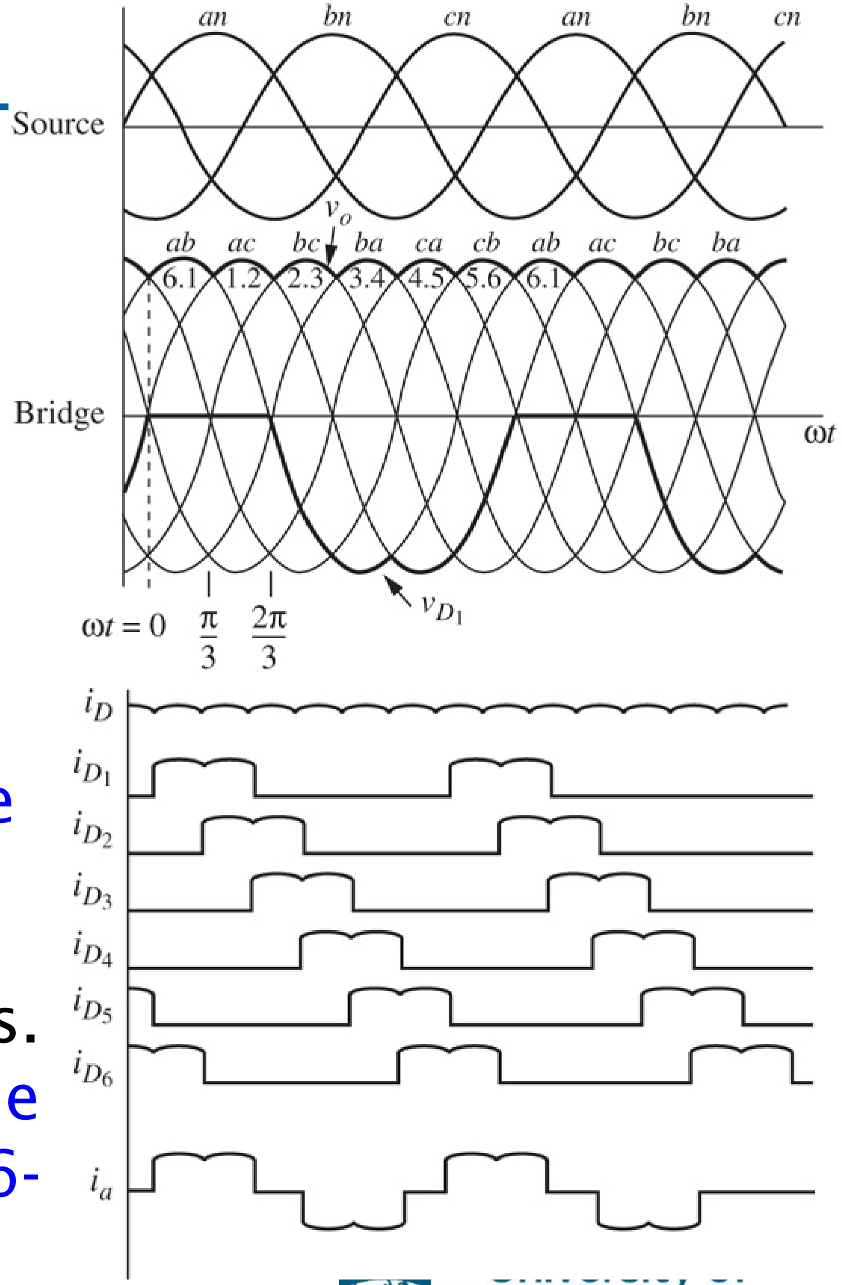




- KVL also shows that only one diode in the bottom half may conduct at one time (D2, D4, or D6). The conducting diode will have its cathode connected to the phase voltage that is lowest at that instant.
- As a consequence of items 1 and 2 above, D1 and D4 cannot conduct at the same time. Similarly, D3 and D6 cannot conduct simultaneously, nor can D5 and D2.

Waveform





- The output voltage across the load is one of the line-to-line voltages of the source. The on-diodes are determined by which line-to-line voltage is the highest at that instant. For example, when v_{ac} is the highest line-to-line voltage, the output is v_{ac}.
- There are 6 combinations of line-to-line voltages. A transition of the highest line-to-line voltage must take place every 360/6 = 60 degree (a 6-pulse rectifier).

Frequency and Output Voltage

- The fundamental frequency of the output voltage is $6f_s$.
- The periodic output voltage defined as

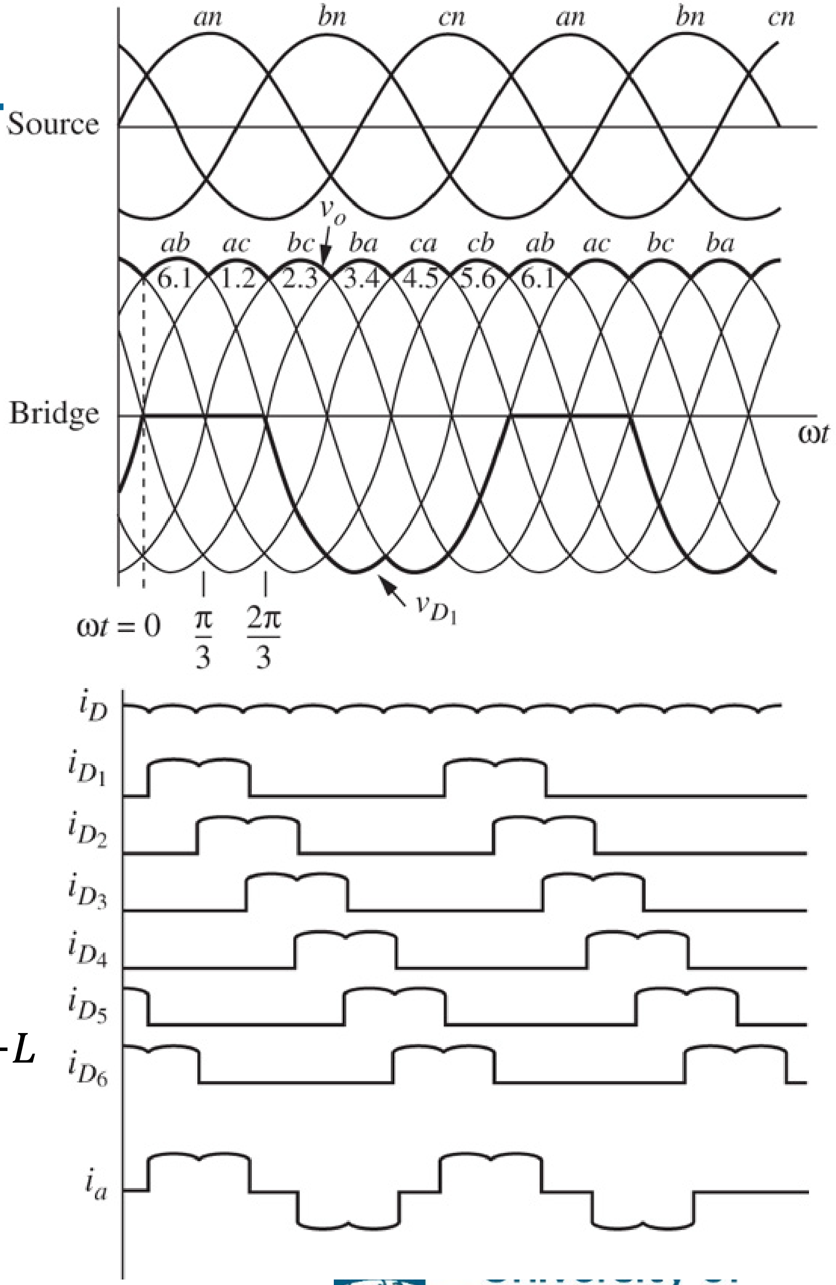
$$v_o(\omega t) = V_{m,L-L}\sin\omega t \qquad \text{for } {}^{\pi}/_{3} \le \omega t \le {}^{2\pi}/_{3}$$

with period p/3 for Fourier series,

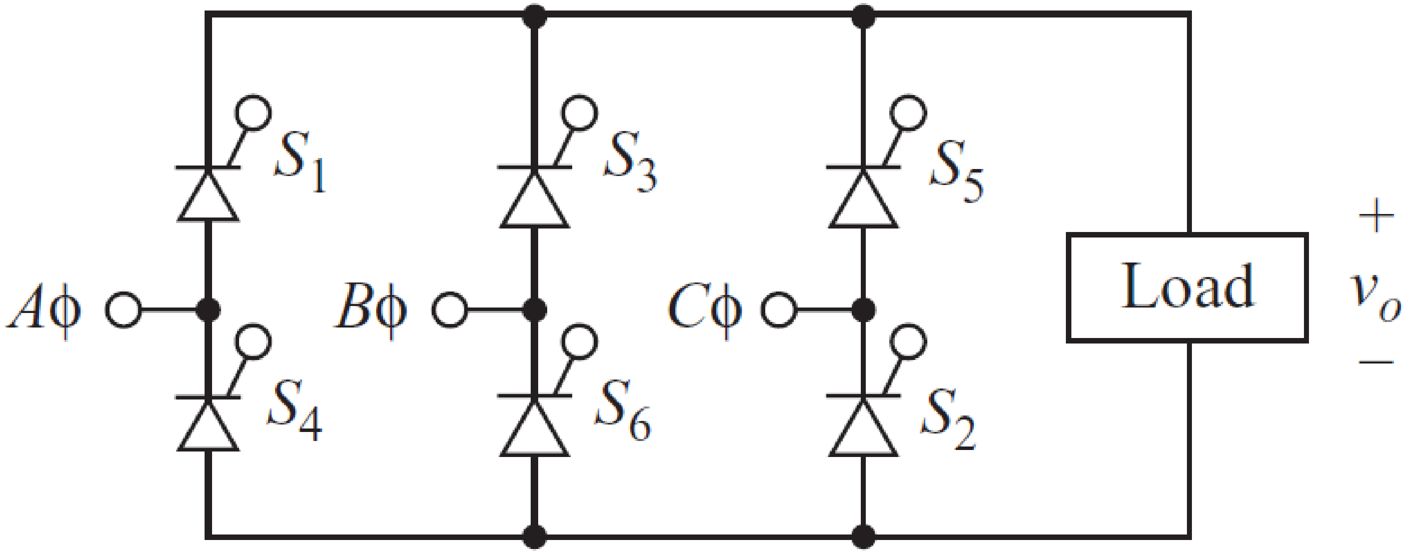
$$v_o(\omega t) = V_o + \sum_{n=6,12,18\ldots}^{\infty} V_n \cos(n\omega_0 t + \pi)\,.$$

$$V_o = \frac{1}{\pi/3}\int_{\pi/3}^{2\pi/3} V_{m,L-L}\sin\omega t\, d(\omega t) = \frac{3V_{m,L-L}}{\pi} = 0.955V_{m,L-L}$$

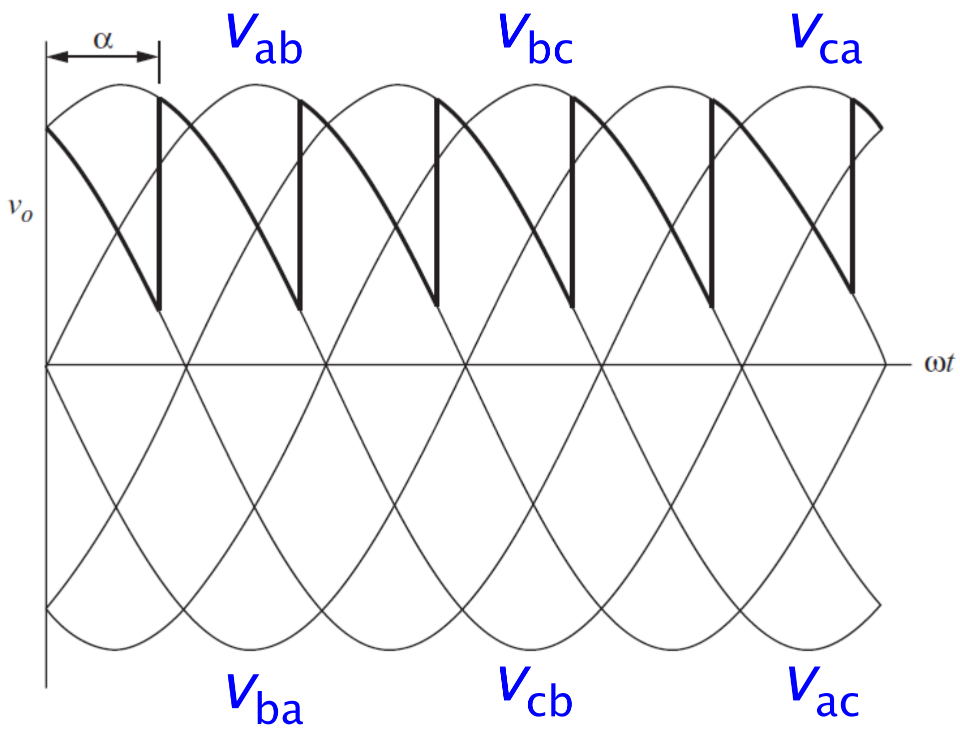
$$V_n = \frac{6V_{m,L-L}}{\pi(n^2-1)} \quad \text{n=6, 12, 18,....}$$



Three Phase Controlled Rectifier



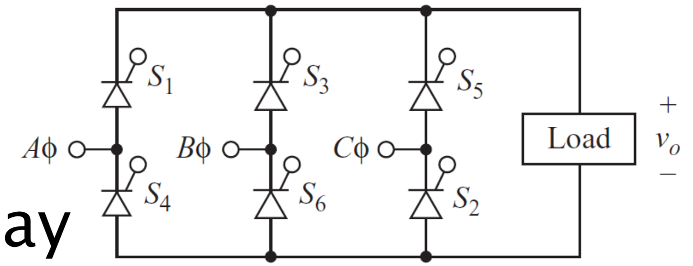
Waveform



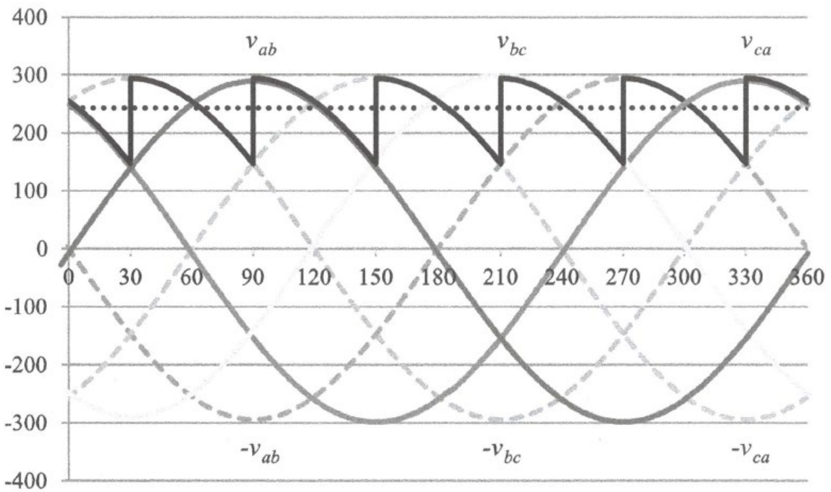
Line to line voltage

- Three phase rectifier can be controlled by substituting thyristors for diodes.
- The delay angle is referenced from where the thyristor would begin to conduct if it were a diode.

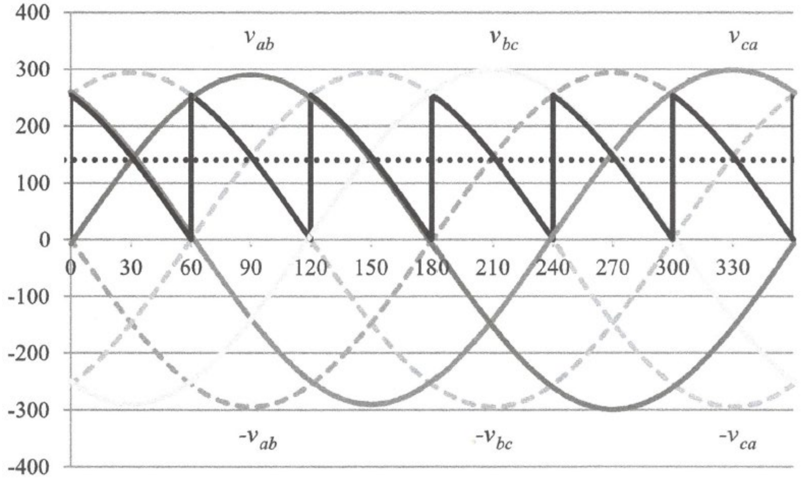
Waveform with different delay angle



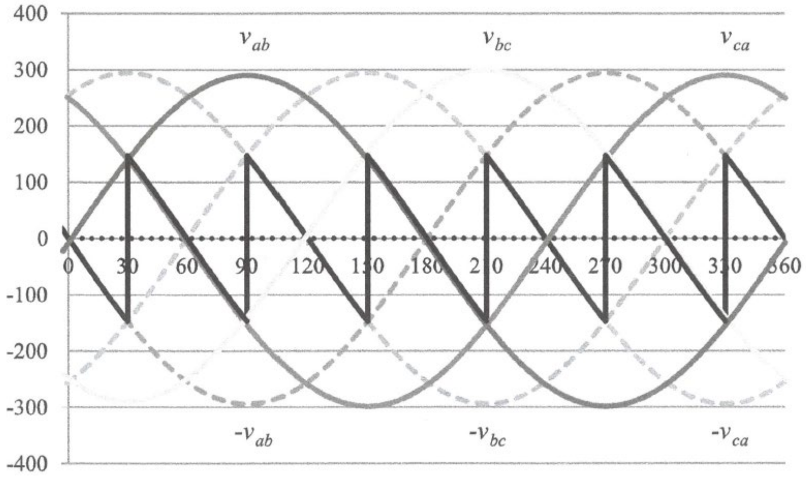
30º delay



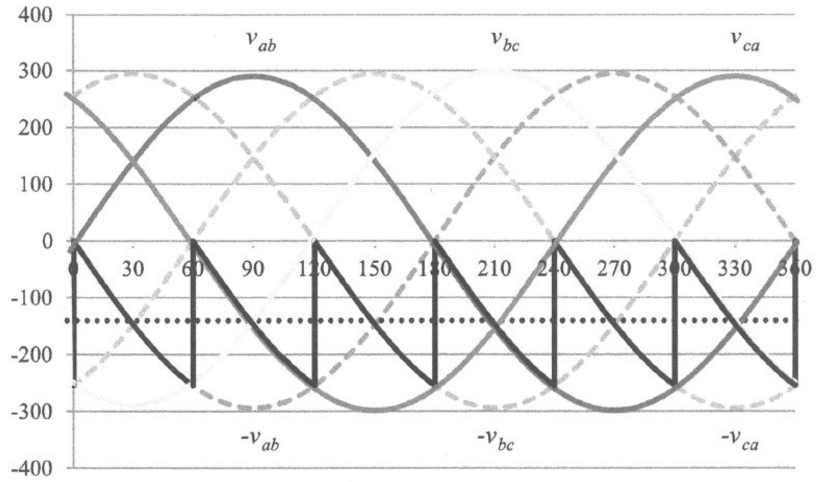
60º delay



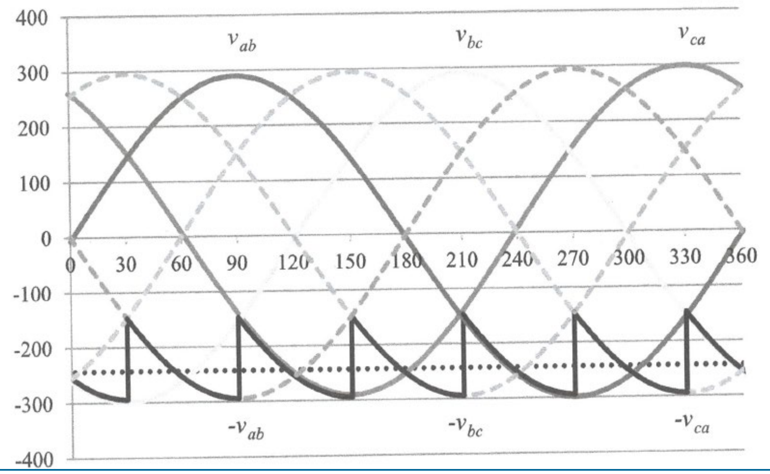
90º delay



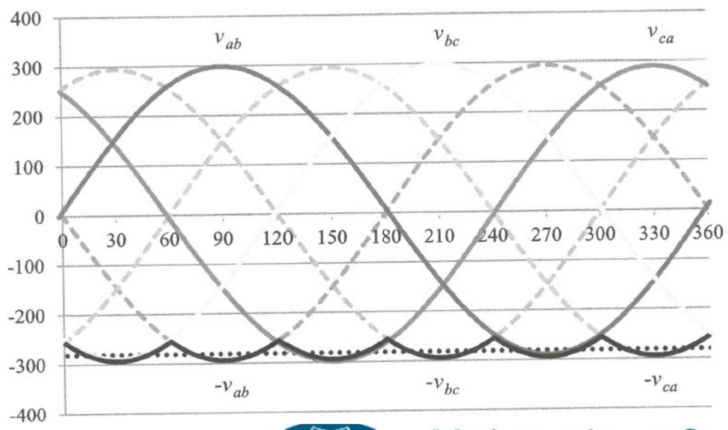
120º delay



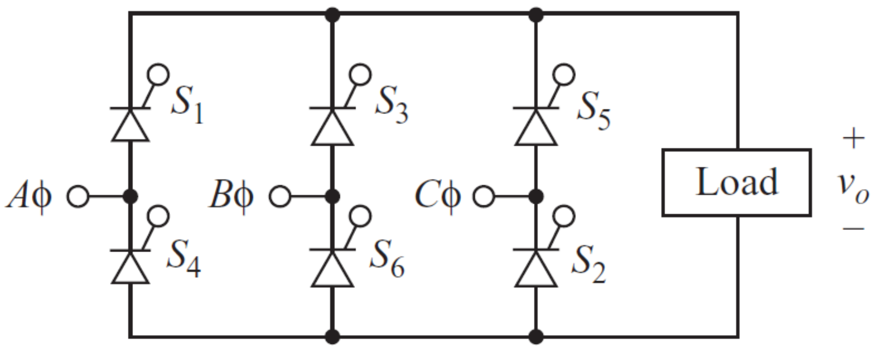
150º delay



180º delay



Average Output Voltage



For controlled rectifier with continuous load current (heavy inductive load) the average output voltage is given by,

$$V_O = p\frac{V_m}{\pi}\sin\frac{\pi}{p}\cos\alpha$$

where, p is the pulse number and V_m is the peak of line voltage.

- For single phase converter, $p = 2$ and hence, $$V_o = \frac{2V_m}{\pi}\cos\alpha$$
- For three phase converter, $p = 6$ and hence, $$V_o = \frac{3V_m}{\pi}\cos\alpha$$

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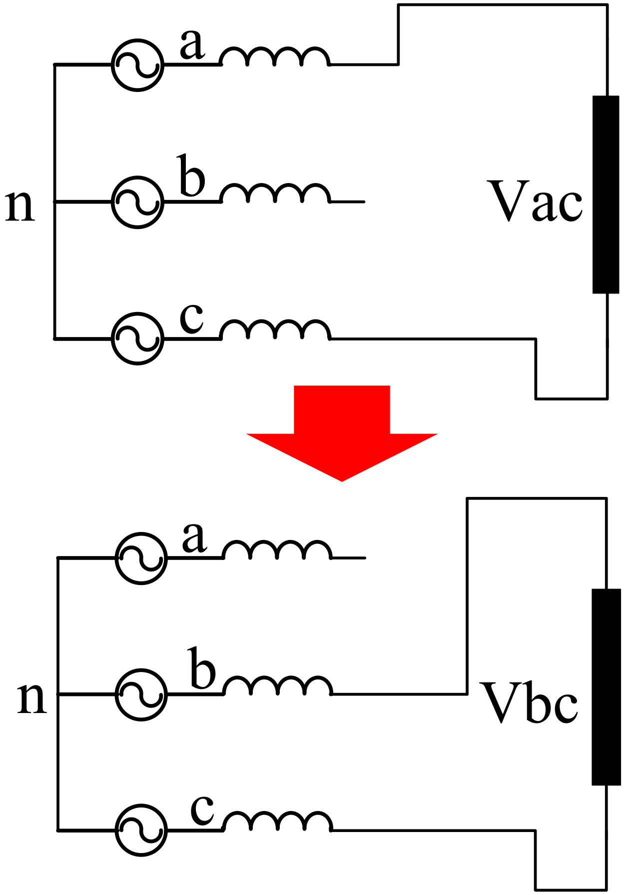
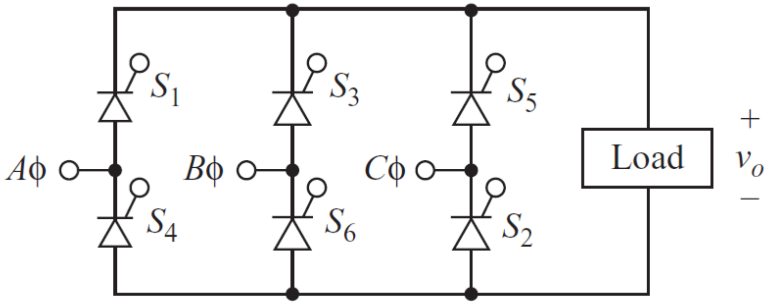
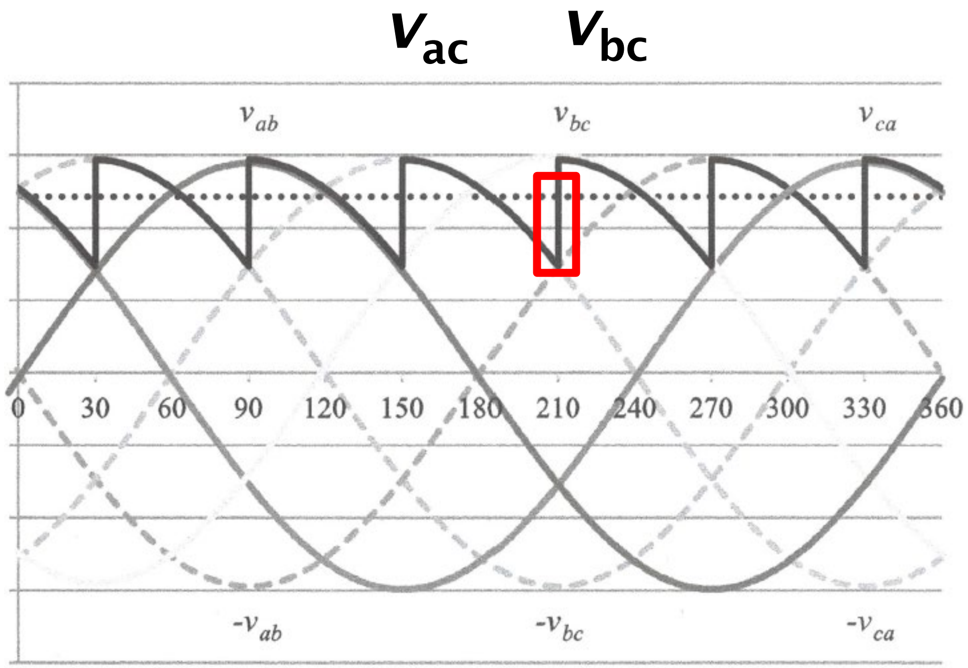
Commutation/Overlap

- Ideally, thyristors should turn on and off instantaneously.

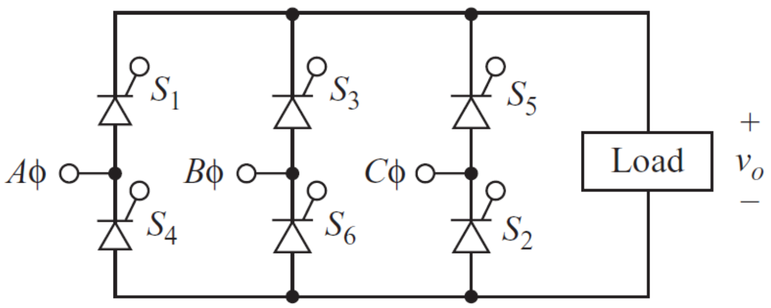


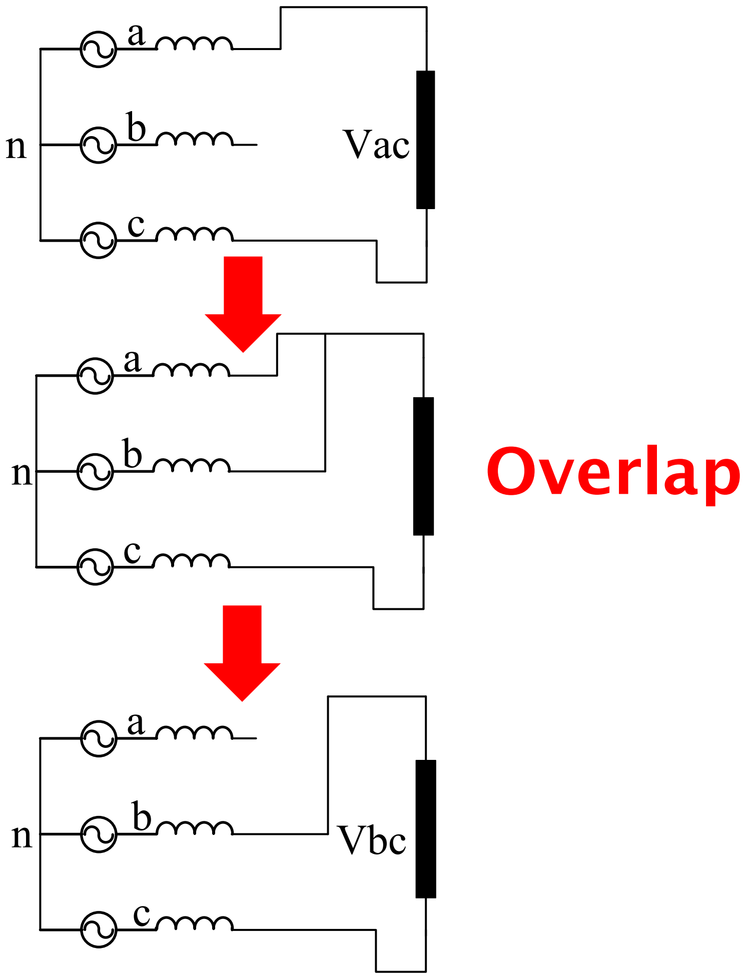


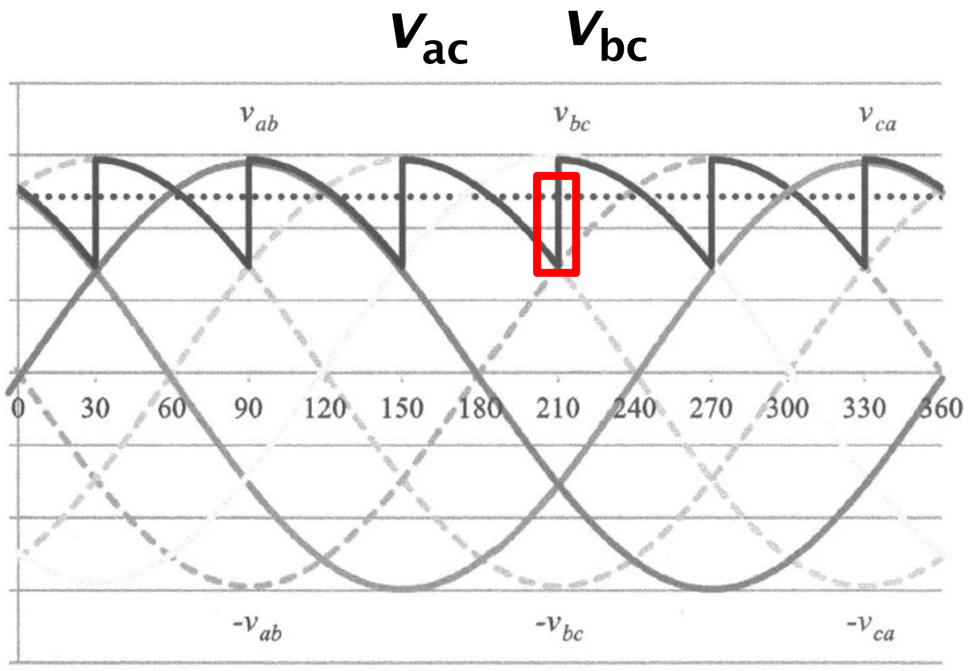


Commutation/Overlap

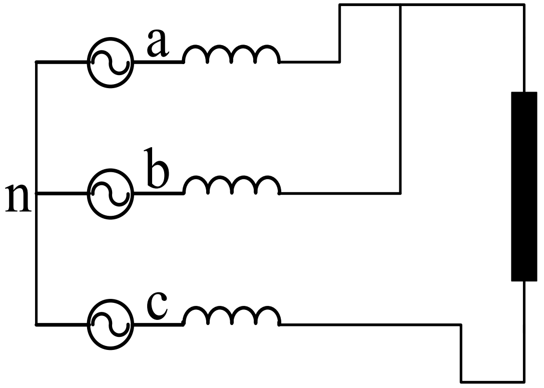
- However, practical device has a finite turn on and off time

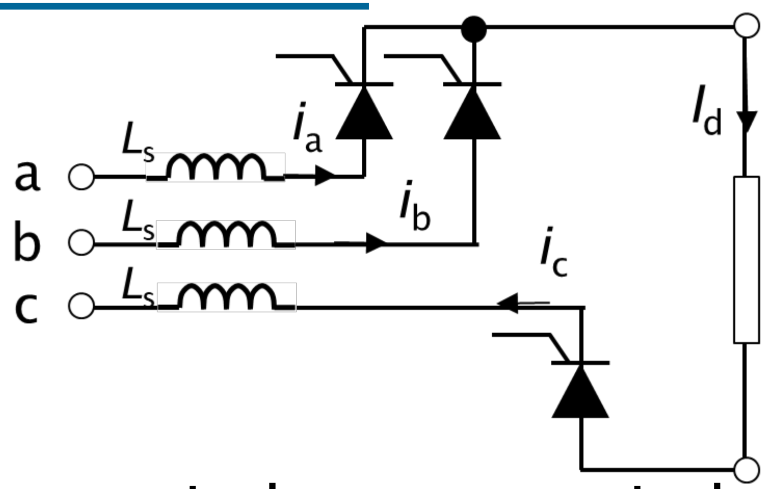




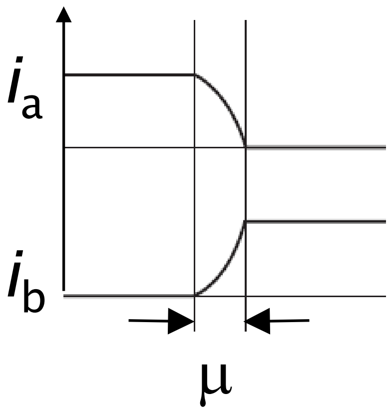


Commutation/Overlap





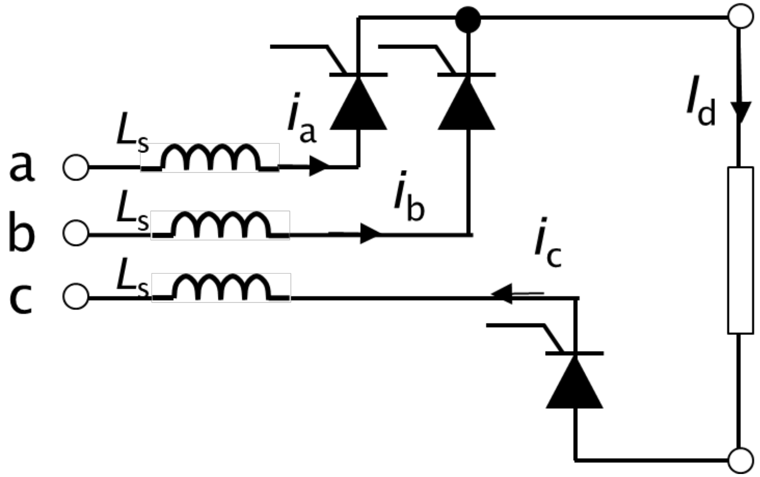
- In addition, inductive current (due to source inductance or inductive load) cannot change instantaneously. Current must be transferred gradually from one diode pair to the other over a commutation interval μ.

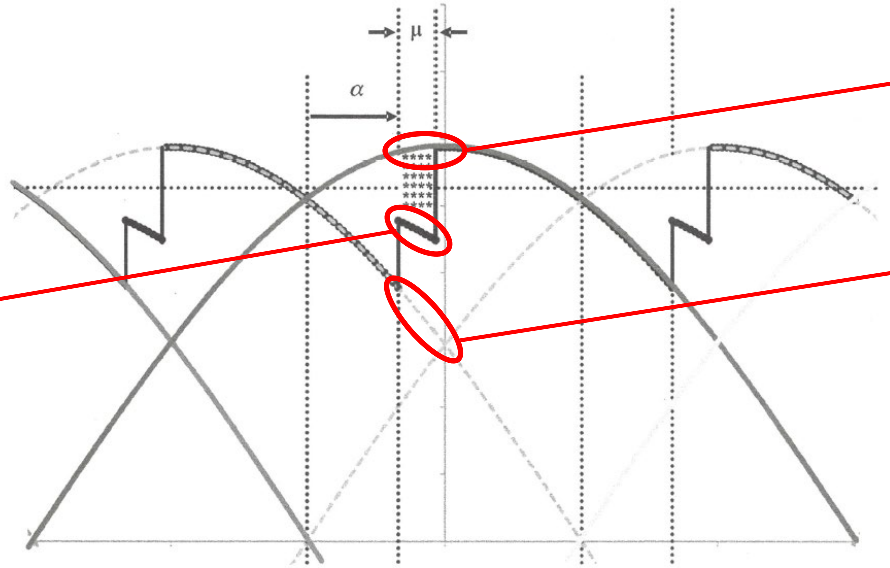


- Triggering the next thyristor results in two thyristors with current, hence short circuit occurs between two lines.

Commutation/Overlap

During the transfer of current from one thyristor to the next in the sequence, the voltage at the cathodes of the two thyristors is halfway between that of the two line voltages.





Voltage from phase B

Output voltage due to overlap

Voltage from phase A

Commutation/Overlap - Equations

Due to overlapping, the average output voltage is reduced by

$$V_{av} = \frac{3\omega L_s I_d}{\pi}$$

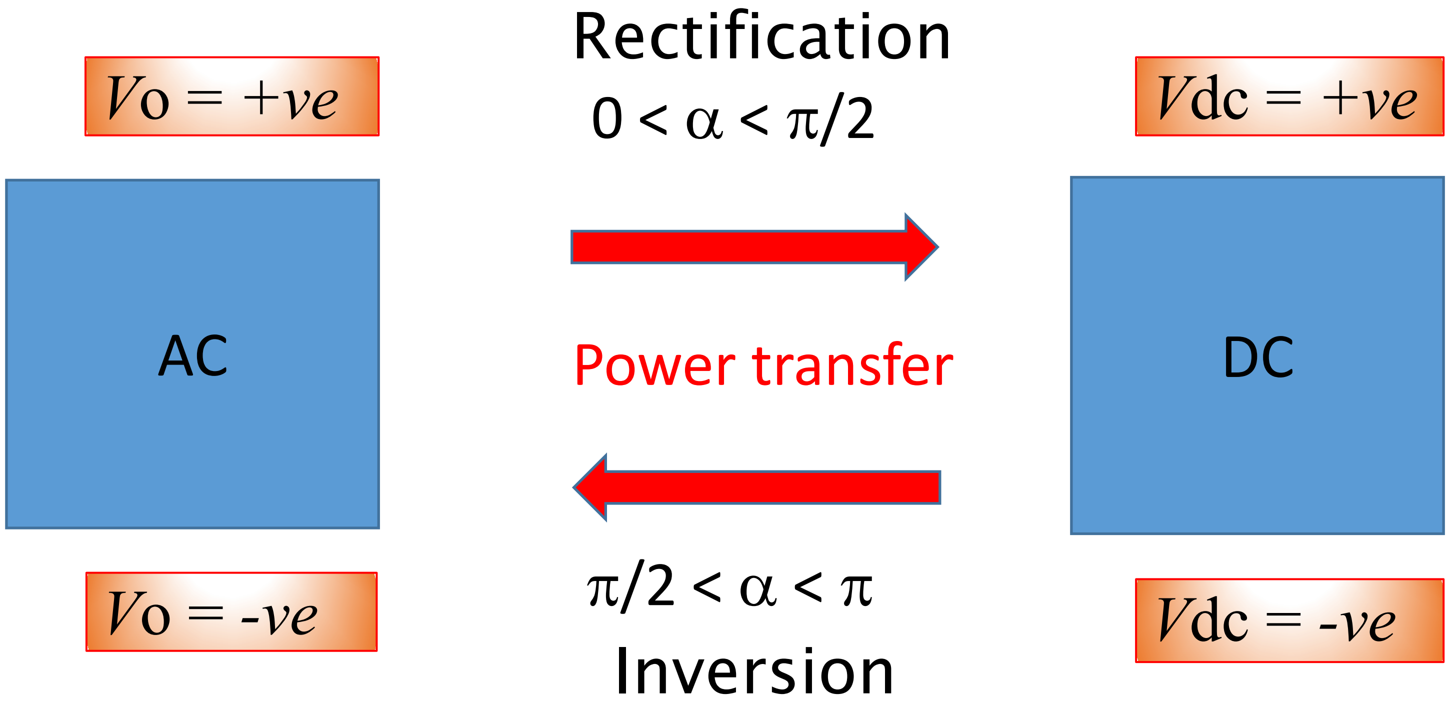
Hence the average output voltage from a three phase controlled rectifier with overlapping is

$$V_o = \frac{3V_m}{\pi}\cos\alpha - \frac{3\omega L_s I_d}{\pi}$$

A general equation of average output voltage for a p pulse converter/rectifier with overlapping is

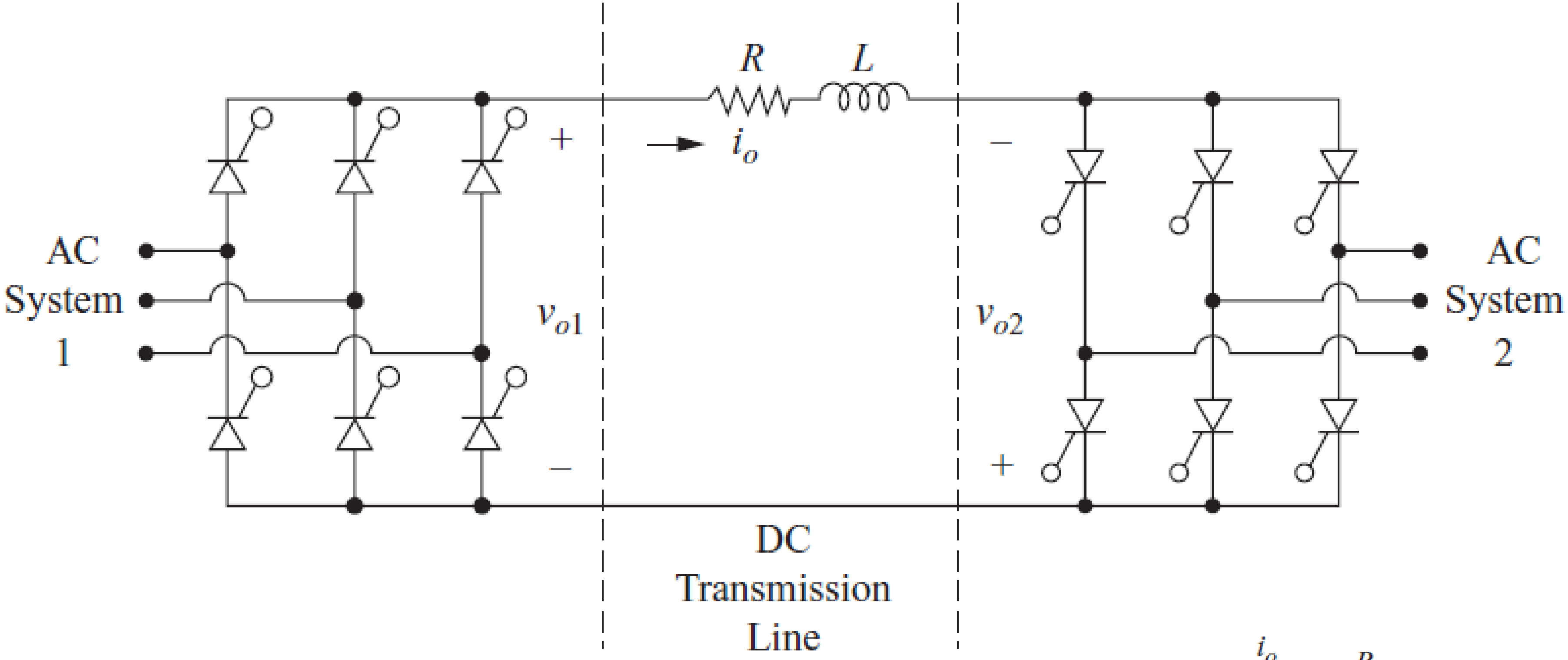
$$V_o = \frac{pV_m}{\pi}\sin\frac{\pi}{p}\cos\alpha - \frac{p\omega L_s I_d}{2\pi}$$

Three phase Converter Operating as Inverter

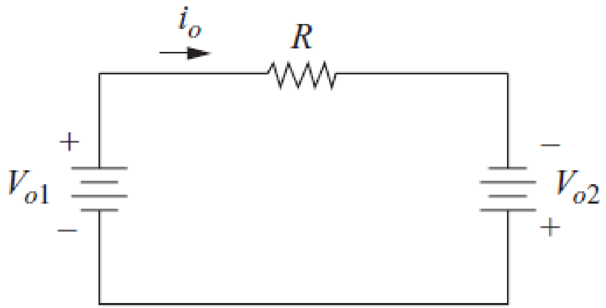


By adjusting the firing/delay angle, bidirectional power transfer can be achieved between ac and dc terminals.

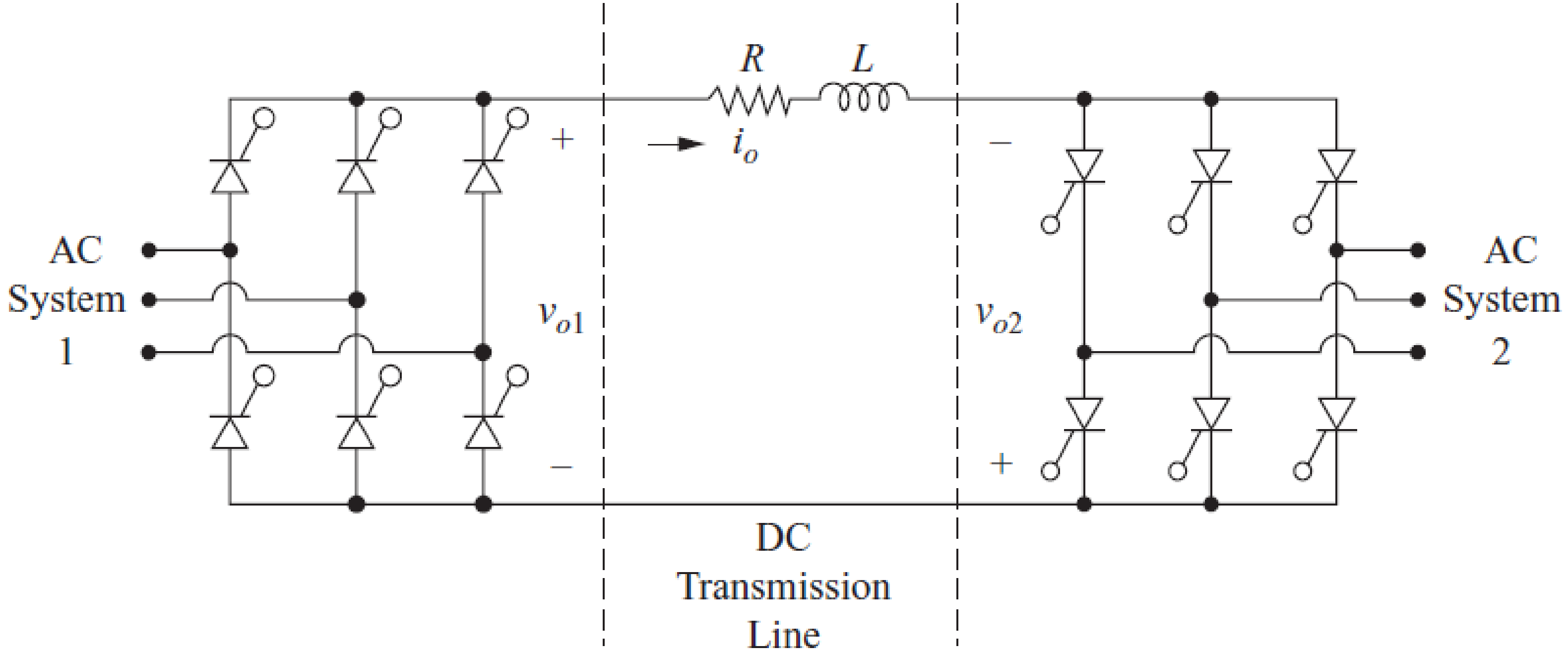
DC Transmission

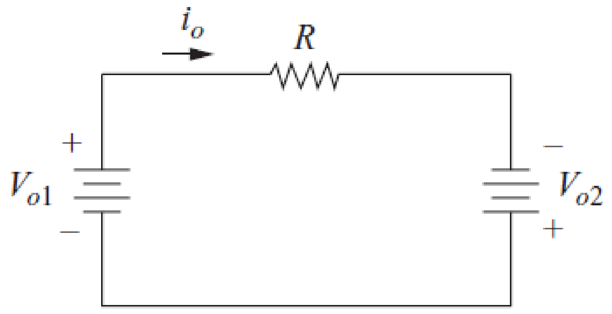


Notice that the direction of current is fixed as thyristors are unidirectional current conducting device.



DC Transmission





- V_{o1} and V_{o2} are controlled such that one is positive (rectification) and the other one is negative (inversion).

- Power transfer can be controlled properly from AC system 1 to AC system 2 and vice versa.

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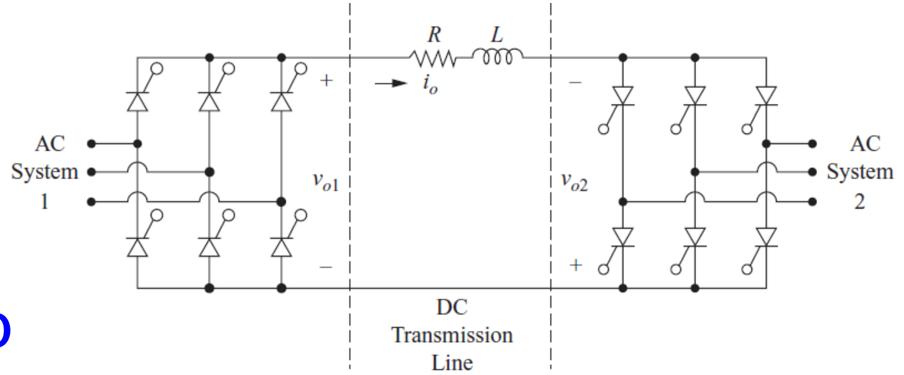
DC Transmission



Advantages

1. The inductance of the transmission line has zero impedance to dc, whereas the inductive impedance for lines in an ac system is relatively large.
2. The capacitance that exists between conductors is an open circuit for dc. For ac transmission lines, the capacitive reactance provides a path for current, resulting in additional I^2R losses in the line. In applications where the conductors are close together, the capacitive reactance can be a significant problem for ac transmission lines, whereas it has no effect on dc lines.
3. There are two conductors required for dc transmission rather than three for conventional three-phase power transmission. (There will likely be an additional ground conductor in both dc and ac systems.)

DC Transmission

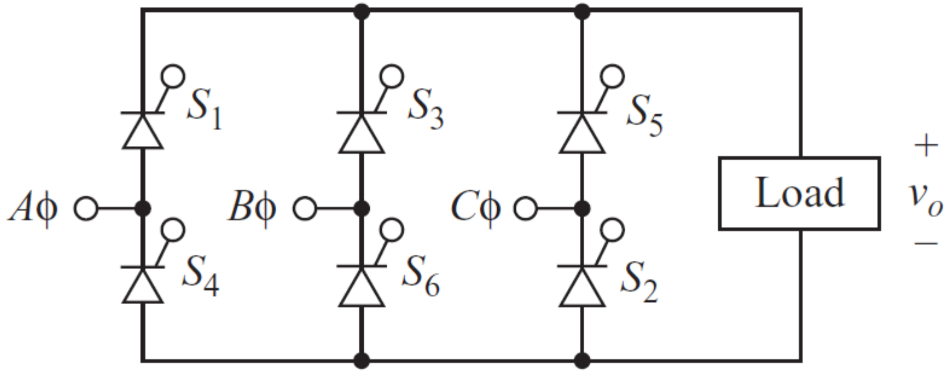
Advantages

4. Transmission towers are smaller for dc than ac because of only two conductors, and right-of-way requirements are less.
5. Power flow in a dc transmission line is controllable by adjustment of the delay angles at the terminals. In an ac system, power flow over a given transmission line is not controllable.
6. Power flow can be modulated during disturbances on one of the ac systems, resulting in increased system stability.
7. The two ac systems do not need to be in synchronization. Furthermore, the two ac systems do not need to be of the same frequency nor voltage. A 50-Hz system can be connected to a 60-Hz system via a dc link.

Disadvantages

- Costly ac-dc converter, filters, and control system are required at each end of the line to interface with the ac system.

Summary - Three phase rectifier



- 6 diodes/thyristors are used for three phase full-wave rectification.
- The circuit is called a six-pulse rectifier as the six transitions occur for each period of the source voltage.
- The fundamental frequency of the output voltage is $6f_s$, where f_s is the frequency of the three-phase source.
- Power transfer can be controlled by adjusting the phase, i. e. firing/delay angle of triggering the thyristors in the rectifier circuits.
- Overlap associated with thyristor switching should be taken into account in three phase analysis.
- DC transmission is an application of the rectifiers and inverters operated by rectifiers with power flow of the opposite direction.

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