Unit 2

AC-DC Converters

(only for private circulation for non-commercial and educational purposes)

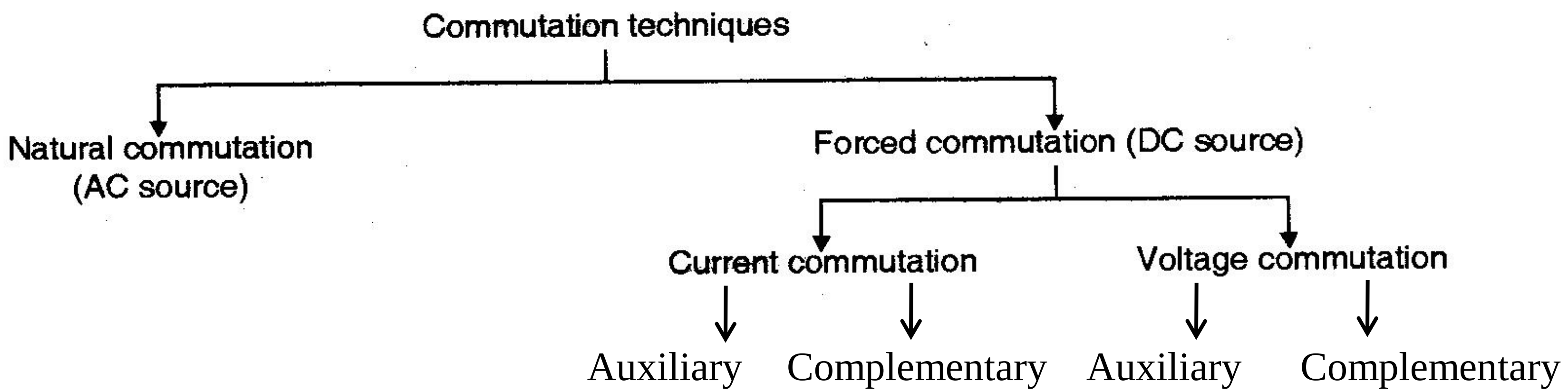
SCR Turn-off (commutation)-1

Introduction to Commutation :

The process of turning off of a conducting SCR is known as "commutation". Once the SCR is fired (turned on), the gate loses control over it.

Depending on the nature of the source (ac or dc) the commutation can be natural or forced.

The classification of commutation techniques is shown below



Current commutation : If the SCR is turned off by reducing its anode current below the holding current value, then the commutation is called as "current commutation".

Voltage commutation : If the conducting SCR is turned off by applying a large reverse voltage across it then the commutation is called as "voltage commutation".

SCR Turn-off (commutation)-2

Forced commutation circuits for SCR turn-off were used in DC-AC inverters and DC-DC converters (choppers). As SCRs have been replaced in these circuits by MOSFETs and IGBTs, these forced commutation circuits are no longer in use. However, line frequency LCCs (line commutated converters) and AC-AC voltage controllers are still extensively used and hence natural or line commutation is very much relevant.

Natural or Line Commutation (Class F):

When the SCR is turned off, due to its forward current going below the holding current, naturally, it is said to be naturally commutated.

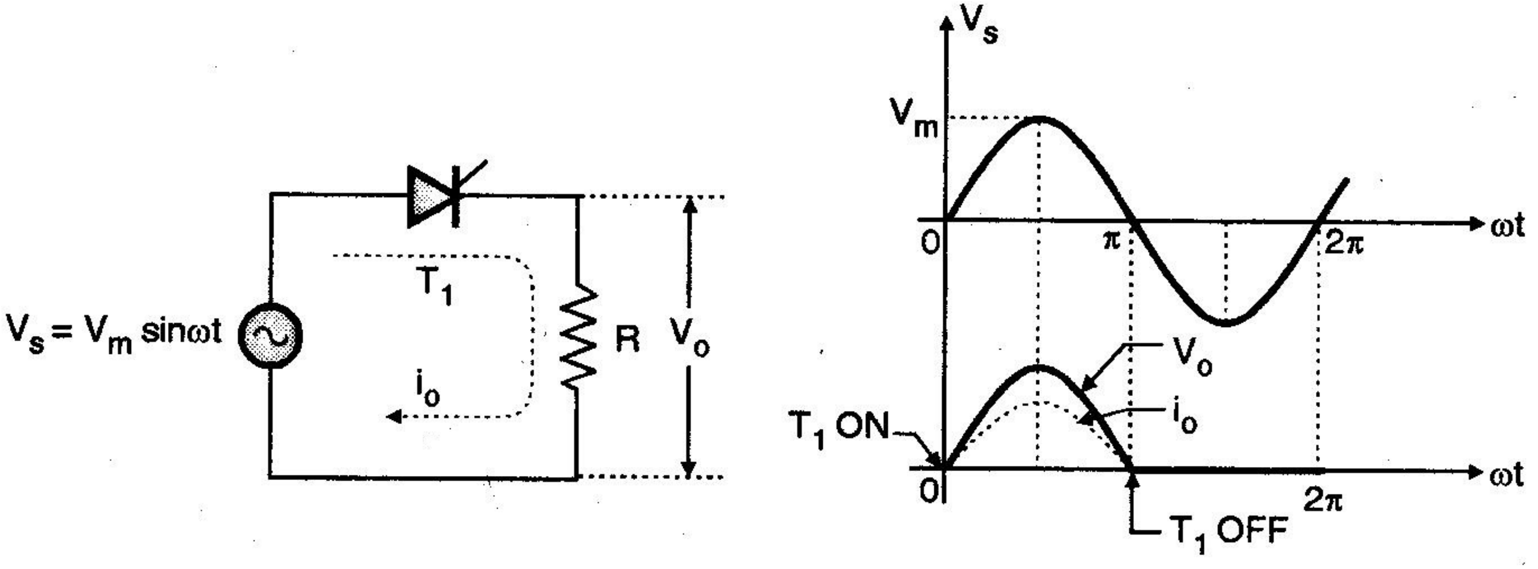
The natural commutation usually takes place when ac supply is used at the input of the thyristorised circuits.

Refer Fig. 2.1 (a), in which the source voltage is ac and the load is resistive. Therefore the load voltage and current will have the same shape and they will be in phase with each other.

The current flowing through the SCR T_1 is same as that flowing through R. As shown in Fig. 2.1 (b), the SCR current passes through a natural zero and a reverse voltage appears across the SCR there after.

The conducting SCR is then turned off due to its anode current going to zero naturally. Hence it is known as natural commutation.

SCR Turn-off (commutation)-3



(a) Circuit diagram **(b) Waveform**

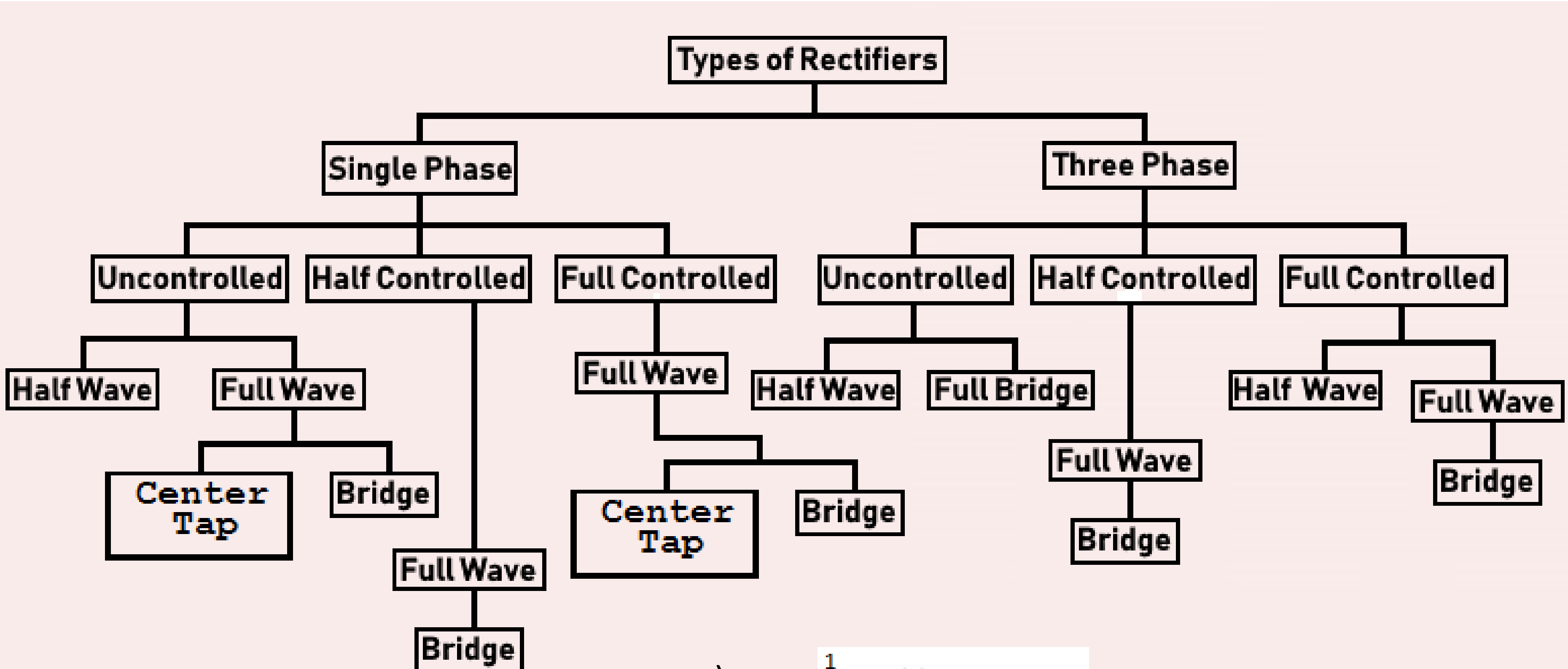
FIGURE 2.1

Advantages of natural commutation :

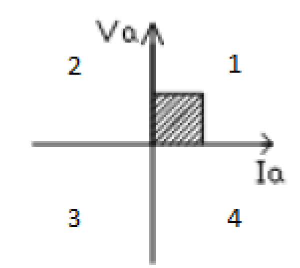
It does not require any external commutation components.

It is reliable and simple.

Overview of Types of Rectifiers (AC-DC converters)

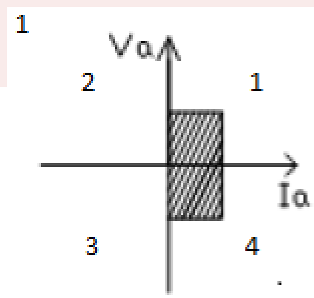


a)



Uncontrolled & Half-controlled

b)

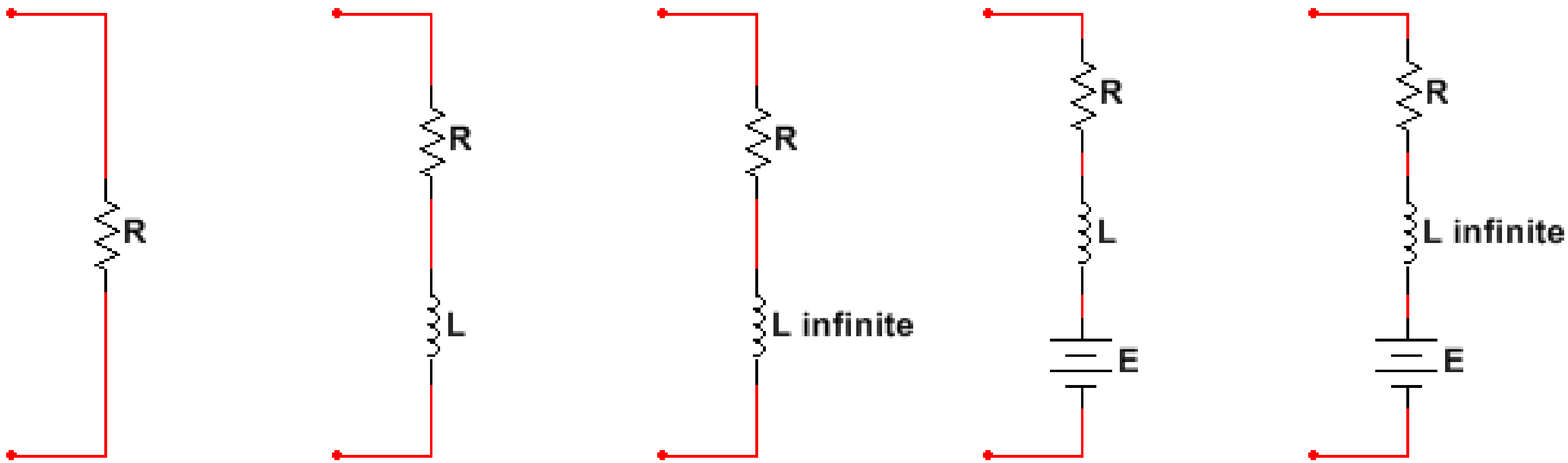


Fully controlled

c)

FIGURE 2.2

Different types of loads



R Load

R-L Load

R-L infinite or Level or Highly inductive or Ripple-free Load

R-L-E Active Load

R-L-E Active Level or Highly inductive or Ripple-free Load

FIGURE 2.7

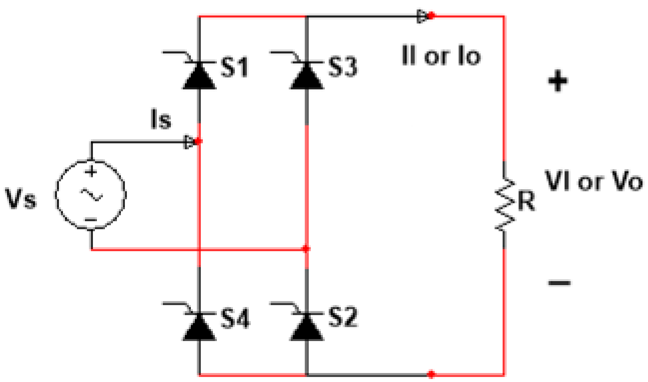
Evolution of FCB

Uncontrolled Diode Bridge Rectifier

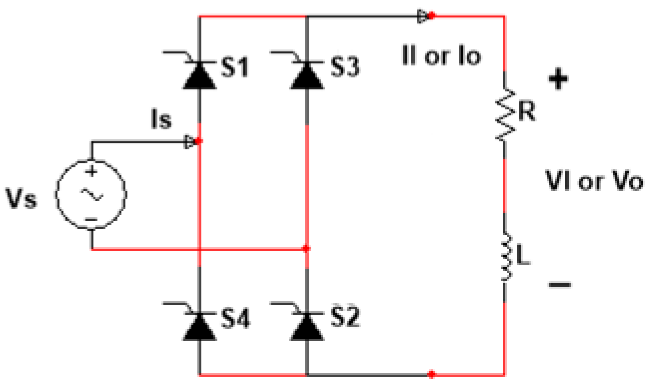
Fully Controlled Bridge (FCB)

FIGURE 2.8

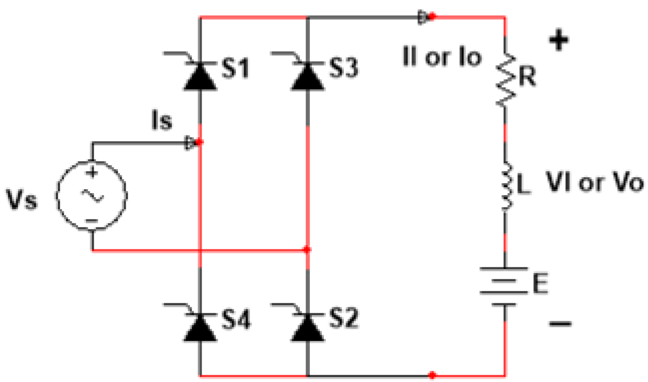
FCB with different loads



Fully Controlled Bridge
(FCB) with R load



Fully Controlled Bridge
(FCB) with R-L load



Fully Controlled Bridge
(FCB) with R-L-E load

FIGURE 2.9

Operation of FCB with R load:

The single phase full converter consists of four thyristors SCR_1 to SCR_4 connected in the bridge configuration driving a resistive load as shown in Fig. 2.3.

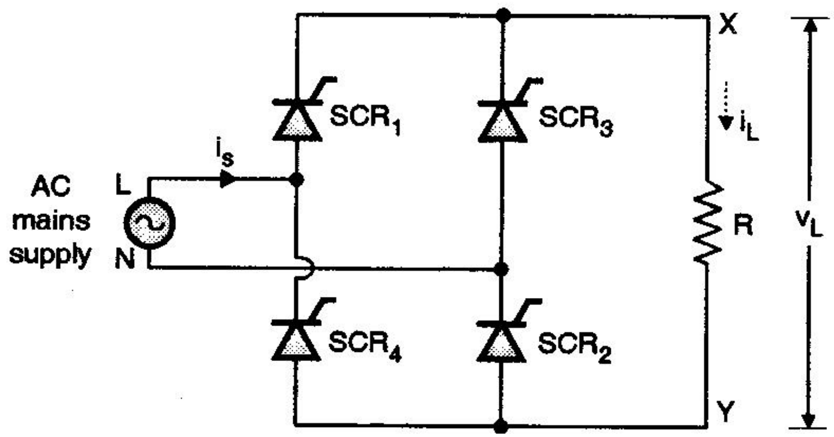


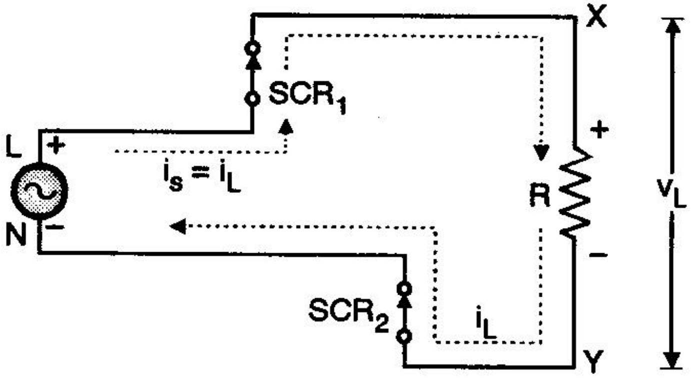
Fig. 2.3: Single phase full converter with resistive load

- These four thyristors can be divided into two groups each consisting of two SCRs. The full converter circuit is being operated on single phase ac mains as shown in Fig. 2.3.

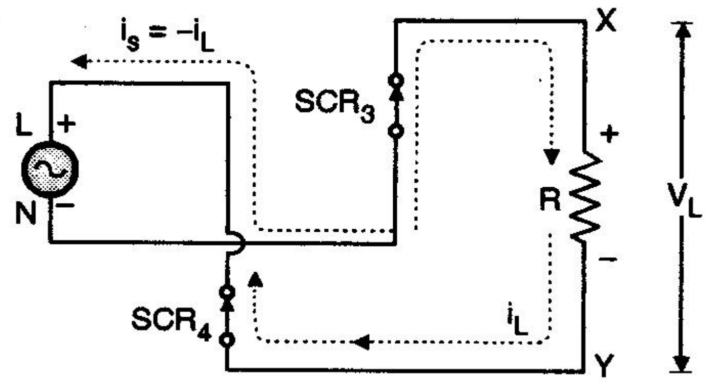
Mode I ($\alpha \le \omega t \le \pi$) :

- In the positive half cycle of the input ac mains voltage the thyristors SCR_1 and SCR_2 are forward biased and hence can be turned on at the desired value of firing angle α.
- As soon as the thyristors SCR_1 and SCR_2 are turned on at α the ac mains gets connected across the load as shown in Fig. 2.4 (a).

FCB with R load - 2



(a) Equivalent circuit for mode I
(α to π)



(b) Equivalent circuit for mode III
(π + α) to 2 π

Fig. 2.4

- The load voltage is thus equal to the instantaneous supply voltage. The current flows from L through SCR_1, load R, SCR_2 back to N as shown.
- The load current is positive and has the same shape as that of ac mains input voltage. The load voltage and load current are in phase.
- At instant π, the supply voltage goes to zero. The load current also becomes zero and the conducting SCRs, SCR_1 and SCR_2 are turned off due to **Natural Commutation.**

Mode II (π to π + α) :

All the SCRs remain off during the period π to π + α. The load voltage and load current are zero during this mode of operation.

FCB with R load - 3

Mode III [$(\pi + \alpha) \leq \omega t \leq 2\pi$] :

- The ac input voltage becomes negative after π. This makes SCR_3 and SCR_4 forward biased.
- These SCRs are turned on at $(\pi + \alpha)$ in the negative half cycle of input ac mains voltage. The equivalent circuit of this mode is as shown in Fig. 2.4 (b).
- The current now flows from N through SCR_3, load R, SCR_4 back to L as shown in Fig. 2.4 (b).
- Thus the load voltage still remains positive (X is positive w.r.t. Y) and equal to instantaneous supply voltage. The load current is also positive but the supply current i_s changes its direction and becomes negative.
- The SCR_3 and SCR_4 continue to conduct during the entire negative half cycle i.e. from $(\pi + \alpha)$ to 2π.
- At $\omega t = 2\pi$ the supply voltage goes to zero, the load current is also zero and the thyristors SCR_3 and SCR_4 are turned off at 2π due to Natural Commutation.

Mode IV ($0 \leq \omega t \leq \alpha$) :

During this interval, all the SCRs remain off. The load voltage and load current are zero during this mode of operation.

Waveforms : The voltage and current waveforms are as shown in Fig. 2.6.

Thyristor currents : The current through an SCR is equal to the instantaneous load current when the SCR is conducting. The conduction angle i.e. the time for which a thyristor conducts is $(\pi - \alpha)$ radians for this circuit. The peak thyristor current is $I_m = V_m / R$ as shown in Fig. 2.6.

FCB with R load - 4

Thyristor voltage :

- All the SCR are assumed to be ideal switches. i.e. when they are conducting, the voltage across them is zero, and when they are nonconducting they offer infinite (∞) impedance.
- The voltage waveform for SCR_1 is as shown in Fig. 2.6. The voltage across it is 0 from α to π when it is conducting, half the instantaneous input voltage (positive or negative) for the intervals 0 to α and π to $\pi + \alpha$ when all the thyristors are off and equal to negative supply voltage during $\pi + \alpha$ to 2π when SCR_3 and SCR_4 conduct.
- In this way the peak reverse voltage across each thyristor is $-V_m$.

Quadrant of operation :

- As can be seen from the waveforms of Fig. 2.6 the instantaneous load voltage as well as the load current both are always positive.
- Thus load always receives power from the source. The converter thus works only as rectifier.
- The full converter with resistive load operates only in the first quadrant as shown in Fig. 2.5.

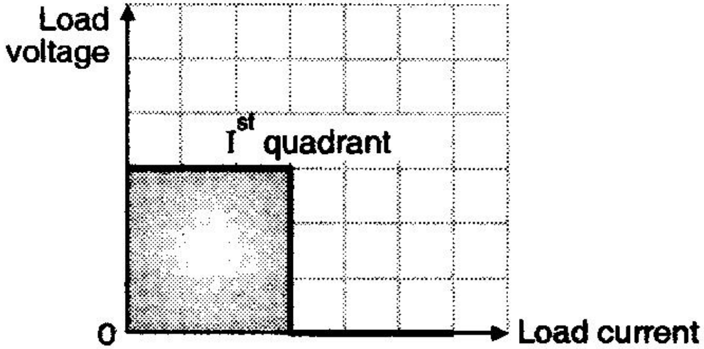


Fig. 2.5 : Quadrant of operation for full converter with resistive load

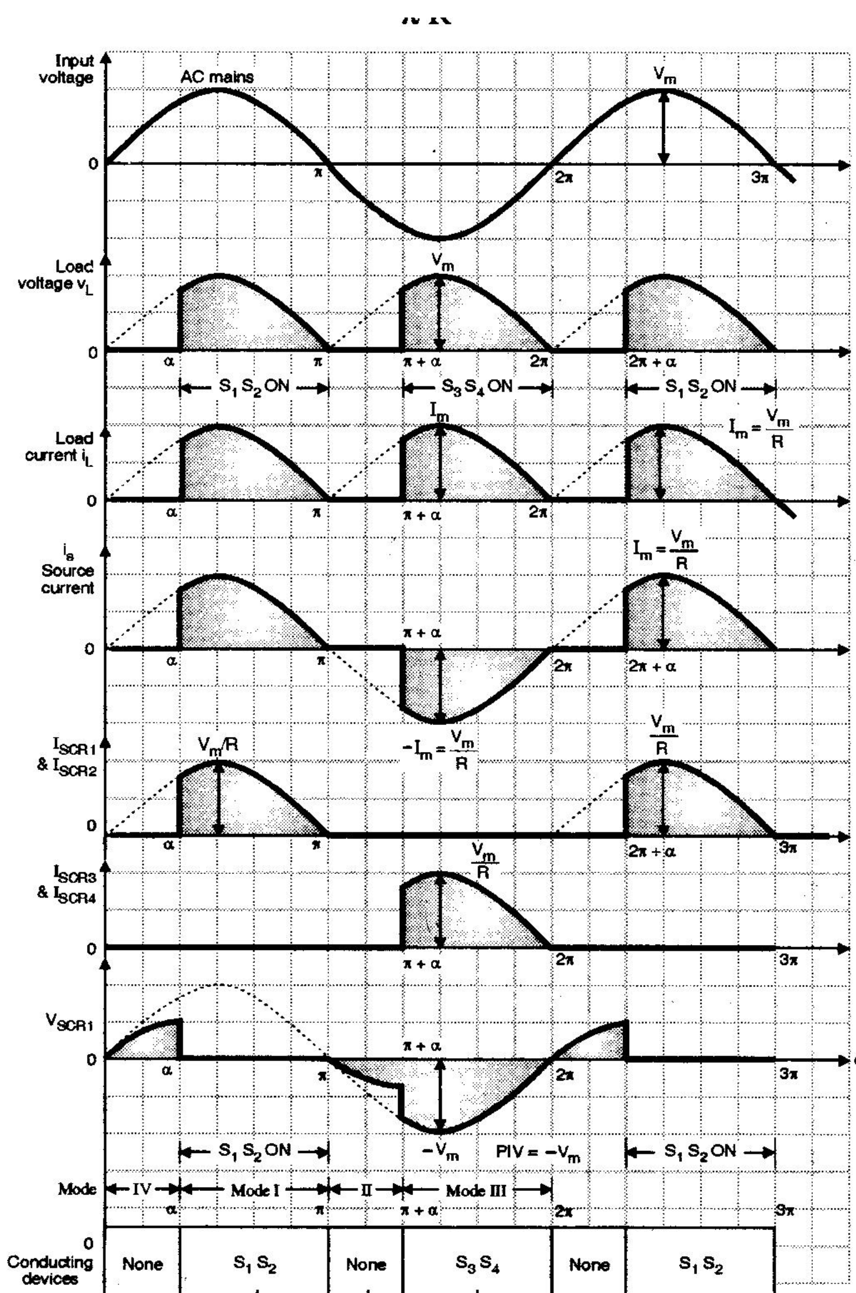


Fig. 2.6 : Waveforms for single phase FCB with R load

FCB with R load - 6

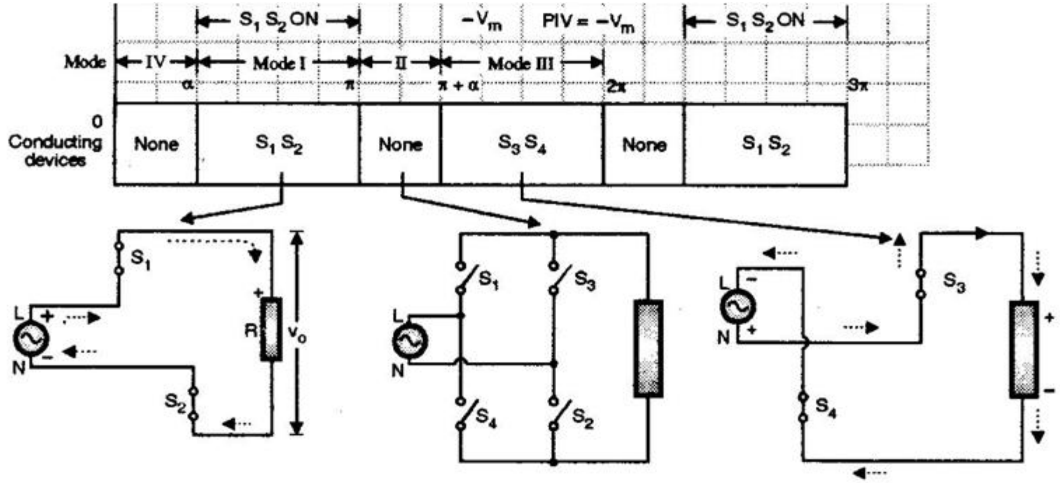


Fig. 2.6 : Waveforms for single phase FCB with R load

Performance parameters of LCCs- 1

PERFORMANCE PARAMETERS

1. The *average* value of the output (load) voltage, V_{dc}
2. The average value of the output (load) current, I_{dc}
3. The output *dc power*,

$$P_{dc} = V_{dc} I_{dc}$$

4. The *rms* value of the output voltage, V_{rms}
5. The *rms* value of the output current, I_{rms}
6. The output *ac power*,

$$P_{ac} = V_{rms} I_{rms}$$

7. The *efficiency* (or *rectification ratio*)

$$\eta = \frac{P_{dc}}{P_{ac}}$$

Performance parameters of LCCs- 2

The output voltage can be considered to consist of two components viz.

a) the *DC component* V_{dc}
b) the *AC component* or ripple V_{ac}

8. The *rms* (effective) value of the AC component is:

$$V_{ac} = \sqrt{V_{rms}^2 - V_{dc}^2}$$

9. The *form factor*, which is a measure of the shape of the waveform, is:

$$FF = \frac{V_{rms}}{V_{dc}}$$

For a sine wave, $FF = \pi/(2\sqrt{2}) = 1.111$

10. The *ripple factor*, which is a measure of the ripple content, is:

$$RF = \frac{V_{ac}}{V_{dc}}$$

Performance parameters of LCCs-3

11. The ripple factor can also be expressed in terms of the form factor as:

$$\mathrm{RF} = \sqrt{\left(\frac{V_{\mathrm{rms}}}{V_{\mathrm{dc}}}\right)^2 - 1} = \sqrt{\mathrm{FF}^2 - 1}$$

and **FF = √(1 + RF^2)**

12. The *transformer utilization factor* is defined as

$$\mathrm{TUF} = \frac{P_{\mathrm{dc}}}{V_{sec} I_{sec}}$$

where V_{sec} and I_{sec} are the rms voltage and rms current of the transformer secondary

Performance parameters of LCCs-4

13. The angle ϕ by which the fundamental component of the supply current lags the fundamental component of the supply voltage is known as the *displacement angle*.

The *displacement factor* is defined as:

$$\mathrm{DF} = \cos\phi$$

14. The *harmonic factor* of the input supply current is:

$$\mathrm{HF} = \left(\frac{I_s^2 - I_1^2}{I_1^2}\right)^{1/2} = \left[\left(\frac{I_s}{I_1}\right)^2 - 1\right]^{1/2}$$

where I_1 is the fundamental rms value of the input supply current and I_s is the total rms value of the input supply current.

15. The input *current distortion factor* is:

$$\mathrm{CDF} = \frac{I_1}{I_s}$$

Performance parameters of LCCs-5

16. The input *power factor* is:

PF = Real power / Apparent power

which results in:

$$PF = \frac{V_s I_1}{V_s I_s} \cos \phi = \frac{I_1}{I_s} \cos \phi$$

$$= \text{CDF} \times \text{DF}$$

Analysis of Full Converter with Resistive Load :

Average load voltage : Referring to the load voltage waveform shown in Fig. 2.6 the average load voltage is given by,

$$V_{Ldc} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin \omega t \, d\omega t \qquad ...(2.1)$$

here $V_m = \sqrt{2}V_s$ where V_s is the rms supply voltage

$$V_{Ldc} = \frac{-V_m}{\pi}[\cos \omega t]_{\alpha}^{\pi}$$

$$V_{Ldc} = \frac{V_m}{\pi}[1+\cos\alpha] = \frac{\sqrt{2}\,V_s}{\pi}[1+\cos\alpha] = \frac{2\sqrt{2}\,V_s}{\pi}\,\frac{[1+\cos\alpha]}{2} \qquad ...(2.2)$$

Now the maximum value of V_{Ldc} occurs when $\alpha = 0$ and is:

$$\mathbf{V_{Ldcmax} = 2V_m / \pi = 2\sqrt{2}\, V_s / \pi = 0.9003\, V_s} \qquad ...(2.2\ a)$$

Hence the normalized value of V_{Ldc} can be expressed as:

$$\mathbf{V_{Ldcnorm}} = V_{Ldc} / V_{Ldcmax} = \mathbf{(1 + \cos\alpha) / 2} \qquad ...(2.2\ b)$$

FCB with R load - 8

Average load current : Due to resistive nature of the load, the average load current is given by,

$$\text{Average load current } I_{L\,dc} = V_{L\,dc} / R \quad \text{...(2.3)}$$

$$I_{L\,dc} = \frac{V_m}{\pi R}[1 + \cos\alpha] \quad \text{...(2.4)}$$

Similarly, the maximum value of I_{Ldc} occurs when $\alpha = 0$ and is:

$$\mathbf{I_{Ldcmax} = 2V_m / (\pi R) = 2\sqrt{2}\, V_s / \pi R = 0.9003\, V_s / R} \quad \textbf{...(2.4 a)}$$

Hence the normalized value of I_{Ldc} can be expressed as:

$$\mathbf{I_{Ldcnorm}} = I_{Ldc} / I_{Ldcmax} = \mathbf{(1 + \cos\alpha) / 2} \quad \textbf{...(2.4 b)}$$

RMS load voltage :

Referring to the load voltage waveform of Fig. 2.6 we get,

$$V_{L\,rms} = \left\{\frac{1}{\pi}\int_{\alpha}^{\pi} V_m^2 \sin^2 \omega t\, d\omega t\right\}^{1/2} \quad \text{...(2.5)}$$

$$= \left\{\frac{V_m^2}{2\pi}\int_{\alpha}^{\pi}(1 - \cos 2\,\omega t)\, d\omega t\right\}^{1/2}$$

FCB with R load - 9

$$\therefore \quad V_{L\,rms} = \frac{V_m}{\sqrt{2}}\left\{\frac{1}{\pi}\int_{\alpha}^{\pi} 1 \cdot d\omega t - \frac{1}{\pi}\int_{\alpha}^{\pi} \cos 2\ \omega t\, d\omega t\right\}^{1/2}$$

$$\frac{V_m}{\sqrt{2}} \qquad = \frac{V_m}{\sqrt{2}}\left\{\frac{1}{\pi}\left[\omega t\right]_{\alpha}^{\pi} - \frac{1}{\pi}\left[\frac{\sin 2\,\omega t}{2}\right]_{\alpha}^{\pi}\right\}^{1/2} = \frac{V_m}{\sqrt{2}}\left\{\frac{1}{\pi}\left[\pi - \alpha\right] - \frac{1}{2\,\pi}\left[\sin 2\,\pi - \sin 2\,\alpha\right]\right\}^{1/2}$$

$$= \frac{V_m}{\sqrt{2}}\left\{\frac{1}{\pi}\left[\pi - \alpha\right] - \frac{1}{2\,\pi}\left[0 - \sin 2\,\alpha\right]\right\}^{1/2}$$

$$V_{L\,rms} = \frac{V_m}{\sqrt{2}}\left\{\frac{(\pi - \alpha) + \frac{1}{2}\sin 2\,\alpha}{\pi}\right\}^{1/2} = V_s\left\{\frac{(\pi - \alpha) + \frac{1}{2}\sin 2\,\alpha}{\pi}\right\}^{1/2} \qquad \text{...(2.6)}$$

Now the maximum value of V_{Lrms} occurs when $\alpha = 0$ and is:

$$\mathbf{V_{Lrmsmax} = V_m / \sqrt{2} = V_s} \qquad \textbf{...(2.6 a)}$$

Hence the normalized value of V_{Lrms} can be expressed as:

$$\mathbf{V_{Lrmsnorm}} = V_{Lrms} / V_{Lrmsmax} = \left\{\frac{(\pi - \alpha) + \frac{1}{2}\sin 2\,\alpha}{\pi}\right\}^{1/2} \qquad \textbf{...(2.6 b)}$$

RMS load current : Due to resistive nature of the load, the rms load current is given by

$$I_{Lrms} = V_{Lrms} / R \qquad \text{...(2.7)}$$

Thyristor currents : Referring to the waveform for the current through SCR_1 we get,

1. **Average thyristor current :**

$$I_{TH\,(av)} = \frac{1}{2\pi} \int_{\alpha}^{\pi} I_m \sin \omega t \, d\omega t \qquad \text{...(2.8)}$$

$$\therefore \quad I_{TH\,(av)} = \frac{-I_m}{2\pi} [\cos \omega t]_{\alpha}^{\pi} = \frac{-I_m}{2\pi} (\cos \pi - \cos \alpha) = \frac{I_m}{2\pi} (1 + \cos \alpha)$$

$$\text{But} \quad I_m = V_m / R$$

$$\therefore \quad I_{TH\,(av)} = \frac{V_m}{2\pi R} (1 + \cos \alpha)$$

Refer to Equation (2.4)

$$I_{Ldc} = \frac{V_m}{\pi R} (1 + \cos \alpha)$$

$$\therefore \quad I_{TH\,(av)} = \frac{I_{Ldc}}{2} \qquad \text{...(2.9)}$$

FCB with R load - 11

2. RMS thyristor current (I_{TH} (rms)) :

$$I_{TH\,(rms)} = \left\{\frac{1}{2\pi}\int_{\alpha}^{\pi} I_m^2 \sin^2 \omega t \, d\omega t\right\}^{1/2} = \left\{\frac{I_m^2}{2\pi}\int_{\alpha}^{\pi} \frac{1-\cos 2\omega t}{2} d\omega t\right\}^{1/2}$$

$$= \left\{\frac{I_m^2}{4\pi}\left[(\pi-\alpha)+\frac{1}{2}\sin 2\alpha\right]\right\}^{1/2}$$

$$= \frac{I_m}{2}\left\{\frac{1}{\pi}\left[\pi-\alpha+\frac{1}{2}\sin 2\alpha\right]\right\}^{1/2} \qquad ...(2.10)$$

but $I_m = V_m / R$

$$\therefore I_{TH}\,(rms) = \frac{V_m}{2R}\left\{\frac{1}{\pi}\left[\pi-\alpha+\frac{1}{2}\sin 2\alpha\right]\right\}^{1/2}$$

$$= \frac{V_m}{\sqrt{2}\times\sqrt{2}\,R}\left\{\frac{1}{\pi}\left[\pi-\alpha+\frac{1}{2}\sin 2\alpha\right]\right\}^{1/2} \qquad ...(2.11)$$

Refer to Equation (2 .6)

$$\therefore \quad I_{TH}\,(rms) = \frac{V_{L\,rms}}{\sqrt{2}\,R}$$ but $V_{L\,rms} / R = I_{L\,rms}$

$$\therefore \quad I_{TH}\,(rms) = \frac{I_{L\,rms}}{\sqrt{2}} \qquad ...(2.12)$$

FCB with R load - 12

3. Peak thyristor current :

$$I_{TH\ (peak)} = V_m / R \quad \ldots(2.13)$$

Form factor

As defined above **FF** = V_{rms} / V_{Ldc}

$$= \sqrt{(\pi\ (\pi - \alpha + \sin(2\alpha)/2)\ )} \ / \ (\sqrt{2}\ (1 + \cos\alpha)) \quad \ldots(2.14)$$

Ripple factor

As defined above **RF** = $V_{Lac} / V_{Ldc} = \sqrt{(FF^2 - 1)}$

$$= \sqrt{(\ (\pi\ (\pi - \alpha + \sin(2\alpha)/2)\ )\ /\ (2\ (1 + \cos\alpha)^2\ )\ )} \quad \ldots(2.15)$$

Output DC power

$$\mathbf{P_{Ldc}} = V_{Ldc} \times I_{ldc} = V_{Ldc}^2 / R \quad \ldots(2.16)$$

Output AC power

$$\mathbf{P_{Lac}} = V_{Lrms} \times I_{Lrms} = V_{Lrms}^2 / R \quad \ldots(2.17)$$

Efficiency or Rectification ratio

As defined above $\boldsymbol{\eta} = P_{Ldc} / P_{Lac}$

$$= V_{Ldc}^2 / V_{Lrms}^2 = 1/FF^2 \qquad \textbf{...(2.18)}$$

Input supply current

From Fig. 2.6, above, it is seen that the waveform of the input supply current i_s is identical to the load current i_L in the +ve half cycle and is equal to $-i_L$ in the -ve half cycle. Hence

$$\mathbf{I_{srms}} = I_{Lrms} \qquad \textbf{...(2.19)}$$

Input power factor

PF = Real power / Apparent power

$$= (V_{Lrms} \times I_{Lrms}) / (V_{srms} \times I_{srms}) \qquad \textbf{...(2.20)}$$

using (2.19) & (2.6),

$$PF = V_{Lrms} / V_{srms} = \left\{ \frac{(\pi - \alpha) + \frac{1}{2}\sin 2\alpha}{\pi} \right\}^{1/2} \qquad \textbf{...(2.21)}$$

Operation of FCB with R-L load:

- In practice the load may not always be purely resistive. It can be purely inductive or a combination of a resistance and an inductance. The load current can be continuous or discontinuous depending on the value of load inductance.
- However the discussion here is made with an assumption that the load inductance is large enough so that the current is continuous and ripple free, equal to I_o.

- The single phase full converter consists of four thyristors SCR_1 to SCR_4, connected in a bridge configuration, driving a R-L load as shown in Fig.2.7.

- The four thyristors SCR_1 to SCR_4 operate in two pairs, one pair conducting at any given instant of time. The firing angle (α) in both the half cycles is same.
- The operation can be explained by considering different time intervals as follows :

FCB with R-L load - 4

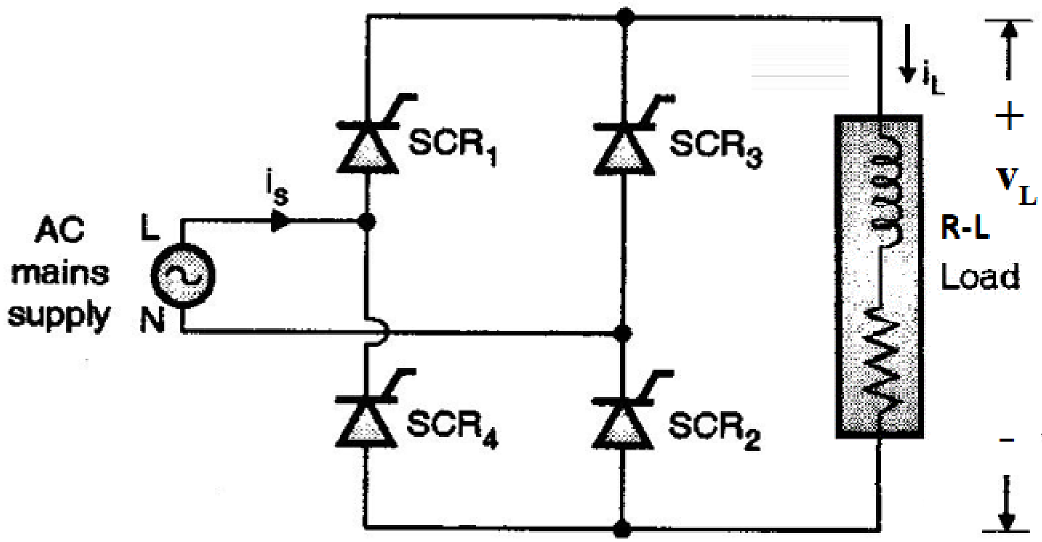
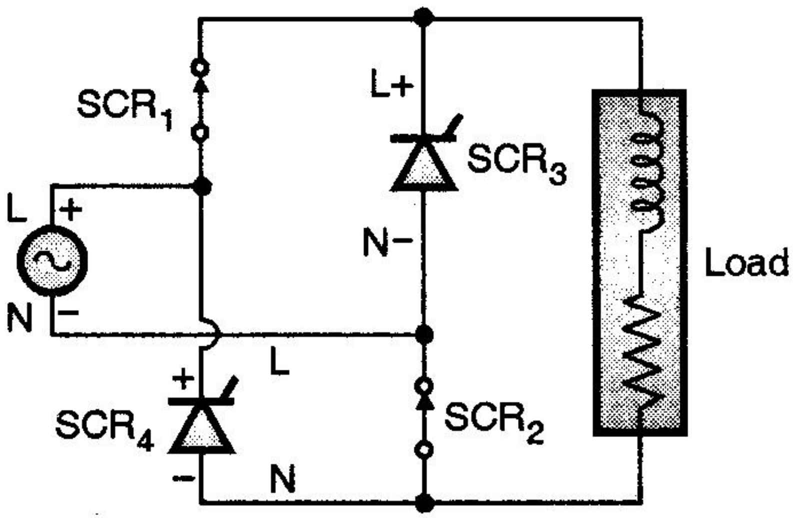


Fig. 2.7: Single phase full converter with R-L load

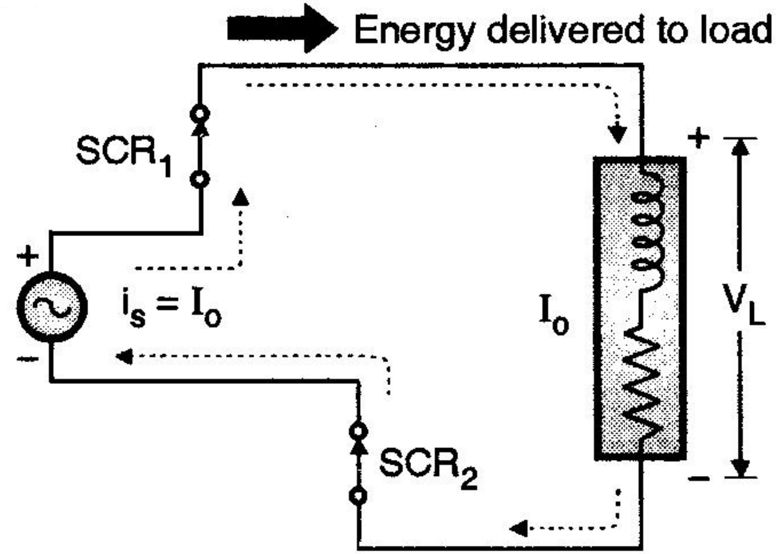
Mode I ($\alpha \leq \omega t \leq \pi$) :

- In the positive half cycle of the input ac supply L is positive with respect to neutral N, therefore SCRs 1 and 2 are forward biased and can be turned on at the desired value of α.
- At instant α, SCRs 1 and 2 are triggered. As the thyristors are working as ideal switches, they connect the input ac supply across the load. Therefore the load voltage at α, equals the instantaneous supply voltage.

FCB with R-L load - 3



(a) At $\omega t = \alpha$, SCR_3 and SCR_4 are turned off due to line commutation



(b) Equivalent circuit for mode I (α to π)

Fig. 2.8

- The already conducting pair of SCRs 3 and 4 is commutated due to the application of Line voltage across them in opposite direction (making them reverse biased). This process of commutating the thyristors is known as Line commutation.
- Once the SCRs 3 and 4 are commutated, the SCRs 1 and 2 continue to conduct. The load voltage is positive equal to the instantaneous ac supply voltage. The load current is positive, constant and ripple free equal to I_o. As the polarity of load voltage and load current both is positive the load inductance will store the energy. **(See Fig. 2.8 (b)).**

FCB with R-L load - 4

Mode II ($\pi \le \omega t \le \pi + \alpha$) :

- At instant π the input ac supply voltage passes through zero, and after π radians it becomes negative. However, the inductive load will try to oppose any change in current through it.
- In order to maintain the load current constant and in the same direction, a self induced voltage appears across the load. The polarity of this voltage is as shown in Fig. 2.8(c).
- This self induced voltage is high enough to maintain the SCRs 1 and 2 forward biased inspite of the negative supply voltage. In this way SCRs 1 and 2 continue to conduct even after the supply voltage has become negative.
- The load voltage is negative and equal to the instantaneous ac supply voltage whereas the load current continues to be positive. Therefore the load acts as source and the stored energy in the inductance is returned back to the ac supply.

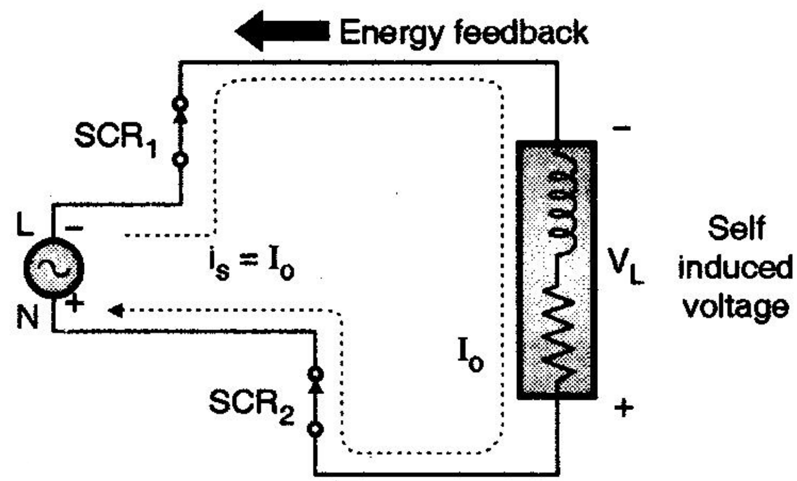
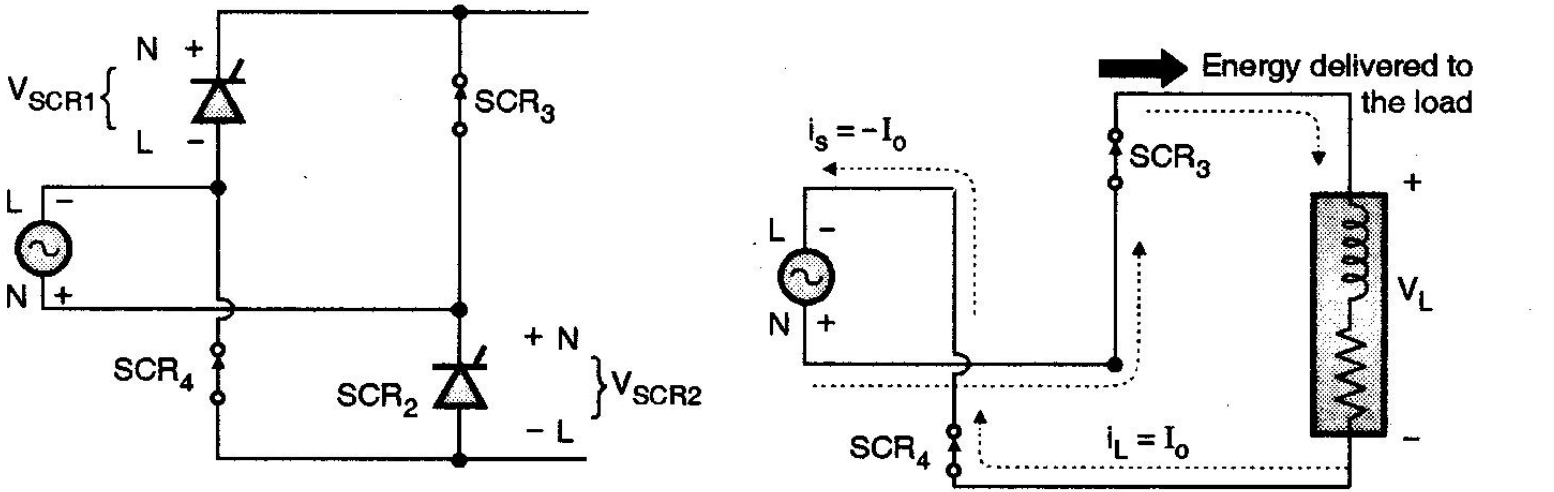


Fig. 2.8(c) : Equivalent circuit for mode II (Energy feedback)

FCB with R-L load - 5

Mode III $[(\pi + \alpha) \leq \omega t \leq 2\pi]$:

- At instant $(\pi + \alpha)$, the other pair of SCRs i.e. SCRs 3 and 4 are turned on. This will connect the negative input voltage across the conducting SCRs 1 and 2.
- This reverse line voltage will commutate the conducting SCRs due to line commutation (see Fig. 2.9(a)).



(a) Line commutation of SCR_1 and SCR_2 at $\omega t = (\pi + \alpha)$

(b) Equivalent circuit of mode III $[(\pi + \alpha)$ to $2\pi]$

Fig. 2.9

FCB with R-L load - 6

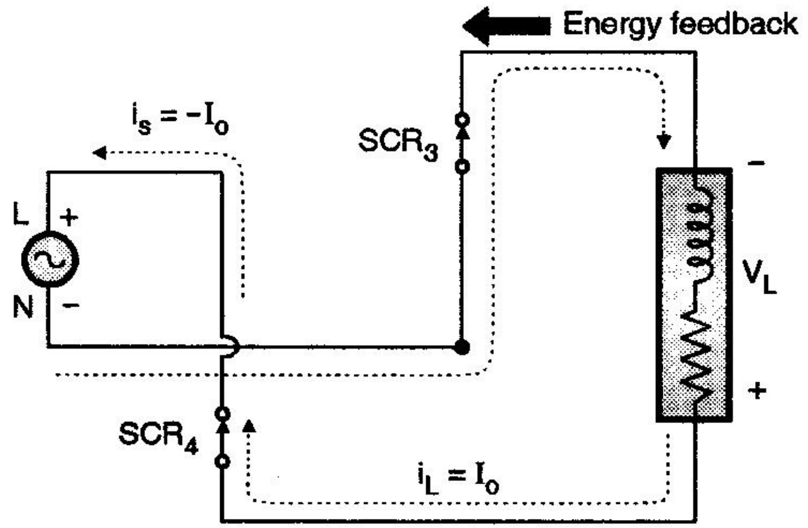


Fig. 2.9 (c) : Equivalent circuit for mode IV (0 to α) or (2 π to 2 π + α) energy feedback

- The conduction is transferred from SCRs 1 and 2 to SCRs 3 and 4. The load voltage again becomes positive. Whereas the load current continues to be positive. Thus the load will store energy in this mode.
- SCRs 3 and 4 continue to conduct in the negative half cycle of the ac supply from $(\pi + \alpha)$ to 2α. The equivalent circuit of mode III is as shown in Fig. 2.9 (b).
- As both the load voltage and current are of same polarity the load stores energy.

FCB with R-L load - 7

Mode IV (0 to α or 2π to $2\pi + \alpha$) :

- At instant 0 or 2π the input ac voltage passes through zero and becomes positive. However the inductive load will try to oppose any change in the current through it in order to maintain the load current constant and in the same direction, a self induced voltage appears across the load.
- The induced voltage is negative as shown in the Fig. 2.9 (c).
- This maintains the conducting SCRs 3 and 4 forward biased, inspite of the change in the polarity of the input supply.
- In this way SCRs 3 and 4 continue to conduct even after the supply voltage reverses the polarity. The load voltage is thus negative and equal to the instantaneous supply voltage whereas the load current continues to be positive. Therefore the load acts as source and the stored energy in the inductance is returned back to the ac supply.
- The conducting pair of SCRs 3 and 4 is commutated due to line commutation at the instant α or $(2\pi + \alpha)$ when SCRs 1 and 2 are turned on as explained in Fig. 2.8(a). The operation then repeats itself.

2

Conduction period for SCRs :

As can be seen from the Fig.2.10 every SCR will conduct for a period of π radians as compared to $(\pi - \alpha)$ radians with the resistive load.

Current through the SCRs :

The current through each SCR is constant equal to I_o over its entire conduction period of π radians, as shown in the waveform of Fig.2.10.

FCB with R-L load - 8

Supply current i_s :

- The input supply current i_s is a square wave with equal positive and negative values.
- When the pair SCR_1 and SCR_2 is on, the supply current is positive equal to I_o whereas when SCR_3 and SCR_4 conduct, the supply current is negative equal to $-I_o$ as shown in Fig. 2.10.

FCB with R-L load - 9

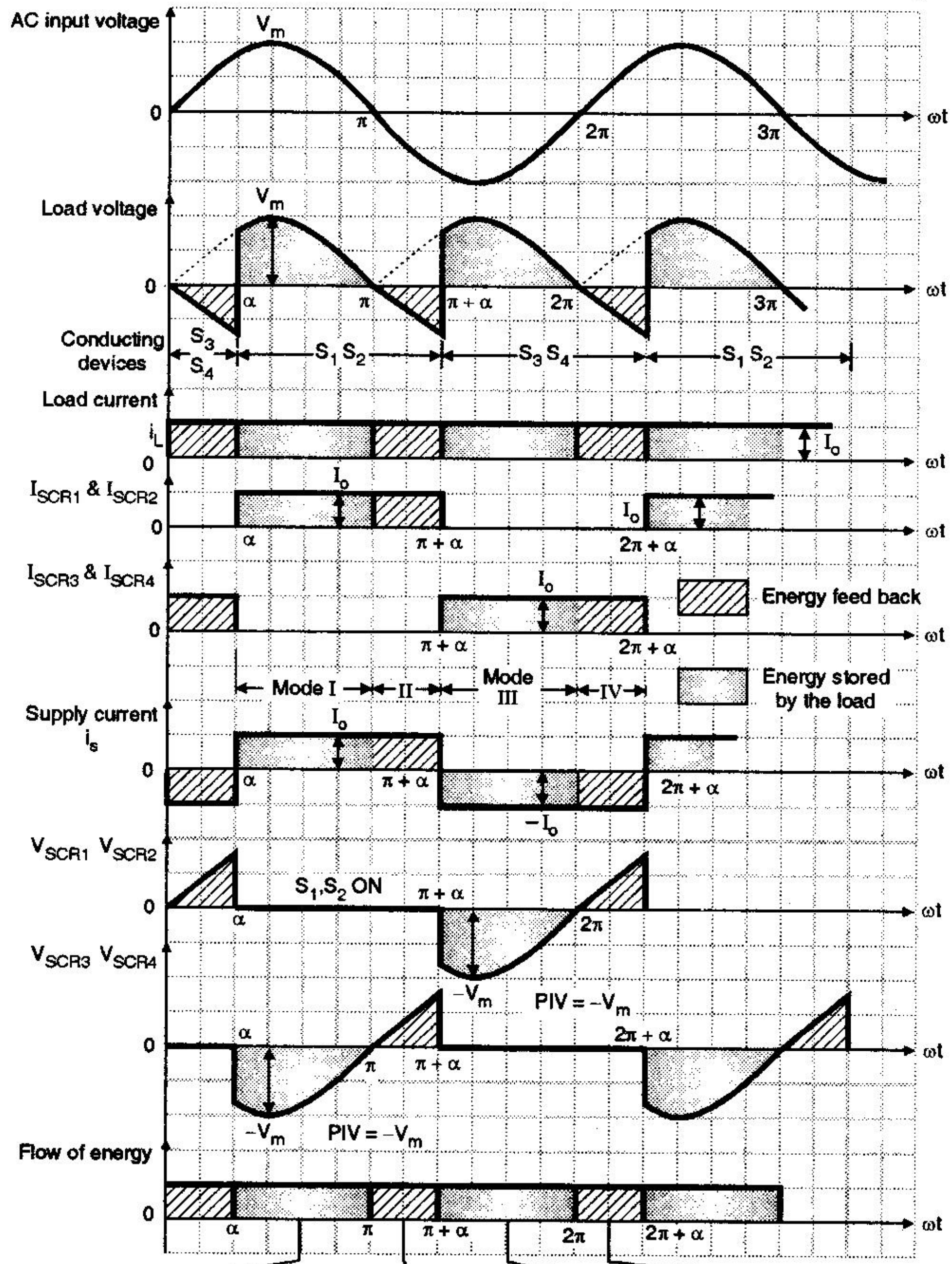


Fig. 2.10: Voltage and current waveforms for FCB with highly inductive R-L load

FCB with R-L load - 10

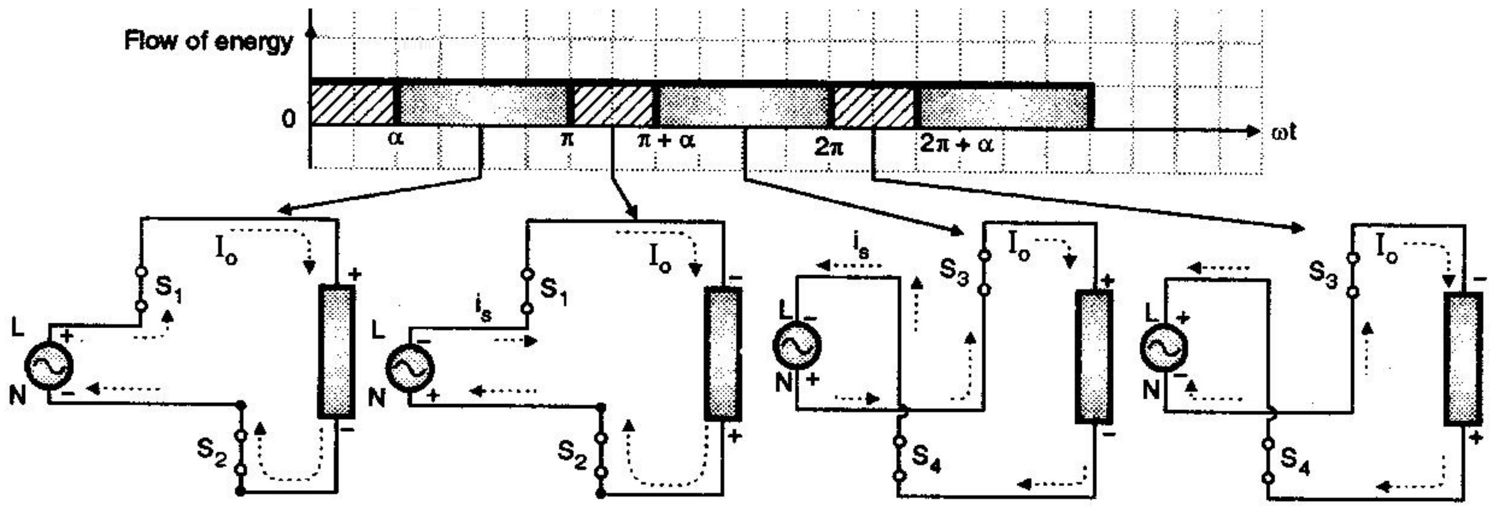


Fig. 2.10 : Voltage and current waveforms for full converter with highly inductive load

Output voltage analysis of FCB with heavily inductive R-L load:

Average load voltage (V_{Ldc}) :

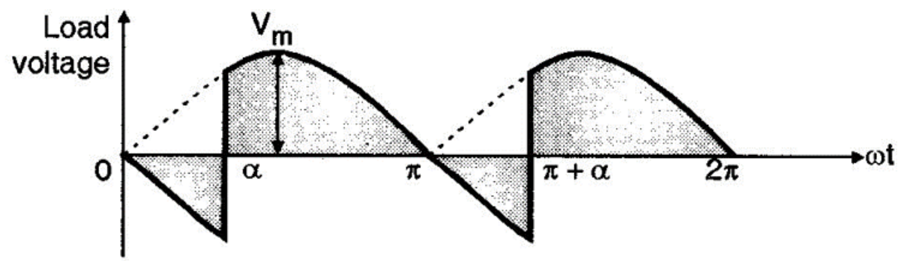


Fig. 2.11 : Load voltage with inductive load

Referring to Fig. 2.11 the average load voltage can be obtained out as follows,

$$V_{Ldc} = \frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} V_m \sin \omega t \, d\omega t \quad \text{...(2.22)}$$

$$= \frac{-V_m}{\pi} [\cos(\pi + \alpha) - \cos \alpha] = \frac{-V_m}{\pi} [\cos \pi \cos \alpha - \cos \alpha]$$

$$= -V_m / \pi [-2 \cos \alpha]$$

$$\therefore \quad V_{Ldc} = \frac{2 V_m}{\pi} \cos \alpha = \frac{2\sqrt{2} V_s}{\pi} \cos \alpha \quad \text{...(2.23)}$$

FCB with R-L load – 12

RMS load voltage ($V_{L\ rms}$) :

Referring to Fig. 2.11 the expression for rms load voltage can be obtained as follows,

$$V_{L\,rms} = \left\{ \frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} V_m^2 \sin^2 \omega t \, d\omega t \right\}^{1/2}$$

$$= \left\{ \frac{V_m^2}{2\pi} \int_{\alpha}^{\pi+\alpha} (1 - \cos 2\,\omega t) \, d\omega t \right\}^{1/2}$$

$$= \left\{ \frac{V_m^2}{2\pi} \left[\pi + \frac{1}{2} \sin (2\pi + 2\alpha) - \frac{1}{2} \sin 2\alpha \right] \right\}^{1/2}$$

$$= \left\{ \frac{V_m^2}{2\pi} \left[\pi + \frac{1}{2} \sin 2\,\alpha - \frac{1}{2} \sin 2\alpha \right] \right\}^{1/2} = \left\{ \frac{V_m^2}{2\pi} \times \pi \right\}^{1/2}$$

$$V_{L\,rms} = V_m / \sqrt{2} = V_s \qquad \text{...(2.24)}$$

FCB with R-L load – 13

Form factor :

$$FF = \frac{V_{L\,rms}}{V_{Ldc}} = \frac{V_m / \sqrt{2}}{\frac{2\,V_m}{\pi}\cos\alpha}$$

$$FF = \frac{\pi}{2\sqrt{2}\cos\alpha} \qquad \text{...(2.25)}$$

Ripple factor :

$$RF = (FF^2 - 1)^{1/2}$$

$$= \left[\frac{\pi^2}{8\cos^2\alpha} - 1\right]^{1/2} \qquad \text{...(2.26)}$$

2 Quadrant operation of FCB with heavily inductive R-L load:

With highly inductive load, there are two different possible operating modes as :

1. Rectification for $\alpha \leq 90°$
2. Inversion for $\alpha > 90°$

The load voltage waveforms for different values of α are as shown in Figs. 2.12(a), (b) and (c).

1. Operation for $\alpha < 90°$ (Rectification) :

- The load voltage waveform is as shown in Fig. 2.12(a), which shows that the area under the positive half is greater than that under negative one. Therefore the average load voltage V_{Ldc} is positive.
- The time for which the energy is stored by the load is longer than the time for which it is returned back. Therefore the net energy transfer in one cycle is from source to load.
- The source is "AC" while load is "DC". Therefore the net flow of energy is from AC side to DC side. Therefore the operation is called as "**Rectification**".

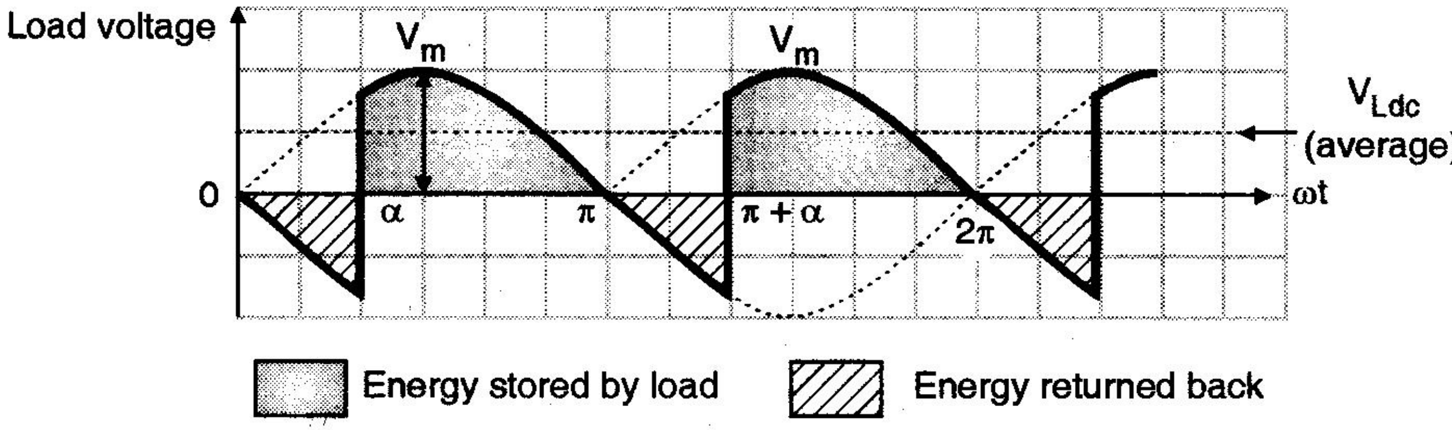


Fig. 2.12 (a) : Load voltage for $\alpha < 90°$ (Rectification)

2. Operation for $\alpha = 90°$:

- The load voltage waveform for $\alpha = 90°$ is as shown in Fig. 2.12 (b).
- As can be seen clearly, the area under positive and negative halves of load voltage waveforms are equal. Therefore the average load voltage is zero and the net power transferred to the load is zero.
- This is because the amount of power delivered to the load and the amount of power returned back from the load to source in one cycle are exactly equal.

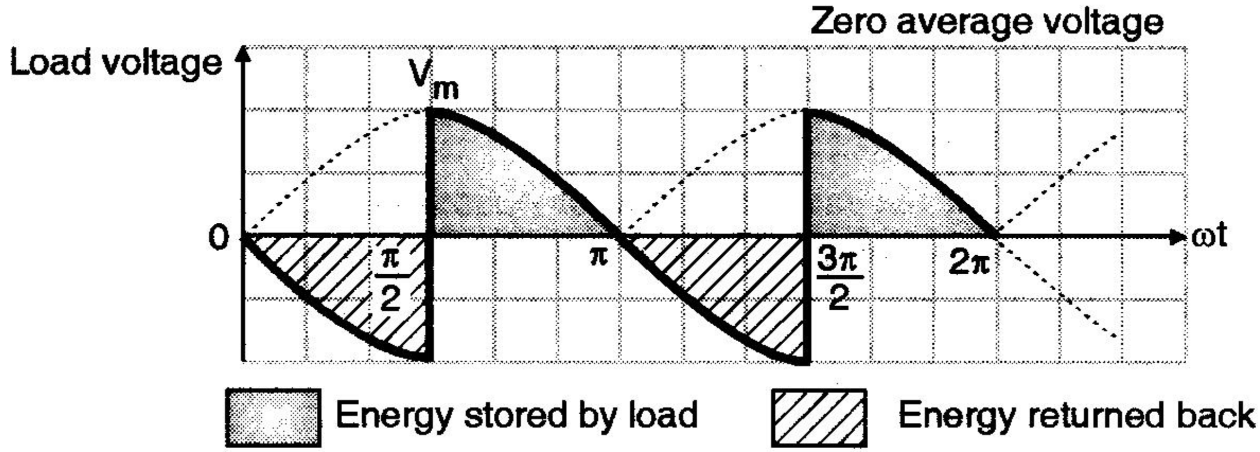


Fig. 2.12 (b) : Load voltage for α = 90°

3. Operation for α > 90° (Inversion) :

- The load voltage waveform for α > 90° is as shown in Fig. 2.12 (c).
- According to the equation for average load voltage $V_{Ldc} = \frac{2\,V_m}{\pi}\cos\alpha$, the value of cos α for α > 90° is negative, therefore the average output voltage is negative for α > 90°.
- It is seen clearly from Fig. 2.12 (c) that the area under the negative half is greater than that under the positive one. This shifts the average load voltage below zero.
- The load stores energy during positive half of the load voltage waveform and returns it back during the negative half. The net power flow in one cycle is from load to source. This is **inverter operation**.

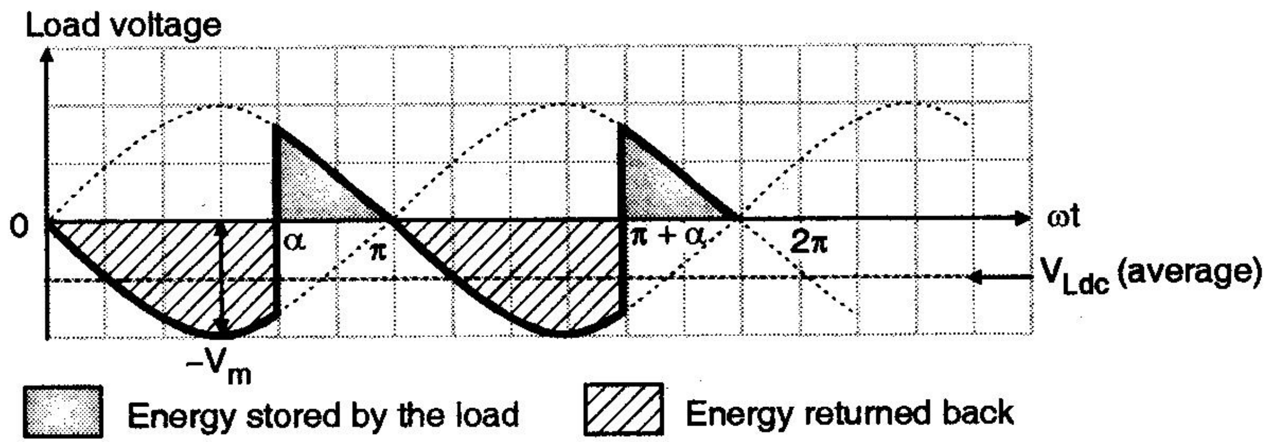


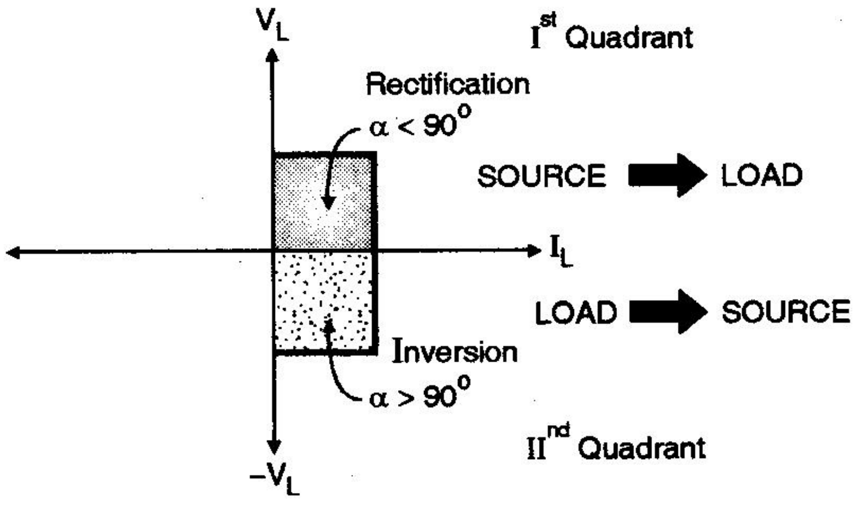
Fig. 2.12 (c) : Load voltage for α > 90°

Conclusions :

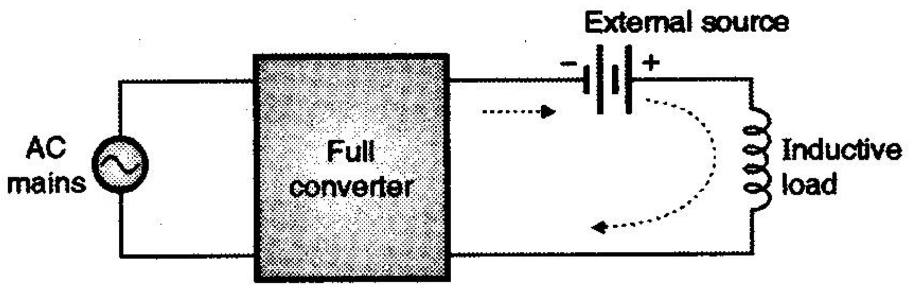
1. For α < 90° the average load voltage is positive and as the load current is positive, the net flow of power takes place from source to load. Thus the converter works as a rectifier and in the first quadrant of the load voltage load current characteristics.
2. For α = 90° the average load voltage is zero and the net power transferred to the load is zero.
3. For α > 90°, the average load voltage becomes negative and as the load current is positive, the net flow of power takes place from load to source. Thus the converter works as inverter.

Quadrantal operating diagram for FCB with R-L load:

- The two quadrant operation of the full converter can be shown graphically as shown in Fig. 2.13 (a). As can be seen the load current always remains positive whereas the load voltage will change its polarity depending on the value of α.
- It is important to note that the inverter mode of operation is practically possible if and only if there is an additional energy source in series with the inductive load on the dc side, or if there is an active load, as shown in Fig. 2.13 (b).



(a) Two quadrant operation of full converter



(b) Connection of external source for inverter operation

Fig. 2.13

Variation of average load voltage with firing angle :

The expressions for the average load voltage with resistive and inductive loads are as follows :

$$V_{Ldc} = \frac{V_m}{\pi}(1 + \cos\alpha) = \frac{V_s\sqrt{2}}{\pi}(1 + \cos\alpha) \quad \text{...with R load} \quad \text{...(2.2)}$$

and $$V_{L\,dc} = \frac{2\,V_m}{\pi}\cos\alpha = \frac{2\sqrt{2}\,V_s}{\pi}\cos\alpha \quad \text{...with RL load} \quad \text{...(2.23)}$$

The variation in firing angle is from 0° to 180°.

FCB with R-L load – 20

The Table 2.1 shows the average load voltage for different values of α and Fig. 2.14 shows graphically the variation of average voltage with α.

Table 2.1

α Degrees	0°	30°	60°	90°	120°	150°	180°
V_{Ldc} volts RL load	$0.63\ V_m$	$0.55\ V_m$	$0.31\ V_m$	0	$-0.31\ V_m$	$-0.55\ V_m$	$-0.63\ V_m$

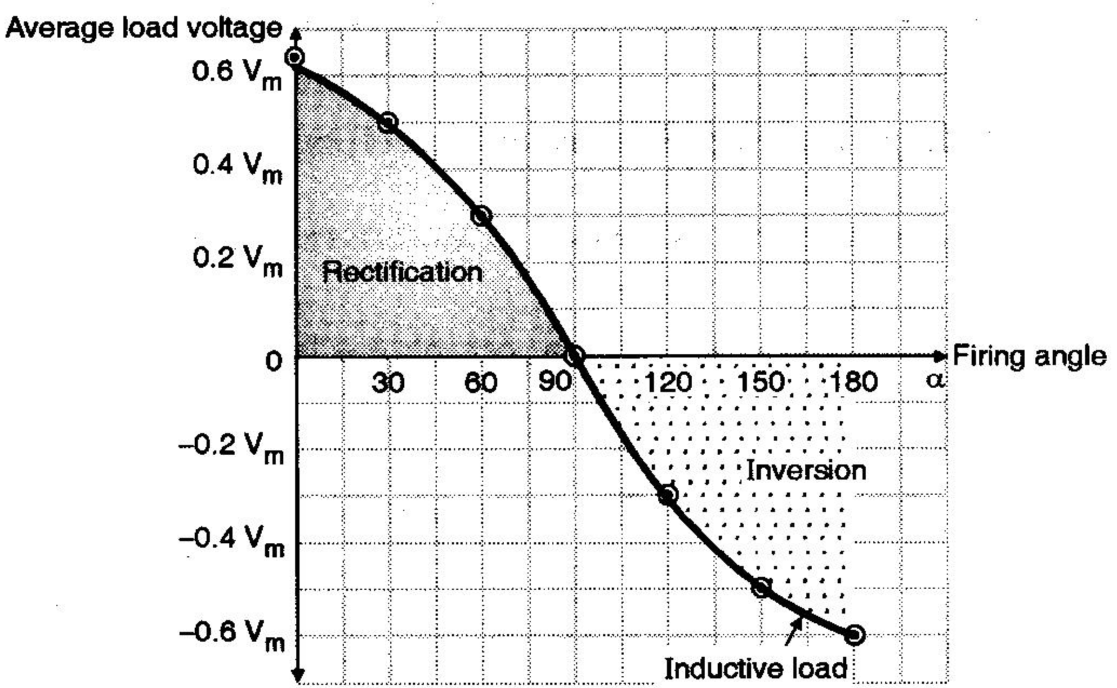


Fig. 2.14 : Variation of average load voltage with full converter

FCB with R-L load – 21

Output load current of FCB with heavily inductive R-L load:

- Unlike a DC circuit where all voltages and currents are constant in the steady state, in a AC circuit all voltages and currents are continuously changing. Hence for AC circuits the term “Repetitive Steady State” is used which means that the waveforms of all voltages and currents in one cycle are identical to those in the next cycle as well as the previous cycle.

- Thus the values of all voltages and currents at the start of a cycle are the same as those at the end of the cycle which is the same as those at the start of the next cycle.

- For the load inductance L

  $\Delta I_{LL} = I_{LLstart} – I_{LLend} = 0$, average inductance voltage V_{LL} over a complete cycle $= L\, \Delta I_{LL}/\Delta t = 0$

  Applying KVL to the load

  Average load voltage = average inductor voltage + average resistor voltage

  = 0 + average resistor voltage = R×average load current

  Hence average load current $\mathbf{I_{Ldc}}$ **=** average load voltage $\mathbf{V_{Ldc}}$ **/R**

  and $\mathbf{I_{Lrms} = I_{Ldc}}$ for level (ripple-free, highly inductive) load

Input Performance Parameters for FCB with level (ripple-free) load:

Expressions for the following input parameters will now be obtained

1. Input displacement factor or Fundamental power factor (DSF or FPF).

$$\text{DSF or FPF} = \cos \phi_1$$

2. Input current distortion factor $CDF = \dfrac{I_{s1\,rms}}{I_{s\,rms}}$

3. Input power factor PF = CDF × FPF.

4. Harmonic factor $HF = \left[\dfrac{I^2_{s\,rms} - I^2_{s1\,rms}}{I^2_{s1\,rms}}\right]^{1/2}$

5. Active power.

6. Reactive power.

- To obtain all these expressions, we need to obtain the expressions for the rms value of supply current and the rms value of the fundamental component of supply current.
- We can obtain them by carrying out the Fourier analysis of supply current waveform.

Analysis of supply current waveform for FCB with level load:

In order to evaluate the values of different performance parameters it is necessary to analyze the supply current waveform using Fourier analysis. For this refer to the supply current waveform shown in Fig. 2.15 .

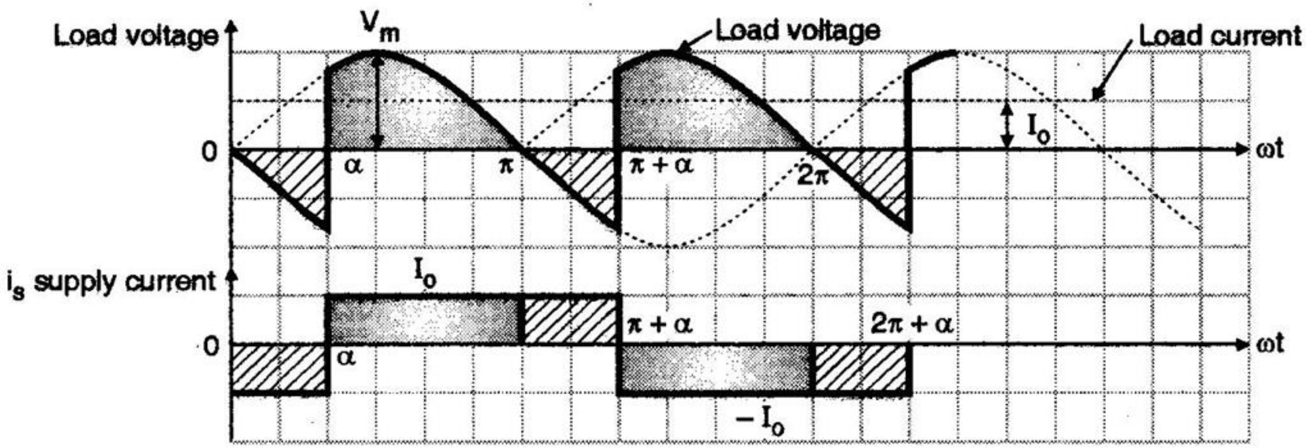


Fig. 2.15 : Load voltage and supply current waveforms for full converter with RL load

1. In general the supply current can be expressed in the Fourier series, as

$$i_s(t) = \sum_{n=1}^{\infty} (a_n \cos n\,\omega t + b_n \sin n\,\omega t) \qquad \text{...(2.27)}$$

$$= \sum_{n=1}^{\infty} c_n \sin(n\,\omega t + \phi_n) \qquad \text{...(2.28)}$$

where

$$c_n = \left(a_n^2 + b_n^2\right)^{1/2} \text{ and } \phi_n = \tan^{-1}(a_n / b_n). \qquad \text{...(2.29)}$$

FCB with R-L load – 24

2. The values of the Fourier coefficients can be found as follows,

$$a_n = \frac{1}{\pi} \int_{\alpha}^{2\pi+\alpha} i_s(t) \cos n\,\omega t \; d\omega t$$

From Fig. 4.10.8,

$$i_s(t) = +I_o \qquad \text{...... for } \alpha \le \omega t \le (\pi + \alpha)$$

$$\text{and} = -I_o \qquad \text{...... for } (\pi + \alpha) \le \omega t \le (2\pi + \alpha)$$

$$\therefore \quad a_n = \frac{1}{\pi}\left\{ \int_{\alpha}^{\pi+\alpha} I_o \cos n\,\omega t \; d\omega t - \int_{\pi+\alpha}^{2\pi+\alpha} I_o \cos n\,\omega t \; d\omega t \right\}$$

$$\therefore \quad a_n = \frac{I_o}{\pi}\left\{ \left[\frac{\sin n\,\omega t}{n}\right]_{\alpha}^{\pi+\alpha} - \left[\frac{\sin n\,\omega t}{n}\right]_{\pi+\alpha}^{2\pi+\alpha} \right\}$$

$$= \frac{I_o}{n\pi}\{ \sin n(\pi+\alpha) - \sin n\alpha - \sin n(2\pi + \alpha) + \sin n(\pi+\alpha) \}$$

$$= \frac{I_o}{n\pi}\{ 2 \sin n(\pi+\alpha) - \sin n\alpha - \cos 2\pi n \sin n\alpha \}$$

But $\cos 2\pi n = 1$

$$\therefore \quad a_n = \frac{I_o}{n\pi}\{2\sin n\pi \cos n\alpha + 2\cos n\alpha \sin n\alpha - \sin n\alpha - \sin n\alpha\}$$

But $\sin n\pi = 0$

$$\therefore \quad a_n = \frac{I_o}{n\pi}\{2\cos n\pi \sin n\alpha - 2\sin n\alpha\}$$

But $\cos n\pi = +1$ for $n = 2, 4, 6.....$

$\therefore \quad a_n = 0$ for $n = 2, 4, 6......$

and $\cos n\pi = -1$ for $n = 1, 3, 5......$

$$\therefore \quad a_n = \frac{I_o}{n\pi}\{-2\sin n\alpha - 2\sin n\alpha\} = \frac{-4 I_o}{n\pi}\sin n\alpha.$$

$$\therefore \quad a_n = \frac{-4 I_o}{n\pi}\sin n\alpha \quad \text{for} \quad n = 1, 3, 5, ...$$

$$\text{and} \quad a_n = 0 \quad \text{for} \quad n = 2, 4, 6, ... \qquad ...(2.30)$$

FCB with R-L load – 26

3. Similarly $b_n = \dfrac{1}{\pi}\displaystyle\int_{\alpha}^{2\pi+\alpha} i_s(t)\sin n\,\omega t\, d\omega t$

$$= \frac{1}{\pi}\left\{\int_{\alpha}^{\pi+\alpha} I_o \sin n\,\omega t\, d\omega t - \int_{\pi+\alpha}^{2\pi+\alpha} I_o \sin n\,\omega t\, d\omega t\right\}$$

$$\therefore\quad b_n = \frac{-I_o}{\pi}\left\{[\cos n\omega t]_{\alpha}^{\pi+\alpha} - [\cos n\omega t]_{\pi+\alpha}^{2\pi+\alpha}\right\}$$

$$= \frac{-I_o}{\pi}\{\cos n(\pi+\alpha) - \cos n\alpha - \cos n(2\pi+\alpha) + \cos n(\pi+\alpha)\}$$

$$= \frac{-I_o}{\pi}\{2\cos n(\pi+\alpha) - \cos n\alpha - \cos 2\pi n \cos n\alpha + \sin 2\pi n \sin n\alpha\}$$

But $\sin 2\pi n = 0$

$$\therefore\quad b_n = \frac{-I_o}{\pi}\{2\cos n(\pi+\alpha) - \cos n\alpha - \cos 2\pi n \cos n\alpha\}$$

But $\cos 2\pi n = 1$

$$\therefore\quad b_n = \frac{-I_o}{\pi}\{2\cos n(\pi+\alpha) - \cos n\alpha - \cos n\alpha\}$$

$$= \frac{-I_o}{\pi}\{2\cos n\pi \cos n\alpha - 2\cos n\alpha\}$$

FCB with R-L load – 27

$$\text{But} \quad \cos 2\pi n = 1$$

$$\therefore \quad b_n = \frac{-I_o}{\pi}\{2\cos n(\pi+\alpha) - \cos n\alpha - \cos n\alpha\}$$

$$= \frac{-I_o}{\pi}\{2\cos n\pi \cos n\alpha - 2\cos n\alpha\}$$

$$\text{But} \quad \cos n\pi = +1 \qquad \text{for} \quad n = 2, 4, 6....$$

$$\therefore \quad b_n = 0$$

$$\text{and} \quad \cos n\pi = -1 \qquad \text{for} \quad n = 1, 3, 5....$$

$$\therefore \quad b_n = \frac{-I_o}{\pi}\{-2\cos n\alpha - 2\cos n\alpha\}$$

$$\therefore \quad b_n = \frac{4\, I_o}{n\,\pi}\cos n\alpha \qquad \text{for} \quad n = 1, 3, 5, ...$$

$$\text{and} \quad b_n = 0 \qquad \text{for} \quad n = 2, 4, 6, ... \qquad ...(2.31)$$

FCB with R-L load – 28

4. Therefore the peak value of the n^{th} harmonic component of current is,

$$c_n = \left(a_n^2 + b_n^2\right)^{1/2}$$

Substituting values of a_n and b_n from Equations (4.10.9) and (4.10.10) we get,

$$c_n = \left[\frac{16\, I_o^2}{n^2 \pi^2} \sin^2 n\alpha + \frac{16\, I_o^2}{n^2 \pi^2} \cos^2 n\alpha\right]^{1/2}$$

$$c_n = \frac{4\, I_o}{n\,\pi} \qquad \text{...(2.32)}$$

and $\phi_n = \tan^{-1} a_n / b_n = \tan^{-1} [-\tan n\alpha]$

$$\phi_n = -n\alpha \qquad \text{...(2.33)}$$

5. ϕ_n is known as the displacement angle of the n^{th} harmonic current. In order to find out the fundamental component of the supply current we substitute n = 1 in all these equations.

∴ peak value of fundamental current

$$c_1 = \frac{4\, I_o}{\pi} \qquad \text{...(2.34)}$$

and $\phi_1 = -\alpha$ ...(2.35)

The negative sign indicates that the fundamental component of supply current lags behind the supply voltage.

Conclusions :

1. The fundamental component of supply current has peak value of $4 I_o / \pi$ and
2. The fundamental component of supply current lags behind the supply voltage by an angle α.

6. The rms value of the fundamental supply current is given by,

$$I_{s1\,rms} = \frac{c_1}{\sqrt{2}} = \frac{4 I_o}{\sqrt{2}\,\pi} \quad ...(2.36)$$

$$I_{s1\,rms} = \frac{2\sqrt{2}\, I_o}{\pi} \quad ...(2.37)$$

and the rms value of the supply current i_s is given by,

$$I_{s\,rms} = I_o \quad ...(2.38)$$

$\therefore$ **RMS value of fundamental component,** $\quad I_{s1\,rms} = \dfrac{2\sqrt{2}\, I_o}{\pi}$

RMS value of supply current, $\quad I_{s\,rms} = I_o$

Displacement angle for fundamental component, $\quad \phi_1 = -\alpha$

So now let us obtain the values of performance parameters for the full converter as follows :

Performance parameters :

Input Displacement Factor :

$$DSF = \cos\phi_1 = \cos(-\alpha) = \cos\alpha \quad ...(2.39)$$

FCB with R-L load – 30

Input Power Factor :

$$PF = \frac{V_{s1\,rms}\, I_{s1\,rms} \cos\phi_1}{V_{s\,rms}\, I_{s\,rms}} = \frac{I_{s1\,rms}}{I_{s\,rms}} \cos\phi_1$$

Substituting the values of $I_{s1\,rms}$ $I_{s\,rms}$ and ϕ_1

$$PF = \frac{2\sqrt{2}\, I_o}{\pi\, I_o} \times \cos\alpha$$

$$\therefore \quad PF = \frac{2\sqrt{2}}{\pi} \cos\alpha = 0.9 \cos\alpha \qquad \text{...(2.40)}$$

Input Current Distortion Factor : (CDF)

$$CDF = \frac{I_{s1\,rms}}{I_{s\,rms}} = \frac{2\sqrt{2}\, I_o}{\pi\, I_o} = \frac{2\sqrt{2}}{\pi} = 0.9 \qquad \text{...(2.41)}$$

Input Harmonic Factor :

$$HF = \frac{\left[I^2_{s\,rms} - I^2_{s1\,rms}\right]^{1/2}}{I_{s1\,rms}} = \frac{\left[I_o^2 - \left(\frac{2\sqrt{2}\, I_o}{\pi}\right)^2\right]^{1/2}}{(2\sqrt{2}\, I_o / \pi)}$$

$$\therefore \quad HF = \frac{\left[I_o^2 - \frac{8\, I_o^2}{\pi^2}\right]^{1/2}}{(2\sqrt{2}\, I_o / \pi)} = \frac{I_o}{\pi} \frac{[\pi^2 - 8]^{1/2}}{2\sqrt{2}\, I_o / \pi} = \left[\frac{\pi^2}{8} - 1\right]^{1/2}$$

$$\therefore \quad HF = \left[\frac{\pi^2}{8} - 1\right]^{1/2} = 0.4834 \qquad \text{...(2.42)}$$

Active Power (P_A) :

We have already defined the active power as :

$$P_A = V_{s1\,rms} I_{s1\,rms} \cos \phi_1$$

Substituting the values of $I_{s1\,rms}$ and ϕ_1 we get,

$$P_A = V_{s1\,rms} \cdot \frac{2\sqrt{2}\, I_o}{\pi} \cdot \cos \alpha$$

But $\sqrt{2}\, V_{s1\,rms} = V_m$

$$\therefore \quad P_A = \frac{2\, V_m I_o}{\pi} \cos \alpha \qquad ...(2.43)$$

Reactive Power (P_R) :

As already defined, the reactive power is given by,

$$P_R = V_{s1\,rms} I_{s1\,rms} \sin \phi_1 = V_{s1\,rms} \cdot \frac{2\sqrt{2}\, I_o}{\pi} \cdot \sin \alpha$$

But $\sqrt{2}\, V_{s1\,rms} = V_m$

$$\therefore \quad P_R = \frac{2\, V_m I_o}{\pi} \sin \alpha \qquad ...(2.44)$$

FCB with R-L load – 32

Advantages of Full Converter :

Following are some of the advantages of a full converter :

- It can operate in the rectification as well as inversion modes.
- Load stored energy can be returned back to source for reutilization.
- Regeneration is possible. So in dc motor control, it is possible to incorporate the regenerative braking.

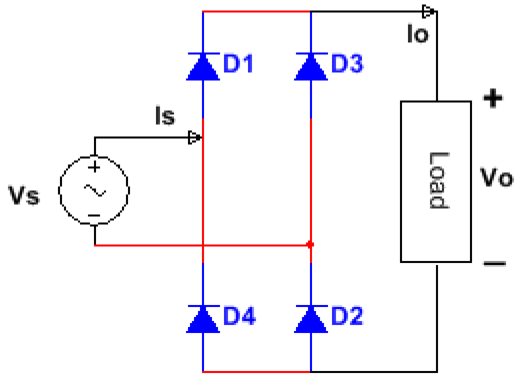
Disadvantages of Full Converter :

- Small values of FPF and PF.
- More harmonics in the source current waveform.
- Low active power and high reactive power at larger values of α.

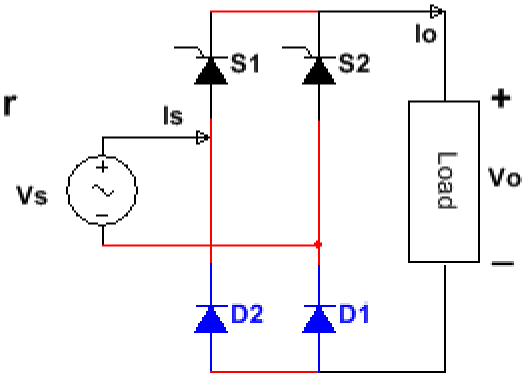
Application :

Full converters are popularly used in reversible regenerative dc motor drives.

Evolution of HCB

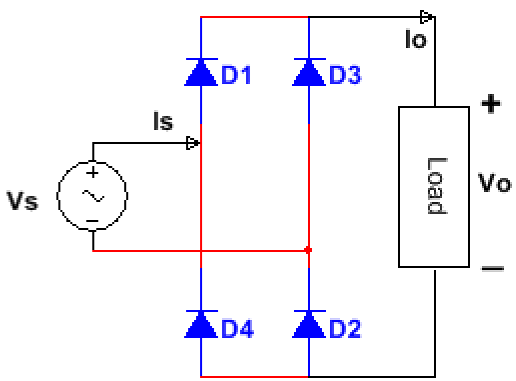


Replace only upper diodes with SCRs

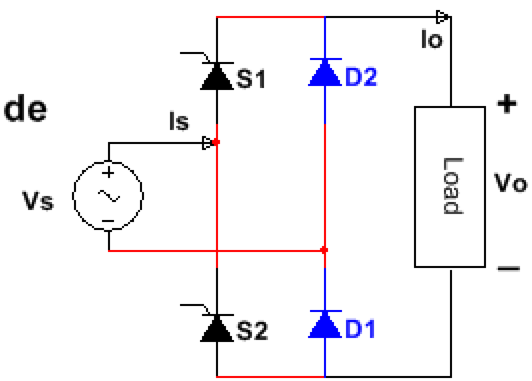


Uncontrolled Diode Bridge Rectifier

Symmetrical Half-Controlled Bridge (Symmetrical HCB) or Semi-converter



Replace only left-side diodeswith SCRs

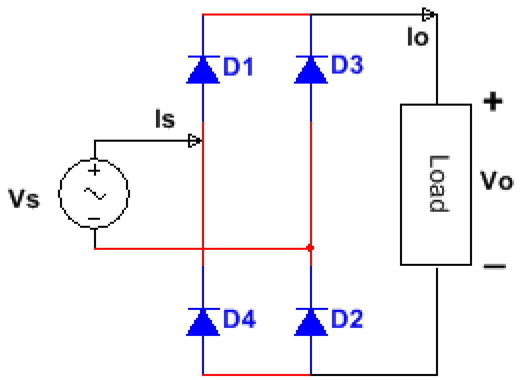


Uncontrolled Diode Bridge Rectifier

Asymmetrical Half-Controlled Bridge (Asymmetrical HCB) or Semi-converter

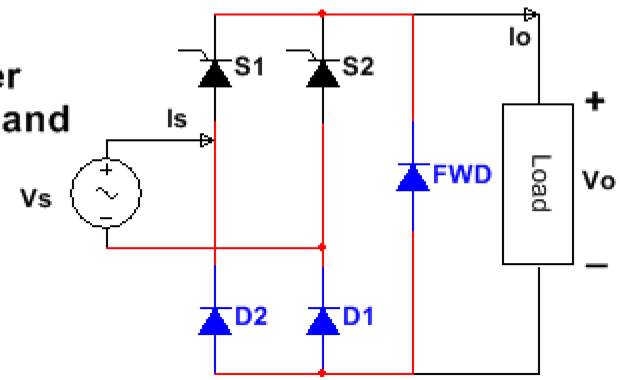
FIGURE 2.16

Evolution of HCB



Uncontrolled Diode Bridge Rectifier

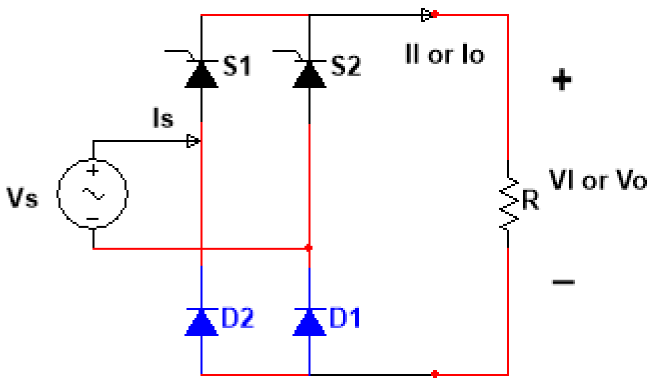
Replace only upper diodes with SCRs and add FWD



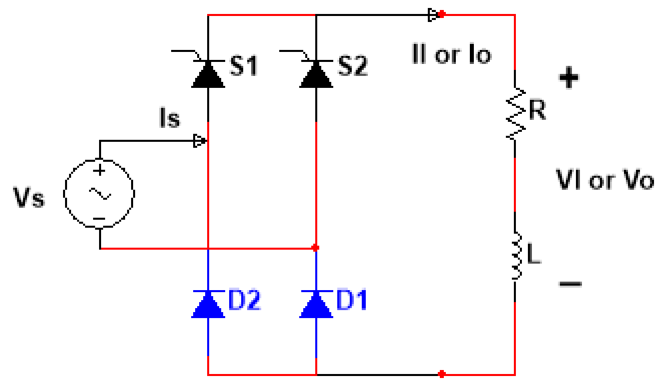
Symmetrical Half-Controlled Bridge (Symmetrical HCB) or Semi-converter with FWD

FIGURE 2.17

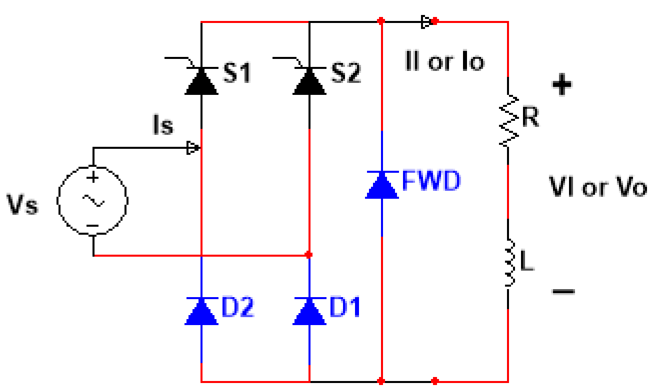
Symmetrical HCB with different loads



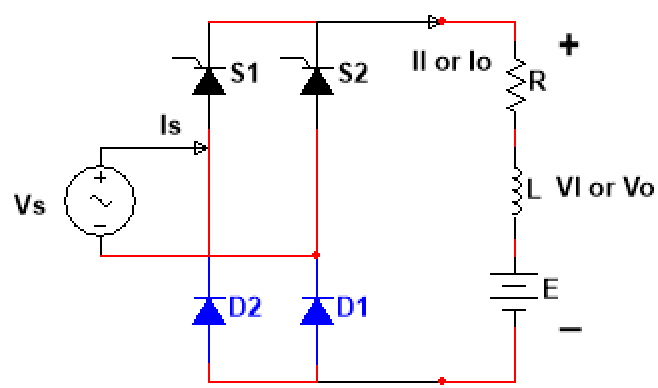
Half Controlled Bridge (S-HCB) with R load



Half Controlled Bridge (S-HCB) with R-L load



Half Controlled Bridge (S-HCB) with FWD and R-L load



Half Controlled Bridge (S-HCB) with R-L-E load

FIGURE 2.18

HCB general -1

- The HCB is a full-wave one quadrant converter which operates only in Quadrant 1.
- Two configurations exist viz. symmetrical (S-HCB) and asymmetrical (A-HCB).
- In S-HCB both the arms are the same with one SCR and one diode in series.
- In A-HCB, one arm has two SCRs in series while the other arm has two diodes in series.
- The load voltage, load current and supply current waveforms and magnitudes are the same for both converters. Internally, however, conduction durations of SCR and diode differ.
- In a S-HCB, both SCRs and diodes conduct for half-cycle in each cycle. Thus

$$I_{S1avg} = I_{S2avg} = I_{D1avg} = I_{D2avg} = I_{Ldc}/2 \qquad \ldots(2.45)$$

&

$$I_{S1rms} = I_{S2rms} = I_{D1rms} = I_{D2rms} = I_{Lrms}/\sqrt{2} \qquad \ldots(2.46)$$

HCB general -2

- In a A-HCB, both SCRs conduct for (π - α) and both diodes conduct for (π + α) in each cycle.

Thus

$$I_{S1avg} = I_{S2avg} = (\pi - \alpha)/2\pi \times I_{ldc} \quad \ldots(2.47)$$

$$I_{D1avg} = I_{D2avg} = (\pi + \alpha)/2\pi \times I_{ldc} \quad \ldots(2.48)$$

&

$$I_{S1rms} = I_{S2rms} = \sqrt{((\pi - \alpha)/2\pi)} \times I_{Lrms} \quad \ldots(2.49)$$

$$I_{D1rms} = I_{D2rms} = \sqrt{((\pi + \alpha)/2\pi)} \times I_{Lrms} \quad \ldots(2.50)$$

- Thus current ratings of SCRs and diodes in a S-HCB are the **same** whereas the current rating of SCRs is **less** than that of the diodes in an A-HCB for the same load current rating.

- As the cost of power devices increases with the current rating and as SCRs cost more than diodes, **the cost of power devices of an A-HCB is less than that of a S-HCB**.

HCB general -3

- However, the gate control circuit for an A-HCB is more complex and expensive as compared to that for a S-HCB. This is because the SCR cathodes in the former circuit are at different potentials whereas they are connected together in the latter circuit. Hence separate isolated gate drive circuits are required for the two SCRs in the A-HCB whereas a common isolated gate drive circuit is sufficient for the S- HCB with both SCR gates connected together. Here, both SCRs get gate pulses at the same time but only the forward biased SCR turns-on in each half-cycle.

- For the S-HCB, freewheeling occurs for inductive loads through a SCR and its diode in the same arm, whereas for the A-HCB it occurs through diodes D1 & D2.

- In the S-HCB the “Half-waving” fault can occur in case of failure of the gate drive circuit for an SCR for a heavy inductive or motor load. Here the S-HCB behaves like an uncontrolled diode half-wave rectifier.

- “Half-waving” cannot occur in the A-HCB due to the inherent free-wheeling path available through diodes D1 & D2.

HCB with R load – 1

Operation of HCB with R load:

The operation of a HCB with R load is identical to a FCB with R load, the only difference being that for a FCB S1 & S2 conduct in the +ve half cycle, whereas in a HCB S1 & D1 conduct in the +ve half cycle. Similarly, for a FCB S3 & S4 conduct in the -ve half cycle, whereas in a HCB S2 & D2 conduct in the -ve half cycle. For a FCB $i_{S1} = i_{S2}$ and $i_{S3} = i_{S4}$, whereas for a HCB $i_{S1} = i_{D1}$ and $i_{S2} = i_{D2}$.

Except for the above, all waveforms and formulae are the same for FCB and HCB with R load.

Symmetrical HCB with R-L load – 1

In order to discuss the operation with inductive load, the symmetrical configuration of Fig. 2.19 (a) is used.

The instantaneous load voltage v_o, instantaneous load current i_o and the instantaneous supply current are as shown in the Fig. 2.19 (a).

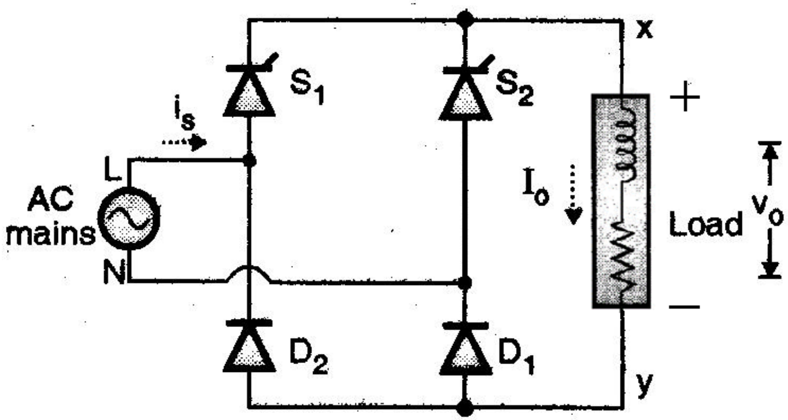


Fig. 2.19 (a) : Circuit diagram (symmetrical configuration)

- The load current $i_o = I_o$, is assumed to be continuous and ripplefree. Different voltage and current waveforms are as shown in Fig. 2.19 (g).
- The operation can be divided into four modes of operation.

Symmetrical HCB with R-L load – 2

Mode I ($\alpha \le \omega t \le \pi$) :

- At instant $\omega t = \alpha$, SCR S_1 is turned on. The equivalent circuit is as shown in Fig. 2.19 (b). This is identical to the operation with resistive load.
- The load voltage $V_o = V_m \sin \omega t$, it is positive (point x positive with respect to point y).
- The input supply current i_s is positive and equal to I_o. The load current is positive, continuous and ripplefree.
- As both the output voltage and current are positive, the inductive load will store the energy in this mode of operation i.e. the flow of power is from source to load.

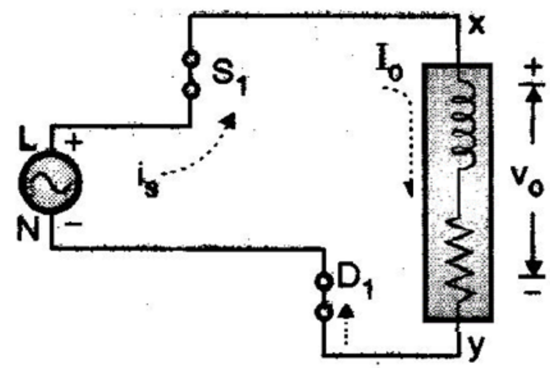


Fig. 2.19 (b) : Load stores energy, Mode I (α to π)

- The current through SCR_1, $I_{SCR1} = I_o$ and $I_{D1} = I_o$ as shown in Fig. 2.19 (g).

Symmetrical HCB with R-L load – 3

Mode II ($\pi \leq \omega t \leq \pi + \alpha$) (Freewheeling) :

- At instant $\omega t = \pi$, the ac voltage goes to zero and after π it becomes negative.
- Due to this negative input voltage the conducting SCR S_1 and diode D_1 will try to turn off.
- Due to this there is a change in the load current. As the load is highly inductive it will try to oppose any change in the current flowing through it.
- Thus the load inductance will try to maintain the load current unchanged by inducing a self induced voltage across the load as shown in Fig. 2.19 (c).
- As seen from the figure, the load voltage is negative (point y positive with respect to x).
- The magnitude of this self induced negative voltage is L di/dt, where L is load inductance and i is load current.

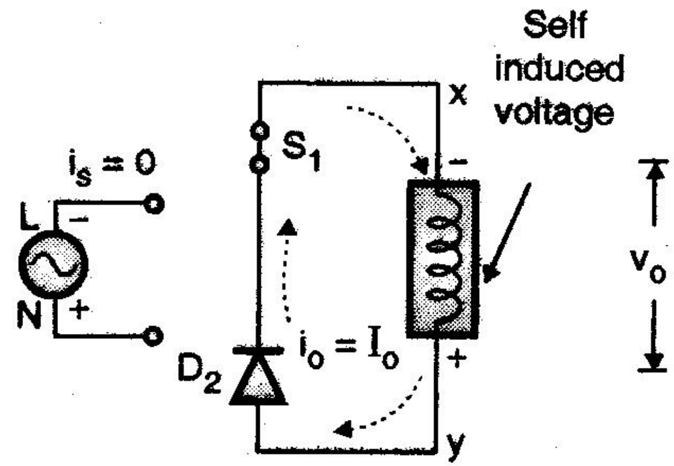
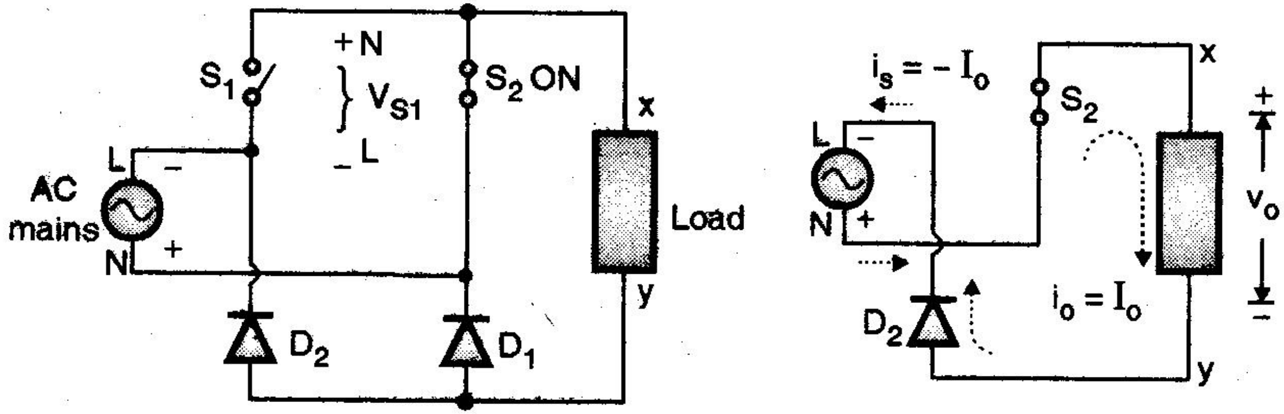


Fig. 2.19 (c) : Mode II freewheeling

Symmetrical HCB with R-L load – 4

Freewheeling :

- This self induced load voltage will bring diode D_2 (which is connected in series with SCR_1) into conduction at instant π and D_1 is turned off.
- SCR S_1 continues to conduct. In this way the load is short circuited by the conducting devices S_1 and D_2 (see Fig. 2.19 (g)).
- The load current now freewheels through S_1 and D_2. If the devices are considered to be ideal, then the load voltage will be zero.



(d) Line commutation of S_1 at $(\pi + \alpha)$ (e) Mode III load stores energy

Fig. 2.19

- The freewheeling takes place due to stored energy in the inductive load and during freewheeling this stored energy is dissipated in the device S_1 and D_2.
- The ac supply current $i_s = 0$ as shown in Fig. 2.19 (c). This mode of operation continues upto $\omega t = (\pi + \alpha)$ where SCR S_2 is turned on to turn off S_1.

Symmetrical HCB with R-L load – 5

Mode III ($\pi + \alpha \le \omega t \le 2\pi$) :

Line commutation of SCR S_1 :

- Mode III begins at instant $\omega t = (\pi + \alpha)$. At this instant the ac input voltage is negative as shown in Fig. 4.5.2(d).
- This forward biases SCR S_2. Thus when SCR S_2 is triggered at $(\pi + \alpha)$, the positive N point get connected to the cathode of conducting SCR S_1.
- Thus the voltage across S_1 is negative and equal to the instantaneous ac mains voltage. This negative voltage turns off SCR S_1 and the commutation is known as **line commutation.** This is voltage commutation.
- Once S_1 is turned off, the current starts flowing through SCR S_2, load, D_2 as shown in Fig. 4.5.2(e).
- The load voltage becomes positive and equal to instantaneous supply voltage. Supply current is negative, $i_s = -I_o$.
- As the load voltage and current both are positive the load will store the energy.

Symmetrical HCB with R-L load – 6

Mode IV [0 to α or (2 π to 2 π + α)] (Freewheeling) :

- At instant $\omega t = 2\pi$ or 0, the ac supply reverses its voltage polarity and becomes positive.
- As explained for mode II (π to π + α) here also the freewheeling starts.
- This time it is through the already conducting SCR S_2 and diode D_1 as shown in Fig. 2.19(f).
- The load voltage is zero and the supply current also is zero in this mode.

4.5.2
4.5.2

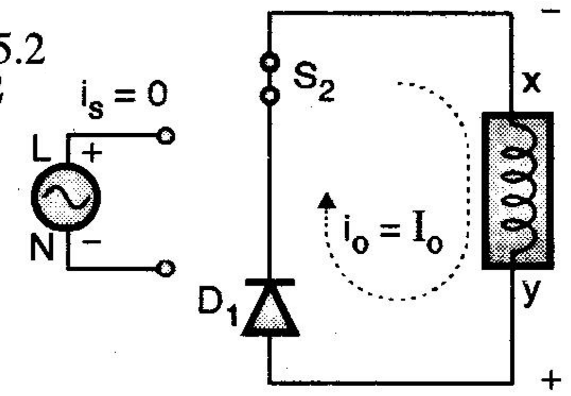


Fig. 2.19(f) : Mode IV freewheeling

- At instant $\omega t = (2\pi + \alpha)$ or α, SCR S_1 is turned on which turns off SCR S_2 due to the line commutation.

Symmetrical HCB with R-L load – 7

- The operation of semiconverter can be summarized as shown in Table 2.2.

Table 2.2

Mode	**I** $(\alpha - \pi)$	**II** $(\pi - \pi + \alpha)$	**III** $(\pi + \alpha - 2\pi)$	**IV** $(0 - \alpha)$
Conducting Devices	S_1 D_1	S_1 D_2	S_2 D_2	S_2 D_1
Load voltage	Positive	Zero	Positive	Zero
Load current	Positive	Positive	Positive	Positive
Power flow	Source to load	**Freewheeling**	Source of load	**Freewheeling**

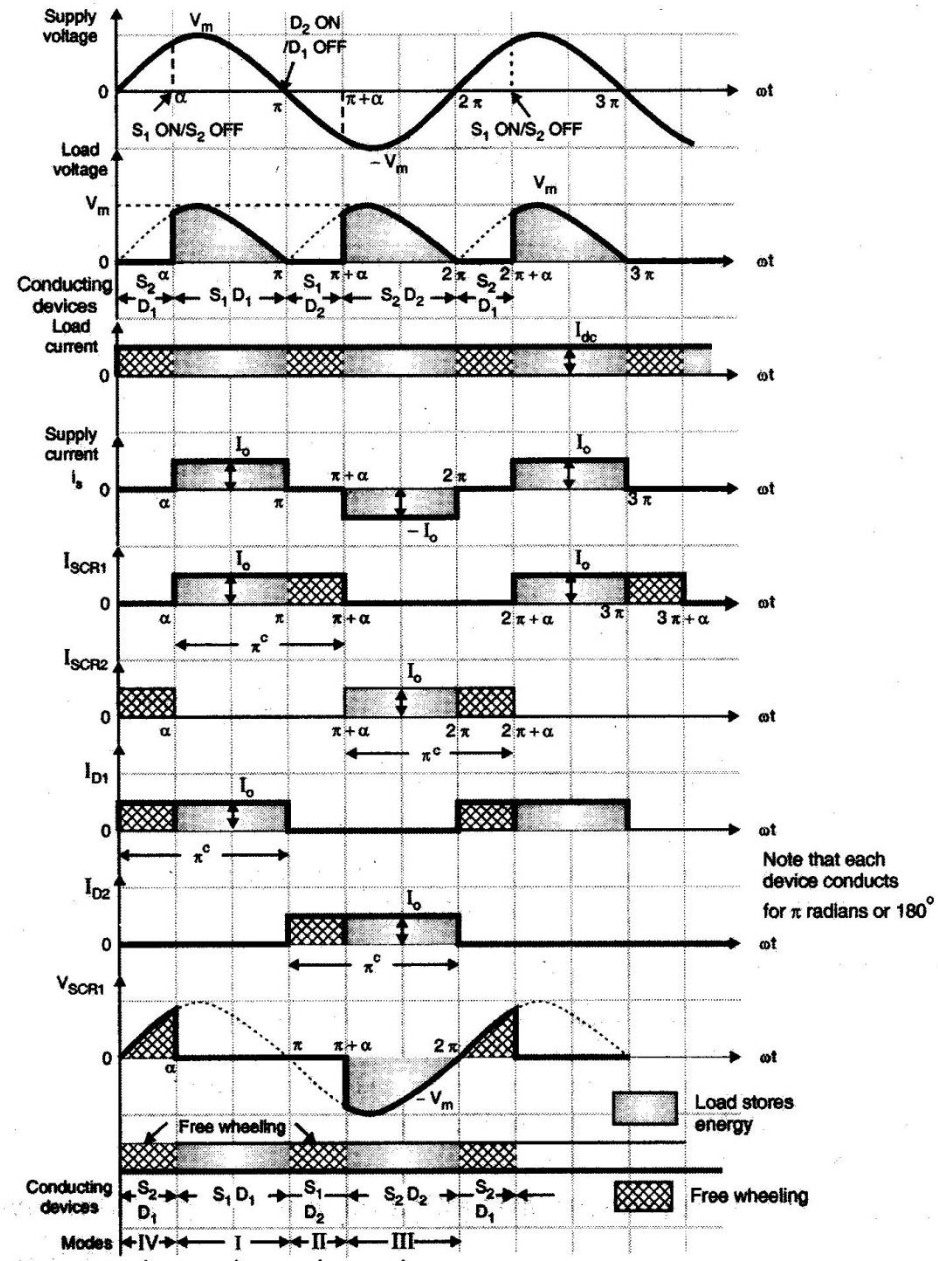


Fig. 2.19 (g): Voltage and current waveforms for single phase semiconverter symmetrical configuration with R-L load

Symmetrical HCB with R-L load – 9

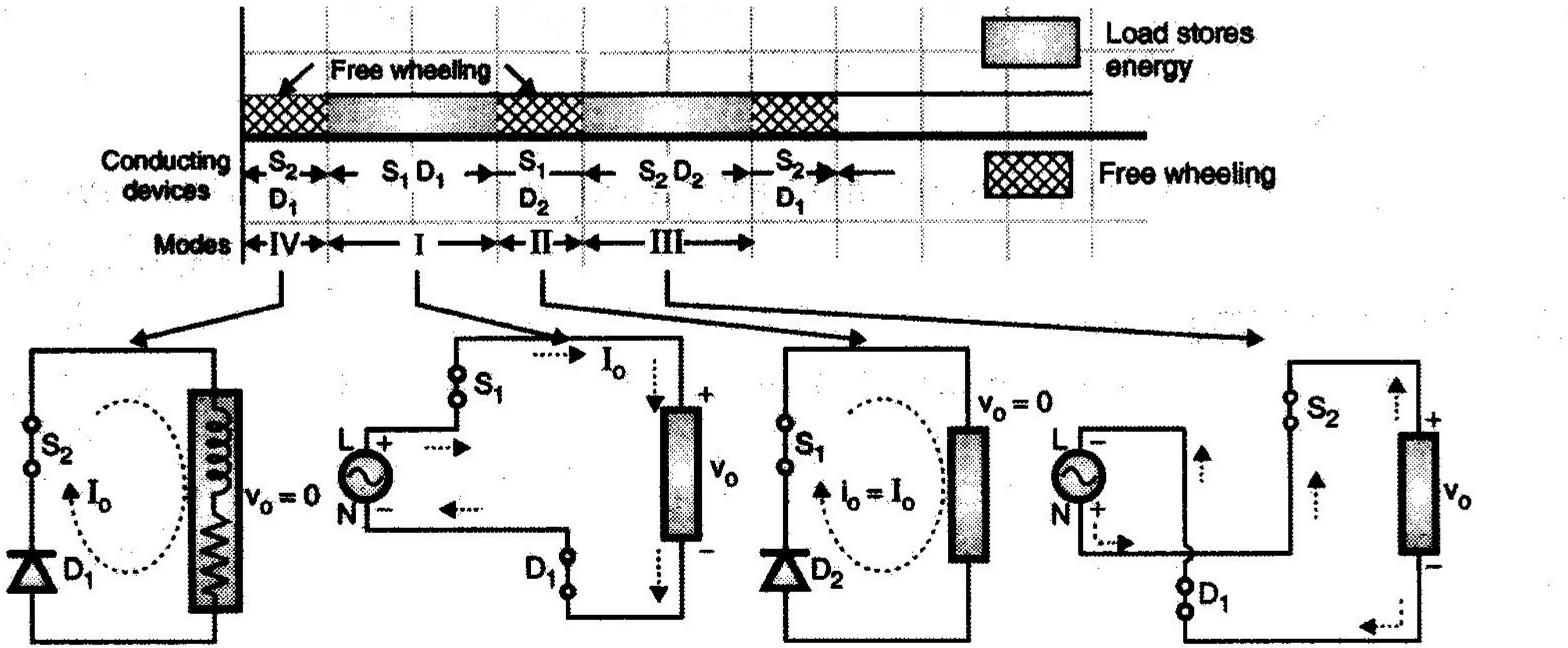
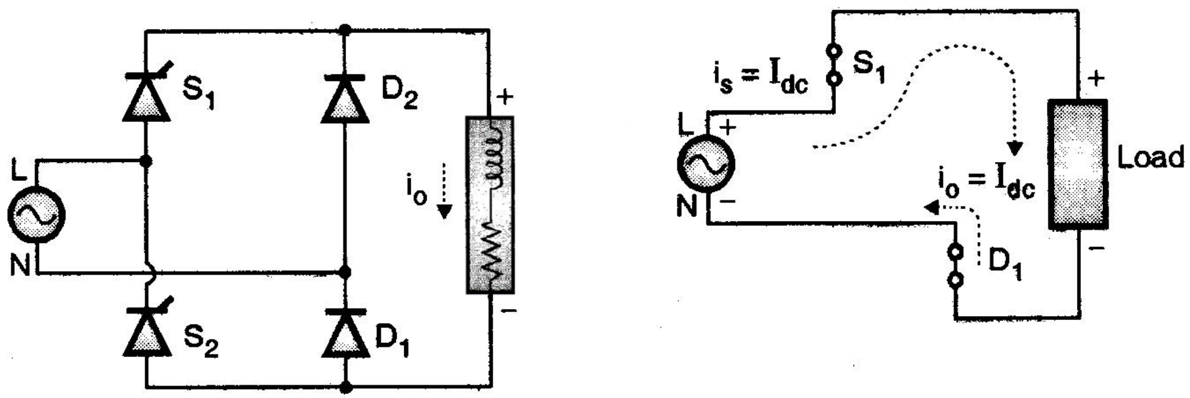


Fig. 2.19 (g) : Voltage and current waveforms for single phase semiconverter symmetrical configuration with RL load

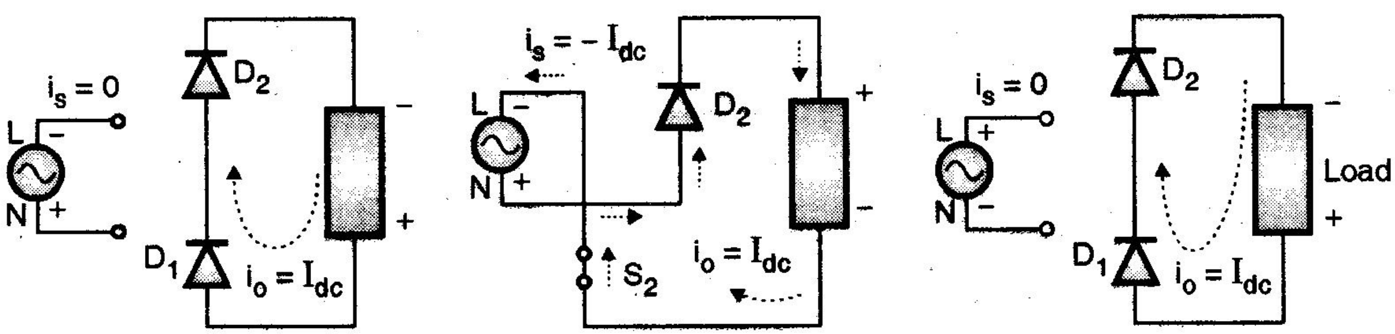
Asymmetrical HCB with R-L load – 1

Operation of A-HCB with level (ripple-free, highly inductive) load:



(a) Asymmetrical configuration of semiconverter

(b) Mode I (α to π) energy stored by the load



(c) Mode II (π to π + α) freewheeling

(d) Mode III (π + α to 2 π) energy stored by load

(e) Mode IV (2 π to 2 π + α or 0 to α) freewheeling

Fig. 2.20

Asymmetrical HCB with R-L load – 2

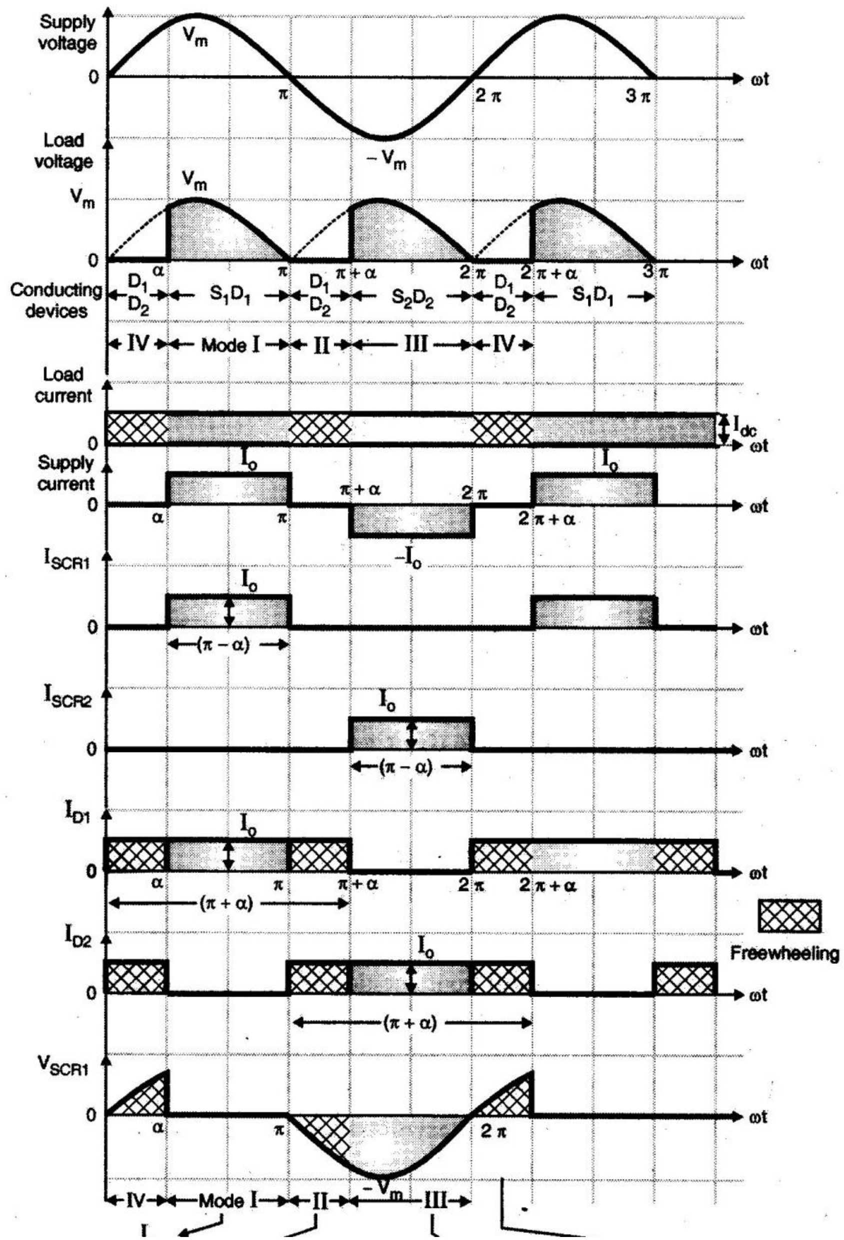


Fig. 2.20 (g): Voltage and current waveforms for single phase semiconverter asymmetrical configuration with R-L load

Asymmetrical HCB with R-L load – 3

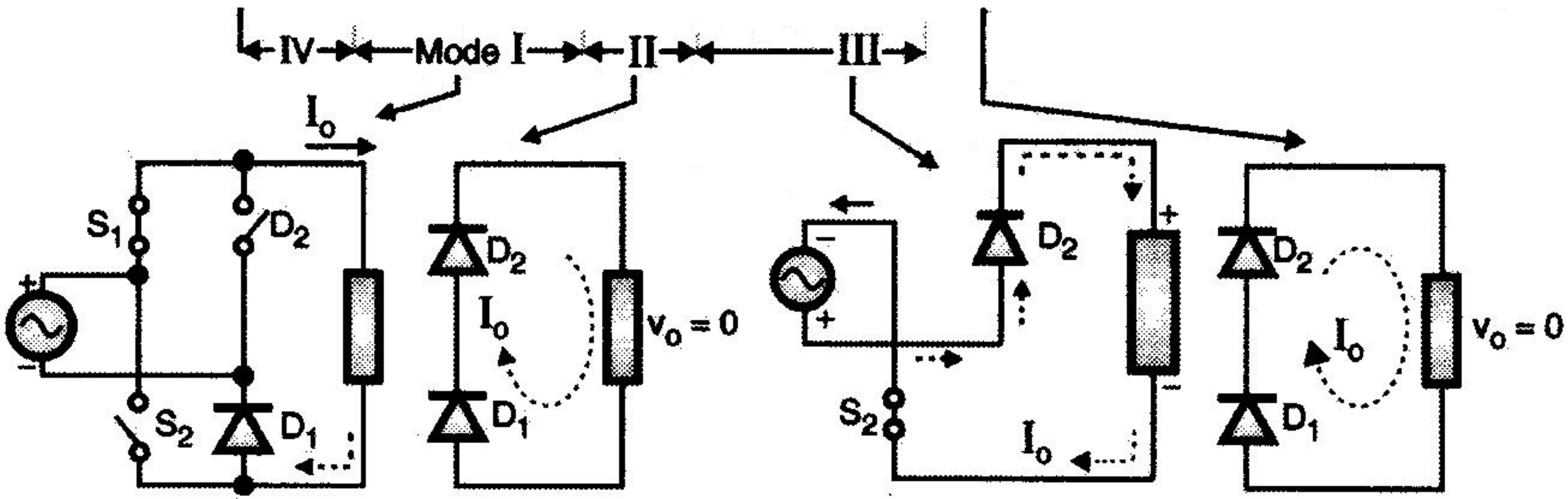


Fig. 2.20(f) : Voltage and current waveforms for the semiconverter asymmetrical configuration with RL load

Comparison between S-HCB & A-HCB for R-L load – 1

Comparison between configurations of semiconverter :

1. **Freewheeling action :**
   - The operation of asymmetrical configuration is very similar to that of the symmetrical configuration and can be understood from equivalent circuits of Figs. 2.20(a) to (e).
   - However the freewheeling takes place through the diodes D_1 and D_2. (For symmetrical configuration freewheeling takes place through S_1 D_2 or S_2 D_1).

2. **Conduction angle for the devices in the asymmetrical configuration :**

   (a) The conduction angle of SCRs S_1 and S_2 is $(\pi - \alpha)$ radians.(Fig. 2.20(f))

   (b) The conduction angle of diodes D_1 and D_2 is $(\pi + \alpha)$ radians.

   However, the conduction angle for all the devices in the symmetrical configuration is π radians.

Comparison between S-HCB & A-HCB for R-L load – 2

3. Gating signals :

- In the asymmetrical configuration, the cathodes of SCRs S_1 and S_2 are at different potentials therefore the gate driving signals to them must be isolated from each other.
- For symmetrical connection the cathodes of S_1 and S_2 are connected together, therefore gate driving signals to them need not be isolated from each other.

4. Output voltage waveform :

- It is same for both the configurations. Therefore the average, rms load voltage equations are identical for both the configurations.

5. Input/output performance parameters :

- As the source current waveforms is same for both the configurations, all the performance parameters have the identical values.

6. Quadrant of operation :

- Both the configurations operate in the first quadrant only. So both work only as rectifiers. The power flow is unidirectional from source to load.

Discontinuous and continuous conduction for HCB with RL load:

- In practical circuits the RL load will always be a combination of some finite resistance R with inductance L.
- The actual values of L and R will decide the amount of energy stored by the load and the time taken by the RL load to release that energy in the process of freewheeling.
- Therefore there will be two modes of operation of the semiconverter operating with a practical RL load, depending on the nature of the load current.

  (a) Continuous conduction mode (b) Discontinuous conduction mode.

Continuous conduction mode :

- The waveforms of load voltage and load current for continuous and discontinuous modes are as shown in Figs. 2.21 (a) and Fig. 2.21 (b) respectively.
- The operation of the semiconverter remains same. In the continuous conduction mode, the load current increases and decreases gradually and has a finite ripple but due to higher value of load inductance, the load current does not go to zero.
- The conduction angle for the devices (symmetrical configuration) will remain π radians.
- During the freewheeling intervals the load current decreases from I_{max} to I_{min} as shown in Fig. 2.21 (a).
- This mode is preferred in dc motor control application as it yields better results.

Symmetrical HCB with R-L load – 11

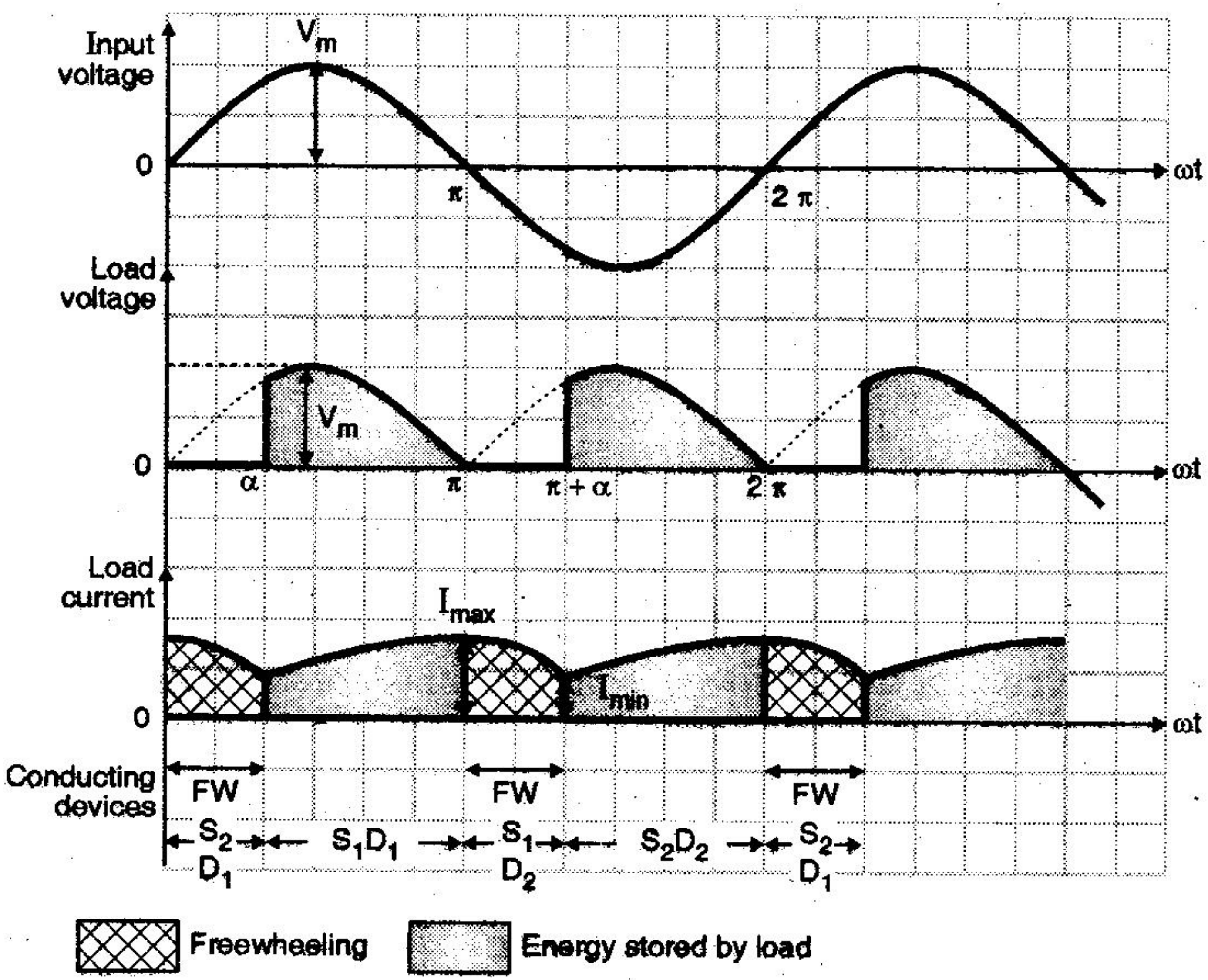


Fig. 2.21 (a) : Continuous conduction mode (symmetrical configuration)

Symmetrical HCB with R-L load – 12

Discontinuous conduction mode :

- In the discontinuous conduction mode however, the load current decreases to zero in the freewheeling interval even before the next SCR is turned on (see Fig. 2.21 (b)).
- The load current ripple content increases and the conduction angle for the devices decreases. This mode of operation is not suitable for the applications like dc motor speed control.

  The reasons for discontinuous conduction are :

1. Low value of load inductance 2. High value of load resistance 3. Large value of firing angle α.

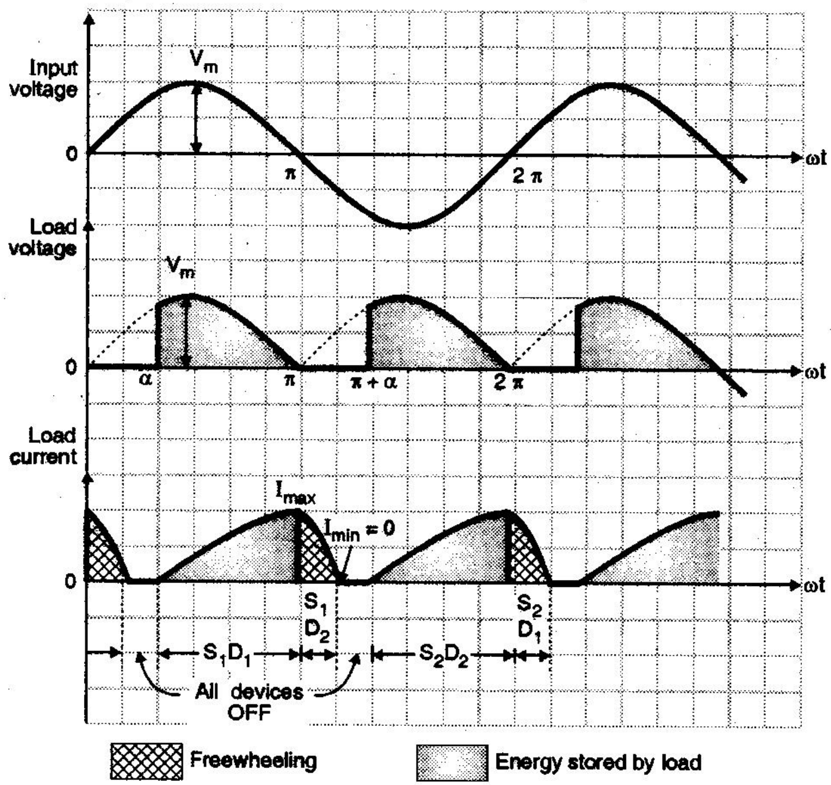


Fig. 2.21 (b) : Discontinuous conduction mode

Symmetrical HCB with R-L load and FWD – 1

Operation with RL load :

- In order to discuss the operation with inductive load, the symmetrical configuration of Fig. 2.22 is used.
- The instantaneous load voltage v_L, instantaneous load current i_L and the instantaneous supply current are as shown in the Fig. 2.26 .

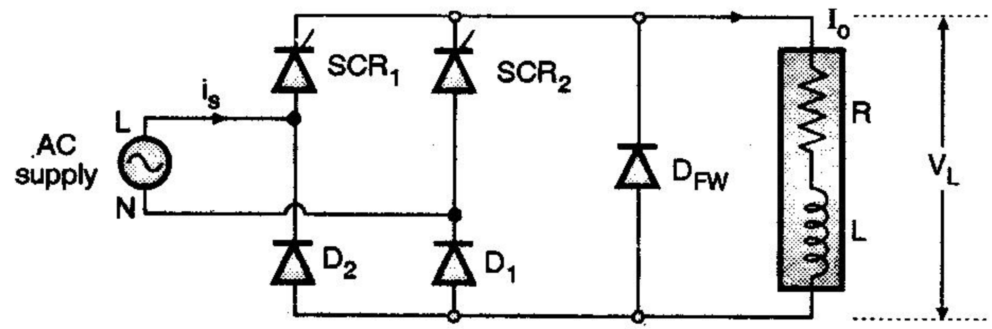


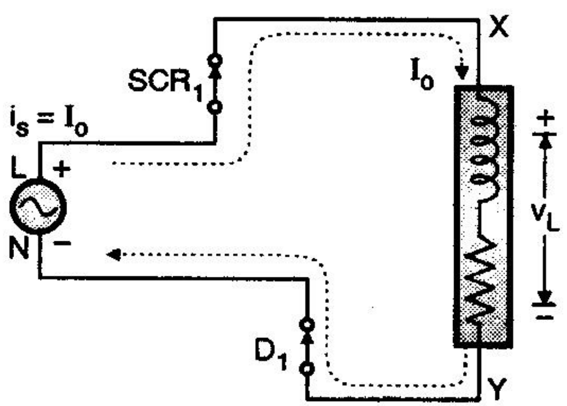
Fig. 2.22 : Semiconverter with inductive load

- The load current $i_L = I_o$, is assumed to be continuous and ripplefree. Different voltage and current waveforms are as shown in Fig. 2.26 .
- The operation can be divided into four modes of operation.

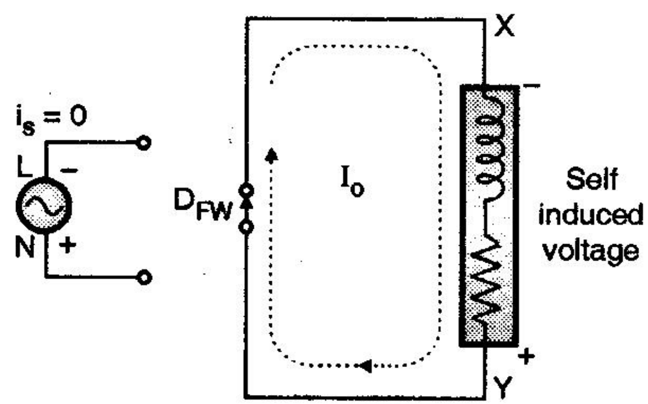
Symmetrical HCB with R-L load and FWD – 2

Mode I ($\alpha \leq \omega t \leq \pi$) :

- At instant $\omega t = \alpha$, SCR_1 is turned on. The equivalent circuit is as shown in Fig. 2.23 (a). Diode D_1 is forward biased in the positive half cycle. Hence conduction will take place through SCR_1 and D_1
- The load voltage $V_o = V_m \sin \omega t$, it is positive (point X positive w.r.t. point Y).
- The input supply current i_s is positive and equal to I_o. The load current is positive, continuous and ripplefree.
- As both the output voltage and current are positive, the inductive load will store the energy in this mode of operation i.e. the flow of power is from source to load.
- The current through SCR_1, $I_{SCR1} = I_o$ and $I_{D1} = I_o$ as shown in Fig. 2.26.



(a) Mode I equivalent circuit (α to π) load stores energy



(b) Mode II equivalent circuit (π to $\pi + \alpha$) freewheeling

Fig. 2.23

Symmetrical HCB with R-L load and FWD – 3

Mode II ($\pi \le \omega t \le \pi + \alpha$) : (Freewheeling) :

At instant $\omega t = \pi$, the ac voltage goes to zero and after π it becomes negative. Due to this negative input voltage the conducting SCR_1 and diode D_1 will try to turn off.

- Due to this there is a change in the load current. As the load is highly inductive it will try to oppose any change in the current flowing through it.
- Thus the load inductance will try to maintain the load current unchanged by inducing a self induced voltage across the load as shown in Fig. 2.23 (b).
- As seen from this figure, the load voltage is negative (point y positive with respect to x). The magnitude of this self induced negative voltage is L di/dt, where L is load inductance and i is load current.

Freewheeling :

- This self induced load voltage will bring diode D_{FW} (which is connected across load) into conduction at instant π.
- SCR_1 and D_1 are turned off. In this way the load is short circuited by the conducting D_{FW} (see Fig. 2.26). The load current now freewheels through D_{FW}. If the diode is considered to be ideal, then the load voltage will be zero.
- The freewheeling takes place due to stored energy in the inductive load and during freewheeling this stored energy is dissipated in the freewheeling diode. The ac supply current $i_s = 0$ as shown in Fig. 2.23 (b). This mode of operation continues upto $\omega t = (\pi + \alpha)$ where SCR_2 is turned on.

Symmetrical HCB with R-L load and FWD – 4

Mode III ($\pi + \alpha \le \omega t \le 2\pi$) :

- Mode III begins at instant $\omega t = (\pi + \alpha)$. At this instant the ac input voltage is negative as shown in Fig. 2.24 . This forward biases SCR_2 and D_2.
- At $\omega t = \pi + \alpha$ the current starts flowing through SCR_2, load and D_2 as shown in Fig. 2.24 . The load voltage becomes positive and equal to instantaneous supply voltage.
- Supply current is negative, $i_s = -I_o$. As the load voltage and current both are positive the load will store the energy.

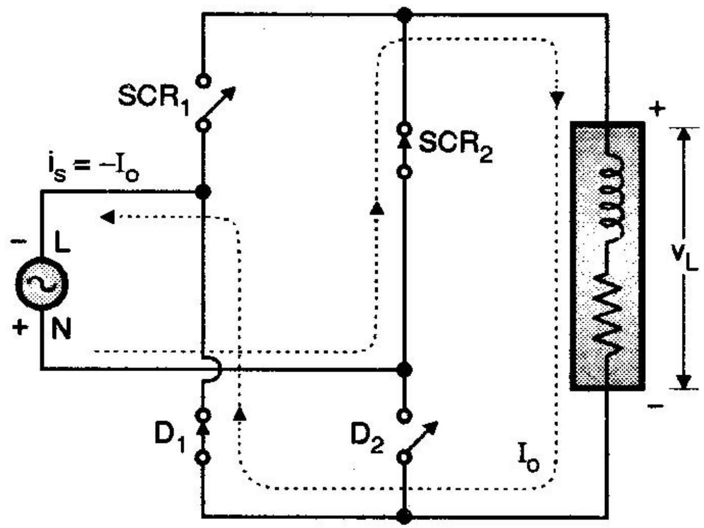


Fig. 2.24 : Equivalent circuit for mode III ($\pi + \alpha$) to 2π load stores energy

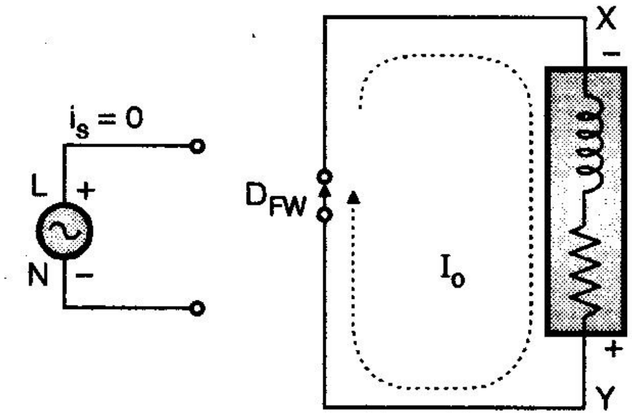


Fig. 2.25 : Equivalent circuit for mode IV (0 to α) freewheeling

Symmetrical HCB with R-L load and FWD – 5

Mode IV [0 to α or (2π to $2\pi + \alpha$)] (Freewheeling) :

At instant $\omega t = 2\pi$ or 0, the ac supply reverses its voltage polarity and becomes positive. As explained for mode II (π to $\pi + \alpha$) here also the freewheeling starts through D_{FW}. The load voltage is zero and the supply current also is zero in this mode.

At instant $\omega t = (2\pi + \alpha)$ or α, SCR_1 is turned on which turns off D_{FW} due to the line commutation.

The operation of semiconverter can be summarised as shown in the Table 2.3.

Table 2.3

Mode	I ($\alpha - \pi$)	II ($\pi - \pi + \alpha$)	III ($\pi + \alpha - 2\pi$)	IV ($0 - \alpha$)
Conducting Devices	S_1 D_1	D_{FW}	S_2 D_2	D_{FW}
Load voltage	Positive	Zero	Positive	Zero
Load current	Positive	Positive	Positive	Positive
Power flow	Source to load	Freewheeling	Source to load	Freewheeling

Note : The load voltage waveform and supply current waveform for all the configurations of a semiconverter are identical. So the analysis is applicable to all the configurations.

Symmetrical HCB with R-L load and FWD – 6

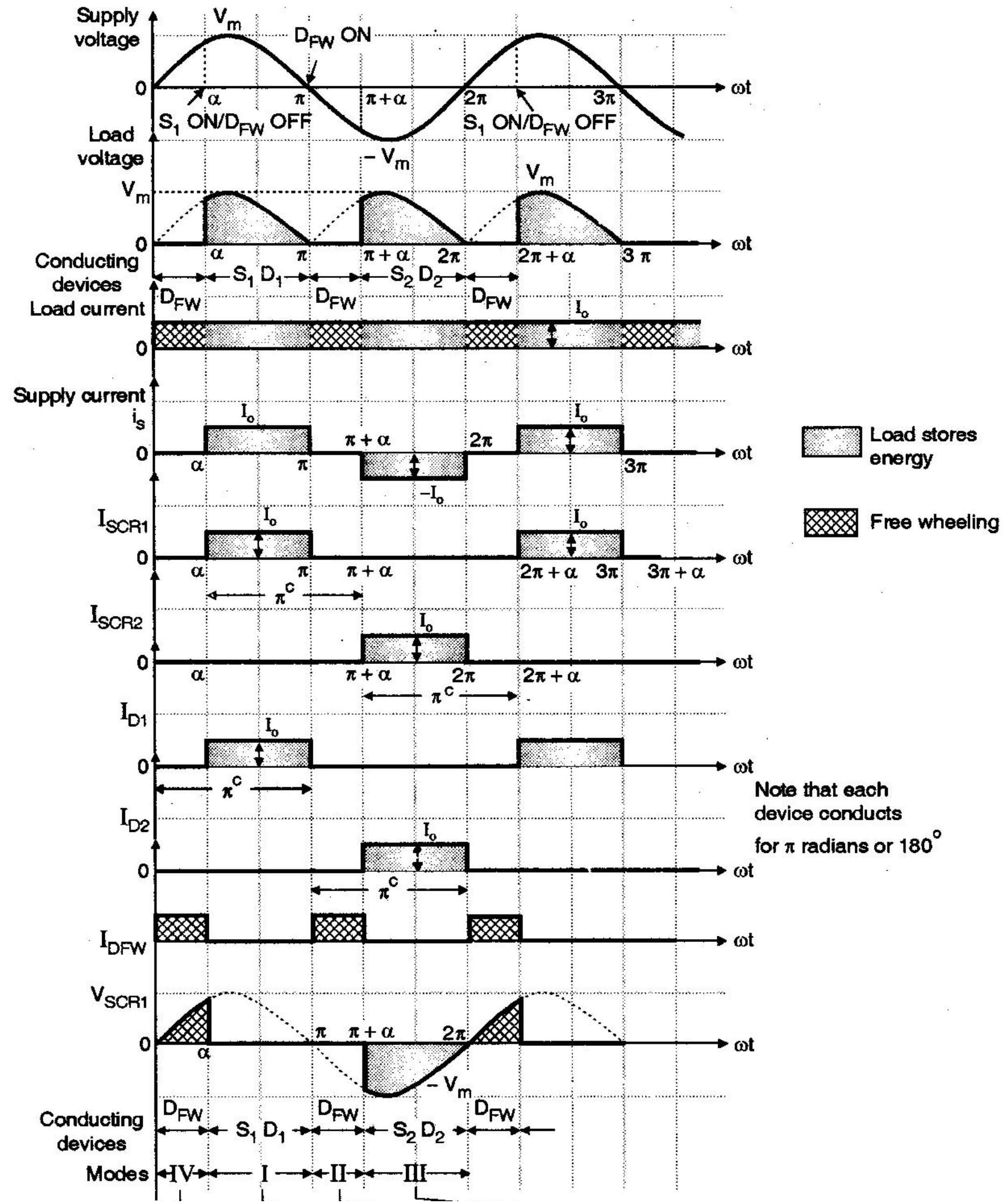


Fig. 2.26: Voltage and current waveforms for single phase semiconverter symmetrical configuration with R-L load and FWD

Symmetrical HCB with R-L load and FWD – 7

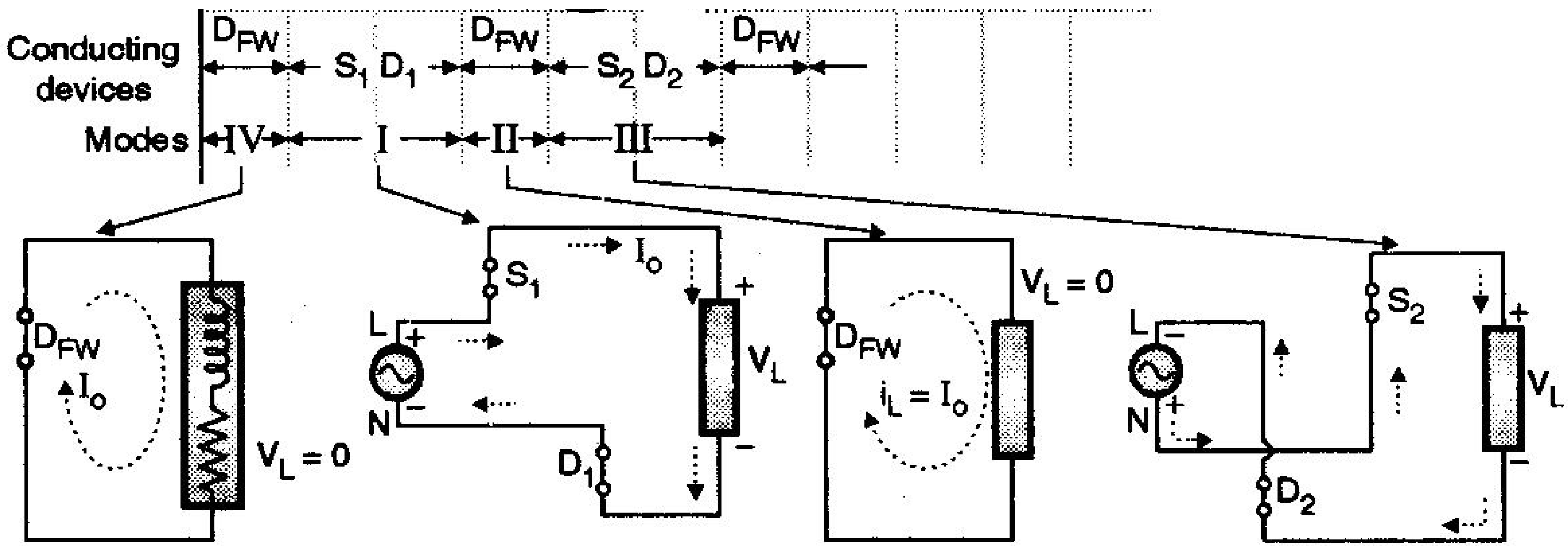


Fig. 2.26: Voltage and current waveforms for single phase semiconverter with free wheeling diode

HCB with R-L load – 1

Output voltage analysis:

This analysis is applicable to all HCB configurations.

Comparing the waveforms for HCB with level (ripple-free, highly inductive) load in Fig. 2.26 with those for FCB with R load in Fig. 2.6, it is seen that the load voltage waveforms are identical. Hence all performance related parameters related to the load (output) voltage will be identical for these cases. Specifically expressions for:

1. Average load voltage V_{Ldc} (2.1 to 2.2 (b))
2. RMS load voltage V_{Lrms} (2.5 to 2.6 (b))
3. Form Factor FF (2.14)
4. Ripple Factor RF (2.15)
5. Load DC power P_{Ldc} (2.16)
6. Load AC power P_{Lac} (2.17)

are the same for the HCB with level load.

HCB with R-L load – 2

Here $I_{Ldc} = I_{Lrms} = V_{Ldc} / R$ for a level load

Variation of average load voltage with α :

Table 2.4 lists the values of average load voltage for different values of α and Fig. 2.27 shows the variation of V_{Ldc} with α.

Table 2.4

α	0°	30°	60°	90°	120°	150°	180°
V_{Ldc}	$0.63\ V_m$	$0.6\ V_m$	$0.48\ V_m$	$0.32\ V_m$	$0.16\ V_m$	$0.04\ V_m$	0

HCB with R-L load – 3

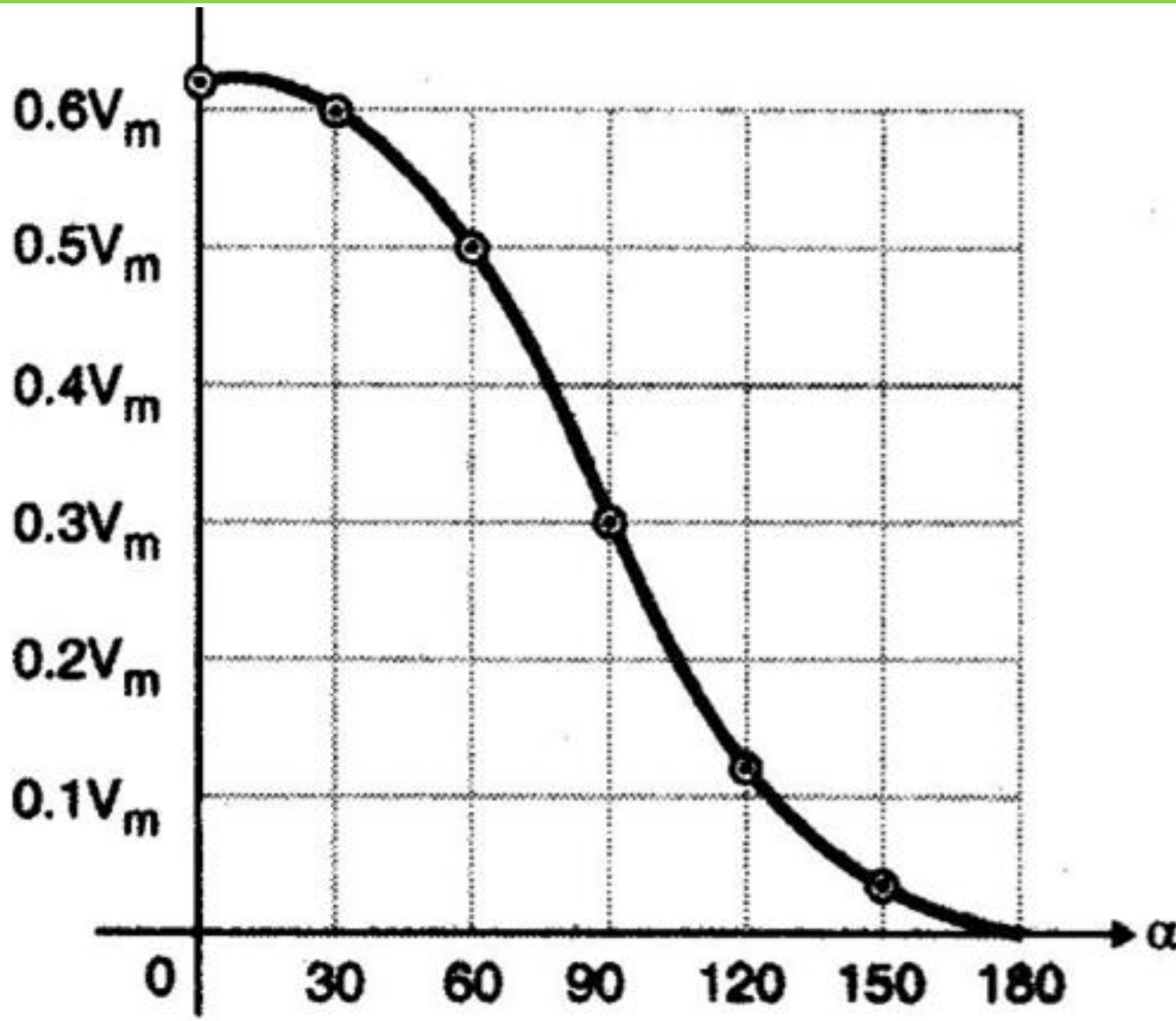


Fig. 2.27 (a) Variation of V_{Ldc} with α

HCB with R-L load – 4

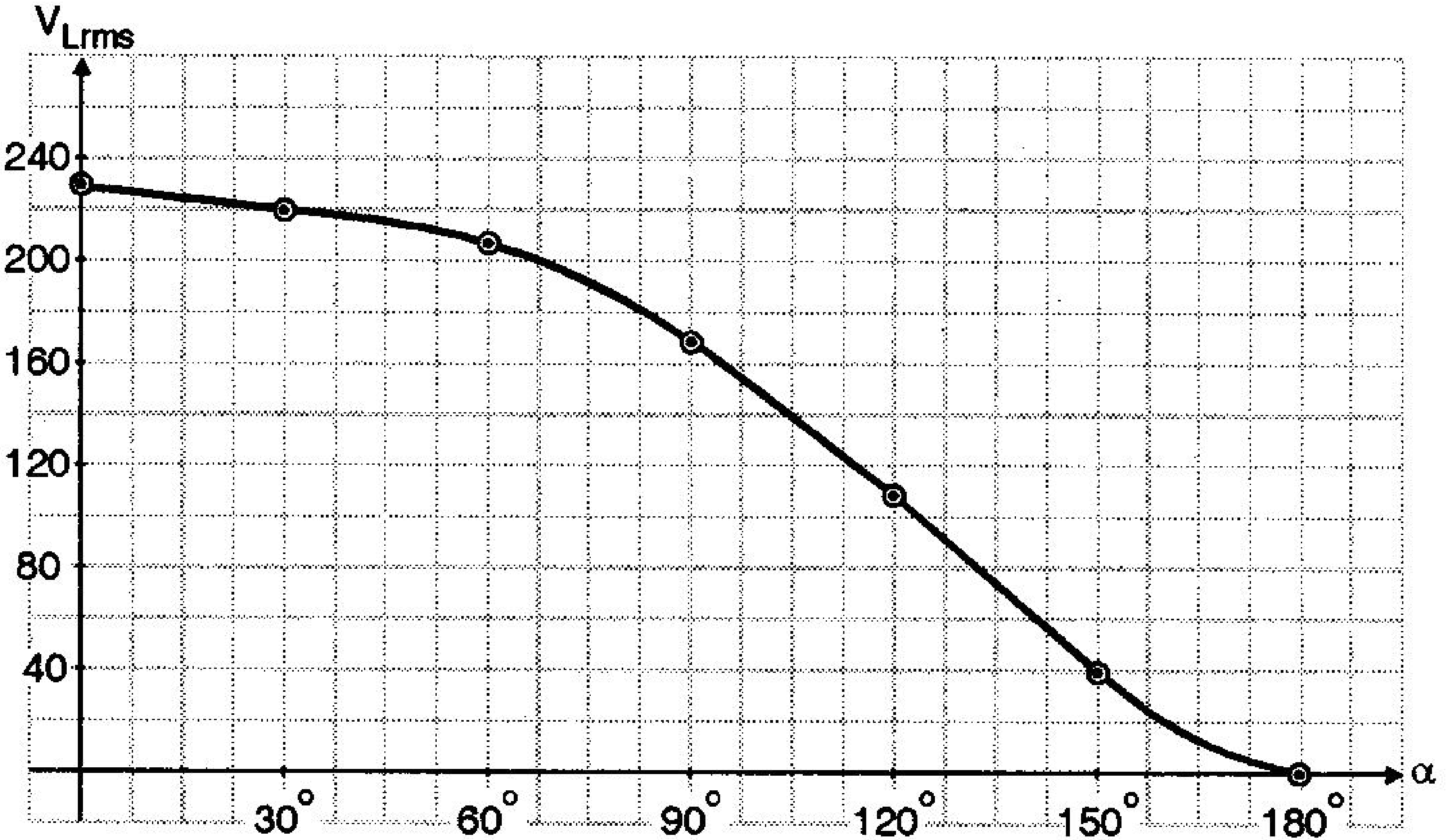


Fig. 2.27 (b) Variation of RMS load voltage with α

HCB with R-L load – 5

Rectifier operation

As the average load voltage is always positive the direction of flow of power is always from ac mains to dc load. That means the semiconverter always works as a **rectifier.**

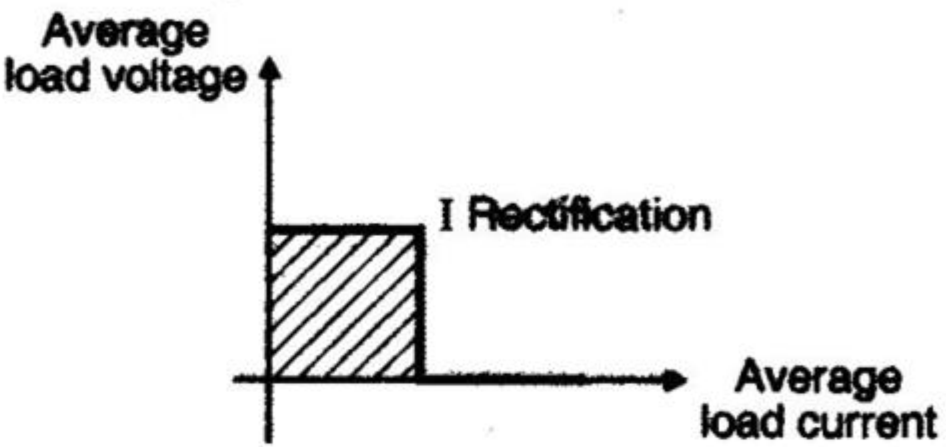


Fig. 2.27 (c) Quadrant of operation

HCB with R-L load – 6

Single quadrant operation :

- Due to the inherent freewheeling action, the instantaneous load voltage can not be negative. Therefore the average load voltage is always positive.
- The load current I_o is continuous and ripple free and hence positive.
- Therefore the semiconverter with highly inductive load operates only in the first quadrant of load voltage load current characteristics.

Analysis of supply current waveform for HCB with level load:

The source current waveform which is to be expressed in the form of Fourier series is as shown in Fig. 2.28.

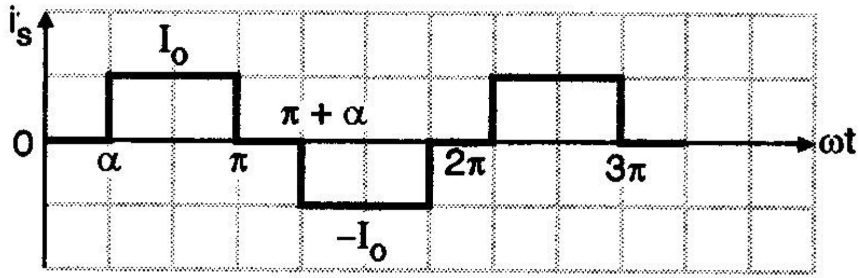


Fig. 2.28 : Source current waveform

- The supply current i_s can be expressed in Fourier series as,

$$i_s(t) = I_{av} + \sum_{n=1}^{\infty} c_n \cdot \sin(n\omega t + \phi_n) \qquad \text{...(2.51)}$$

$$\text{where} \quad c_n = (a_n + b_n)^{1/2}$$

$$\text{and} \quad \phi_n = \tan^{-1}(a_n / b_n)$$

- The average value of supply current is $I_{av} = 0$. Since it is symmetrical about the x axis as shown in Fig. P. 4.7.1.

$$\therefore \quad i_s(t) = \sum_{n=1}^{\infty} c_n \sin(n\omega t + \phi_n)$$

HCB with R-L load – 8

- To calculate the values of c_n and ϕ_n we have to obtain the values of Fourier coefficients a_n and b_n.
- Where the Fourier coefficients are
$$a_n = \frac{1}{\pi}\int_{\alpha}^{2\pi} i_s(\omega t)\cos n\omega t\, d\omega t \qquad \ldots(2.52)$$
- But from the Fig. 2.28
$$i_s(\omega t) = I_o \qquad \text{For } \alpha \le \omega t \le \pi$$
$$\text{and} = -I_o \qquad \text{For } \pi+\alpha \le \omega t \le 2\pi$$

Steps to be followed :

Step 1 : Obtain the expressions for Fourier coefficients a_n and b_n.
Step 2 : Calculate c_n and ϕ_n.
Step 3 : Express $i_s(\omega t)$ in terms of Fourier series.

Step 1 : To obtain a_n :

$$\therefore \quad a_n = \frac{1}{\pi}\left\{\int_{\alpha}^{\pi} I_o \cos n\omega t\, d\omega t - \int_{\pi+\alpha}^{2\pi} I_o \cos n\omega t\, d\omega t\right\}$$

$$\therefore \quad a_n = \frac{I_o}{\pi}\left[\left(\frac{\sin n\omega t}{n}\right)_{\alpha}^{\pi} - \left(\frac{\sin n\omega t}{n}\right)_{\pi+\alpha}^{2\pi}\right]$$

$$= \frac{I_o}{n\pi}[\sin n\pi - \sin n\alpha - \sin 2\pi n + \sin n(\pi+\alpha)] \qquad \because \sin n\pi = \sin 2\pi n = 0$$

$$= \frac{I_o}{n\pi}[-\sin n\alpha + \sin n(\pi+\alpha)]$$

HCB with R-L load – 9

$$\therefore \quad a_n = \frac{I_o}{n\pi}[-\sin n\alpha + \sin n\pi \cos n\alpha + \cos n\pi \sin n\alpha]$$

$$= \frac{I_o}{n\pi}[-\sin n\alpha + \cos n\pi \sin n\alpha] \qquad \because \quad \sin n\pi \cos n\alpha = 0$$

But $\cos n\pi = 1$ if $n = 2, 4, 6 \ldots..$

and $\cos n\pi = -1$ if $n = 1, 3, 6 \ldots..$

$$\therefore \quad a_n = \frac{-2 I_o}{n\pi} \sin n\alpha \qquad \text{for } n = 1, 3, 5 \ldots$$

$$\text{and} \quad a_n = 0 \qquad \text{for } n = 2, 4, 6 \ldots \qquad \ldots(2.53)$$

Step 2 : To obtain b_n :

$$b_n = \frac{1}{\pi}\int_{\alpha}^{2\pi} i_s(t) \sin n\omega t \, d\omega t \qquad \ldots(2.54)$$

$$= \frac{1}{\pi}\left\{\int_{\alpha}^{\pi} I_o \sin n\omega t \, d\omega t - \int_{\pi+\alpha}^{2\pi} I_o \sin n\omega t \, d\omega t\right\}$$

$$\therefore \; b_n = \frac{I_o}{n\pi}\left[(-\cos n\omega t)_{\alpha}^{\pi} + (\cos n\omega t)_{\pi+\alpha}^{2\pi}\right] = \frac{I_o}{n\pi}[\cos 2\pi n - \cos n(\pi + \alpha) - \cos n\pi + \cos n\alpha]$$

$$= \frac{I_o}{n\pi}[1 - \cos n\pi \cos n\alpha + \sin n\pi \sin n\alpha - \cos n\pi + \cos n\alpha] \qquad \because \quad \sin n\pi \sin n\alpha = 0$$

$$= \frac{I_o}{n\pi}[1 - \cos n\pi \cos n\alpha - \cos n\pi + \cos n\alpha]$$

HCB with R-L load – 10

But $\cos n\pi = 1$ if $n = 2, 4, 6 \ldots..$

and $\cos n\pi = -1$ if $n = 1, 3, 5, \ldots..$

$\therefore$ for n even $$b_n = \frac{I_o}{n\pi}[1 - \cos n\alpha - 1 + \cos n\alpha] = 0$$

and for n odd $$b_n = \frac{I_o}{n\pi}[1 + \cos n\alpha + 1 + \cos n\alpha] = \frac{2\,I_o}{n\pi}[1 + \cos n\alpha]$$

$$\therefore \quad b_n = \frac{2\,I_o}{n\pi}(1 + \cos n\alpha) \qquad \text{for} \quad n = 1, 3, 5 \ldots.$$

$$\text{and} \quad b_n = 0 \qquad \text{for} \quad n = 2, 4, 6 \ldots.. \qquad \ldots(2.55)$$

Step 3 : To obtain c_n :

The peak value of the n^{th} component (n^{th} harmonic) is given by,

$$c_n = \left[a_n^2 + b_n^2\right]^{1/2} = \left[\frac{4\,I_o^2}{n^2\,\pi^2}\sin^2 n\alpha + \frac{4\,I_o^2}{n^2\,\pi^2}(1 + \cos n\alpha)^2\right]^{1/2}$$

HCB with R-L load – 11

$$c_n = \left[\frac{4\,I_o^2}{n^2\,\pi^2}(\sin^2 n\alpha + 1 + 2\cos n\alpha + \cos^2 n\alpha)\right]^{1/2}$$

$$c_n = \left[\frac{4\,I_o^2}{n^2\,\pi^2}(2 + 2\cos n\alpha)\right]^{1/2} = \left[\frac{8\,I_o^2}{n^2\,\pi^2}(1 + \cos n\alpha)\right]^{1/2}$$

But $\quad (1+\cos n\alpha) = 2\cos^2\frac{n\alpha}{2}$

$$\therefore \quad c_n = \left[\frac{16\,I_o^2}{n^2\,\pi^2}\cos^2\frac{n\alpha}{2}\right]^{1/2}$$

$$\therefore \quad c_n = \frac{4\,I_o}{n\pi}\cos\frac{n\,\alpha}{2} \qquad \text{...(2.56)}$$

Step 4 : To obtain ϕ_n (Displacement angle) :

- (The displacement angle ϕ_n is defined as the phase angle between the ac supply voltage and the n^{th} harmonic of supply current.)

HCB with R-L load – 12

- The displacement angle ϕ_n for the n^{th} harmonic is given by

$$\phi_n = \tan^{-1}(a_n / b_n) = \tan^{-1}\left[\frac{-(2 I_o / n\pi)\sin n\alpha}{\frac{2 I_o}{n\pi}(1+\cos n\alpha)}\right]$$

$$= \tan^{-1}\left[\frac{-\sin n\alpha}{1+\cos n\alpha}\right] = -\tan^{-1}\left[\frac{2\sin n\alpha/2 \cos n\alpha/2}{2\cos^2 n\alpha/2}\right] = -\tan^{-1}[\tan n\alpha/2]$$

$$\therefore \quad \phi_n = \frac{-n\alpha}{2} \qquad \text{...(2.57)}$$

- This expression indicates that the n^{th} harmonic component of the supply current lags behind the supply voltage by an angle $(n\alpha/2)$.

Step 5 : Expression for source current $i_s(\omega t)$:

- Substituting the values of c_n and ϕ_n from Equations (6) and (7) into Equation (1) we get,

$$i_s(\omega t) = \sum_{n=1,3,5\ldots}^{\infty} \frac{4 I_o}{n\pi}\cos n\alpha \cdot \sin\left(n\omega t - \frac{n\alpha}{2}\right)$$

This is the Fourier series representation of source current $i_s(\omega t)$.

The rms value of the fundamental component of supply current is given by,

$$I_{s1\,rms} = \frac{c_1}{\sqrt{2}} \qquad \text{...(2.58)}$$

HCB with R-L load – 13

Substituting n = 1 in Equation (6) we get the value of c_n

$$\therefore \quad I_{s1\,rms} = \frac{4\,I_o}{\pi\sqrt{2}}\cos\left(\frac{\alpha}{2}\right)$$

$$\therefore \quad I_{s1\,rms} = \frac{2\sqrt{2}\,I_o}{\pi}\cos\left(\frac{\alpha}{2}\right) \qquad ...(2.59)$$

This is the required expression.

$$I_{s\,rms} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi} I_o^2\, d\omega t\right]^{1/2} \qquad ...(2.60)$$

$$= \left[\frac{I_o^2}{\pi}(\omega t)_{\alpha}^{\pi}\right]^{1/2}$$

$$\therefore \quad I_{s\,rms} = I_o\left[\frac{\pi-\alpha}{\pi}\right]^{1/2} \qquad ...(2.61)$$

This is the required expression for the rms value of supply current.

Performance Parameters for a Semiconverter :

Some of the important performance parameters are as follows :

1. Input displacement factor (DSF)
2. Current distortion factor (CDF)
3. Supply power factor (PF)
4. Harmonic factor.
5. Active power.
6. Reactive power.

1. Input Displacement Factor (DSF) or Fundamental Power Factor (FPF) :

- It is defined as the cosine of input displacement angle ϕ_1, which is the angle between fundamental component of supply current and the associated ac mains voltage.
- It is also known as the fundamental power factor (FPF).

$$\text{DSF for single phase semiconverter} = \cos\phi_1$$

- But from Equation (7), $\phi_1 = -\alpha/2$

$$\therefore \quad \text{DSF} = \cos(-\alpha/2) \qquad \text{DSF} = \cos(\alpha/2) \qquad \text{...(2.62)}$$

- Ideally DSF = 1 and practically it should be as close as possible to 1.

2. Current Distortion Factor (CDF) :

- It is defined as the ratio of rms value of fundamental component of supply current to the rms value of supply current.

$$\therefore \quad \text{CDF} = \frac{I_{s1\ rms}}{I_{s\ rms}} \qquad \text{...(2.63)}$$

HCB with R-L load – 15

$$= \frac{\dfrac{2\sqrt{2}\, I_o}{\pi} \cos(\alpha/2)}{I_o\left[(\pi-\alpha)/\pi\right]^{1/2}}$$

$$\therefore \quad \text{CDF} = \frac{2\sqrt{2}\cos(\alpha/2)}{\left[\pi(\pi-\alpha)\right]^{1/2}} \qquad \text{...(2.64)}$$

- Ideally the value of CDF should be 1 or 100 % and practically it should be as close as possible to 1.

3. Supply Power Factor (PF) :

- It is defined as the ratio of total mean input power to the total rms input power to the converter.

$$\therefore \quad \text{P.F.} = \frac{V_{s1\,(rms)} \times I_{s1\,(rms)} \times \cos\phi_1}{V_{s\,(rms)} \times I_{s\,(rms)}} \qquad \text{...(2.65)}$$

where $V_{s1\,(rms)}$ = RMS value of fundamental component of supply voltage.

$V_{s\,(rms)}$ = RMS value of supply voltage.

But $V_{s1\,(rms)}$ = $V_{s\,(rms)}$, because ac mains voltage is purely sinusoidal.

$$\therefore \quad \text{PF} = \frac{I_{s1\,(rms)}}{I_{s\,(rms)}} \cdot \cos\phi_1 \qquad \text{...(2.66)}$$

HCB with R-L load – 16

- The ratio of currents in Equation (4.7.5) is CDF and $\cos\phi$ is FPF.

$$\therefore \quad PF = CDF \times FPF \qquad ...(2.67)$$

- Substituting the values of CDF and FPF from Equations (4.7.3) and (4.7.1) respectively, we get,

$$PF = \frac{2\sqrt{2}\cos(\alpha/2)}{[\pi(\pi-\alpha)]^{1/2}} \times \cos(\alpha/2) = \frac{2\sqrt{2}\cos^2(\alpha/2)}{[\pi(\pi-\alpha)]^{1/2}} \qquad ...(2.68)$$

- But $2\cos^2(\alpha/2) = 1 + \cos\alpha$

$$\therefore \quad PF = \frac{\sqrt{2}(1+\cos\alpha)}{[\pi(\pi-\alpha)]^{1/2}} \qquad ...(2.69)$$

- Ideally the value of PF should be 1 and practically it should be as close as possible to 1.

4. Input Harmonic Factor (HF) :

- It is the ratio of total harmonic contents in the supply current waveform to the fundamental component of supply current.

$$\therefore \quad HF = \frac{\left[I_{s\,rms}^2 - I_{1\,rms}^2\right]^{1/2}}{I_{1\,rms}} \qquad ...(2.70)$$

$$= \left[\frac{I_{s\,rms}^2}{I_{1\,rms}^2} - 1\right]^{1/2} = \left[\frac{1}{CDF^2} - 1\right]^{1/2} \qquad ...(2.71)$$

- Substituting the value of CDF from Equation (4.7.3) we get,

$$HF = \left[\frac{\pi\,(\pi - \alpha)}{8\cos^2(\alpha/2)} - 1\right]^{1/2}$$

- But $\quad 2\cos^2(\alpha/2) = (1 + \cos\alpha)$

$$\therefore \quad HF = \left[\frac{\pi\,(\pi - \alpha)}{4\,(1 + \cos\alpha)} - 1\right]^{1/2} \qquad ...(2.72)$$

- The harmonic factor indicates percentage of harmonics in the supply current waveform. Ideally the value of HF should be zero and practically it should be as low as possible.

HCB with R-L load – 18

5. Active Power in Semiconverter :

- As per definition of active power $P_A = V_{s\,rms}\ I_{s1\,rms} \cos \phi_1$ ...(2.73)

where $V_{s\,rms}$ is the rms supply voltage

- $\therefore$ Substituting the values of $I_{s1\,rms}$ and ϕ_1, we get,

$$P_A = \frac{V_{s\,rms} \cdot 2\sqrt{2}\, I_o}{\pi} \cos(\alpha/2) \cdot \cos(\alpha/2)$$

$$P_A = \frac{V_{s\,rms} \cdot 2\sqrt{2}\, I_o}{\pi} \cos^2(\alpha/2)$$

$$\therefore \quad P_A = \frac{2\sqrt{2}\, V_{s\,rms}\, I_o}{\pi} \cos^2(\alpha/2) \qquad \text{but } \sqrt{2}\ V_{s\,rms} = V_m$$

$$\therefore \quad P_A = \frac{2\, V_m\, I_o}{\pi} \cos^2(\alpha/2) \qquad \text{...(2.74)}$$

$$\text{But } 2\cos^2(\alpha/2) = (1 + \cos\alpha)$$

$$\therefore \quad P_A = \frac{V_m\, I_o}{\pi} (1 + \cos\alpha) \qquad \text{...(2.75)}$$

- Active power is the "useful" part of total input power. Therefore active power should be as high as possible.

6. Reactive Power :

$$P_R = V_{s\,rms}\, I_{s1\,rms} \sin \phi_1 \qquad \text{...(2.76)}$$

Substituting the values we get,

$$P_R = V_{s\,rms} \times \frac{2\sqrt{2}\, I_o}{\pi} \cos(\alpha/2) \sin(\alpha/2)$$

Rearranging the terms we get,

$$P_R = \frac{\sqrt{2}\, V_{s\,rms}\, I_o}{\pi} \cdot 2 \sin(\alpha/2) \cos(\alpha/2)$$

But $2 \sin(\alpha/2) \cos(\alpha/2) = \sin \alpha$

$$\therefore \quad P_R = \frac{\sqrt{2}\, V_{s\,rms}\, I_o}{\pi} \sin \alpha \quad \text{but } \sqrt{2}\; V_{s\,rms} = V_m$$

$$\therefore \quad P_R = \frac{V_m\, I_o}{\pi} \sin \alpha \qquad \text{...(2.77)}$$

- The reactive power is the useless part of the total input power. This power only travels between the load and source. Therefore P_R should be as small as possible.

4.7.2 Advantages of Semiconverters :

The semiconverter has following advantages over full converter :

1. Higher average output voltage at the same value of α.
2. Higher displacement factor ($\cos \alpha / 2$) and power factor as compared to that of a full converter.
3. Reduced reactive power input. Therefore it is preferred over full converter when regenerative braking in not required.

4.7.3 Disadvantages of Semiconverters :

Some of the disadvantages of a semiconverter are :

- It can operate only in one quadrant.
- Energy feedback from load to source is not possible.
- Not suitable for the regenerative braking of DC motors.

4.7.4 Application :

Semiconverters are popularly used in the unidirectional DC motor controllers.

FCB vs HCB - 1

4.11.2 Comparison of Semiconverter and Full Converter :

The performance of the single phase semiconverter and full converter is compared based on various performance parameter as shown in Table 2.1.

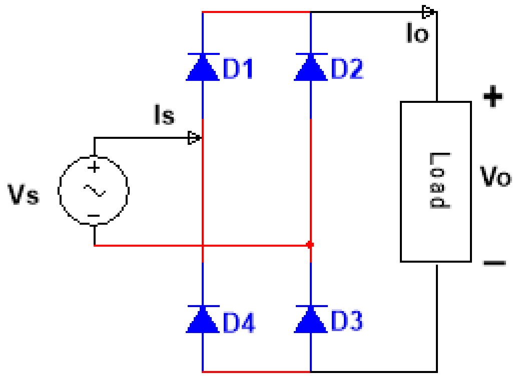
Table 2.1

Sr. No.	Parameter	Full converter	Semiconverter
1.	Average load voltage (RL load)	$V_{Ldc} = \frac{2\,V_m}{\pi}\cos\alpha$	$V_{Ldc} = \frac{V_m}{\pi}(1+\cos\alpha)$
2.	RMS load voltage	$V_{L\,rms} = \frac{V_m}{\sqrt{2}}$	$V_{L\,rms} = \frac{V_m}{\sqrt{2}}\left[\frac{1}{\pi}\left(\pi-\alpha+\frac{\sin 2\alpha}{2}\right)\right]^{1/2}$
3.	Form factor (FF)	$FF = \frac{\pi}{2\sqrt{2}\cos\alpha}$	$FF = \frac{V_{L\,rms}}{V_{Ldc}}$
4.	Ripple factor (RF)	$RF = \left[\frac{\pi^2}{8\cos^2\alpha} - 1\right]^{1/2}$	$RF = [FF^2 - 1]^{1/2}$
5.	Rectification efficiency	$\eta = \frac{8\cos^2\alpha}{\pi^2}$	$\eta = \frac{1}{FF^2}$

FCB vs HCB - 2

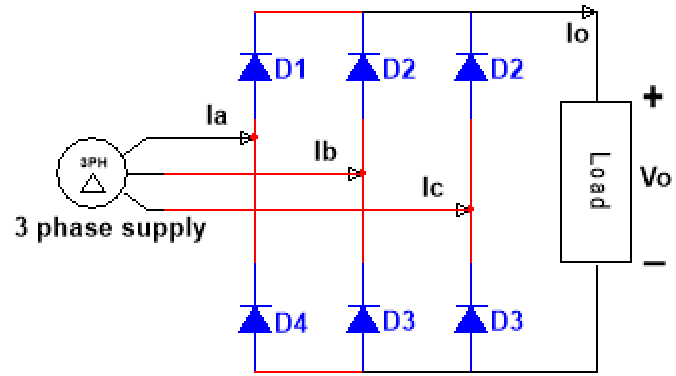
Sr. No.	Parameter	Full converter	Semiconverter
6.	Quadrant of operation	Two quadrant converter (Rectification and inversion)	Single quadrant converter (Rectification only)
7.	RMS supply current	$I_{s\,rms} = I_o$	$I_{s\,rms} = I_o \left[\frac{\pi - \alpha}{\pi}\right]^{1/2}$
8.	RMS value of fundamental component of supply current	$I_{s1\,rms} = \frac{2\sqrt{2}\, I_o}{\pi}$	$I_{s1\,rms} = \frac{2\sqrt{2}\, I_o}{\pi} \cos\left[\frac{n\,\alpha}{2}\right]$
9.	Fundamental displacement angle	$\phi_1 = -\alpha$	$\phi_1 = -\frac{\alpha}{2}$
10.	Fundamental power factor (FPF)	FPF = $\cos\alpha$	FPF = $\cos(\alpha / 2)$
11.	Input power factor (PF)	$PF = \frac{2\sqrt{2}}{\pi} \cos\alpha$	$PF = \frac{\sqrt{2}\,(1 + \cos\alpha)}{[\pi\,(\pi - \alpha)]^{1/2}}$
12.	Harmonic factor (HF)	$HF = \left[\frac{\pi^2}{8} - 1\right]^{1/2}$	$HF = \left[\frac{\pi\,(\pi - \alpha)}{4\,(1 + \cos\alpha)} - 1\right]^{1/2}$
13.	Freewheeling	Absent	Present
14.	Active power	$P_A = \frac{2\,V_m\,I_o}{\pi} \cos\alpha$	$P_A = \frac{2\,V_m\,I_o}{\pi} \cos^2(\alpha / 2)$
15.	Reactive power	$P_R = \frac{2\,V_m\,I_o}{\pi} \sin\alpha$	$P_R = \frac{2\,V_m\,I_o}{\pi} \sin\alpha$
16.	Supply (Input) current	Square wave	Quasi square wave
17.	Harmonics present in the supply current	Only odd harmonics	Only odd harmonics
18.	Power flow	Bidirectional	Unidirectional

Evolution of 3 phase rectifiers (AC – DC converters) - 1

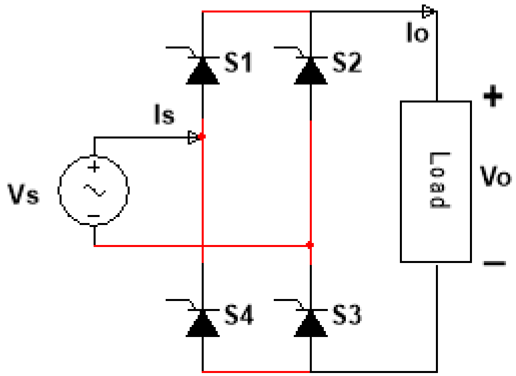


Uncontrolled Single Phase
Diode Bridge Rectifier

Add third arm with two series diodes

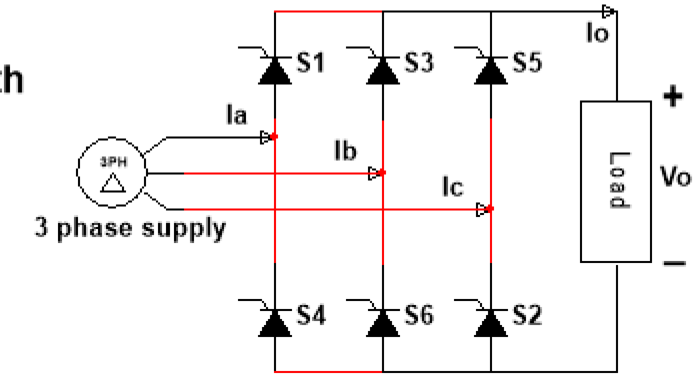


Uncontrolled Three Phase
Diode Bridge Rectifier



Fully Controlled Single Phase
Bridge Rectifier

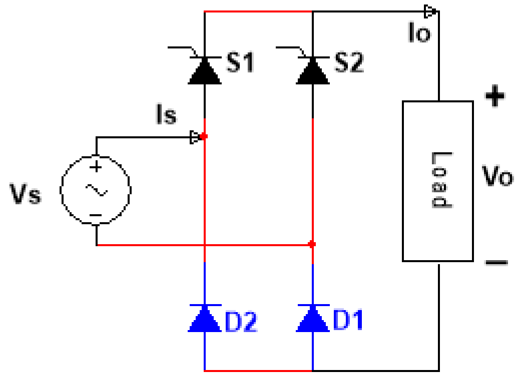
Add third arm with two series SCRs



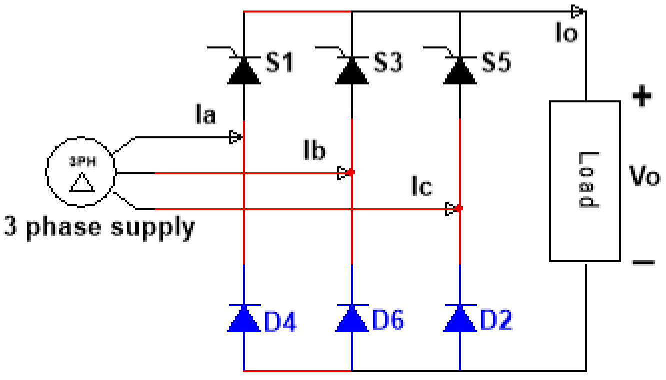
Fully Controlled Three Phase
Bridge Rectifier

FIGURE 2.29

Evolution of 3 phase rectifiers (AC – DC converters) - 2

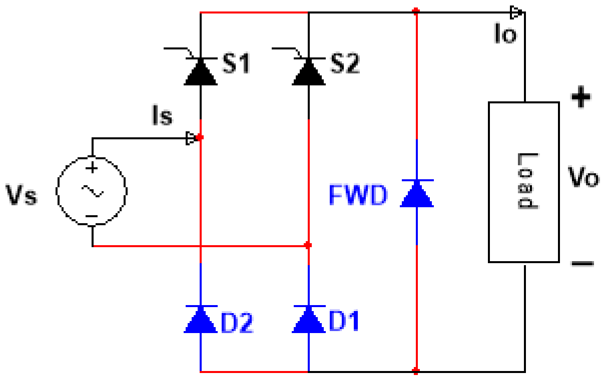


Add third arm with SCR and diode

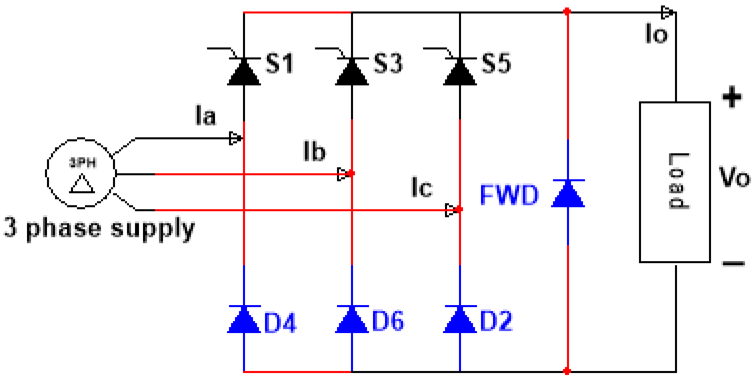


Half Controlled Single Phase Bridge Rectifier

Half Controlled Three Phase Bridge Rectifier



Add third arm with SCR and diode



Half Controlled Single Phase Bridge Rectifier with FWD

Half Controlled Three Phase Bridge Rectifier with FWD

FIGURE 2.30

3 phase line and phase voltages - 1

- In a balanced 3 phase system, the 3 phase or line-to-neutral voltages $v_{AN}(t)$ ($v_{RN}(t)$), $v_{BN}(t)$ ($v_{YN}(t)$) and $v_{CN}(t)$ ($v_{BN}(t)$) have the same rms magnitude V_s or peak magnitude $V_{mp} = \sqrt{2}\, V_s$ while $v_{BN}(t)$ lags $v_{AN}(t)$ by 120^o and $v_{CN}(t)$ leads $v_{AN}(t)$ by 120^o as shown in Figs.

- The 6 line-to-line voltages $v_{AB}(t) = v_{AN}(t) - v_{BN}(t) = - v_{BA}(t)$,

$$v_{BC}(t) = v_{BN}(t) - v_{CN}(t) = - v_{CB}(t),$$
$$v_{CA}(t) = v_{CN}(t) - v_{AN}(t) = - v_{AC}(t),$$

have the same rms magnitude $V_L = \sqrt{3}\, V_s$ or peak magnitude $V_{ml} = \sqrt{2}\, V_L$
$= \sqrt{6}\, V_s$

- Referring to Figs. 2.31 and 2.32, it is seen that:

$v_{AB}(t)$ leads $v_{AN}(t)$ by 30^o & $v_{AC}(t)$ lags $v_{AN}(t)$ by 30^o

$v_{BC}(t)$ leads $v_{BN}(t)$ by 30^o & $v_{BA}(t)$ lags $v_{BN}(t)$ by 30^o

$v_{CA}(t)$ leads $v_{CN}(t)$ by 30^o & $v_{CB}(t)$ lags $v_{CN}(t)$ by 30^o

Also each of the 6 line-to-line voltages $v_{AB}(t)$, $v_{AC}(t)$, $v_{BC}(t)$, $v_{BA}(t)$, $v_{CA}(t)$ & $v_{CB}(t)$ lags the preceding voltage by 60^o.

3 phase line and phase voltages - 2

- The instantaneous and rms phasor values of the phase voltages are

$v_{AN}(t) = \sqrt{2}\, V_s \sin(\omega t) \quad = V_{mp} \sin(\omega t)\,, \quad \widehat{V_{AN}} = V_s\angle 0^o$

$v_{BN}(t) = \sqrt{2}\, V_s \sin(\omega t - 120^o) = V_{mp} \sin(\omega t - 120^o), \quad \widehat{V_{BN}} = V_s\angle -120^o$

$v_{CN}(t) = \sqrt{2}\, V_s \sin(\omega t - 240^o) = V_{mp} \sin(\omega t - 240^o), \quad \widehat{V_{BN}} = V_s\angle -240^o$

- The instantaneous and rms phasor values of the line-to-line voltages are

$v_{AB}(t) = \sqrt{2}\, V_L \sin(\omega t + 30^o) = \sqrt{6}\, V_s \sin(\omega t + 30^o)\,, \quad \widehat{V_{AB}} = V_L \angle 30^o$

$v_{AC}(t) = \sqrt{2}\, V_L \sin(\omega t - 30^o) = \sqrt{6}\, V_s \sin(\omega t - 30^o)\,, \quad \widehat{V_{AC}} = V_L \angle -30^o$

$v_{BC}(t) = \sqrt{2}\, V_L \sin(\omega t - 90^o) = \sqrt{6}\, V_s \sin(\omega t - 90^o), \quad \widehat{V_{AC}} = V_L \angle -90^o$

$v_{BA}(t) = \sqrt{2}\, V_L \sin(\omega t - 150^o) = \sqrt{6}\, V_s \sin(\omega t - 150^o), \quad \widehat{V_{AC}} = V_L \angle -150^o$

$v_{AB}(t) = \sqrt{2}\, V_L \sin(\omega t - 210^o) = \sqrt{6}\, V_s \sin(\omega t - 210^o), \quad \widehat{V_{AC}} = V_L \angle -210^o$

$v_{AB}(t) = \sqrt{2}\, V_L \sin(\omega t - 270^o) = \sqrt{6}\, V_s \sin(\omega t - 270^o), \quad \widehat{V_{AC}} = V_L \angle -270^o$

3 phase line and phase voltages - 3

3 phase phasor diagram

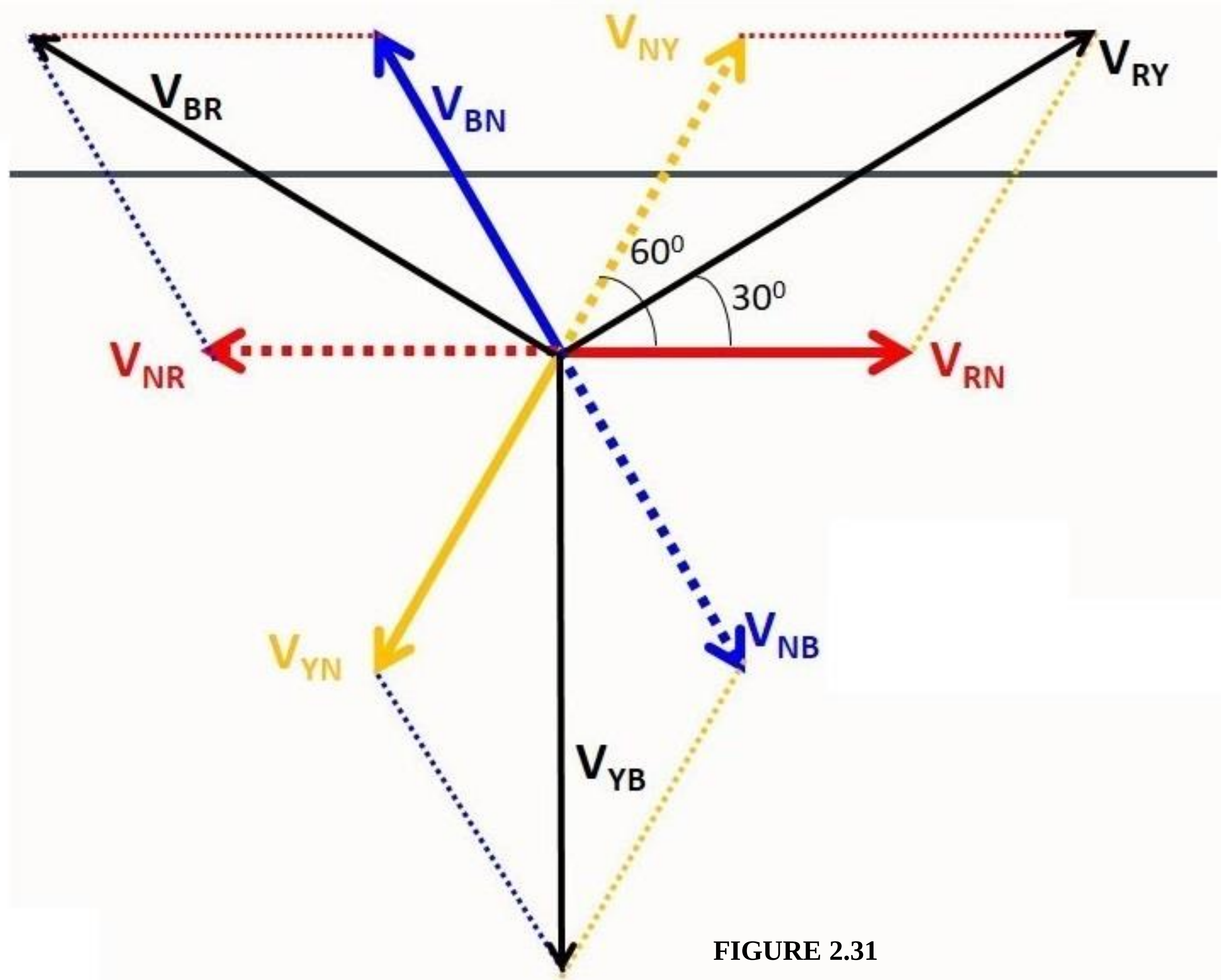


FIGURE 2.31

3 phase line and phase voltages - 4

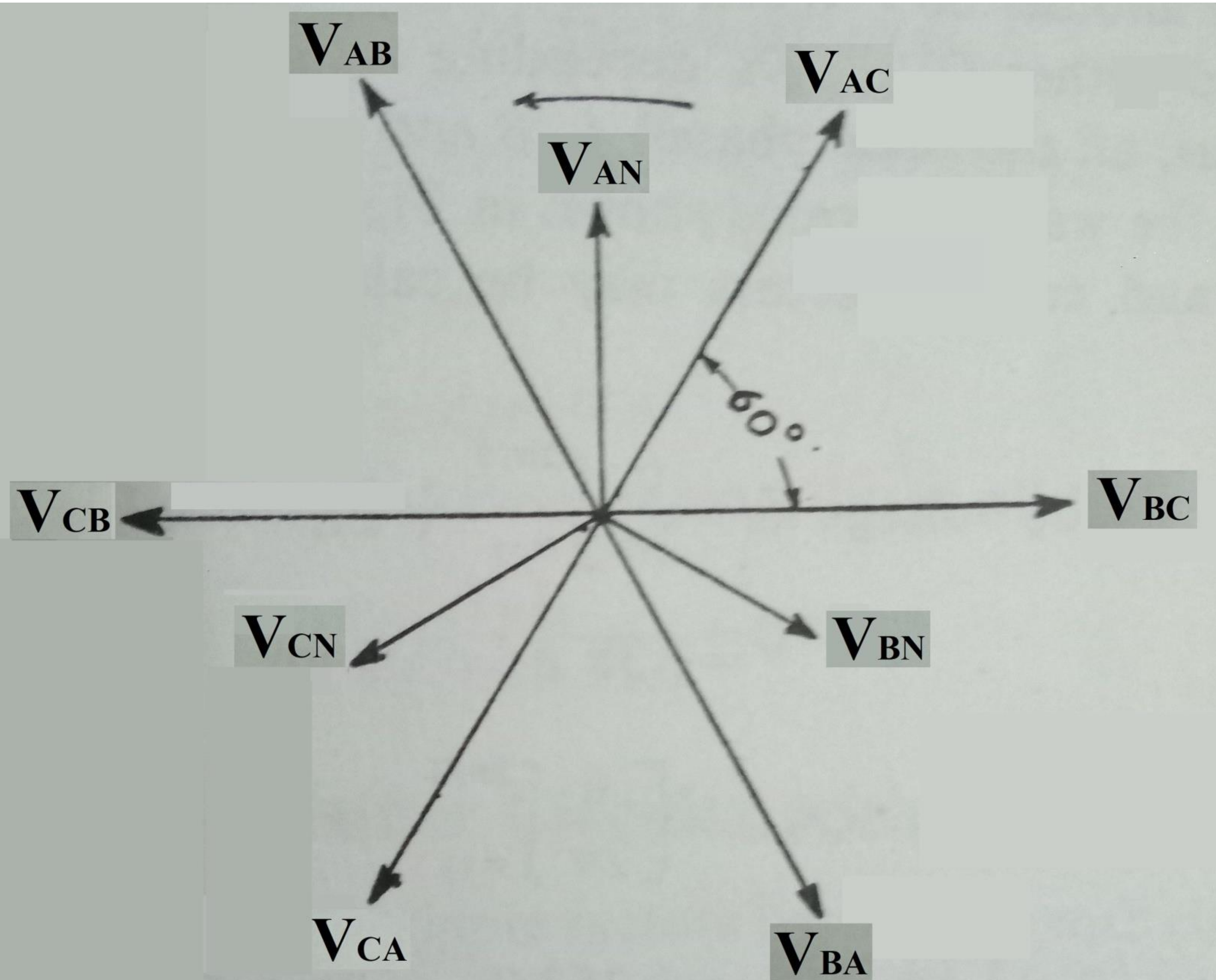


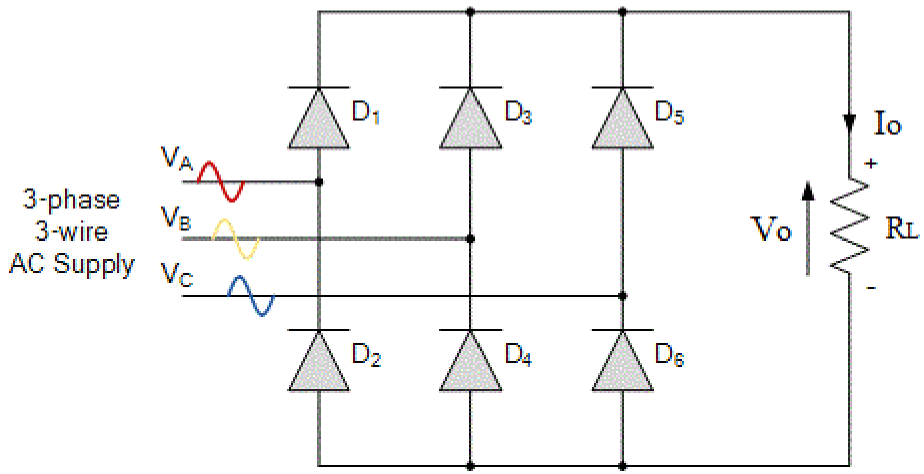
Fig. 2.32 Vector diagram for three-phase bridge rectifier

3 phase diode bridge rectifier with R load-1

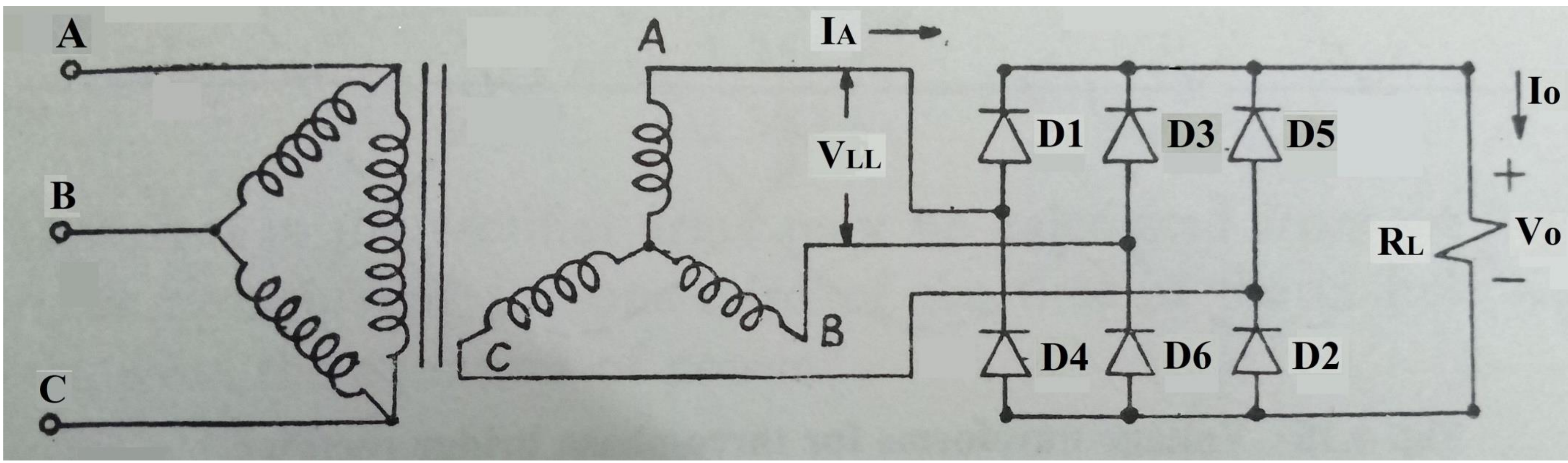
- The 3 phase diode bridge rectifier is very common in high-power applications and is shown in Figs. 2.33 (a) and (b). This is a full-wave rectifier which operates in Quadrant 1. It can work with or without a transformer and gives 6 pulse ripples on the output voltage. The diodes are numbered in order of the conduction sequences and each one conducts for 120º. The conduction sequence of the diodes is 6 pairs in one complete mains cycle viz. 61, 12, 23, 34, 45, and 56. At any given instant, the pair of diodes which is connected to that pair of supply lines having the highest amount of instantaneous line-to-line voltage, will conduct.

- This can be clearly understood from Fig. 2.34 where the diode bridge has been redrawn horizontally. Right hand side diodes D_1, D_3 & D_5 form a +ve OR gate in which the most positive voltage of phases A, B or C appears at the positive load terminal. Similarly, left hand side diodes D_4, D_6 & D_2 form a -ve OR gate in which the most negative voltage of phases A, B or C appears at the negative load terminal. Thus the largest of the 6 line-to-line voltages $v_{AB}(t)$, $v_{AC}(t)$, $v_{BC}(t)$, $v_{BA}(t)$, $v_{CA}(t)$ or $v_{CB}(t)$, at any instant, appears across the load.

3 phase diode bridge rectifier with R load-2



(a)



(b)

FIGURE 2.33

3 phase diode bridge rectifier with R load-3

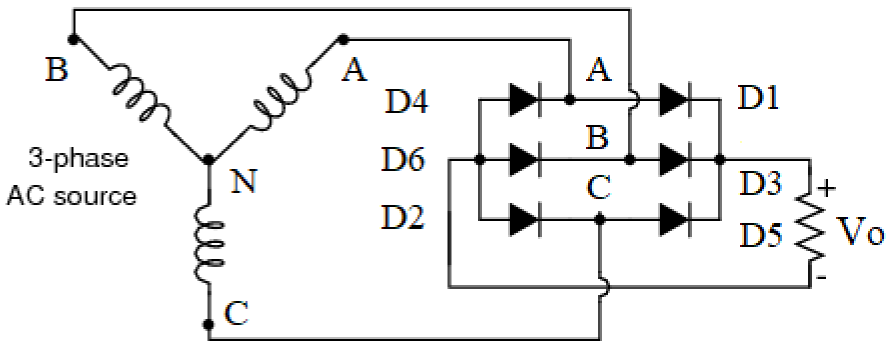


FIGURE 2.34

- The phase and line voltages along with the output (load) voltage, output (load) current, phase A supply current, and diode D_1 current waveforms for a resistive load are shown in Figs. 2.35 & 2.36. It is to noted that the shape of the load current waveform is identical to that of the load voltage since the load is resistive.
- Each diode conducts for 120º in one cycle and each diode current lags the preceding diode current by 60º. Hence the duty cycle of the diode current is $D_{diode} = 120/360 = 1/3$.
- Similarly, each phase supply current is a bidirectional truncated wave with 120º conduction each in the positive and negative half-cycles. Thus the supply current duty cycle is $D_{supply} = 240/360 = 120/180 = 2/3$.

3 phase diode bridge rectifier with R load-4

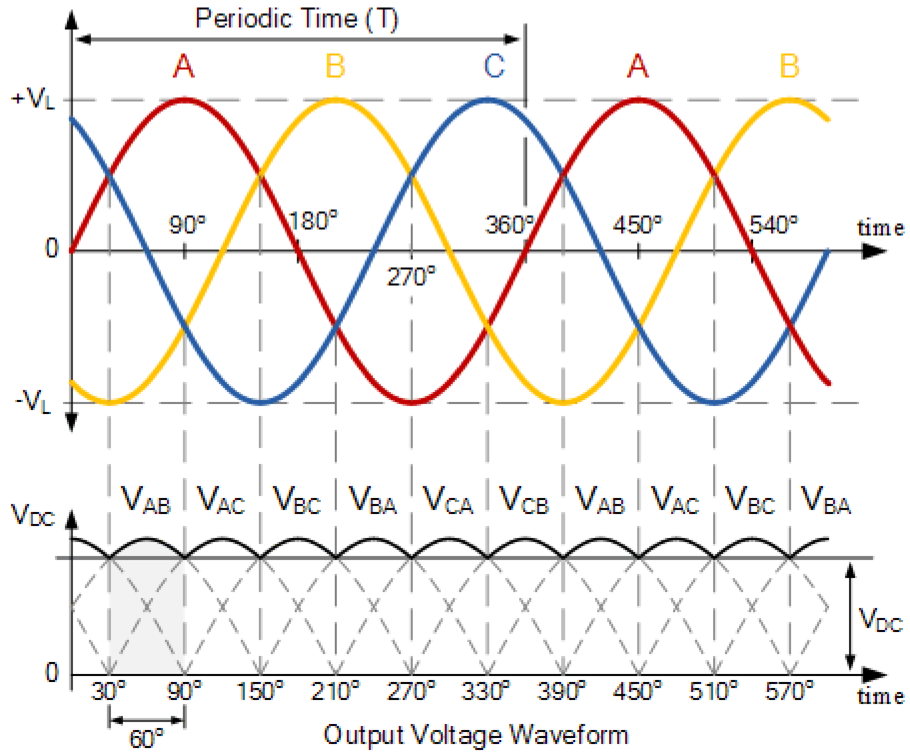


FIGURE 2.35

3 phase diode bridge rectifier with R load-5

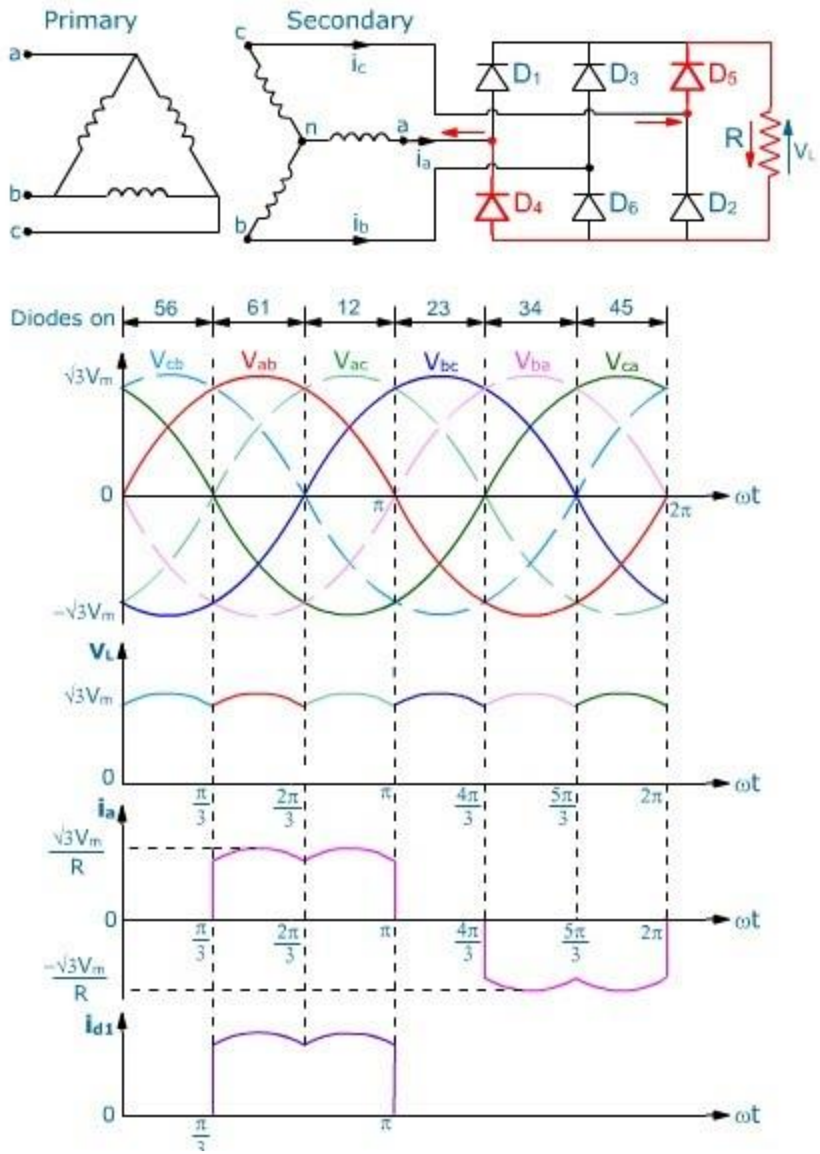


FIGURE 2.36

3 phase diode bridge rectifier with R load-6

The average output voltage is found from

$$V_{dc} = \frac{2}{2\pi/6}\int_0^{\pi/6} \sqrt{3}\, V_m \cos \omega t \, d(\omega t) \tag{2-77}$$

$$= \frac{3\sqrt{3}}{\pi} V_m = 1.6542 V_m \quad = 3\sqrt{6}/\pi \; V_s$$

$$= 2.3391 V_s \tag{2-77a}$$

where V_m is the peak phase voltage.

$$V_{rms} = \left[\frac{2}{2\pi/6}\int_0^{\pi/6} 3V_m^2 \cos^2 \omega t \, d(\omega t)\right]^{1/2} \tag{2-78}$$

$$= \left(\frac{3}{2} + \frac{9\sqrt{3}}{4\pi}\right)^{1/2} V_m = 1.6554 V_m$$

$$= 2.1299 \; V_s \tag{2-78a}$$

3 phase diode bridge rectifier with R load-7

- For a resistive load the average and rms load currents are given by:

  $I_{dc} = V_{dc} /R = 3\sqrt{6}/(\pi R)\ V_s = 2.3391V_s/R$

  $I_{rms} = V_{rms} /R = 2.1299\ V_s/R$

- For a resistive load the average and rms diode currents are given by:

  $I_{Ddc} = I_{dc} /3 = V_{dc} /3R$

  $I_{Drms} = I_{rms} /\sqrt{3} = V_{rms} /(\sqrt{3}\ R)$

- For a resistive load the rms phase supply current is given by:

  $I_{srms} = I_{rms} \sqrt{(2/3)}$

3 phase diode bridge rectifier with level load-1

- The phase and line voltages along with the output (load) voltage waveform for a level (ripple-free, highly inductive) load are the same as for a resistive load. The load current will be constant and hence the diode current waveform will be a rectangular pulse train of duty cycle D_{diode} =120/360 = 1/3. Similarly, the supply current waveform will be a truncated (quasi) square wave of duty cycle D_{supply} = 240/360 = 120/180 = 2/3.

- The expressions for the average and rms output (load) voltages are the same as those for R load.

- The expressions for the average and rms load currents are

  $I_{Ldc} = I_{Lrms} = V_o /R$

- The expressions for the average and rms diode currents are

  $I_{Ddc} = I_{dc} /3 = V_o /3R$

  $I_{Drms} = I_{rms} /\sqrt{3} = I_{dc} /\sqrt{3} = V_o /(\sqrt{3} R)$

- For a resistive load the rms phase supply current is given by:

  $I_{srms} = I_{rms} \sqrt{(2/3)}$