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Lecture (9)

22– 04 - 2019

Power Electronics & their application in Energy storage & Conversion

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D.C. power Transmission System

- Frequency of large systems would produce serious problems of power transfer control in the small capacity link.

- Extensive research has been carried out for the development of high voltage converters.

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- Thyristors of ratings 50 kV and 100 amperes have been developed and now there are many countries in the world where the transmission of power over longer distances and high voltages is being done by D.C.

- D.C transmission line requires converter at each end. At the sending end AC is converted into DC and at the receiving end it is converted back to AC for use.

Rectification

- A valve normally conducts in one direction only from anode to cathode and while it is conducting there is a small drop of volts across it.
- While analyzing the rectifier circuits, the valves, the transformers are assumed to be ideal i.e. without any voltage drop and the DC load is assumed to have infinite inductance from which it follows that the direct current is constant i.e. free from ripples.

Continue

- Transformer secondary can be connected to give 3-phase, 6-phase and 12-phase supply to the rectifier valves.
- The larger the number of phases, lower is the ripple content in the DC output. But 6-phase connection is found to be sufficiently good from all practical viewpoints.
- To begin with, a 3-phase arrangement will be described but analysis will be done for a general n-phase system.

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- The 3-phase system is the simplest converter circuit but is not practical because the direct current in the secondary windings saturates the transformer core.
- This could be avoided by using zig-zag connections.
- The 3-phase system as shown in Fig. 1 is, however, useful in explaining other connections.

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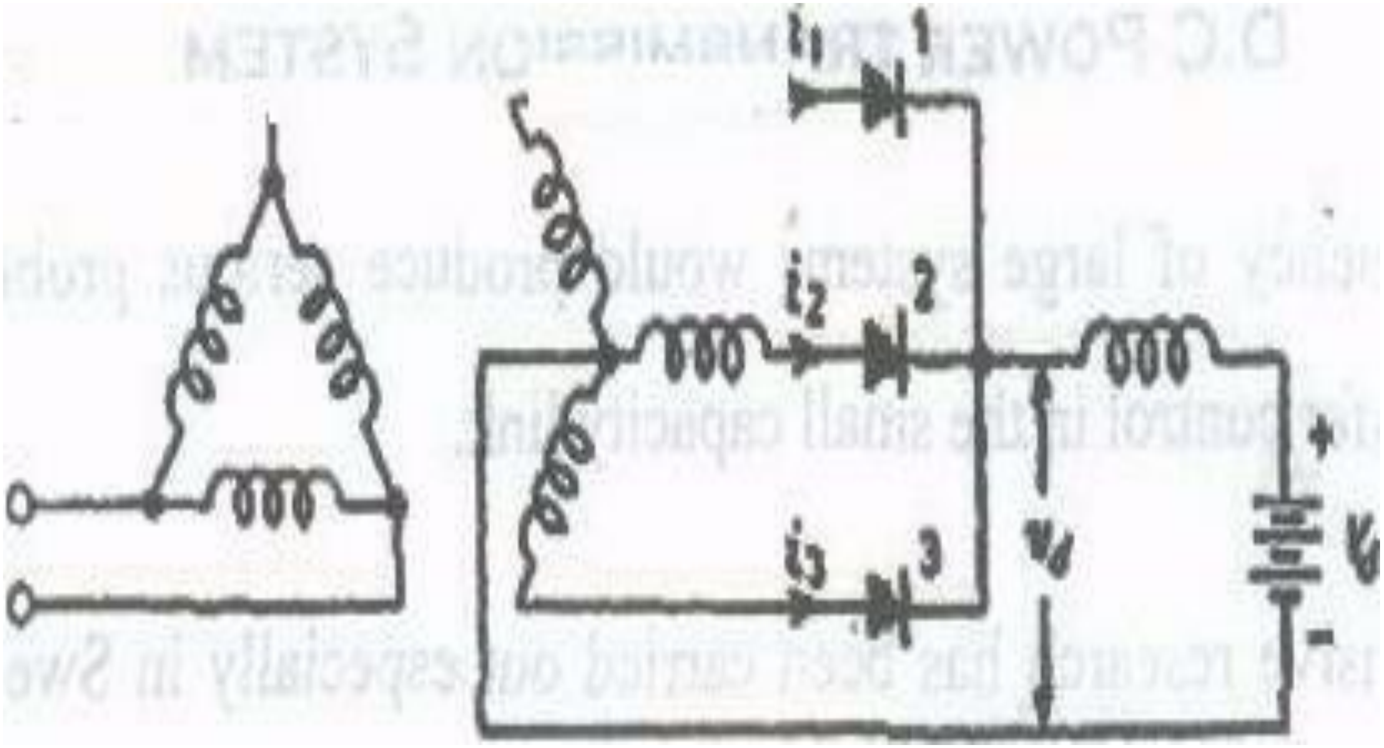

Figure 1: 3-Phase Rectifier

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- Figure: 1 shows the current and voltage wave-form in the three phases of the supply transformer.

- When grid control is not used, conduction will take place between the cathode and the anode of highest potential and, therefore, the output voltage is indicated by the thick line and the current output will be continuous .

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- From the voltage wave-form it. is clear that the change-over from one anode to the other take place at an electrical angle calculated as follows:

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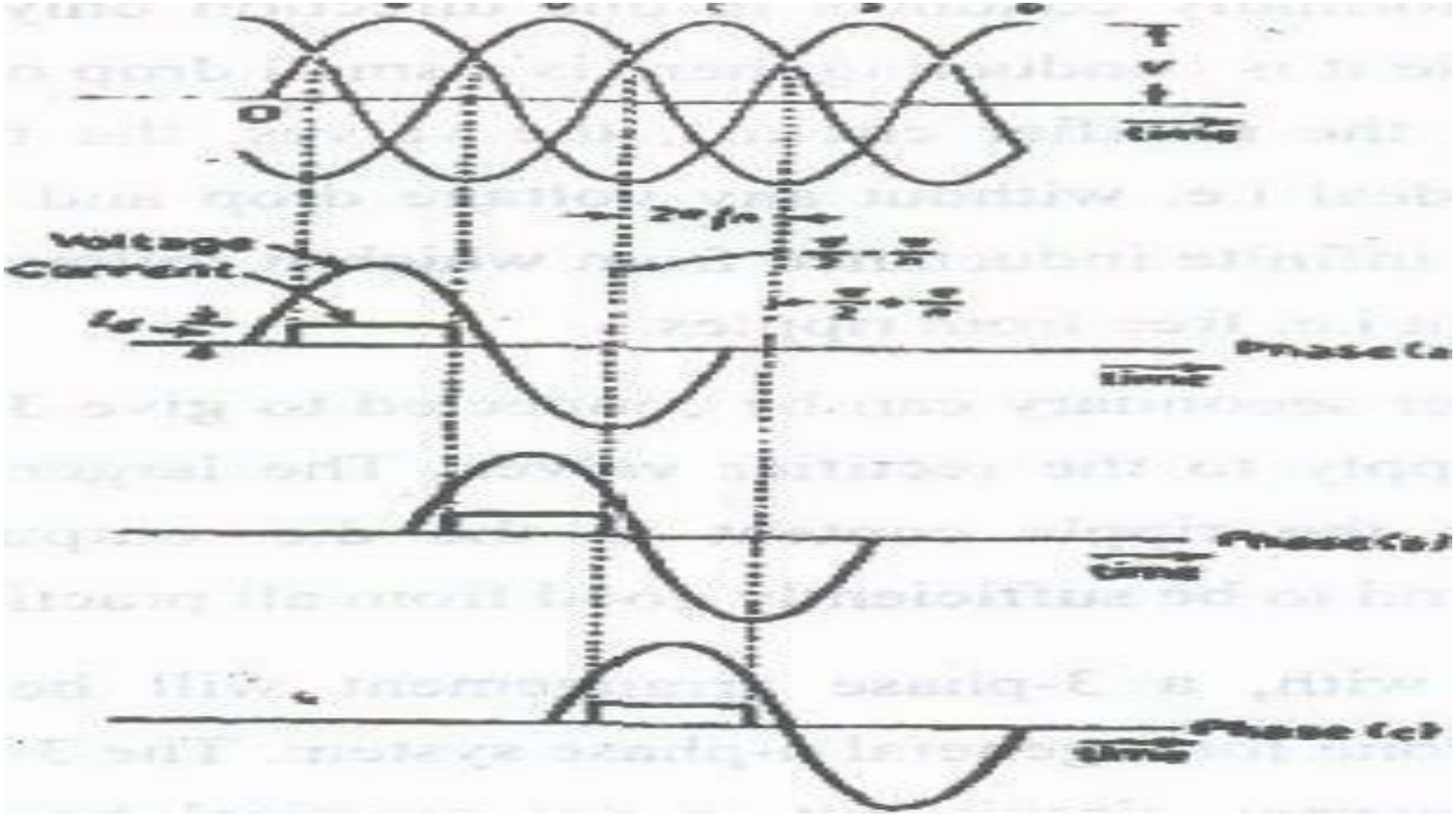

Figure: 2 wave-forms of anode voltage and rectified current In each phase

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- Taking point '0' as the reference, the conduction starts from 30" and continues up to 150° i.e. $(\pi/2 - \pi/3)$ to $(\pi/2 + \pi/3)$
- in general for an n-phase or n-anode system the change-over takes place at $(\pi/2 - \pi/n)$ and conduction continues up to $(\pi/2 + \pi/n)$. Now since conduction takes place only during the positive half cycle, the average value of the d.c. voltaae will be

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$$V_0 = \frac{1}{2\pi/n}\int_{\pi/2-\pi/n}^{\pi/2+\pi/n} V_m \sin\theta\, d\theta = -\frac{nV_m}{2\pi}\left[\cos\theta\right]_{\pi/2-\pi/n}^{\pi/2+\pi/n}$$

$$= \frac{V_m \sin \pi/n}{\pi/n} \qquad (2.1)$$

For $3\phi, n = 3$, and

$$V_0 = \frac{V_m \sin \pi/3}{\pi/3}\ \frac{3V_m}{\pi} = \frac{3\sqrt{3}}{2} = \frac{3\sqrt{3}}{2} V_m = 0.83\,V_m = 0.83\,V_m \qquad (2.2)$$

For $6\phi, n = 6$, and

$$V_0 = \frac{V_m \sin \pi/6}{\pi/6} = \frac{3V_m}{\pi} \qquad (2.3)$$

Continue

- The wave of anode current is a rectangular pulse of height /a and length 120°.
- Its average value is $I_d/3$ and the r.m.s value $I_d/\sqrt{3} = 0.577\ I_d$.
- The transformer secondary current is the same as the anode current.
- The current in actual practice can't reduce to zero instantly nor it can rise to a finite value instantly because of the finite inductance of the system.

Continue

- Hence two anodes conduct simultaneously over a period known as the commutation period or overlap period (overlap angle γ) Say initially anode a is conducting.
- When anode b commences to conduct, it short circuits the a and b phases which results in zero current in a and Id in b finally.
- This is shown in figure: 3.

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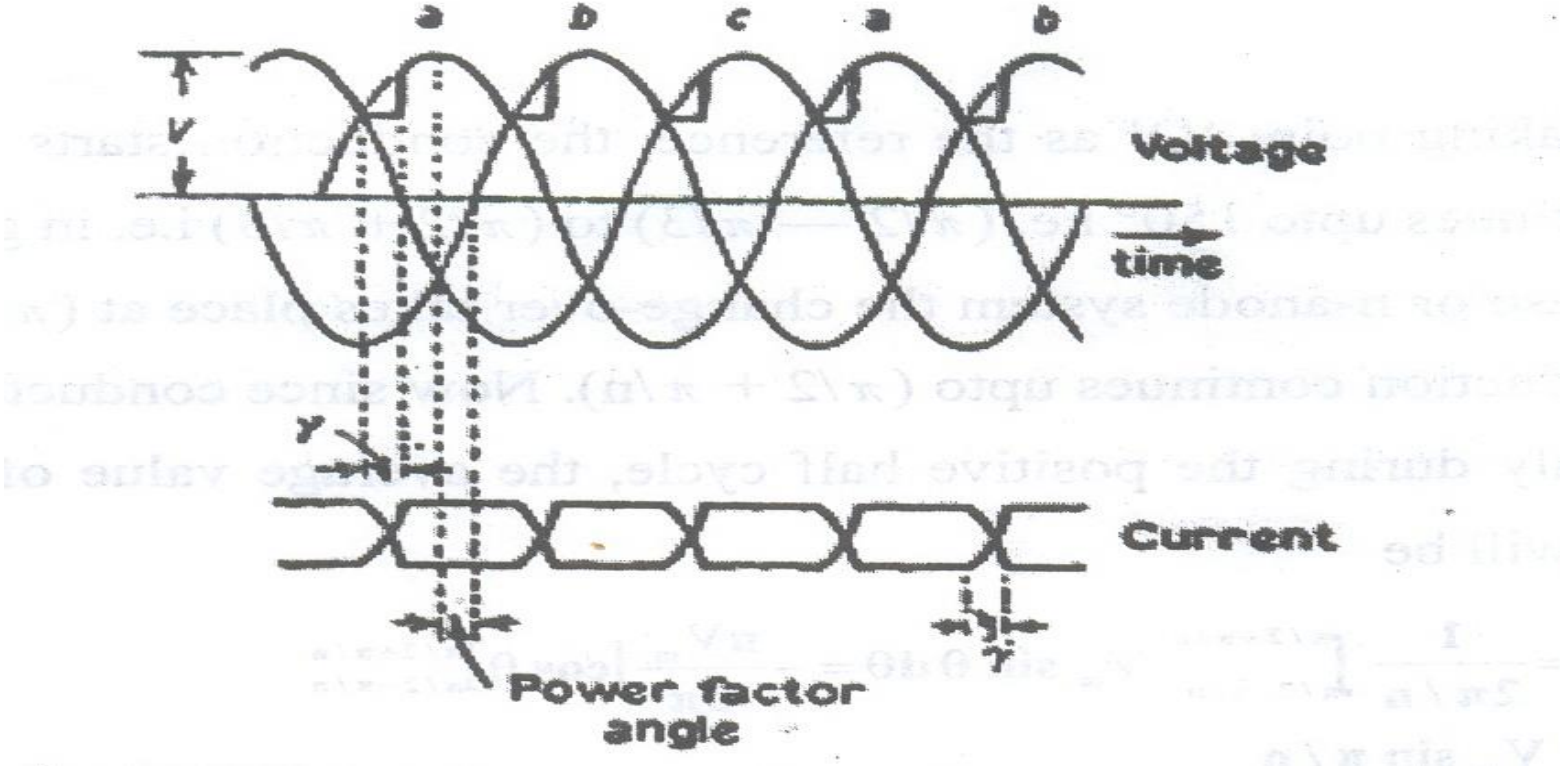

Figure: 3 Voltage and current wave forms with commutation angle γ

Continue

- The instant of conduction of an anode can be controlled by applying a suitable pulse at a suitable instant to a third electrode known as grid which is placed in between the cathode and anode.
- Once the conduction starts, the grid of course loses control over the conduction process.
- Figure: 4 shows the use of grid control for the firing of the anodes, Say a positive pulse is applied to the grid such that the conduction is delayed by an angle γ.

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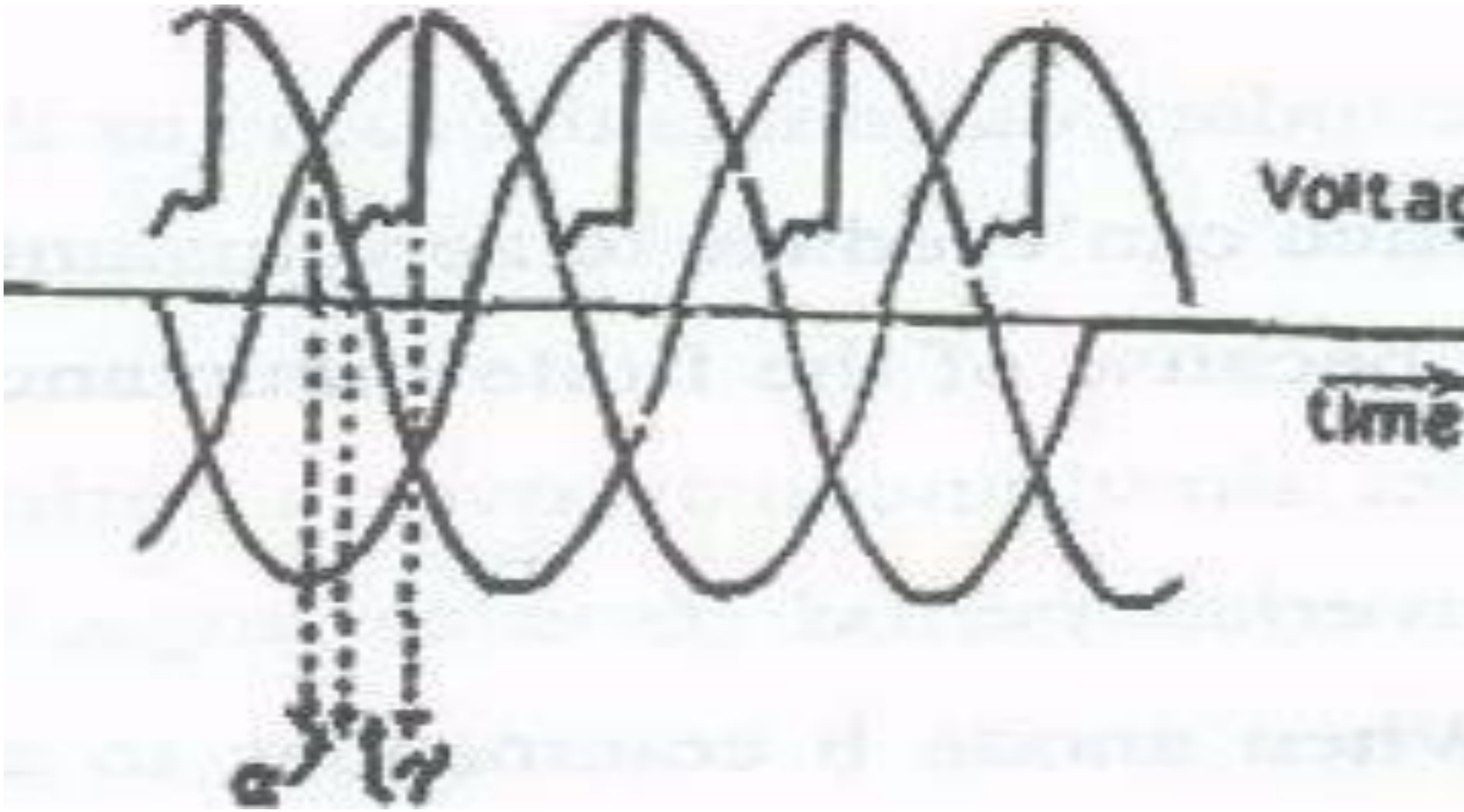

Figure 2.5 Voltage wave form with grid control

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- When the delay is γ considering n-phase system the average output voltage will be

$$V_0 = \frac{1}{2\pi/n}\int_{(\pi/2)-(\pi/n)+\alpha}^{(\pi/2)+(\pi/n)+\alpha} V_m \sin\theta\, d\theta = \frac{nV_m}{2\pi}\left[-\cos\theta\right]_{(\pi/2)+(\pi/n)+\alpha}^{(\pi/2)+(\pi/n)+\alpha}$$

$$= \frac{nV_m}{2\pi}\left[\sin\left(\frac{\pi}{n}+\alpha\right)+\sin\left(\frac{\pi}{n}-\alpha\right)\right]$$

$$= \frac{nV_m}{\pi}\sin\frac{\pi}{n}.\cos\alpha$$

$$= V_0 \cos\alpha$$

Continue

- This means the d.c. output voltage with grid control is obtained by multiplying the d.c. output voltage without control with cosine of the angle by which the firing is delayed.

The 3-phase Bridge Rectifier or Gratz Circuit

- The bridge rectifier is the most practical circuit used for converting a.c. into d.c. for HVDC transmission. For a given alternating voltage the output direct voltage is doubled as the two anodes conduct simultaneously and hence the power is doubled.
- There is no current in the windings of the transformer bank and the rms current is less than twice that of the 3-phase circuit; thereby the winding is used efficiently.

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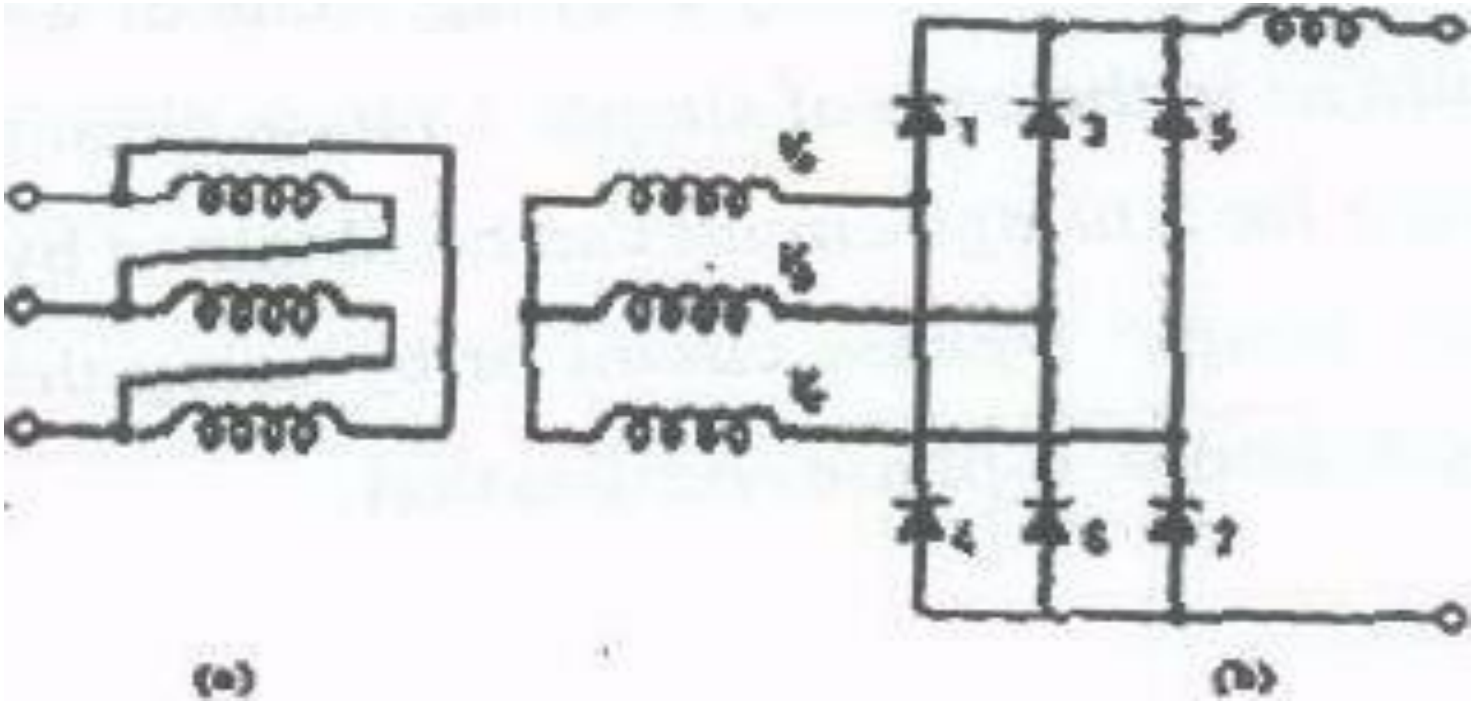
- For waveform and the bridge circuit refer to figure: 5



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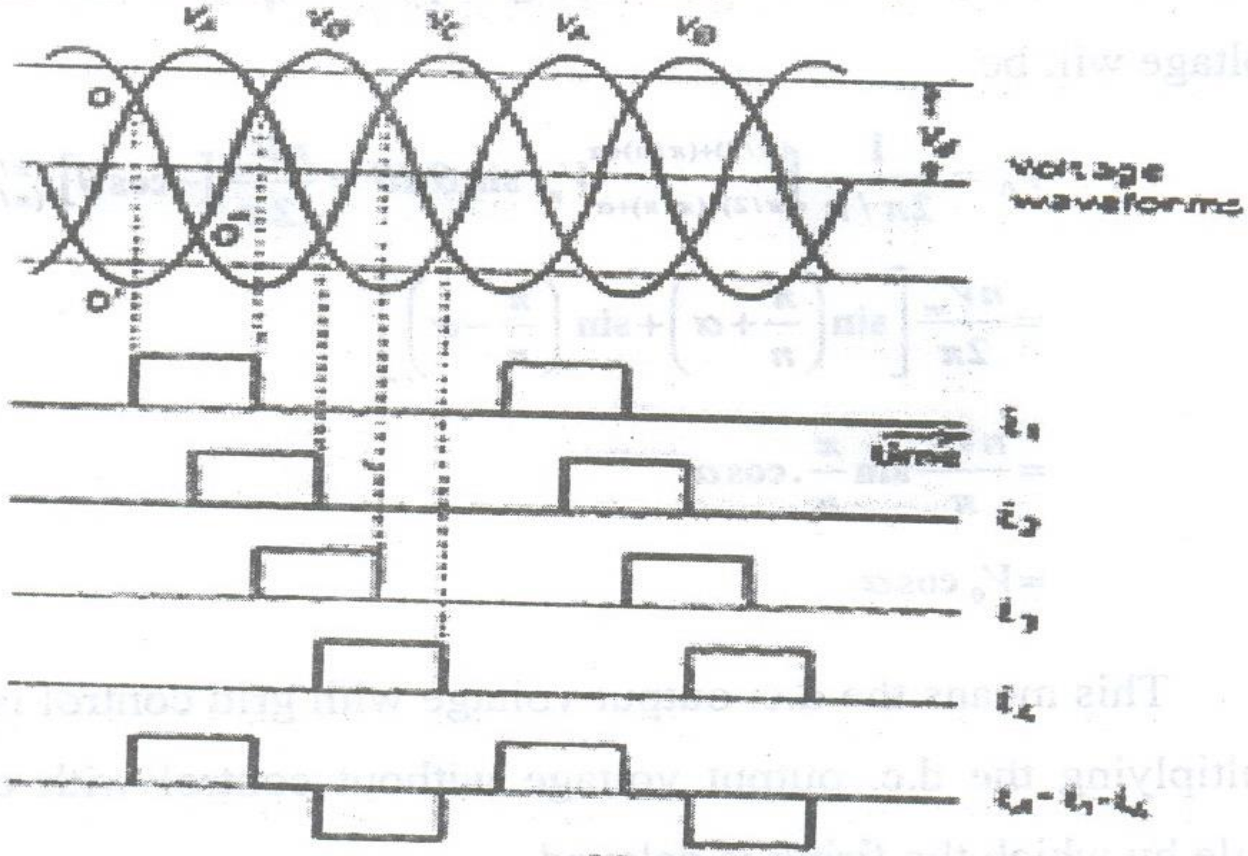

(c)

Fig . 2.5 (a) Bridge rectifier circuit; (b) Voltage waveforms; (c) Current waveform

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- The sequence of operation of the bridge circuit can be explained as follows:
- Let V_a be the most positive at the beginning of the sequence say point 0 in Fig. 5 (b).
- Corresponding to this point V_b is most negative; Therefore, the conduction will take place between phase a and b from a to b.
- The rectifiers will be 1 and, 6 (Fig. 5(a)).

Continue

- V_b continues to be most negative from 0' to 0'' and after 0'' , V_c becomes most negative and then conduction takes place between phases a and *e* from a to c through the rectifiers 1 and 2.
- Next diode 3 takes over from 1 and current returns through 2.
- The complete sequence of the diodes conducting is, therefore, land 6, land 2 ,3 and 2,3 and 4, 5 and 4,5 and6and 1 and 6 again.

Continue

- The grid control and overlapping will modify the magnitude of voltage and can be taken into account as in the case of simple 3-phase circuit.
- The output voltage for a bridge circuit can be obtained by either doubling the voltage of the simple 3-phase circuit or by using the line voltage in the formula for six diodes, 6-phase rectification.

Continue

We know that the output voltage of a 3-phase circuit is $\frac{3\sqrt{3}}{2\pi} V_m$

There fore, for a bridge circuit it will be ;

$$\frac{3\sqrt{3}}{\pi} V_m$$

The output voltage for an n-phase circuit is $\frac{V_m \sin \pi / n}{\pi / n}$

For 6-phase circuit n = 6 and maximum value of voltage is √ 3Vm.

Substituting these values,

$$V_0 = \frac{\sqrt{3}\, V_m \sin \pi / 6}{\pi / 6} = \frac{\sqrt{3}\, V_m}{\pi} .6. \frac{1}{2} = 3\sqrt{3} \frac{V_m}{\pi} \qquad (2.5)$$

Current relationship in a bridge circuit

- In case of a bridge circuit, two valves conduct simultaneously.
- These two valves correspond to two different phases i.e. two phases are short circuited.
- Let L be the inductance in henries for each phase and be the current at any instant; then the equ I_s ion describing the circuit will be

Continue

$$2L\frac{di_s}{dt}=\sqrt{3}V_m \sin \omega t$$

$$or \quad \frac{di_s}{dt}=\sqrt{3}\frac{V_m}{2L}\sin \omega t\, dt \qquad or \quad i_s=-\sqrt{3}\frac{V_m}{2L}.\frac{1}{\omega}\cos \omega t + A$$

at the beginning when $\omega t=\alpha, i_s=0$ *and at the end when* $\omega t=\alpha+\gamma,\ i_s=I_d$

$$\therefore A=\frac{\sqrt{3}V_m}{2\omega L}\cos\alpha$$

Continue

$$I_d = \frac{\sqrt{3}V_m}{2\omega L}\left[\cos\alpha - \cos(\alpha+\gamma)\right]$$

$$= \frac{V_l}{\sqrt{2}\,X}\left[\cos\alpha - \cos(\alpha+\gamma)\right] \qquad (2.6)$$

Continue

where V_L is the rms line to line voltage. Now for the bridge circuit

$$V_0 = \frac{3\sqrt{3}V_m}{\pi}$$

$$\therefore \sqrt{3}V_m = \frac{\pi V_0}{3}$$

$$\therefore I_d = \frac{V_0}{6X}[\cos\alpha - \cos(\alpha+\gamma)] \qquad (2.7)$$

We know that bridge output voltage after taking into account gird control and overlap γ is

$$V_d = \frac{V_0}{2}[\cos\alpha + \cos(\alpha+\gamma)] \qquad (2.8)$$

Here V_o is the bridge rectifier voltage without grid control and overlap. Now adding the two equations (2.7) and (2.8),

$$\frac{2V_d}{V_o} + \frac{6XI_d}{\pi V_o} = 2\cos\alpha$$

or

$$\frac{V_d}{V_o} + \frac{3XI_d}{\pi V_0} = \cos\alpha$$

or

$$V_d = V_0 \cos\alpha - \frac{3XI_d}{\pi} \qquad (2.9)$$

Continue

- Figure: 6 shows the equivalent circuit represented by equation (2.9). It is to be noted that the drop $3X_1$ represents the voltage drop due to commutation and not a physical resistance drop.
- V can be varied by varying the V_0 which in turn can be varied by changing the tap change of the transformer and by changing α

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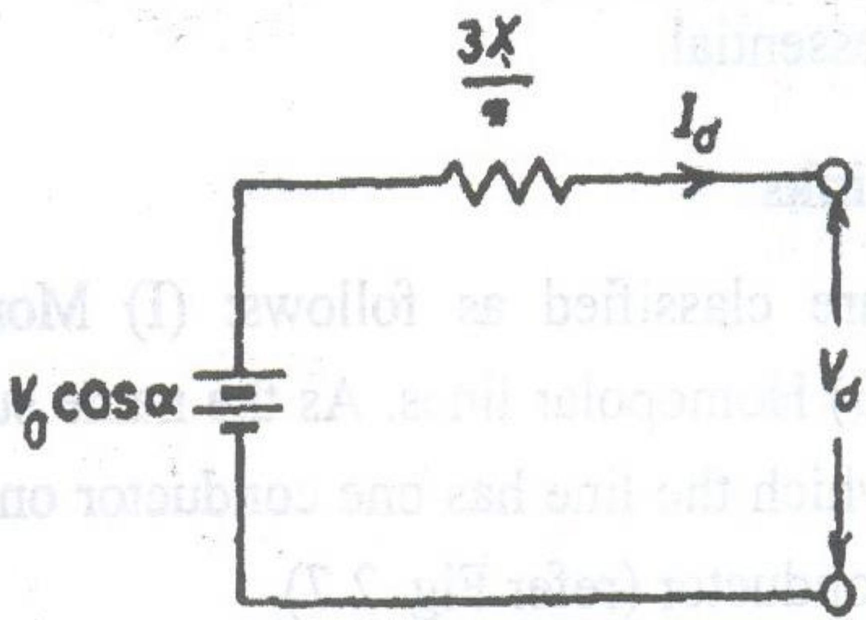

Fig . 2.6 Equivalent circuit representing operation of a bridge rectifier

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- In fact there are various circuits used for rectification, of which, the best converter circuit for high voltage d.c. transmission is the 3-phase bridge circuit. This has the following advantages:

(i)The transformer connections are very simple. It does not require any tapping. The secondary connection may be connected in Y or in delta.

Continue

(ii)For a given power output, the rating of the transformer secondary is less than any other circuits. Therefore, the rating of the primary of the transformer is less than any other circuit.

(iii) For a given output voltage, the PIV of the valves is only half that of any of the other circuits and therefore for a given PIV the output voltage is twice that of some other circuits.

(iv) Arc backs can be suppressed by grid control and a bypass valve.

Inversion

- In case of valves the conduction takes place in only one direction and, therefore, the current in a converter cannot be reversed.
- With rectifier operation the output current Id and output voltage V_d are such that power is absorbed by a load.

Continue

- For inverter operation it is required to transfer power from the direct current to the alternating current system which can only be obtained by the reversal of the average direct voltage The voltage then opposes the current as in a d.c. motor and is called a counter voltage.
- Therefore, for inversion, an alternating voltage system must exist on the primary side of the transformer and grid control of the converter is essential.

Kinds of d.c. Links

- D.C. lines are classified as follows:

(I) Monopolar lines.

(2) Bipolar lines.

(3) Homopolar lines.

Monopolar lines.

- As the name suggests monopolar lines are those in which the line has one conductor only and the earth is used as the return conductor (refer Fig. 2.7(a)).
- The line is normally operating with negative polarity as the corona loss and the radio interference are reduced.

Bipolar lines

- The bipolar lines have two conductors. one operating with +ve polarity and the other negative polarity.
- There are two converters of equal voltage rating and connected in series at each end of the d.c. line. Refer to Fig. 2.7 (b).
- The rating of the bipolar line is expressed as ±650 kV for example and is pronounced as plus and minus 650 kV.

Bipolar lines

- The junction of the converters may be grounded at one end or at both the ends. If it is grounded at both the ends each line can be operated independently.

Homopolar lines.

- The homopolar lines have two or more conductors having the same polarity usually negative for the reason of corona and radio interference and always operate with ground as the return.

Homopolar lines.

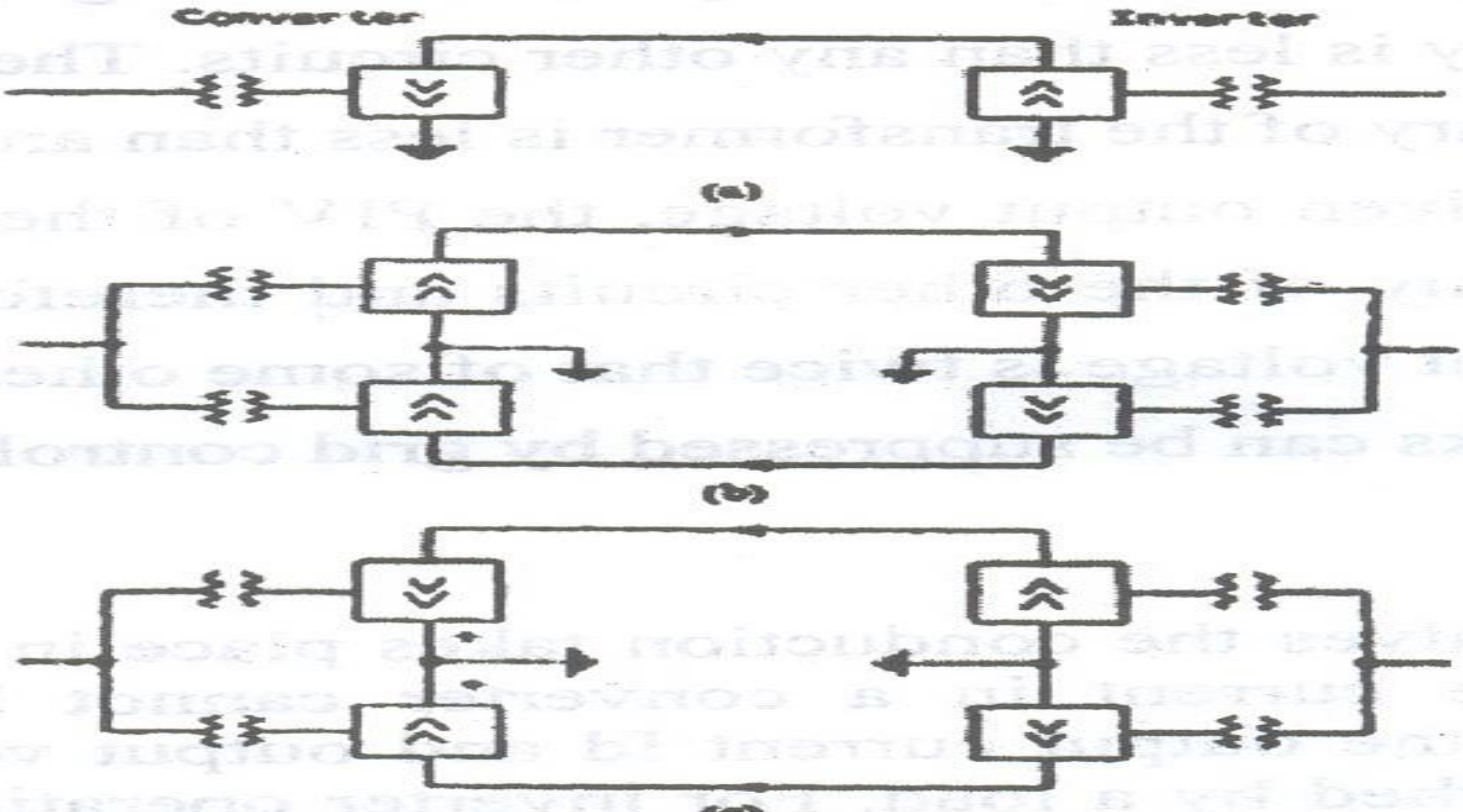

Fig . Kinds of d.c. links: (a) Monopolar, (b) Bipolar, and (c) Homopolar lines


Thank you