NBKRIST

POWER ELECTRONICS

LECTURE NOTES

UNIT-3

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT-III

Three phase controlled rectifiers: Three pulse and six pulse converters **-** midpoint and bridge connections, average load voltage with R and RL loads - effect of source inductance - presence of harmonics in source current -THD calculation.

Different Types of Three Phase Controlled Rectifiers

- Half wave controlled rectifiers.
- Full wave controlled rectifiers.
- Semi converter (half controlled bridge converter).
- Full converter (fully controlled bridge converter).

Three phase Half wave Converter or Three Pulse Converter:

- Three single phase half-wave converters are connected together to form a three phase half-wave converter as shown in the fig.3.1.

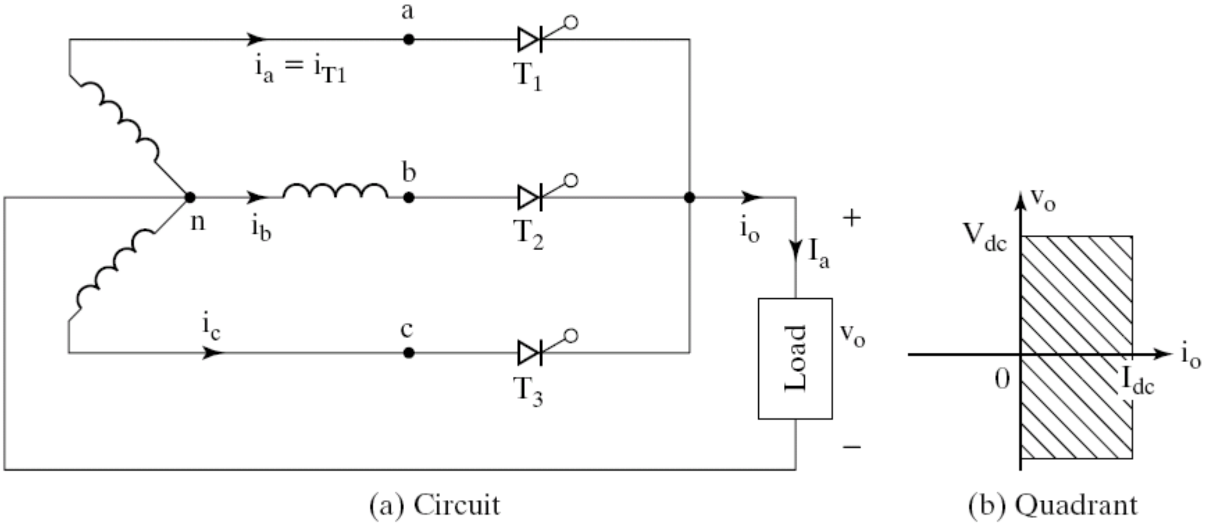


Fig.3.1. Three phase Half wave Converter

- The 3-phase input supply is applied through the star connected supply transformer as shown in the fig.2.23. The common neutral point of the supply is connected to one end of the load while the other end of the load connected to the common cathode point.
- When the thyristor T_1 is triggered at $\omega t = \left(\frac{\pi}{6} + \alpha\right) = \left(30^0 + \alpha\right)$, the phase voltage v_{an} appears across the load when T_1 conducts. The load current flows through the supply phase winding $'a-n'$ and through thyristor T_1 as long as T_1 conducts.
- When thyristor T_2 is triggered at $\omega t = \left(\frac{5\pi}{6} + \alpha\right) = \left(150^0 + \alpha\right)$, T_1 becomes reverse biased and turns-off. The load current flows through the thyristor T_2 and through the supply phase winding $'b-n'$. When T_2 conducts the phase voltage v_{bn} appears across the load until the thyristor T_3 is triggered.
- When the thyristor T_3 is triggered at $\omega t = \left(\frac{3\pi}{2} + \alpha\right) = \left(270^0 + \alpha\right)$, T_2 is reversed biased and hence T_2 turns-off. The phase voltage v_{cn} appears across the load when T_3 conducts.
- The related wave forms are as shown in Fig.3.2.

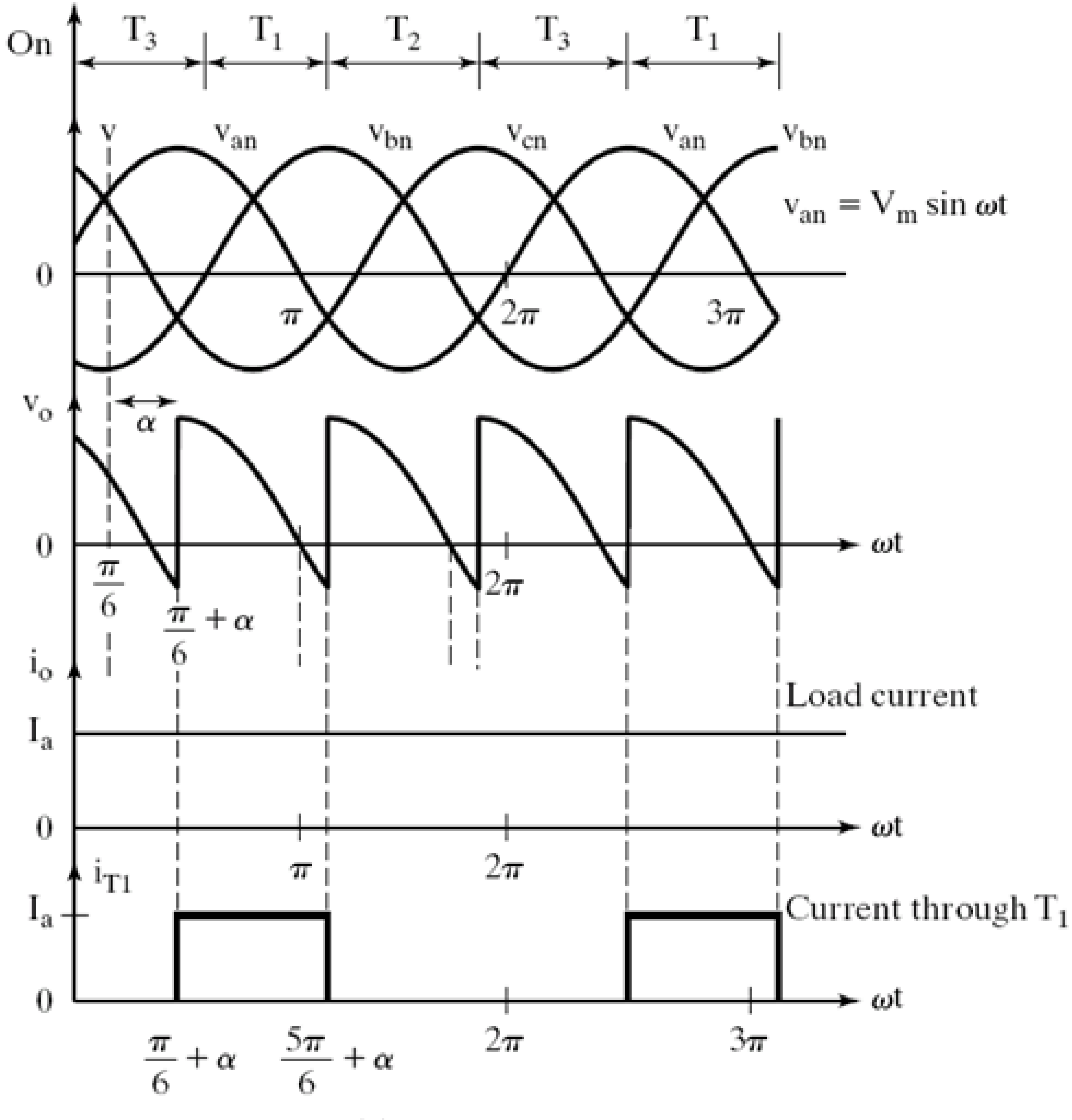


Fig.3.2: The related wave forms

- When T_1 is triggered again at the beginning of the next input cycle the thyristor T_3 turns off as it is reverse biased naturally as soon as T_1 is triggered. The figure shows the 3-phase input supply voltages, the output voltage which appears across the load, and the load current assuming a constant and ripple free load current for a highly inductive load and the current through the thyristor T_1.For a purely resistive load where the load inductance L = 0 and the trigger angle $\alpha > \left(\frac{\pi}{6}\right)$, the load current appears as discontinuous load current and each thyristor is naturally commutated when the polarity of the corresponding phase supply voltage reverses. The frequency of output ripple frequency for a 3-phase half wave converter is $3f_S$, where f_S the input supply frequency is.

- The 3-phase half wave converter is not normally used in practical converter systems because of the disadvantage that the supply current waveforms contain dc components (i.e., the supply current waveforms have an average or dc value).
- Average Output Voltage is given by

$$V_{dc} = \frac{3}{2\pi}\left[\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} v_O.d(\omega t)\right] \Rightarrow V_{dc} = \frac{3V_{Lm}}{2\pi}\cos(\alpha)$$

- Where $V_{Lm} = \sqrt{3}V_m =$ Max. line to line supply voltage for a 3-phase star connected transformer.
- The rms value of output voltage is given by

$$V_{O(RMS)} = \left[\frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} V_m^2 \sin^2 \omega t.d(\omega t)\right]^{\frac{1}{2}} \Rightarrow V_{O(RMS)} = \sqrt{3}V_m\left[\frac{1}{6}+\frac{\sqrt{3}}{8\pi}\cos 2\alpha\right]^{\frac{1}{2}}$$

Three Phase full wave bridge rectifier:

- Three phase full converter is a fully controlled bridge controlled rectifier using six thyristors connected in the form of a full wave bridge configuration. All the six thyristors are controlled switches which are turned on at a appropriate times by applying suitable gate trigger signals.
- The three phase full converter is extensively used in industrial power applications upto about 120kW output power level, where two quadrant operations is required. The fig.3.3 shows a three phase full converter with highly inductive load. This circuit is also known as three phase full wave bridge or as a six pulse converter.
- The thyristors are triggered at an interval of $\left(\frac{\pi}{3}\right)$ radians (i.e. at an interval of 60^0). The frequency of output ripple voltage is $6f_S$ and the filtering requirement is less than that of three phase semi and half wave converters.
  - At $\omega t = \left(\frac{\pi}{6}+\alpha\right)$, thyristor T_6 is already conducting when the thyristor T_1 is turned on by applying the gating signal to the gate of T_1. During the time period $\omega t = \left(\frac{\pi}{6}+\alpha\right)$ to $\left(\frac{\pi}{2}+\alpha\right)$, thyristors T_1 and T_6 conduct together and the line to line supply voltage v_{ab} appears across the load.
  - At $\omega t = \left(\frac{\pi}{2}+\alpha\right)$, the thyristor T_2 is triggered and T_6 is reverse biased immediately and T_6 turns off due to natural commutation. During the time period

$\omega t = \left(\frac{\pi}{2} + \alpha\right)$ to $\left(\frac{5\pi}{6} + \alpha\right)$, thyristor T_1 and T_2 conduct together and the line to line supply voltage v_{ac} appears across the load.

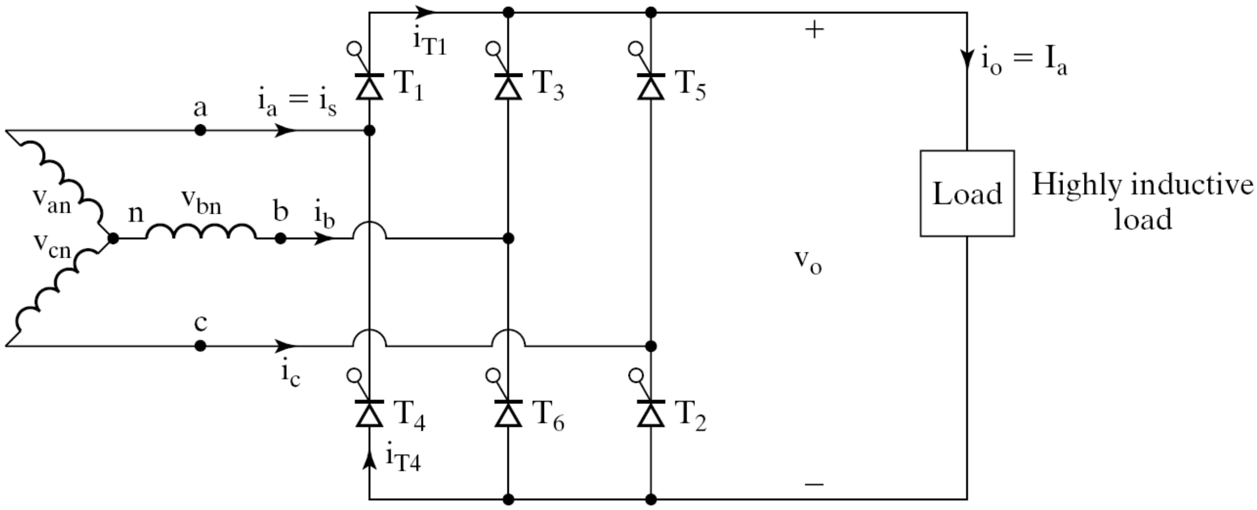


Fig.3.3: Three Phase full wave bridge rectifier

- The thyristors are numbered in the circuit diagram corresponding to the order in which they are triggered. The trigger sequence (firing sequence) of the thyristors is 12, 23, 34, 45, 56, 61, 12, 23, and so on. The fig.3.4 shows the waveforms of three phase input supply voltages, output voltage, the thyristor current through T_1 and T_4 , the supply current through the line 'a'.
- The output load voltage consists of 6 voltage pulses over a period of 2π radians, hence the average output voltage is calculated as

$$V_{O(dc)} = V_{dc} = \frac{6}{2\pi} \int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} v_O . d\omega t \qquad ;$$

$$V_{dc} = \frac{3\sqrt{3}V_m}{\pi} \cos\alpha = \frac{3V_{mL}}{\pi} \cos\alpha$$

- Where $V_{mL} = \sqrt{3}V_m =$ Max. line-to-line supply voltage
- The rms value of the output voltage is found from

$$V_{O(rms)} = \left[\frac{6}{2\pi} \int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} v_O^2 . d(\omega t) \right]^{\frac{1}{2}} \Rightarrow V_{O(rms)} = \sqrt{3}V_m \left(\frac{1}{2} + \frac{3\sqrt{3}}{4\pi} \cos 2\alpha \right)^{\frac{1}{2}}$$

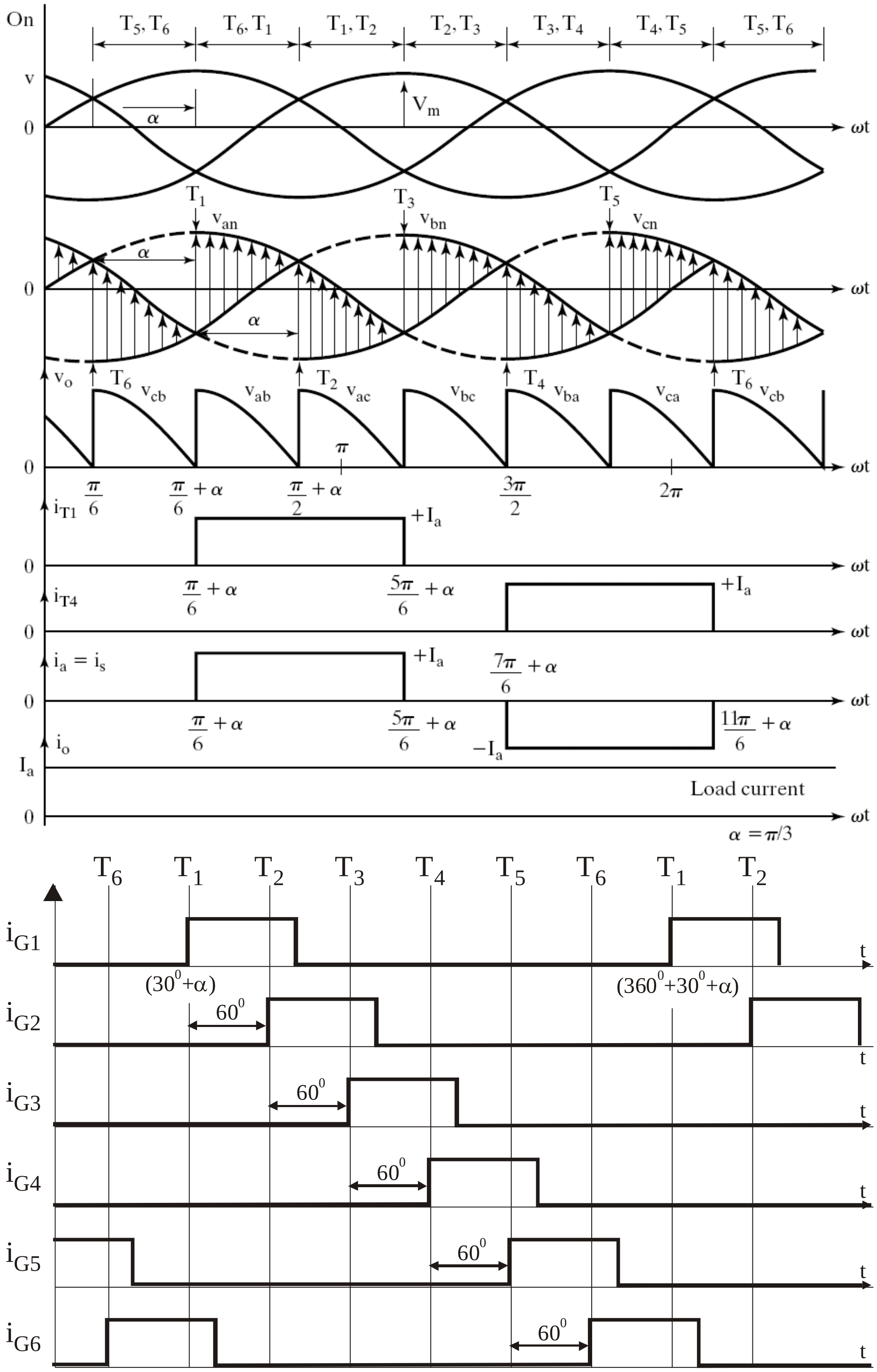


Fig.3.4: The related wave forms

Three phase semi converter (semi-controlled rectifier):

- 3-phase semi-converters are three phase half controlled bridge controlled rectifiers which employ three thyristors and three diodes connected in the form of a bridge configuration. Three thyristors are controlled switches which are turned on at appropriate times by applying appropriate gating signals. The three diodes conduct when they are forward biased by the corresponding phase supply voltages.
- 3-phase semi-converters are used in industrial power applications up to about 120kW output power level, where single quadrant operation is required. The power factor of 3-phase semi-converter decreases as the trigger angle α increases. The power factor of a 3-phase semi-converter is better than three phase half wave converter.
- The fig.3.5 shows a 3-phase semi-converter with a highly inductive load and the load current is assumed to be a constant and continuous load current with negligible ripple.

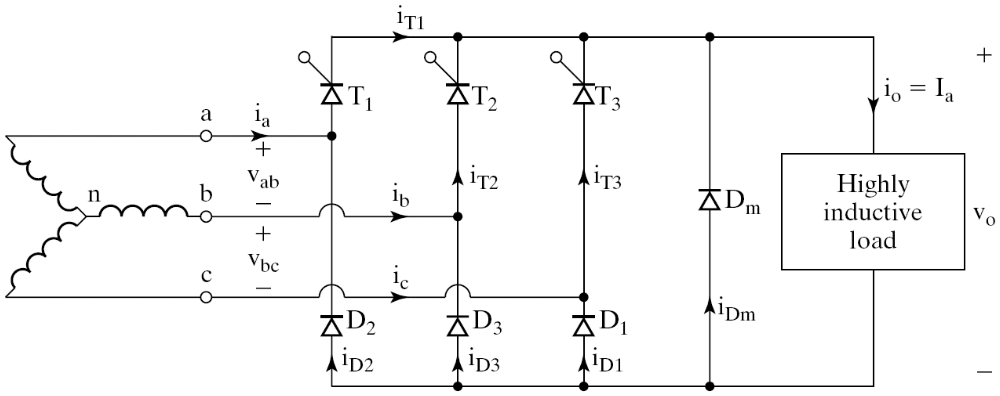


Fig.3.5: Three phase semi converter

- Thyristor T_1 is forward biased when the phase supply voltage v_{an} is positive and greater than the other phase voltages v_{bn} and v_{cn} . The diode D_1 is forward biased when the phase supply voltage v_{cn} is more negative than the other phase supply voltages.
- Thyristor T_2 is forward biased when the phase supply voltage v_{bn} is positive and greater than the other phase voltages. Diode D_2 is forward biased when the phase supply voltage v_{an} is more negative than the other phase supply voltages.
- Thyristor T_3 is forward biased when the phase supply voltage v_{cn} is positive and greater than the other phase voltages. Diode D_3 is forward biased when the phase supply voltage v_{bn} is more negative than the other phase supply voltages.
- The fig.3.6 shows the waveforms for the three phase input supply voltages, the output voltage, the thyristor and diode current waveforms, the current through the free wheeling diode D_m and the supply current i_a . The frequency of the output supply waveform is $3f_S$, where f_S is the input ac supply frequency.

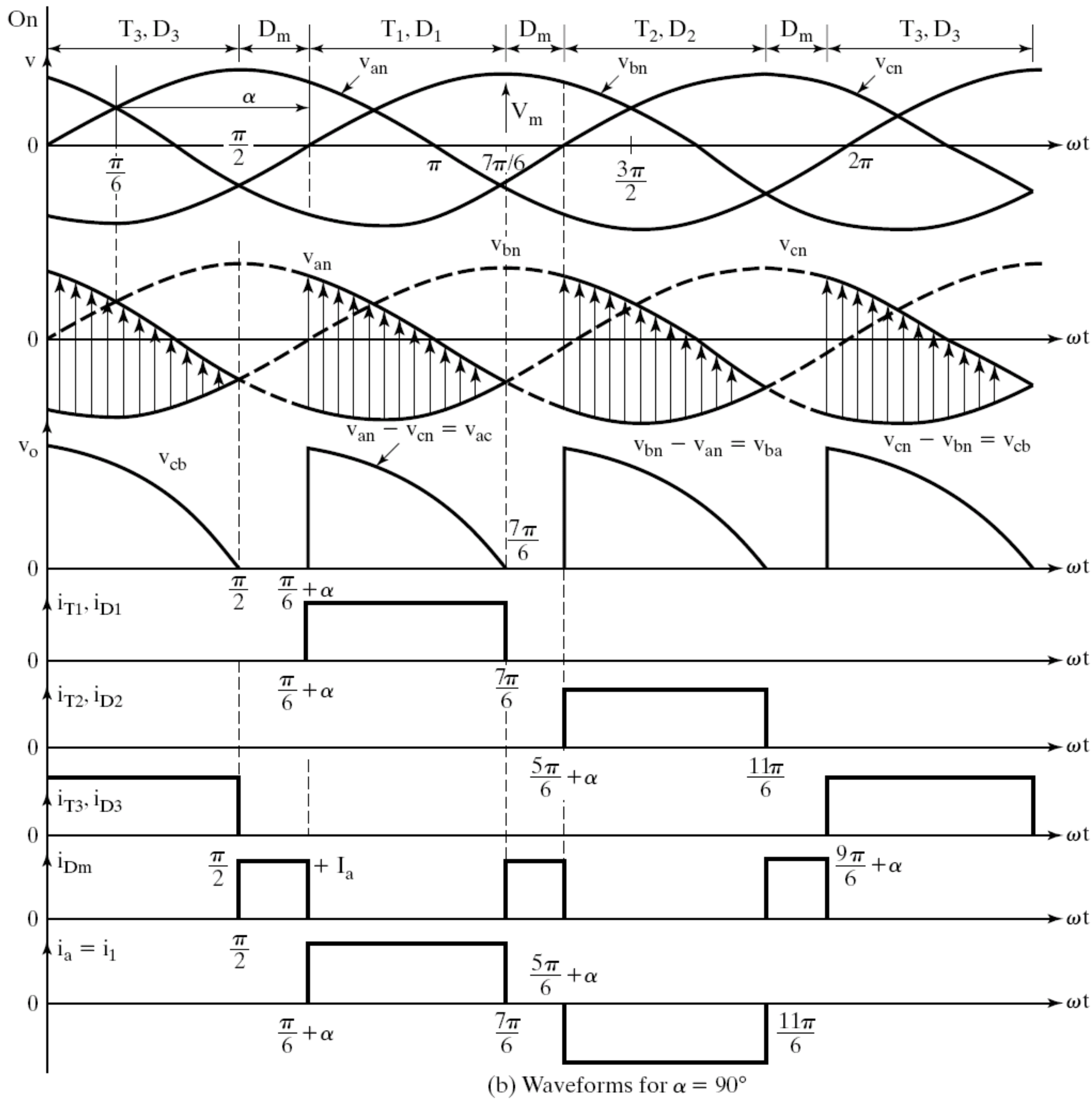


Fig.3.6: The related wave forms

- If the free wheeling diode D_m is not connected across the load, then T_1 would continue to conduct until the thyristor T_2 is triggered at $\omega t = \left(\frac{5\pi}{6} + \alpha\right)$ and the free wheeling action is accomplished through T_1 and D_2, when D_2 turns on as soon as v_{an} becomes more negative at $\omega t = \left(\frac{7\pi}{6}\right)$. If the trigger angle $\alpha \leq \left(\frac{\pi}{3}\right)$ each thyristor conducts for $\frac{2\pi}{3}$ radians $\left(120^0\right)$ and the free wheeling diode D_m does not conduct. The waveforms for a 3-phase semi-converter with $\alpha \leq \left(\frac{\pi}{3}\right)$ is shown in fig.3.7.

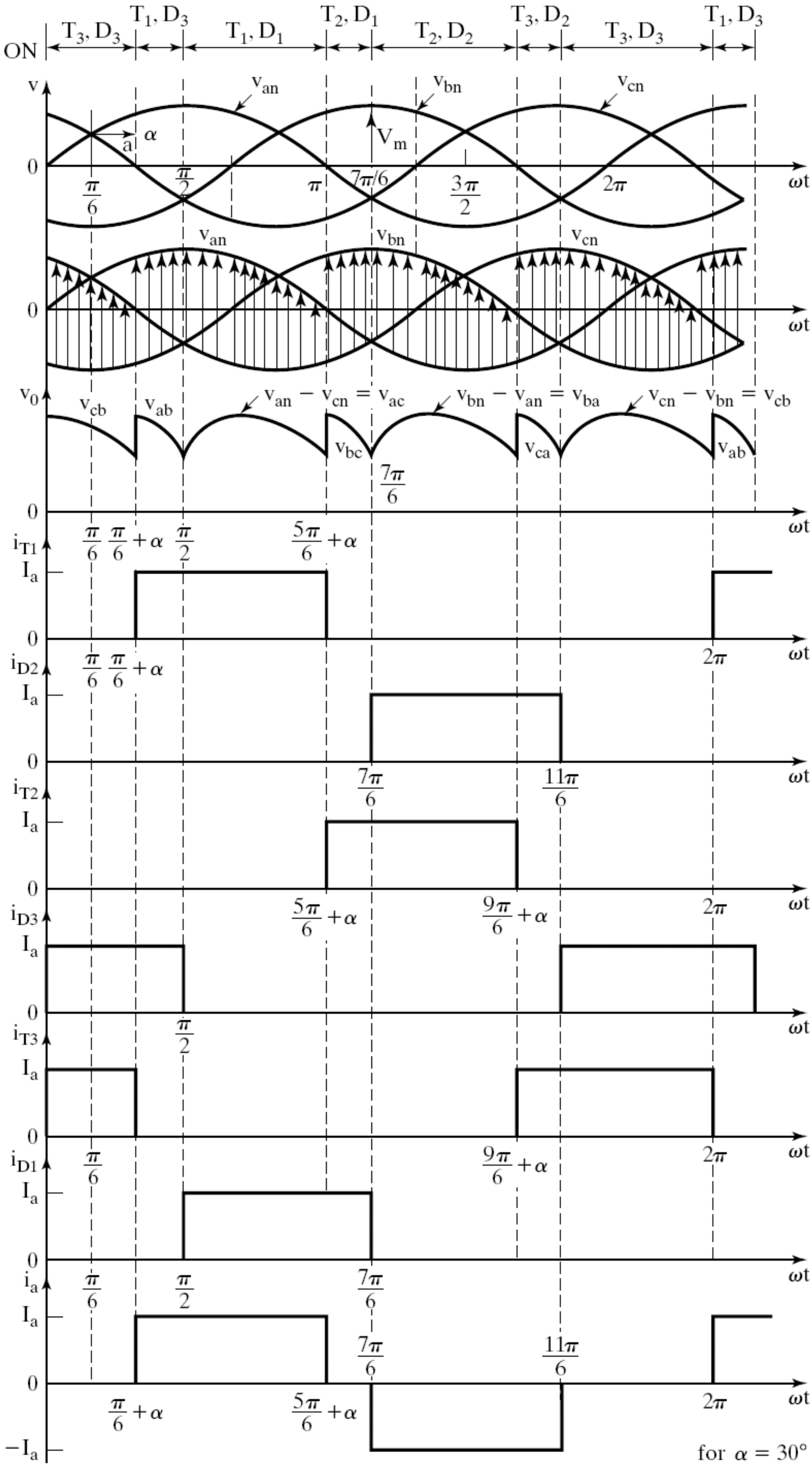


Fig.3.7: The related wave forms without FWD

Average Output Voltage:

- For $\alpha \geq \frac{\pi}{3}$ and discontinuous output voltage: the average output voltage is found from

$$V_{dc} = \frac{3}{2\pi}\int_{\pi/6+\alpha}^{7\pi/6} v_{ac}.d\left(\omega t\right)$$

$$V_{dc} = \frac{3V_{mL}}{2\pi}\left(1+\cos\alpha\right)$$

- The rms output voltage is found from

$$V_{O(RMS)} = \left[\frac{3}{2\pi}\int_{\pi/6+\alpha}^{7\pi/6} 3V_m^2\sin^2\left(\omega t-\frac{\pi}{6}\right)d\left(\omega t\right)\right]^{\frac{1}{2}}$$

$$V_{O(RMS)} = \sqrt{3}V_m\left[\frac{3}{4\pi}\left(\pi-\alpha+\frac{1}{2}\sin 2\alpha\right)\right]^{\frac{1}{2}}$$

- For $\alpha \leq \frac{\pi}{3}$, and continuous output voltage
- The average or dc output voltage is

$$V_{dc} = \frac{3}{2\pi}\left[\int_{\pi/6+\alpha}^{\pi/2} v_{ab}.d\left(\omega t\right)+\int_{\pi/2}^{5\pi/6+\alpha} v_{ac}.d\left(\omega t\right)\right]$$

$$V_{dc} = \frac{3\sqrt{3}V_m}{2\pi}\left(1+\cos\alpha\right)$$

- The RMS value of the output voltage is

$$V_{O(RMS)} = \left[\frac{3}{2\pi}\int_{\pi/6+\alpha}^{\pi/2} v_{ab}^2.d\left(\omega t\right)+\int_{\pi/2}^{5\pi/6+\alpha} v_{ac}^2.d\left(\omega t\right)\right]^{\frac{1}{2}}$$

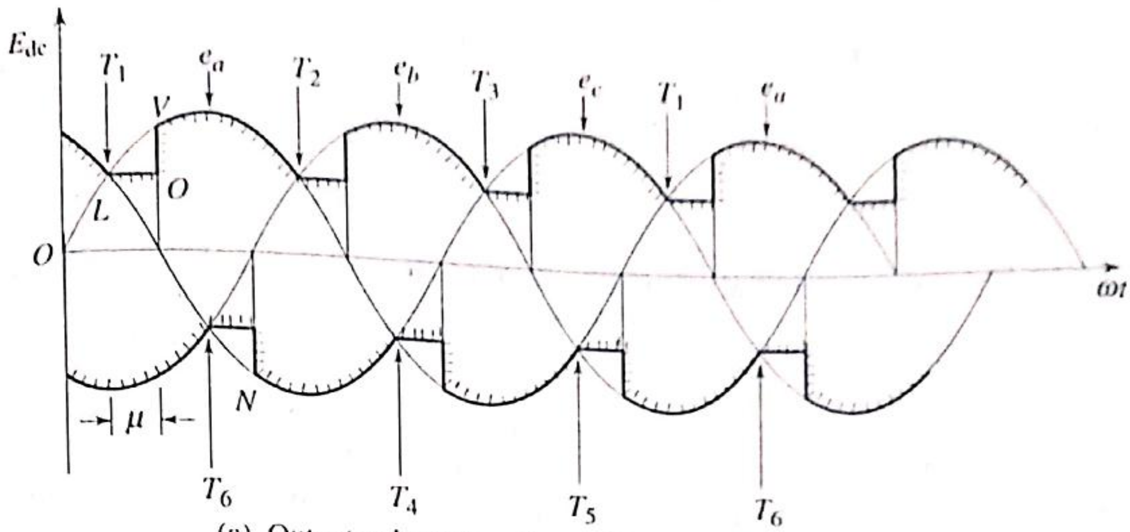
$$V_{O(RMS)} = \sqrt{3}V_m\left[\frac{3}{4\pi}\left(\frac{2\pi}{3}+\sqrt{3}\cos^2\alpha\right)\right]^{\frac{1}{2}}$$

Source Inductance effect on Three Phase Full-Bride controlled rectifier

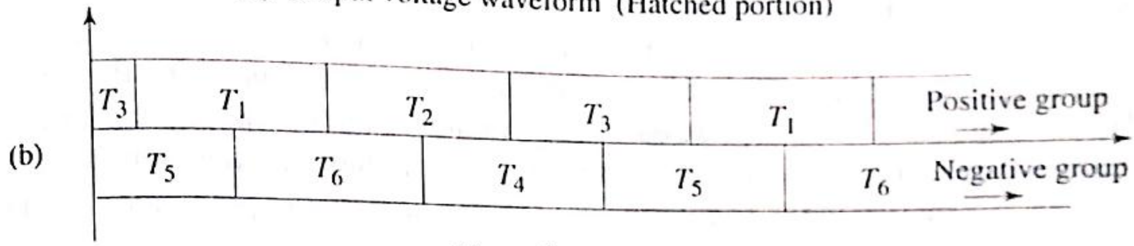
The below figure shows the three phase full bridge controlled rectifier with sours inductance (L_S). Assume load current is constant (I_d). the conduction of various SCRs without overlapping at firing angle α = 0^0 are as follows:

Thyristors T_5T_6 conduct up to ωt = 30^0. from ωt = 30^0 to 90^0 Thyristors T_6T_1 conduct. Similarly, from ωt = 90^0 to 150^0 Thyristors T_1T_2 conduct and so on.

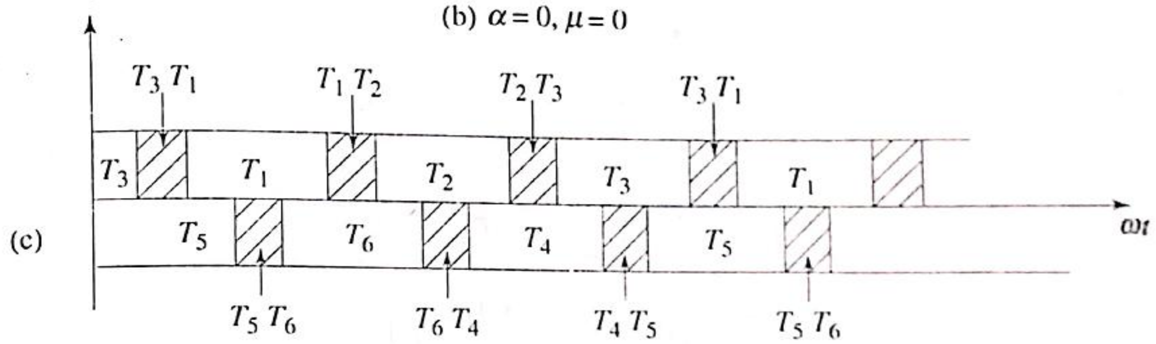
Due to source inductance effect outgoing and incoming SCRs from the same group are conducting for some period called overlapping angle as shown in wave forms

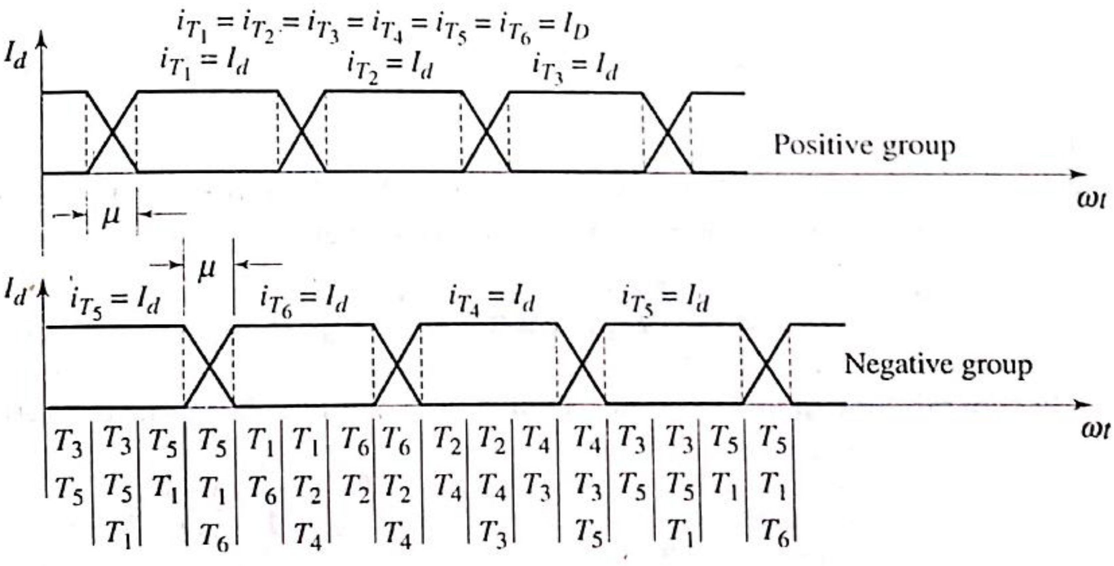


(a) Output voltage waveform (Hatched portion)



(b) $\alpha = 0, \mu = 0$





Voltage and current waveform

Reduction of output voltage due to overlapping

$$= \frac{1}{\pi/3}\int_0^{\mu} e_L \cdot d(\omega t) = \frac{3}{\pi}\int_0^{\mu} L_s \cdot \frac{di}{dt} d(\omega t)$$

$$= \frac{3L_s}{\pi}\int_0^{\mu/\omega} \omega \cdot \frac{di}{dt} dt = \frac{3\omega L_s}{\pi}\int_0^{I_d} di$$

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

Hence,

Output voltage with overlap = output voltage of converter – output voltage drop due to overlap

$$= \frac{3\sqrt{3}}{\pi} E_{mph} \cos\alpha - \frac{3\omega L_s}{\pi} I_d$$

In general, for ‘p’ pulse converter reduction in output voltage due to overlap

$$= \frac{p}{2\pi}\int_0^{\mu} L_s \left(\frac{di}{dt}\right) d(\omega t) = \frac{p\omega L_s}{2\pi}\int_0^{\mu/\omega} \left(\frac{di}{dt}\right) dt$$

$$= \frac{p\omega L_s}{2\pi}\int_0^{I_d} d_i = \frac{p\omega L_s \cdot I_d}{2\pi}$$

Output voltage of fully controlled converter is also given by

$$E_{dc} = \frac{3\sqrt{3}E_{mph}}{\pi}\cos(\alpha + \mu) + \frac{3\omega L_s}{\pi} I_d$$