Unit II

Chapter 3

Single Phase AC - DC Converter

Syllabus

Concept of line and forced commutation, Single phase Semi and Full converters using SCR for R and R-L loads and its performance analysis and numerical, Effect of source inductance, Significance of power factor and its improvement using PWM based techniques.

Chapter Contents

3.1 Commutation :

SPPU : May 07, Dec. 10, May 11

University Questions

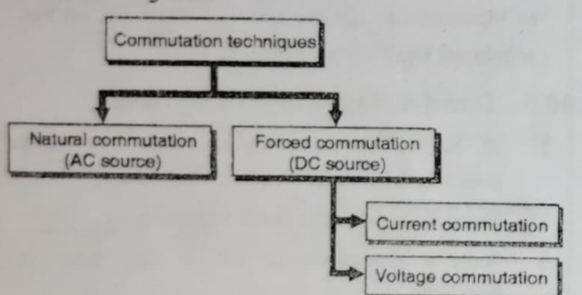
Q. 1 Give types of commutations. **(May 07, 2 Marks)**

Q. 2 What do you mean by commutation of SCR ? **(May 07, Dec. 10, 2 Marks)**

Q. 3 What is commutation ? **(May 11, 2 Marks)**

Definition :

- 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 either natural or forced.
- We can also classify the commutation techniques as voltage commutation and current commutation.
- The classification of commutation techniques is as shown in Fig. 3.1.1.



(I-688) **Fig. 3.1.1 : Classification of commutation techniques**

3.1.1 Commutation Techniques :

- As seen from Fig. 3.1.1 the commutation techniques are broadly categorized into two categories namely natural commutation and forced commutation depending on whether the source voltage is AC or DC.
- The forced commutation circuits are further classified into two categories namely current commutation and voltage commutation.
- These are the two ways of turning off a conducting SCR.

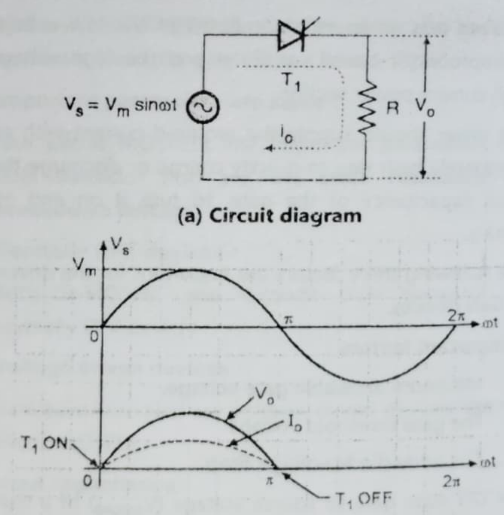
3.1.2 Natural Commutation :

SPPU : May 07

University Questions

Q. 1 Explain natural commutation in details. **(May 07, 2 Marks)**

- 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. 3.1.2(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. 3.1.2(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.



(b) Waveforms

(I-689) **Fig. 3.1.2 : Natural commutation**

- Natural commutation is observed in ac-voltage controllers and phase controlled rectifiers with resistive load.

Advantages of natural commutation :

1. It does not require any external commutation components.
2. It is reliable and simple.

3.1.3 Line Commutation :

SPPU : May 10, May 11

University Questions

Q. 1 Explain the concept of line commutation. **(May 10, 2 Marks)**

Q. 2 Explain the line commutation of SCR.

(May 11, 2 Marks)

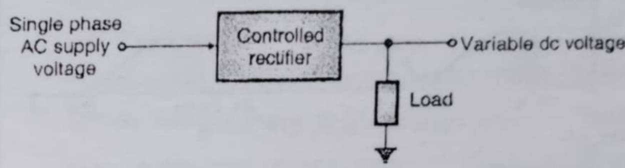
- In an AC circuit, when a conducting SCR is turned off due to application of negative line voltage across it, the commutation is known as the line commutation.
- This is a voltage commutation which is observed in ac-voltage controllers and phase controlled rectifiers with inductive load.
- It also known as the class-F commutation.

3.1.4 Forced Commutation :

- When the SCRs operate on a pure DC input voltage, their forward current cannot be reduced below holding current naturally.
- Therefore the SCRs must be commutated "forcibly" by using additional "commutation circuit."
- This external commutation circuit will turn off the SCRs by means of either current commutation or voltage commutation.
- In the voltage commutation, the conducting SCR is turned off by applying a reverse voltage across it whereas in current commutation, an externally produced reverse current is forced to flow through the conducting SCR to reduce its net forward current below the holding current value.
- Normally the forced commutation is used in the thyristorised inverters or chopper circuits as these circuits operate on DC power supplies.
- Forced commutation techniques are further classified in to two categories as follows :
  1. **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".
  2. **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".

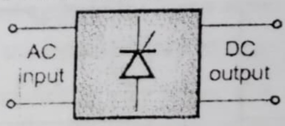
3.2 Phase Controlled Rectifiers (AC to DC Converters) :

- The rectifier circuits using diodes operate on ac supply voltage.
- They convert ac voltage into a fixed dc voltage. Therefore diode rectifiers are known as "uncontrolled rectifiers".
- If we use SCRs in place of diodes then the output dc voltage can be controlled by varying the firing angle or phase angle (α) of the SCR.
- Therefore rectifier circuits using SCRs are known as "**phase controlled rectifiers**". The block diagram of a controlled rectifier is as shown in Fig. 3.2.1(a).



(I-139) **Fig. 3.2.1(a) : Controlled rectifier**

- Also note that these circuits convert the fixed ac voltage at their input into a variable dc voltage at their output. Therefore **phase controlled rectifiers** are also known as **AC to DC** converters.
- The circuit symbol of a controlled rectifier is shown in Fig. 3.2.1(b). A conducting thyristor is turned off due to natural or line commutation.



(I-139) **Fig. 3.2.1(b) : Symbol of controlled rectifier**

- The ac mains voltage itself is used for commutating the thyristors, therefore these converters are known as line commutated converters (LCC).
- These converters are simple and less expensive, and the efficiency of rectification in general is above 95 %.
- Since they convert ac voltage into a variable dc voltage they are known as ac to dc converters, and are used extensively in the industrial applications like dc motor speed control from fractional horsepower to megawatt power level.

3.2.1 Principle of AC-DC Converter :

SPPU : May 10, May 11, Dec. 15, May 16

University Questions

Q. 1 What is the delay angle control of converter ?

(May 10, 2 Marks)

Q. 2 Write a short note on 'Phase controlled rectifiers'.

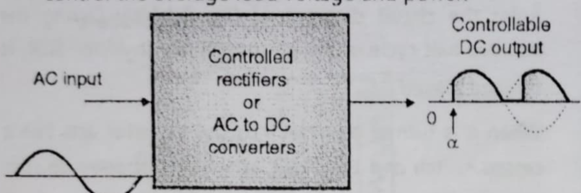
(May 11, 2 Marks)

Q. 3 What are phase controlled converter ? Explain with circuit diagram working of 1 ϕ half controlled converter with suitable load. Draw suitable waveforms and comment on power factor.

(Dec. 15, 6 Marks)

Q. 4 What are phase controlled converters ? Explain with circuit diagram and waveforms working of 1ϕ full controlled converter with suitable load. Comment on rectification, inversion mode and power factor. **(May 16, 10 Marks)**

- The controlled rectifiers are also called as AC to DC converters.
- They use the technique called phase angle control to change the firing angle or delay angle or phase angle to control the average load voltage and power.

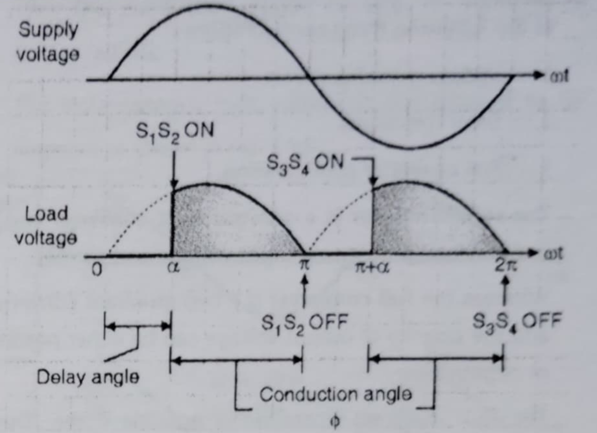


(I-1503) **Fig. 3.2.2 : Phase angle control**

- The phase angle α is controlled in each half cycle of the ac supply.
- At the input of the controlled rectifier an ac voltage is applied whereas at the output we get a variable DC voltage.
- In an AC circuit we can turn on the SCR with the help of a gate triggering circuit at any angle with respect to the applied voltage.
- This angle is called as the **firing angle (α)** and it is measured generally with respect to the zero crossing instant of the AC supply voltage.
- The firing angle can be changed from 0° to 180° (π radians).
- If we vary the firing angle the average load voltage will vary proportionally.
- The **phase angle control method** is a very efficient way of controlling the voltage and power applied to loads such as lamps, heaters, motors etc.
- Those converters that work on the principle of natural communication are called as the **line commutated converters**.

Conduction angle :

Fig. 3.2.3 shows the waveform of supply voltage and load voltage for a line commutated full wave controlled rectifier (AC to DC converter).

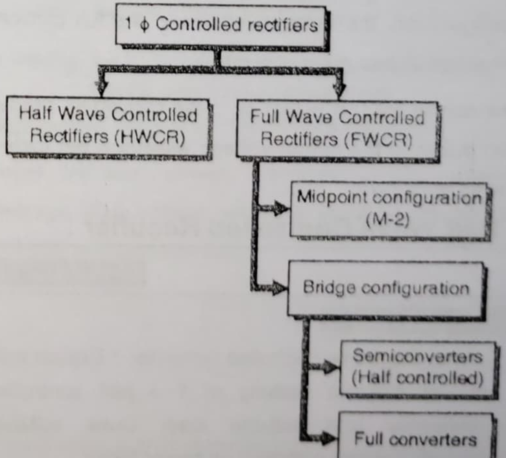


(I-1577) **Fig. 3.2.3 : Concept of firing angle (α) and conduction angle (ϕ)**

- SCRs 1 and 2 conduct simultaneously from instant α and π.
- At π both of them turn off due to natural commutation.
- Then SCRs 3 and 4 conduct from $(\pi + \alpha)$ to 2π. Thus each SCR conducts for a duration of $(\pi - \alpha)$ radians or $(180 - \alpha)$ degrees.
- This angle for which an SCR remains on in one complete cycle of operation is known as its **conduction angle (ϕ)**.
- Note that the conduction angle varies from 0° to 180°.

3.3 Classification of AC to DC Converters :

- The single phase controlled rectifiers can be classified as shown in Fig. 3.3.1.



(I-140) **Fig. 3.3.1 : Classification of controlled rectifiers**

- In half wave controlled rectifiers the load power can be controlled in only one half cycle of the input ac supply whereas full wave controlled converters can control the power in both the half cycles of the input supply.

- The full wave control of power can be obtained by any of the following three configurations :
  1. Midpoint configuration
  2. Semi converters
  3. Full converter configuration.
- The **semiconverter** is a one quadrant converter and it has only one polarity of output voltage and current.
- Whereas the **full converter** is a two quadrant converter and the polarity of output voltage can be either positive or negative.
- The four quadrant operation is possible if the "**Dual converter**" is used which uses two full converters.
- In certain applications, converters are connected in series to operate at higher voltages and to improve the input power factor.
- The analysis of the converter performance can be done with the help of Fourier analysis.
- For resistive loads the load current waveform has the same shape of load voltage waveform and the load current can be discontinuous.
- However in case of RL type of load, the load inductance is assumed to be very large so that the load current is continuous and has negligible ripple.

3.3.1 Two Pulse Converters :

- All the full wave converters including the midpoint configuration, the semiconverter and the full converter are called as two pulse converters.
- The reason for this is that all these converters produce two pulses in the output voltage waveform per cycle of the ac input cycle.

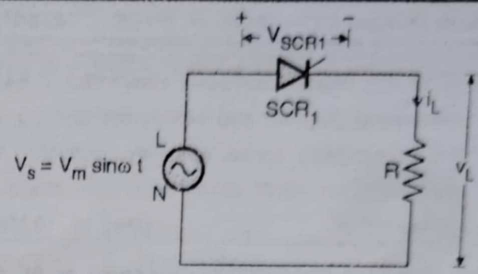
3.4 Half Wave Controlled Rectifier :

SPPU : Dec. 15

University Questions

Q. 1 What are phase controlled converter ? Explain with circuit diagram working of 1 ϕ half controlled converter with suitable load. Draw suitable waveforms and comment on power factor. **(Dec. 15, 6 Marks)**

- To understand the principle of phase controlled rectifier, refer Fig. 3.4.1(a).

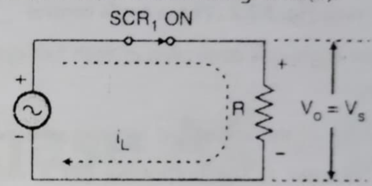


(I-141) **Fig. 3.4.1(a) : Half wave controlled rectifier**

- It is a half wave controlled rectifier (HWCR) with a resistive load.

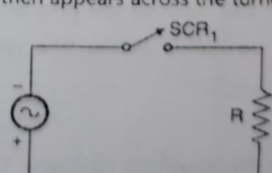
Operation with Resistive Load :

- Refer the circuit diagram of Fig. 3.4.1(a). During the positive half cycle of the ac supply, the thyristor SCR_1 is forward biased.
- When it is turned on at $\omega t = \alpha$ the thyristor acts like a closed switch and the input ac voltage appears as it is across the load, as shown in Fig. 3.4.1(b).



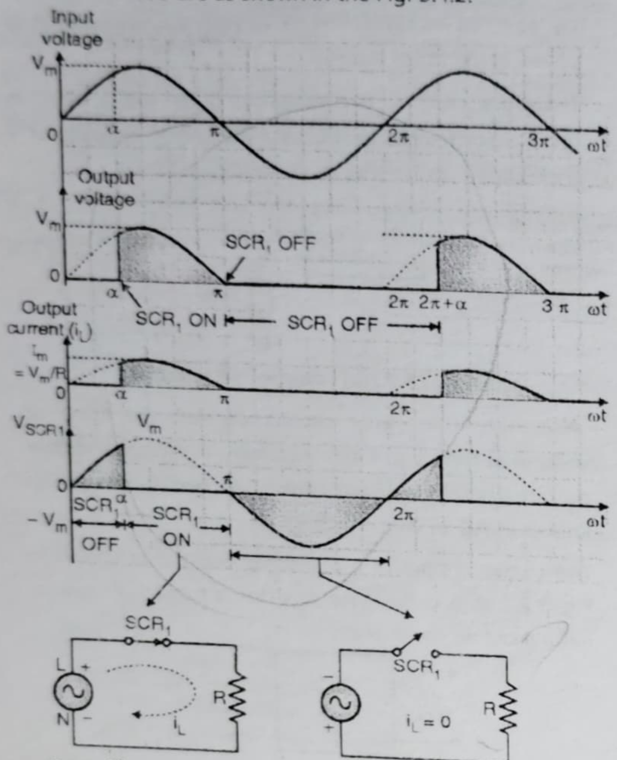
(I-142) **Fig. 3.4.1 (b) : Equivalent circuit for the positive half cycle (α to π)**

- Due to the resistive nature of the load, the load current is in phase with the load voltage and it has the same shape as that of the load voltage waveform.
- The instantaneous value of load current is equal to the ratio of instantaneous supply voltage and load resistance R.
- As the load voltage decreases, the load current also decreases and as this current reduces below the holding current of SCR_1, it is commutated due to **natural commutation** (at $\omega = \pi$).
- In the negative half cycle, the thyristor is reverse biased, and acts like an open switch.
- The load is disconnected from the input and hence the load voltage is zero as shown in Fig. 3.4.1(c). Entire input voltage then appears across the turned off SCR.



(I-142) **Fig. 3.4.1(c) : Equivalent circuit for the negative half cycle (π to 2π)**

- The voltage and current waveforms of a HWCR with resistive load are as shown in the Fig. 3.4.2.



(I-143) Fig. 3.4.2 : Voltage and current waveforms for a HWCR with resistive load

- The voltage across SCR_1 is almost equal to zero when it is in the on state. ($\alpha \le \omega t \le \pi$).

1. **Average output voltage (V_{Ldc}) :**

- From the load voltage waveform in Fig. 3.4.2 the average output voltage V_{Ldc} can be found as follows :

$$V_{Ldc} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin \omega t \, d\omega t \quad ...(3.4.1)$$

$$= \frac{-V_m}{2\pi}[\cos \omega t]_{\alpha}^{\pi}$$

$$V_{Ldc} = \frac{V_m}{2\pi}[1 + \cos \alpha] \quad ...(3.4.2)$$

- Equation (3.4.2) shows that the average load voltage V_{Ldc} can be varied from 0 to V_m/π by varying α between π to 0 radians respectively.

- The average voltage will be maximum when $\alpha = 0$ and it is given by,

$$V_{Ldc\,(max)} = \frac{V_m}{2\pi}[1 + \cos 0] = \frac{V_m}{\pi} \quad ...(3.4.3)$$

2. **Normalized output voltage (V_n) :**

- Normalizing the output voltage with respect to $V_{Ldc\,(max)}$ we get,

Normalized output,

$$V_n = \frac{V_{Ldc}}{V_{Ldc\,(max)}} = \frac{(V_m/2\pi)(1 + \cos \alpha)}{V_m/\pi}$$

$$V_n = 0.5\,(1 + \cos \alpha) \quad ...(3.4.4)$$

3.4.1 Operation of HWCR with (RL) Load :

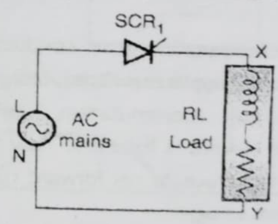
SPPU : Dec. 15

University Questions

Q. 1 What are phase controlled converter ? Explain with circuit diagram working of 1 ϕ half controlled converter with suitable load. Draw suitable waveforms and comment on power factor.

(Dec. 15, 6 Marks)

- The load is assumed to be highly inductive. The operation of the circuit can be described by dividing one cycle of output into two modes of operation.



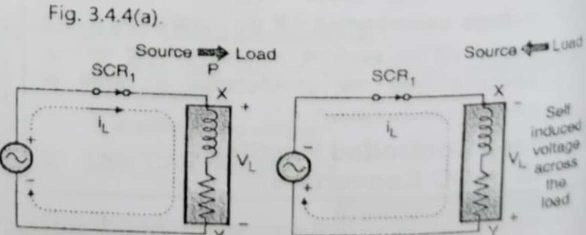
(I-145) Fig. 3.4.3 : Half wave controlled rectifier with RL load

- The equivalent circuits of the two modes are as shown in Figs. 3.4.4(a) and (b) respectively. The load voltage and load current are as shown in Fig. 3.4.5.

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

- In the positive half cycle of input, SCR_1 is turned on at instant α.

- It acts like an ideal closed switch as shown in Fig. 3.4.4(a).



(a) Mode I (α to π) equivalent circuit

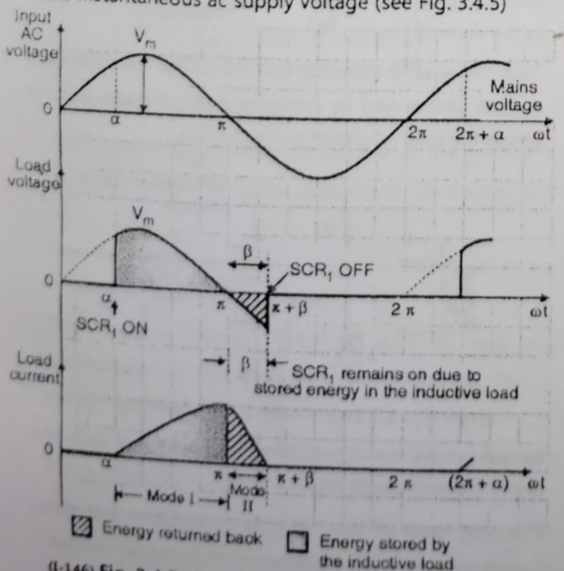
(b) Mode II (π to $\pi + \beta$) equivalent circuit

(I-145) Fig. 3.4.4

- The load voltage is equal to the input voltage with point X positive with respect to point Y. The load current is positive and increases gradually.
- The inductive load stores the energy in this mode of operation.

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

- At $\omega t = \pi$, the input supply voltage passes through a zero and after π it becomes negative.
- Due to reverse input voltage the conducting SCR_1 tries to turn off at $\omega t = \pi$.
- Due to this the load current tries to decrease. According to the principle of induction, the inductive load will try to maintain the current through it unchanged and in the same direction.
- The inductive load will try to oppose the change in current by inducing a self induced voltage across the load with a reverse polarity as shown in Fig. 3.4.4(c).
- This induced voltage makes point X negative with respect to Y.
- This voltage is equal to Ldi/dt, which is higher than the supply voltage.
- Thus the cathode of SCR_1 is at higher negative potential than the negative voltage at its anode.
- This keeps SCR_1 forward biased even in the negative half cycle of the input voltage and it continues to conduct.
- The load current decreases in amplitude but flows in the same direction, but the load voltage is negative equal to the instantaneous ac supply voltage (see Fig. 3.4.5)

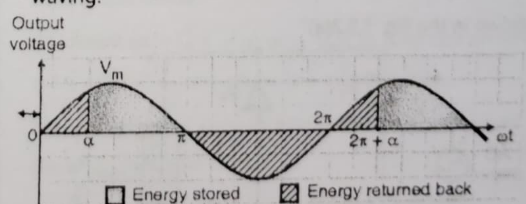


(I-146) **Fig. 3.4.5 : Waveforms for Inductive (RL) load**

- In this way in mode II the load acts as source and returns the stored energy back to the ac supply.
- Thus SCR_1 conducts from π to $\pi + \beta$ due to the stored energy in the inductive load.
- As soon as the energy stored in the load is fed back completely, the load current reaches a zero at $\omega t = (\pi + \beta)$ and SCR_1 is turned off, due to natural commutation.
- The voltage and current waveforms for HWCR operating with RL load are shown in Fig. 3.4.5.
- Refer to the load voltage waveform which has positive as well as negative values.
- However as the area under positive part of this waveform is more than that under the negative part, the average voltage remains positive.

Half waving :

- The duration "β" for which the SCR_1 remains on in the negative half cycle of the input voltage depends on the capacity of the inductive load to store the energy.
- If the inductance is very large, it is possible that the conducting SCR_1 may not turn off at all in the negative half cycle and upto the instant of triggering in the next positive half cycle.
- This will produce a sinusoidal voltage across the load as shown in Fig. 3.4.6. This problem is known as half waving.

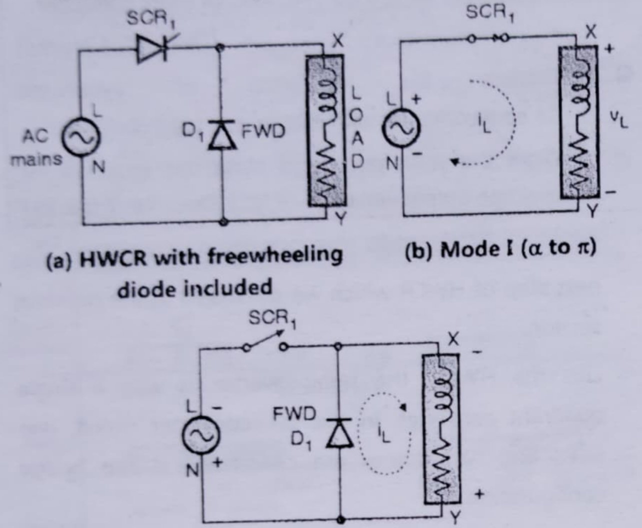


(I-147) **Fig. 3.4.6 : Problem of half waving (SCR_1 does not turn off)**

- The average load voltage will then be equal to zero and there will be no control on the average load voltage.
- To prevent this from happening, a freewheeling diode is connected across the load as shown in Fig. 3.4.8.
- However "Half Waving" is not possible practically, because if we assume the load current to be constant, then the time for which energy is returned back is longer than the time for which it is stored (see Fig. 3.4.6).

3.4.2 Effect of Freewheeling Diode in HWCR :

- The problem of half waving can be overcome by including a freewheeling diode D_1 across the inductive load as shown in Fig. 3.4.7.



(a) HWCR with freewheeling diode included

(b) Mode I (α to π)

(c) Mode II (π to $2\pi + \alpha$) freewheeling

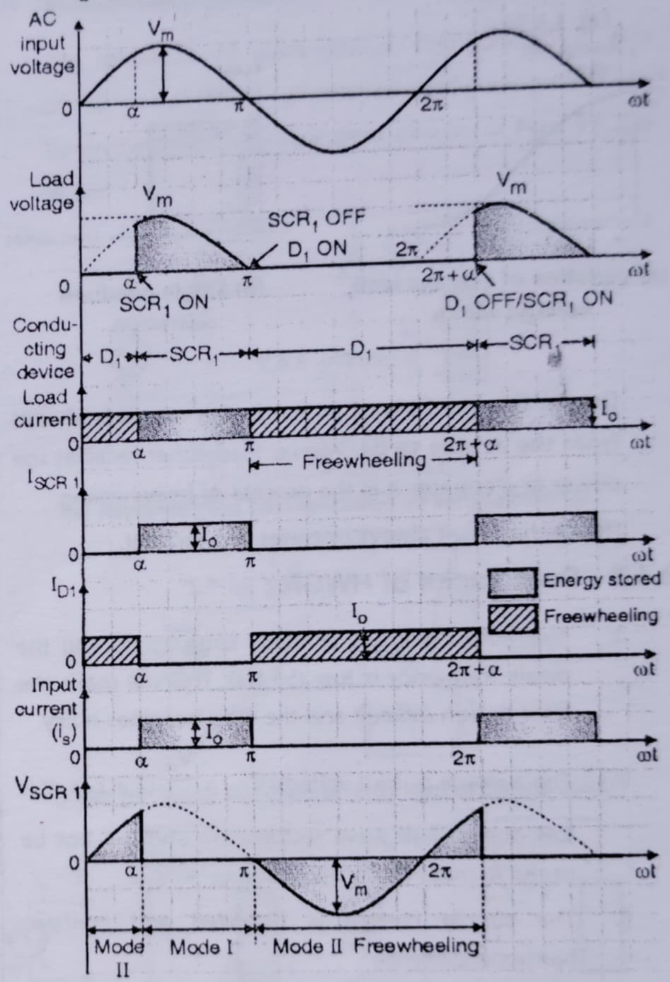
(I-148) **Fig. 3.4.7**

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

- The operation of the circuit again is divided into two modes, in mode I (α to π) the operation of the circuit is same as explained in the section 3.4.1.
- The assumption here is that the load current is continuous and ripple free as shown in Fig. 3.4.7.

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

- At $\omega t = \pi$ the input ac voltage reaches zero and then becomes negative.
- As discussed in the section 3.4.3 there is a self induced negative voltage across the load (Fig. 3.4.7(c)).
- In this circuit, this negative load voltage will forward bias the freewheeling diode D_1. The load current starts flowing from Y which is positive, through D_1 back to X as shown in Fig. 3.4.7(c). This is freewheeling.
- Thus the entire load current is shifted from SCR_1 to D_1 and SCR_1 is turned off at $\omega t = \pi$. The freewheeling takes place due to the stored energy by the inductive load.
- If the freewheeling diode D_1 is ideal then the load voltage is equal to zero during this interval, whereas the load current remains positive.
- In the freewheeling action, the stored energy in the load is dissipated in the winding resistance of inductance and diode D_1 in the form of heat. The supply current is zero during the freewheeling interval ($i_s = 0$).
- Thus the conduction period of SCR_1 is restricted to $(\pi - \alpha)$ radians.
- The instantaneous load voltage is not allowed to be negative as shown in Fig. 3.4.8.



(I-149) **Fig. 3.4.8 : Voltage and current waveforms for HWCR with freewheeling diode**

Average output voltage of HWCR with RL load :

- From the load voltage waveform of Fig. 3.4.8 the average load voltage which is same as the average voltage with resistive load.

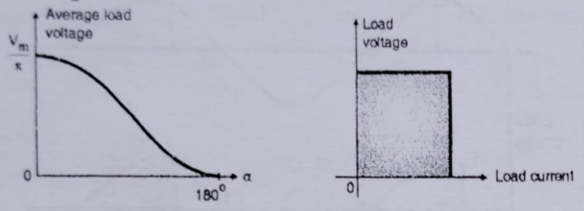
$$V_{Ldc} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin \omega t \, d\omega t$$

$$\therefore \quad V_{Ldc} = \frac{V_m}{2\pi}(1 + \cos \alpha) \qquad ...(3.4.5)$$

- This is same as that obtained with the resistive load.
- The firing angle α can be changed from 0 to 180°. The variation of the average load voltage with α is as shown in Fig. 3.4.9(a). V_{Ldc} varies from V_m/π at $\alpha = 0$ and 0 at $\alpha = 180°$.

Rectifier operation :

- Fig. 3.4.9(a) shows that average load voltage and load current are always positive.
- The circuit therefore operates in the first quadrant of the load voltage load current characteristics as shown in Fig. 3.4.9(b).



(a) Variation of average load voltage with α **(b) Single quadrant operation**

(I-150) **Fig. 3.4.9**

- **Due to this the flow of power in the circuit is always from the ac side to dc side** i.e. load either receives the power or dissipates it in the process of freewheeling.
- Hence the circuit always operates as a rectifier.

3.4.3 Drawbacks of HWCR :

1. The output voltage contains large ripple and the ripple frequency is low (50 Hz). This will make the filter design difficult and the filter becomes bulky.
2. The average output voltage $V_{Ldc} = \frac{V_m}{2\pi}(1 + \cos\alpha)$ is low due to half wave rectification and will not be useful in most of the applications.
3. The supply current is distorted and contains harmonic currents.
4. In addition to that the supply current contains dc component.
5. The input power factor is very poor.

3.5 Half Controlled Converter (Semiconverter) :

SPPU : May 06, May 07, Dec. 10, Dec. 19

University Questions

Q. 1 With the help of a neat circuit diagram, mode equivalent circuits and waveforms of supply voltage, supply current, output voltage, output current, explain the operation of a single-phase half- controlled bridge feeding a level (highly inductive) load. **(May 06, 10 Marks)**

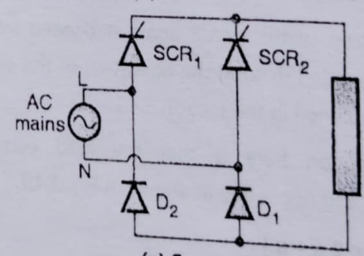
Q. 2 Draw the circuit diagram for RL load of semi-converter. **(May 07, 2 Marks)**

Q. 3 Draw the voltage and current waveform for α = 60°, RL load of semi-converter. **(May 07, 6 Marks)**

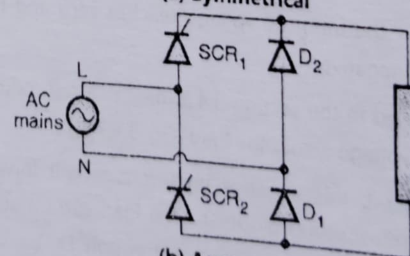
Q. 4 Draw the circuit diagram, voltage and current waveforms for α = 60°, RL load of semi converter. **(Dec. 10, 6 Marks)**

Q. 5 Explain the operation of symmetric 1ϕ semiconverter with continuous load current. Draw the waveforms and state the equation for average output voltage. **(Dec. 19, 7 Marks)**

- The semiconverter or half controlled converter is the next step of HWCR which we discussed in the previous section.
- Like the HWCR, the semiconverter is also a single quadrant converter. In the semiconverter circuit, two SCRs and two diodes are connected in the bridge configuration.
- It is a **full wave converter.** The circuit diagrams for the single phase semiconverter are as shown in Figs. 3.5.1(a) and (b).



(a) Symmetrical



(b) Asymmetrical

(I-152) **Fig. 3.5.1 : Semiconverter configurations**

- As shown in these figures there are two configurations of semiconverter namely asymmetrical and symmetrical.
- The load voltage, load current and even supply current waveforms are identical for both these configurations.
- However the SCRs connected in the symmetrical configuration conduct for a longer duration as compared to the asymmetrical configuration.
- The semiconverter is known for its inherent freewheeling action when operated with inductive loads.

- The freewheeling takes place through a pair of SCR and diode in case of the symmetrical configuration (Fig. 3.5.1(a)) whereas it takes place through diodes D_1 and D_2 for the asymmetrical configuration (Fig. 3.5.1(b)).
- Semiconverters are used for the DC motor control applications.

3.5.1 Operation with Highly Inductive Load :

SPPU : May 06, May 07, Dec. 19

University Questions

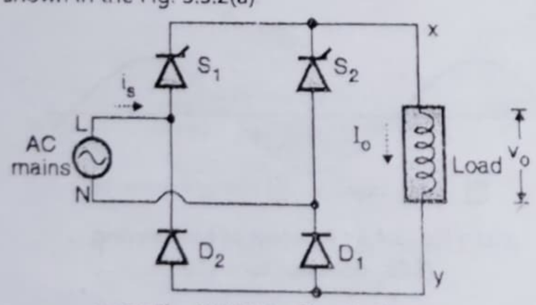
Q. 1 With the help of a neat circuit diagram, mode equivalent circuits and waveforms of supply voltage, supply current, output voltage, output current, explain the operation of a single-phase half- controlled bridge feeding a level (highly inductive) load. **(May 06, 10 Marks)**

Q. 2 Draw the circuit diagram for RL load of semi-converter. **(May 07, 2 Marks)**

Q. 3 Explain the operation of symmetric 1ϕ semiconverter with continuous load current.

Draw the waveforms and state the equation for average output voltage. **(Dec. 19, 7 Marks)**

- In order to discuss the operation with inductive load, the symmetrical configuration of Fig. 3.5.2(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. 3.5.2(a)

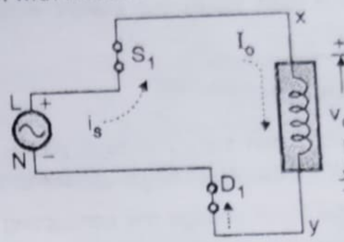


(I-158) **Fig. 3.5.2(a) : Circuit diagram (symmetrical configuration)**

- The load current $i_o = I_o$, is assumed to be continuous and ripple free.
- Different voltage and current waveforms are as shown in Fig. 3.5.2(g).
- The operation can be divided into four modes of operation.

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. 3.5.2(b). This is identical to the operation with resistive load.

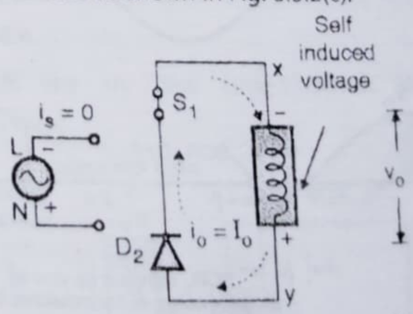


(I-159) **Fig. 3.5.2(b) : Load stores energy, Mode I (α to π)**

- 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.
- The current through SCR_1, $I_{SCR1} = I_o$ and $I_{D1} = I_o$ as shown in Fig. 3.5.2(g).

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 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. 3.5.2(c).



(I-160) **Fig. 3.5.2(c) : Mode II freewheeling**

- 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.

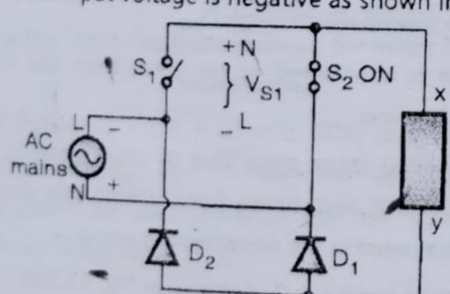
Freewheeling :

- 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. 3.5.2(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.
- 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. 3.5.2(c). This mode of operation continues upto $\omega t = (\pi + \alpha)$ where SCR S_2 is turned on to turn off S_1.

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

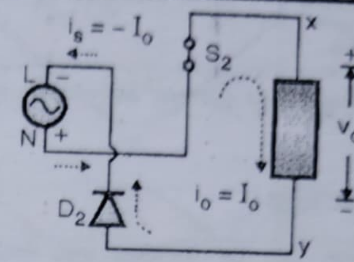
Line commutation of SCR S_1 :

- Mode III begins at instant $\omega t = (\pi + \alpha)$. At this instant the ac input voltage is negative as shown in Fig. 3.5.2(d).



(I-161) **Fig. 3.5.2(d) : Line commutation of S_1 at $(\pi + \alpha)$**

- 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. 3.5.2(e).
- The load voltage becomes positive and equal to instantaneous supply voltage. Supply current is negative, $i_s = -I_o$.

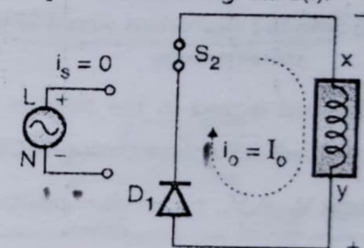


(I-161) **Fig. 3.5.2(e) : Mode III load stores energy**

- As the load voltage and current both are positive the load will store the energy.

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.
- This time it is through the already conducting SCR S_2 and diode D_1 as shown in Fig. 3.5.2(f).



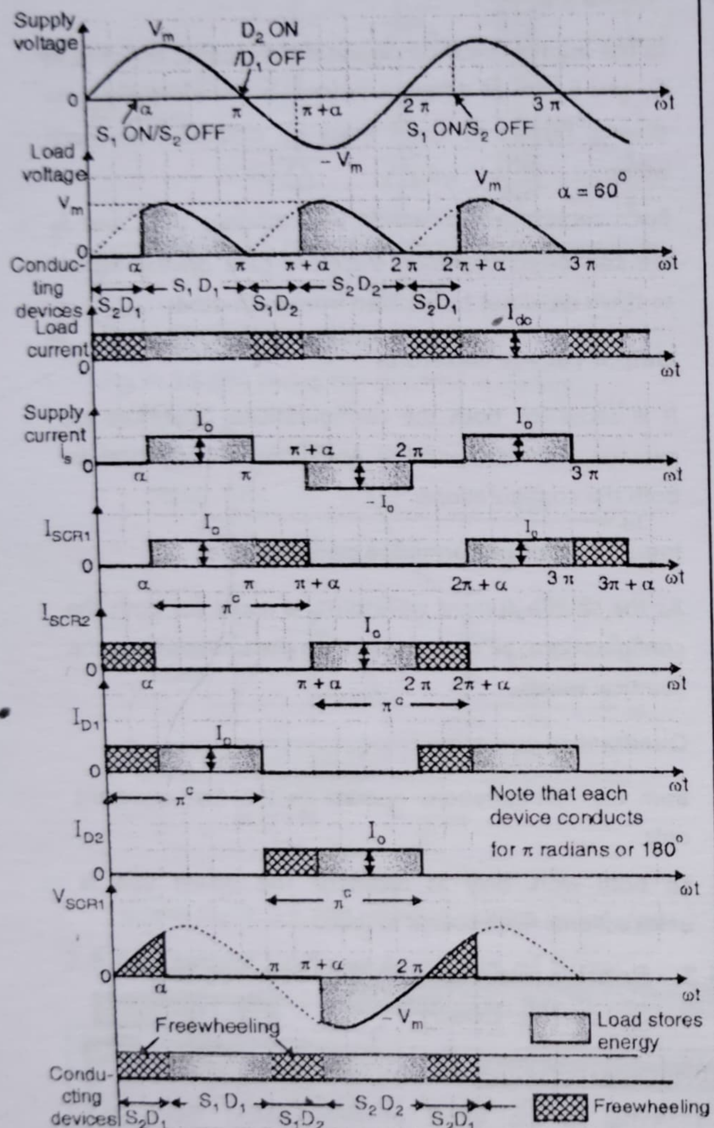
(I-162) **Fig. 3.5.2(f) : Mode IV freewheeling**

- 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 S_1 is turned on which turns off SCR S_2 due to the line commutation.
- The operation of semiconverter can be summarized as shown in the Table 3.5.1(a).

Table 3.5.1(a)

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

Waveforms :



(I-163(a)) **Fig. 3.5.2(g) : Voltage and current waveforms for single phase semiconverter symmetrical configuration with RL load**

Ex. 3.5.1 : Draw the circuit diagram of single phase semiconverter with RL load. Also draw the voltage and current waveforms for $\alpha = 60°$ Explain its operation.

May 07, Dec.10, 6 Marks

Soln. :

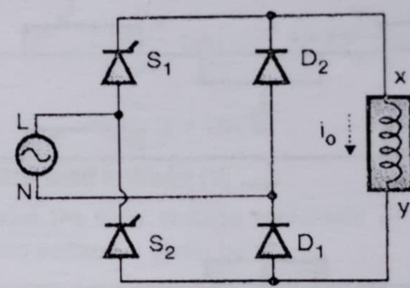
- Refer section 3.5.1 for circuit diagram and operation.
- Refer Fig. 3.5.2(g) for waveforms.

3.5.2 Asymmetrical Configuration Operation with RL Load :

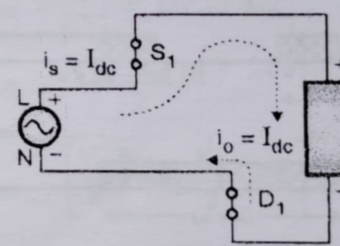
Comparison between configurations of semiconverter :

1. **Freewheeling action :**

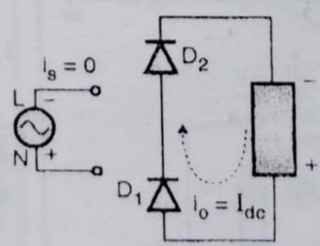
- The operation of asymmetrical configuration is very similar to that of the symmetrical configuration and can be understood from equivalent circuits of Figs. 3.5.3(a) to (e).



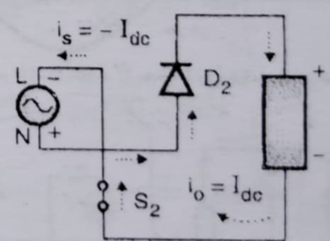
(a) Asymmetrical configuration of semiconverter



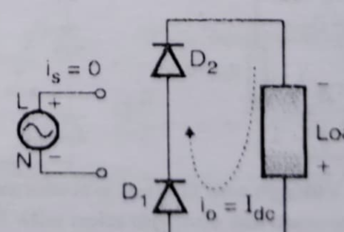
(I-164) **(b) Mode I (α to π) energy stored by the load**



(c) Mode II (π to π + α) freewheeling



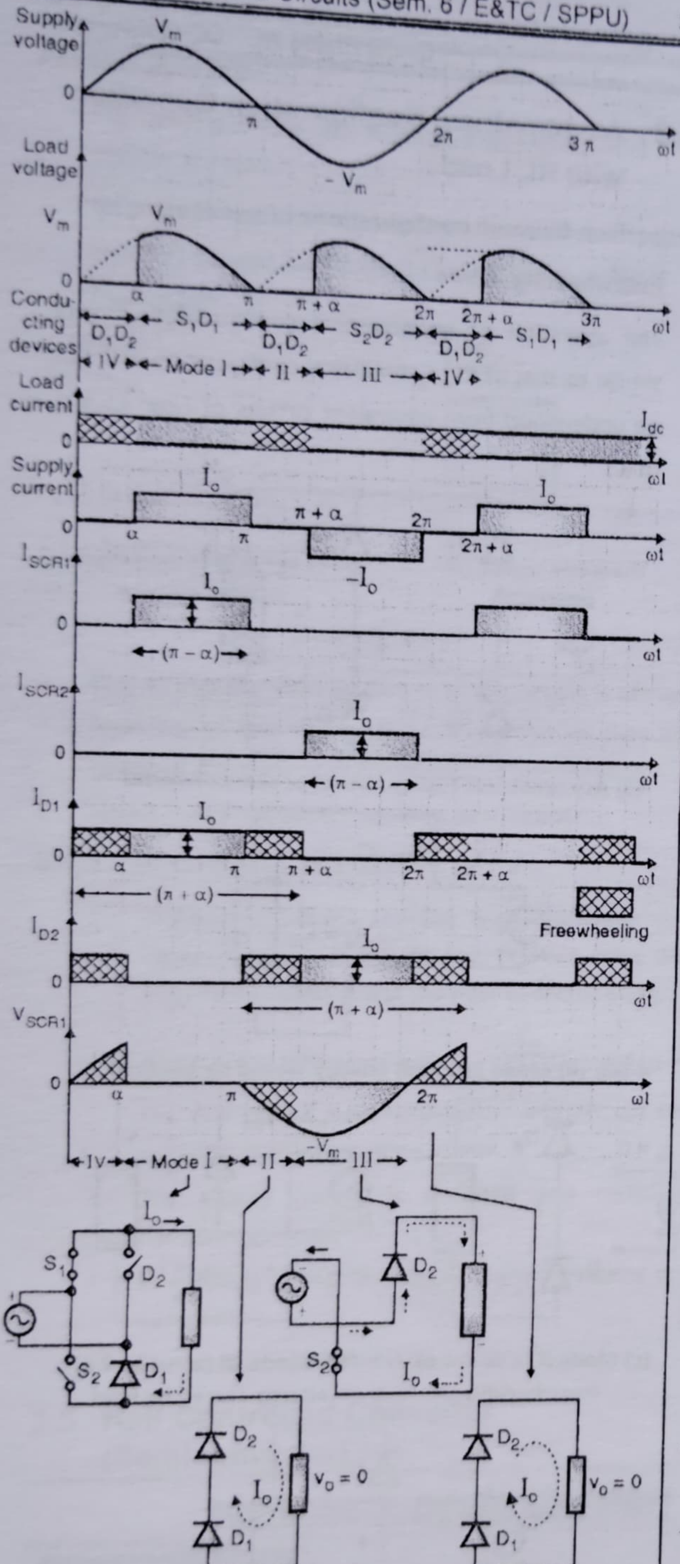
(d) Mode III (π + α to 2 π) energy stored by load



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

(I-165) **Fig. 3.5.3**

- 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).



(I-166) **Fig. 3.5.3(f) : Voltage and current waveforms for the semiconverter asymmetrical configuration with RL load**

2. **Conduction angle for the devices :**

- The conduction angle of SCRs S_1 and S_2 is $(\pi - \alpha)$ radians. (Fig. 3.5.3(f)).
- 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.

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 :**

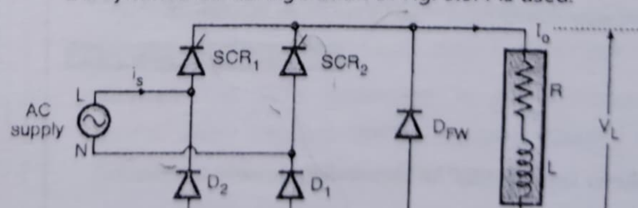
- Both the configurations operate in the first quadrant only.
- So both work only as rectifiers. The power flow is unidirectional from source to load.

3.5.3 Semiconverter with a Freewheeling Diode (RL Load) : SPPU : Dec. 09

University Questions

Q. 1 What is the effect of freewheeling diode in semiconverter ? **(Dec. 09, 4 Marks)**

- Sometimes a freewheeling diode is connected across the load.
- We will discuss the operation of such a semiconverter in this section.
- In order to discuss the operation with inductive load, the symmetrical configuration of Fig. 3.5.4 is used.



(I-153) **Fig. 3.5.4 : Semiconverter with inductive load**

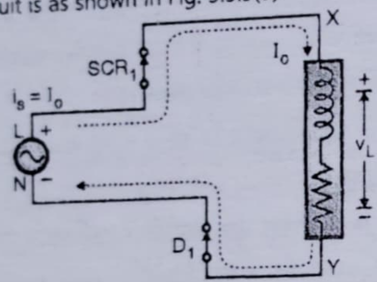
- The load current $i_L = I_o$ is assumed to be continuous and ripple free.
- Different voltage and current waveforms are as shown in Fig. 3.5.8.

Operation with RL load :

- The operation can be divided into four modes of operation.

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. 3.5.5(a).

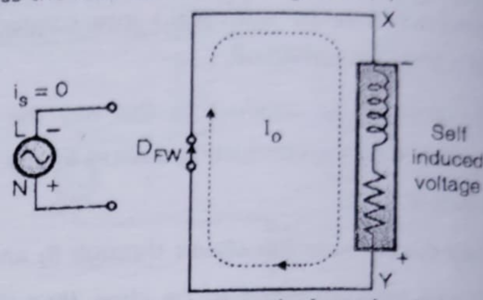


(I-154) **Fig. 3.5.5(a) : Mode I equivalent circuit (α to π) load stores energy**

- 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. 3.5.8.

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_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. 3.5.5(b).



(I-154) **Fig. 3.5.5(b) : Mode II equivalent circuit (π to $\pi + \alpha$) freewheeling**

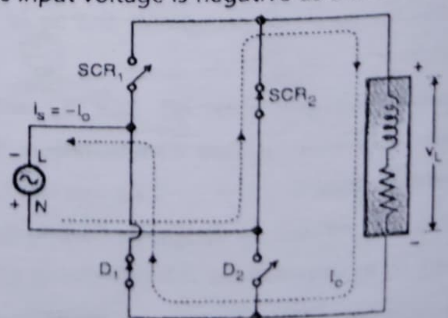
- As seen from this figure, the load voltage is negative (point y positive with respect to x).
- The magnitude of this self induced negative voltage is L di/dt, where L is load inductance and i is load current.

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. 3.5.8). 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. 3.5.5(b).
- This mode of operation continues up to $\omega t = (\pi + \alpha)$ where SCR_2 is turned on.

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

- Mode III begins at instant $\omega t = (\pi + \alpha)$. At this instant the ac input voltage is negative as shown in Fig. 3.5.6.

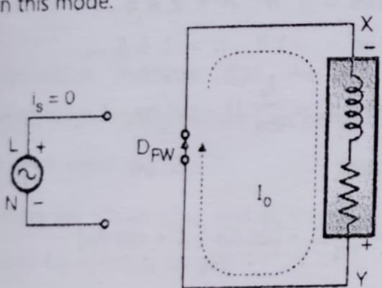


(I-155) **Fig. 3.5.6 : Equivalent circuit for mode III ($\pi + \alpha$) to 2π load stores energy**

- 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. 3.5.6.
- 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.

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 $\pi + \alpha$) here also the freewheeling starts through D_{FW}.
- The load voltage is zero and the supply current also is zero in this mode.



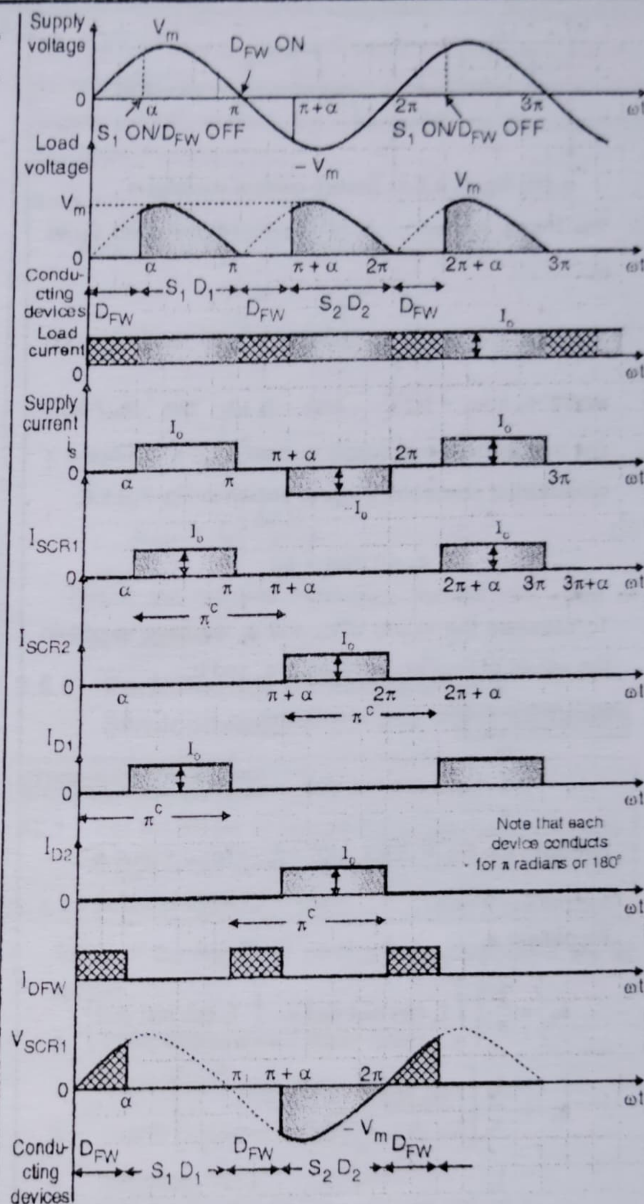
(I-156) **Fig. 3.5.7 : Equivalent circuit for mode IV (0 to α) freewheeling**

- 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 summarized as shown in the Table 3.5.2.

Table 3.5.2

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	**Free-wheeling**	Source to load	**Free-wheeling**

- The instantaneous load voltage v_L, instantaneous load current i_L and the instantaneous supply current are as shown in the Fig. 3.5.8.



(I-157(a)) **Fig. 3.5.8 : Voltage and current waveforms for single phase semiconverter with freewheeling diode**

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.

Ex. 3.5.2 : Draw neat circuit diagram of a 1 phase semi controlled converter feeding R-L load at $\alpha = 90°$. Draw output voltage waveform showing devices conducting during one cycle of input ac voltage.

Soln. :

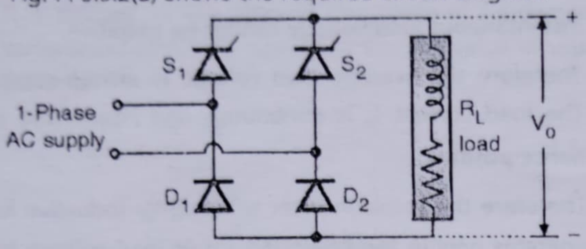
Given : Single phase semiconverter, RL load, $\alpha = 90°$.

To do : 1. Draw circuit diagram

2. Output voltage waveform

1. **Draw circuit diagram :**

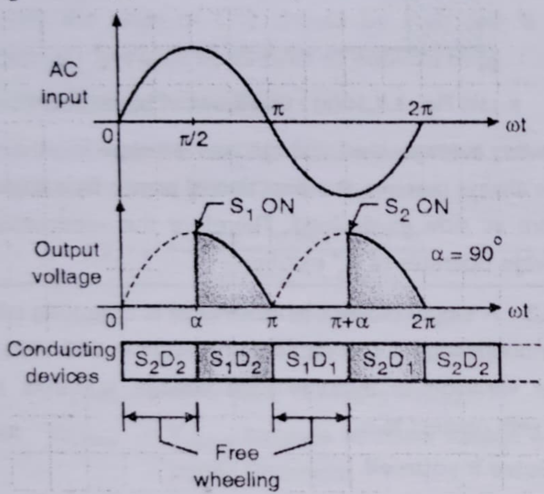
– Fig. P. 3.5.2(a) shows the required circuit diagram.



(I-2069)Fig. P. 3.5.2(a) : A single phase semiconverter with RL load

2. **Draw the output voltage waveform :**

– Fig. P. 3.5.2(b) shows the required waveform.



(I-2070) Fig. P. 3.5.2(b) : Output voltage waveforms

3.5.4 Output Voltage Analysis of Semi converter : SPPU : May 06, May 08, May 10

University Questions

Q. 1 Derive an expression for the rms value of the supply current for the single phase half-controlled bridge. **(May 06, 3 Marks)**

Q. 2 For the single phase asymmetrical half controlled bridge circuit derive expressions for :

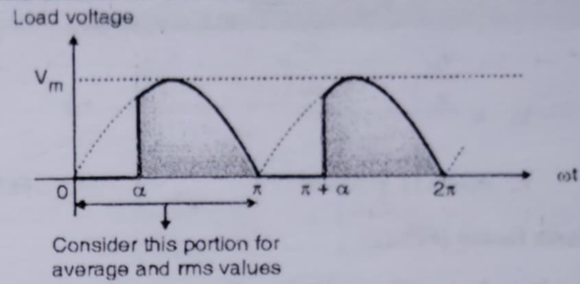
1. Average output voltage 2. rms output voltage **(May 08, 4 Marks)**

Q. 3 Derive the expression for the average output voltage of single phase semiconverter **(May 10, 2 Marks)**

– This analysis is applicable to all the configurations of the semiconverters.

1. **The average load voltages(V_{Ldc}) :**

– Refer to the load voltage waveform of Fig. 3.5.9 the average load voltage is given by,



(I-167) Fig. 3.5.9 : Load voltage of a semiconverter

$$V_{Ldc} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin \omega t \, d\omega t$$

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

$$\therefore \quad V_{Ldc} = \frac{V_m}{\pi}(1 + \cos \alpha) \quad \text{...(3.5.1)}$$

2. **RMS load voltage ($V_{L\,rms}$) :**

– From the load voltage waveform of Fig. 3.5.9 the rms load voltage is given by,

$$V_{L\,rms} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi} V_m^2 \sin^2 \omega t \, d\omega t\right]^{1/2} \quad \text{...(3.5.2)}$$

$$\text{But } \sin^2 \omega t = \frac{1 - \cos 2\omega t}{2}$$

$$\therefore \quad V_{L\,rms} = \left[\frac{V_m^2}{\pi}\int_{\alpha}^{\pi}\frac{(1 - \cos 2\omega t)}{2}\right]^{1/2}$$

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

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

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

$$\therefore \quad V_{L\,rms} = \frac{V_m}{\sqrt{2}}\left\{\frac{1}{\pi}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]\right\}^{1/2} \quad \text{...(3.5.3)}$$

$$\text{But } \frac{V_m}{\sqrt{2}} = V_{s\,rms} = \text{rms supply voltage}$$

$$\therefore \quad V_{L\,rms} = V_{s\,rms}\left\{\frac{1}{\pi}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]\right\}^{1/2} \quad \text{...(3.5.4)}$$

3. **Normalized average output voltage (V_n) :**

– It is defined as,

$$V_n = \frac{V_{Ldc}}{V_{Ldc\,max}}$$

– Substituting $\alpha = 0$ in Equation (3.5.1) we get the maximum value of average voltage.

$$\therefore \quad V_{Ldc} = \frac{V_m}{\pi}(1 + \cos 0) = \frac{2\,V_m}{\pi}$$

- Therefore the normalized voltage is given by,

$$V_n = \frac{\frac{V_m}{\pi}(1+\cos\alpha)}{2V_m/\pi}$$

$$\therefore \quad V_n = 0.5\,(1+\cos\alpha) \qquad ...(3.5.5)$$

4. Form factor (FF) :

- The form factor (FF) for the load voltage is,

$$FF = \frac{V_{Lrms}}{V_{Ldc}} \qquad ...(3.5.6)$$

- Substituting Equations (3.5.1) and (3.5.3) into Equation (3.5.6) we get,

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

$$\therefore \quad FF = \frac{\left[\frac{1}{2\pi}\left(\pi-\alpha+\frac{\sin 2\alpha}{2}\right)\right]^{1/2}}{\left[\frac{1+\cos\alpha}{\pi}\right]} \qquad ...(3.5.7)$$

5. Ripple factor (RF) :

- The voltage ripple factor is,

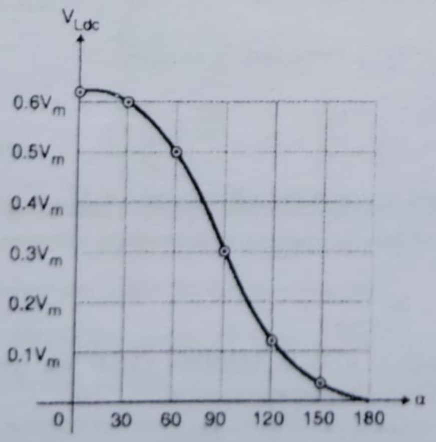
$$RF = (FF^2-1)^{1/2} \qquad ...(3.5.8)$$

Variation of average load voltage with α :

- Table 3.5.3 lists the values of average load voltage for different values of α and Fig. 3.5.10 shows the variation of V_{Ldc} with α.

Table 3.5.3

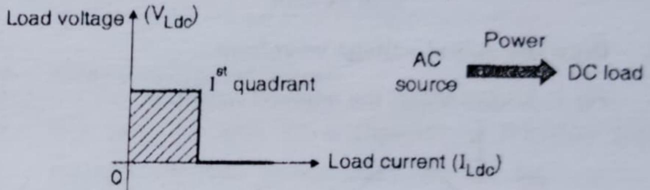
α	0°	30°	60°	90°	120°	150°	180°
V_{Ldc}	0.63 V_m	0.6 V_m	0.48 V_m	0.32 V_m	0.16 V_m	0.04 V_m	0



(I-168) **Fig. 3.5.10 : Variation of V_{Ldc} with α**

Single quadrant operation :

- Due to the inherent freewheeling action, the instantaneous load voltage cannot 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, as shown in Fig. 3.5.10(a).



(I-169) **Fig. 3.5.10(a) : Quadrant of operation**

- As the average load voltage and average load current are always positive, the direction of power flow is always from ac side to dc load. Therefore the semiconverter always operates as a " rectifier ".

Ex. 3.5.3 : A single phase semiconverter is operating with a heavy inductive load. The ac supply voltage is 230 V/50 Hz. Plot the variation of average load voltage and rms load voltage with respect to α.

Ans. : Solve it yourself.

3.5.5 Analysis on the Input Side of Semiconverter :

- This analysis is applicable to all the configurations of the semiconverters.
- In order to analyze the semiconverter on the input side (ac side), it is necessary to express the supply current using Fourier series.
- Following examples illustrate the representation of source current using Fourier series.

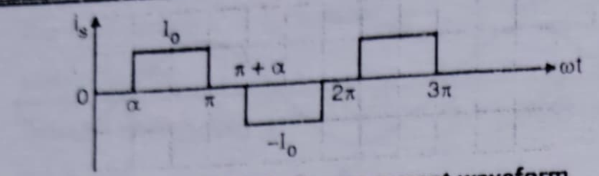
Ex. 3.5.4 : For a single phase semiconverter operating with an inductive load, express the source current in the form of Fourier series. **Dec. 07, May 08, 8 Marks**

OR

Derive an expression for the phase angle of the n^{th} harmonic of the supply current for the single phase half-controlled bridge. **May 06, 3 Marks**

Soln. :

- The source current waveform which is to be expressed in the form of Fourier series is as shown in Fig. P. 3.5.4.



(I-171) **Fig. P. 3.5.4 : Source current waveform**

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

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

where $c_n = (a_n + b_n)^{1/2}$ and $\phi_n = \tan^{-1}(a_n / b_n)$

2. The average value of supply current is $I_{av} = 0$. Since it is symmetrical about the x axis as shown in Fig. P. 3.5.4.

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

3. 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

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

But from the Fig. P. 3.5.2 $i_s(t) = I_o$ For $\alpha \le \omega t \le \pi$

and $= -I_o$ For $\pi + \alpha \le \omega t \le 2\pi$

4. **To obtain a_n :**

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

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

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

$$\because \sin n\pi = \sin 2\pi n = 0$$

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

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

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

$$\because \sin n\pi \cos n\alpha = 0$$

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

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

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

And $a_n = 0$

for $n = 2, 4, 6...$ ...(3)

5. **To obtain b_n :**

$$b_n = \frac{1}{\pi}\int_{\alpha}^{2\pi} i_s(t)\sin n\omega t \, d\omega t \quad ...(4)$$

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

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

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

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

$$\because \sin n\pi \sin n\alpha = 0$$

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

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

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

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

and for n odd,

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

$$= \frac{2 I_o}{n\pi}[1 + \cos n\alpha]$$

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

and $b_n = 0$ for $n = 2, 4, 6...$ ...(5)

6. **To obtain c_n :**

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

$$c_n = \left[a_n^2 + b_n^2\right]^{1/2}$$

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

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

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

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

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

$$\therefore \quad c_n = \left[\frac{16 I_o^2}{n^2 \pi^2}\cos^2 \frac{n\alpha}{2}\right]^{1/2} = \frac{4 I_o}{n\pi}\cos \frac{n\alpha}{2} \quad ...(6)$$

7. **To obtain ϕ_n :**

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

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

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

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

$$= -\tan^{-1}[\tan n\alpha/2]$$

$$\therefore \phi_n = \frac{-n\alpha}{2} \quad ...(7)$$

- This expression indicates that the n^{th} harmonic component of the supply current lags behind the supply voltage by an angle ($n\alpha$ /2).
- Substituting the values of c_n and ϕ_n from Equations (6) and (7) into Equation (1) we get,

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

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

Ex. 3.5.5 : Obtain the expression for the rms value of fundamental component of supply current $I_{s1\ rms}$.

Soln. :

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

$$I_{s1\ rms} = \frac{c_1}{\sqrt{2}} \quad ...(1)$$

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

$$c_n = \frac{4 I_o}{\pi} \cos\frac{\alpha}{2}$$

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

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

- This is the required expression.

Ex. 3.5.6 : For a single phase semiconverter operating with an inductive load, obtain the expression for the rms value of supply current. Assume the load current to be continuous and ripple free equal to I_o.

Soln. :

- Referring to Fig. P. 3.5.2 we can write that,

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

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

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

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

3.5.6 Performance Parameters for a Semiconverter : **SPPU : May 08**

University Questions

Q. 1 For the single phase asymmetrical half controlled bridge circuit derive expressions for supply current distortion factor. **(May 08, 2 Marks)**

- 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), $\phi_1 = -\alpha/2$

$$\therefore \text{DSF} = \cos(-\alpha/2)$$

$$\text{DSF} = \cos(\alpha/2) \quad ...(3.5.9)$$

- 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.

$$\therefore \quad CDF = \frac{I_{s1\,rms}}{I_{s\,rms}} \qquad ...(3.5.10)$$

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

$$\therefore \quad CDF = \frac{2\sqrt{2}\cos(\alpha/2)}{[\pi(\pi-\alpha)]^{1/2}} \qquad ...(3.5.11)$$

- 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.

$$\therefore \quad P.F. = \frac{V_{s1\,(rms)} \times I_{s1\,(rms)} \times \cos\phi_1}{V_{s\,(rms)} \times I_{s\,(rms)}} \qquad ...(3.5.12)$$

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.

$$\therefore \quad PF = \frac{I_{s1\,(rms)}}{I_{s\,(rms)}} \cdot \cos\phi_1 \qquad ...(3.5.13)$$

- The ratio of currents in Equation (3.5.13) is CDF and $\cos\phi$ is FPF.

$$\therefore \quad PF = CDF \times FPF \qquad ...(3.5.14)$$

- Substituting the values of CDF and FPF from Equations (3.5.11) and (3.5.9) respectively, we get,

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

$$= \frac{2\sqrt{2}\cos^2(\alpha/2)}{[\pi(\pi-\alpha)]^{1/2}} \qquad ...(3.5.15)$$

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

$$\therefore \quad PF = \frac{\sqrt{2}\,(1+\cos\alpha)}{[\pi(\pi-\alpha)]^{1/2}} \qquad ...(3.5.16)$$

- 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.

$$\therefore \quad HF = \frac{\left[I_{s\,rms}^2 - I_{1\,rms}^2\right]^{1/2}}{I_{1\,rms}} \qquad ...(3.5.17)$$

$$= \left[\frac{I_{s\,rms}^2}{I_{1\,rms}^2} - 1\right]^{1/2} = \left[\frac{1}{CDF^2} - 1\right]^{1/2} \qquad ...(3.5.18)$$

- Substituting the value of CDF from Equation (3.5.11) we get,

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

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

$$\therefore \quad HF = \left[\frac{\pi(\pi-\alpha)}{4(1+\cos\alpha)} - 1\right]^{1/2} \qquad ...(3.5.19)$$

- 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.

5. **Active Power in Semiconverter :**

- As per definition of active power

$$P_A = V_{s\,rms}\, I_{s1\,rms} \cos\phi_1 \qquad ...(3.5.20)$$

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

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

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

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

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

$$\therefore \quad P_A = \frac{2\,V_m\,I_o}{\pi}\cos^2(\alpha/2) \qquad ...(3.5.21)$$

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

$$\therefore \quad P_A = \frac{V_m\,I_o}{\pi}(1+\cos\alpha) \qquad ...(3.5.22)$$

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

6. **Reactive Power :**

$$P_R = V_{s\,rms}\,I_{s1\,rms}\sin\phi_1 \qquad ...(3.5.23)$$

- 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,

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

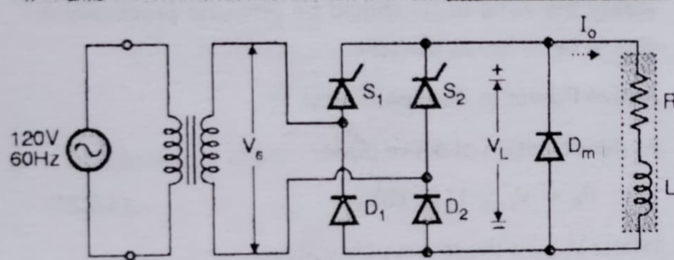
- But $2 \sin(\alpha/2) \cos(\alpha/2) = \sin \alpha$

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

$$\therefore \quad P_R = \frac{V_m I_o}{\pi} \sin \alpha \qquad ...(3.5.24)$$

- 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.

Ex. 3.5.7 : The semiconverter in Fig. P. 3.5.7 is connected to a 120 V, 60 Hz supply. The load current I_o can be assumed to continuous and ripple free. The turns ratio of the transformer is unity. If delay angle $\alpha = \pi / 2$ calculate V_{Ldc}, V_n, V_{Lrms}, HF, DF and PF. **March 19, 6 Marks**



(1-211) **Fig. P. 3.5.7**

Soln. :

Given : $V_{s\,rms} = 120$ V, $\alpha = \pi/2$

- All the expressions derived for the semiconverter circuit without the freewheeling diode are applicable to the semiconverter with freewheeling diode as well. (Fig. P. 3.5.7).

1. **Average output voltage :**

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

$$= \frac{\sqrt{2} \times 120}{\pi}(1 + \cos \pi/2) = 54 \text{ Volts.} \qquad \text{...Ans.}$$

2. **Normalized average output voltage :**

$$V_n = \frac{V_{Ldc}}{V_{Ldc(max)}} = \frac{\frac{V_m}{\pi}(1 + \cos \alpha)}{2\, V_m/\pi} = 0.5\,(1 + \cos \alpha)$$

$$\therefore \quad V_n = 0.5 \times (1 + \cos \alpha)$$

$$= 0.5 \times (1 + \cos \pi/2) = 0.5 \qquad \text{...Ans.}$$

3. **RMS load voltage :**

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

$$= 120\left[\frac{1}{\pi}\left((\pi - \pi/2) + \frac{\sin \pi}{2}\right)\right]^{1/2}$$

$$V_{Lrms} = 84.85 \text{ Volts} \qquad \text{...Ans.}$$

4. **Harmonic factor :**

$$HF = \left[\left(\frac{I_{srms}}{I_{s1rms}}\right)^2 - 1\right]^{1/2}$$

where I_{srms} = rms value of input current.

I_{srms} = rms value of fundamental component of input current.

$$\text{where } I_{srms} = I_o (1 - \alpha/\pi)^{1/2} = I_o\left(1 - \frac{\pi/2}{\pi}\right)^{1/2}$$

$$\therefore \quad I_{srms} = 0.707\, I_o \qquad \text{...Ans.}$$

$$\text{and} \quad I_{s1rms} = \frac{2\sqrt{2}\, I_o}{\pi} \cos(\alpha/2) = \frac{2\sqrt{2}\, I_o}{\pi} \cos(\pi/4)$$

$$\therefore \quad I_{s1rms} = 0.6366\, I_o \qquad \text{...Ans.}$$

$$HF = \left[\left(\frac{0707}{0.636}\right)^2 - 1\right]^{1/2} = 0.483 \qquad \text{...Ans.}$$

$$\therefore \quad HF = 48.3\%$$

5. **Displacement factor :**

$$DF = \cos \alpha/2 = \cos \pi / 4 = 0.707, \text{ or } 70.7\% \qquad \text{...Ans.}$$

6. **Power factor :**

$$PF = \frac{I_{s1rms}}{I_{srms}} \cos \alpha/2 = \frac{0.6366}{0.707} \times \cos \pi/4$$

$$= 0.6366 \text{ lagging}$$

$$PF = 0.6366 \text{ lagging} \qquad \text{...Ans.}$$

Ex. 3.5.8 : For the semiconverter in the previous example, calculate the amplitude of the first four harmonic components present on the input side, for $\alpha = \pi/2$.

OR

For the single phase asymmetrical half controlled bridge circuit derive expressions for rms value of the n^{th} harmonic supply current. **May 08, 2 Marks**

Soln. :

- Let the load current be continuous and ripple free equal to I_o. The rms value of n^{th} harmonic component of the input current is given by,

$$I_n = \frac{1}{\sqrt{2}}\left(a_n^2 + b_n^2\right)^{1/2} \qquad ...(1)$$

- The values of a_n and b_n are

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

$$= 0 \quad \text{... for } n = 2, 4, 6.......$$

and $b_n = \frac{2 I_o}{n\pi}(1 + \cos n\alpha)$

... for n = 1, 3, 5, ...(3)

$= 0$ ... for n = 2, 4, 6....

- Substituting the values of a_n and b_n we get,

$$I_n = \frac{2\sqrt{2} I_o}{n\pi} \cos (n\alpha/2)$$

- As the even harmonics are absent, the lowest order harmonic is the third harmonic.

∴ (a) RMS value of third harmonic (substituting n = 3) is given by,

$$I_3 = \left(\frac{2\sqrt{2}}{3\pi} \cos \frac{3\pi}{4}\right) I_o$$

$$I_3 = -0.2122 I_o \quad \text{...Ans.}$$

(b) RMS value of 5^{th} harmonic

$$= I_5 = \left(\frac{2\sqrt{2}}{5\pi} \cos \frac{5\pi}{4}\right) I_o = -0.127 I_o \quad \text{...Ans.}$$

(c) RMS value of 7^{th} harmonic

$$= I_7 = \left(\frac{2\sqrt{2}}{7\pi} \cos \frac{7\pi}{4}\right) I_o = 0.09 I_o \quad \text{...Ans.}$$

(d) RMS value of 9^{th} harmonic

$$= I_9 = \left(\frac{2\sqrt{2}}{9\pi} \cos \frac{9\pi}{4}\right) I_o = 0.070 I_o \quad \text{...Ans.}$$

- Similarly we can calculate the values of harmonic components for different values of α.
- This has been shown in Table P. 3.5.4.
- Configuration – Semiconverter Dependence of amplitude of harmonic components on firing angle (α)

$$I_n = \frac{2\sqrt{2} I_o}{n\pi} \cos (n\alpha / 2)$$

Table P. 3.5.4

Order of harmonic	at α = 0	at α = π/4	at α = π/2
1. Fundamental	0.9 I_o	0.83 I_o	0.6366 I_o
2. Second	0	0	0
3. Third	0.3 I_o	0.1148 I_o	– 0.2122 I_o
4. Fourth	0	0	0
5. Fifth	0.18 I_o	– 0.068	– 0.127 I_o
6. Sixth	0	0	0
7. Seventh	0.128 I_o	– 0.0689	0.09 I_o

Conclusions :

1. The rms value of fundamental component decreases with increase in the firing angle α
2. Even order harmonics are totally absent.
3. Odd harmonics vary in a random way with α.
4. Amplitudes of all the harmonic components including the fundamental are identical to those for full converter when α = 0. (Refer Table P. 3.5.8)

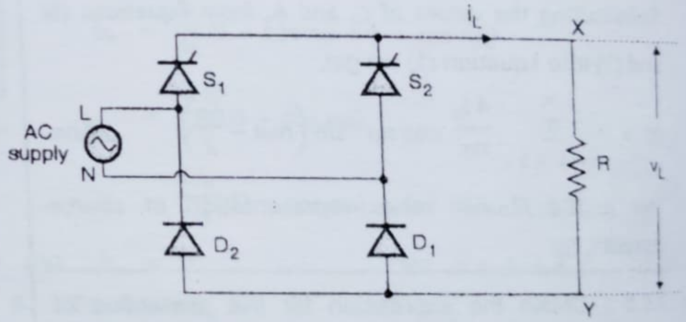
3.5.7 Operation with the Resistive Load (Symmetrical Configuration) :

SPPU : May 12

University Questions

Q. 1 Draw the circuit diagram of single phase semi-converter for 'R' load. Explain the operation with the help of voltage and current waveforms. **(May 12, 8 Marks)**

- Let us consider the symmetrical configuration of Fig. 3.5.11 to understand the operation of the circuit.

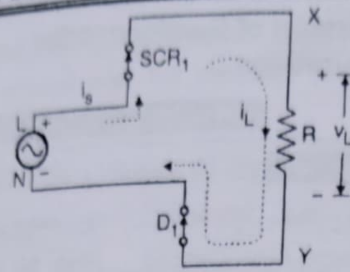


(I-703) **Fig. 3.5.11 : Semiconverter with resistive load**

- The operation of the circuit is divided into four modes.
- Note that the freewheeling does not take place if the load is resistive, because the resistive load can not store any energy.

Mode I (α ≤ ωt ≤ π) :

- As shown in Fig. 3.5.12(a) SCR_1 and diode D_1 are forward biased in the positive half cycle of the input ac supply (L is positive w.r.t. N).
- SCR_1 can be turned on at any value of α between 0 and 180°.
- As soon as SCR_1 is turned on at ωt = α the input ac supply is connected across the load with point x positive w.r.t. y as shown in Fig. 3.5.12(a).

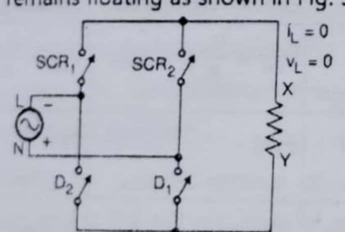


(I-172) **Fig. 3.5.12(a) : Mode I : Equivalent circuit for ($\alpha \le \omega t \le \pi$)**

- The current flows from L, through SCR_1, load, D_1 back to N. The instantaneous load current is thus positive and equal to ($V_m \sin \omega t / R$).

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

- As instant $\omega t = \pi$ or 180°, the ac mains voltage goes to zero.
- The load current which is also the current through SCR_1 and D_1 goes to zero.
- Thus SCR_1 is turned off as the forward current through it goes below the holding current value.
- Thus natural commutation takes place at $\omega t = \pi$ radians to turn off SCR_1 and D_1.
- The load remains floating as shown in Fig. 3.5.12(b).

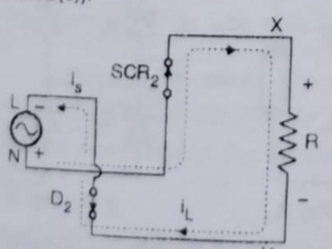


(I-172) **Fig. 3.5.12(b) : Mode II : (π to $\pi + \alpha$) all devices off**

- Both the load voltage and load current will be zero, during this interval of time.

Mode III ($\pi + \alpha$) to 2π :

- At $\omega t = \pi$ the supply voltage polarity reverses. (See Fig. 3.5.12(c)).



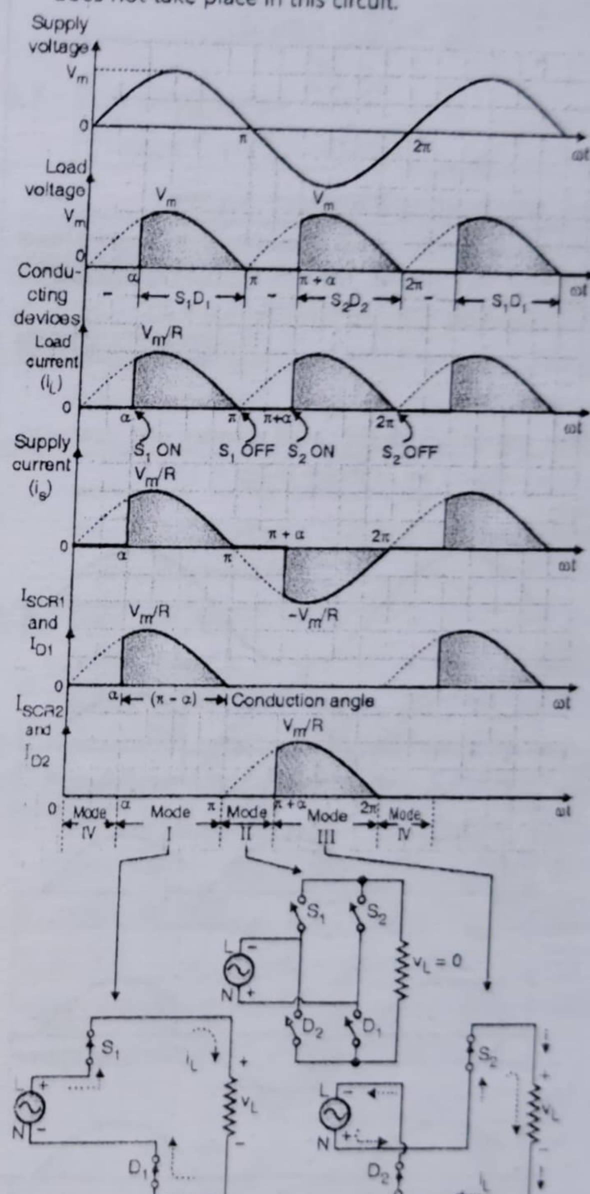
(I-173) **Fig. 3.5.12(c) : Mode III : ($\pi + \alpha$) to 2π**

- This makes neutral N positive with respect to live point L. Thus SCR_2 is forward biased. It can be turned on at the same firing angle α.
- The instant at which SCR_2 is turned on is ($\pi + \alpha$) radians.
- The current flows from N, through SCR_2 load R, D_2 back to live point L as shown in Fig. 3.5.12(c).

- The output voltage V_{xy} is positive again. The load current flows in the same direction as that in mode I.
- The conducting thyristor SCR_2 and D_2 are turned off due to natural commutation at $\omega t = 2\pi$.

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

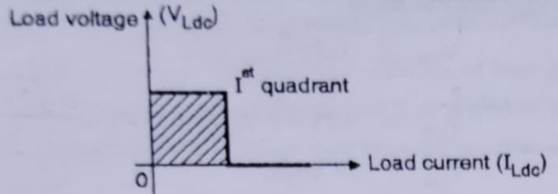
- This mode is identical to the mode II where all the devices remain off. The load voltage and current will be zero in this mode of operation.
- Due to the resistive nature of the load, the freewheeling does not take place in this circuit.



(I-174) **Fig. 3.5.13 : Voltage and current waveforms for single phase semiconverter with R load**

Quadrant of operation :

- As the instantaneous load voltage and load current both are always positive, this circuits operates in the first quadrant of the load voltage load current characteristic as shown in Fig. 3.5.14.



(1-175) **Fig. 3.5.14 : Quadrant of operation of a semiconverter**

- The flow of power is unidirectional always from ac mains to dc load.
- Therefore the circuits works as rectifier for all values of α.

3.5.8 Analysis of Semiconverter with Resistive Load :

1. Average load voltage (V_{Ldc}) :

- From the load voltage waveform of Fig. 3.5.13 the average load voltage is given by,

$$V_{Ldc} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin \omega t \, d\omega t \qquad ...(3.5.25)$$

$$= \frac{-V_m}{\pi} (\cos \omega t)_{\alpha}^{\pi}$$

$$V_{Ldc} = \frac{V_m}{\pi}(1 + \cos \alpha) \qquad ...(3.5.26)$$

- Firing angle α varies between 0 and 180° hence V_{Ldc} will vary from $\frac{2 V_m}{\pi}$ Volts to 0 Volts.

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

- From the load voltage waveform of Fig. 3.5.14 the rms load voltage is given by,

$$V_{L\,rms} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi} V_m^2 \sin^2 \omega t \, d\omega t\right]^{1/2} \qquad ...(3.5.27)$$

But $\sin^2 \omega t = \frac{1 - \cos 2\omega t}{2}$

$$\therefore V_{L\,rms} = \left[\frac{V_m^2}{\pi}\int_{\alpha}^{\pi} \frac{(1 - \cos 2\omega t)}{2}\right]^{1/2}$$

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

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

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

$$\therefore V_{L\,rms} = \frac{V_m}{\sqrt{2}} \left\{\frac{1}{\pi}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]\right\}^{1/2} \qquad ...(3.5.28)$$

But $\frac{V_m}{\sqrt{2}} = V_{s\,rms}$ = rms supply voltage

$$\therefore V_{L\,rms} = V_{s\,rms} \left\{\frac{1}{\pi}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]\right\}^{1/2} \qquad ...(3.5.29)$$

3. Normalized average output voltage (V_n) :

- It is defined as $V_n = \frac{V_{Ldc}}{V_{Ldc\,max}}$
- Substituting $\alpha = 0$ in Equation (3.5.26) we get the maximum value of average voltage.

$$\therefore V_{L\,dc\,max} = \frac{V_m}{\pi}(1 + \cos 0) = \frac{2 V_m}{\pi}$$

- Therefore the normalized voltage is given by,

$$V_n = \frac{\frac{V_m}{\pi}(1 + \cos \alpha)}{2 V_m / \pi}$$

$$\therefore V_n = 0.5 (1 + \cos \alpha) \qquad ...(3.5.30)$$

4. Form factor (FF) :

- The form factor (FF) for the load voltage is,

$$FF = \frac{V_{L\,rms}}{V_{Ldc}} \qquad ...(3.5.31)$$

- Substituting Equations (3.5.26) and (3.5.28) into Equation (3.5.31) we get,

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

$$\therefore FF = \frac{\left[\frac{1}{2\pi}\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)\right]^{1/2}}{\left[\frac{1 + \cos \alpha}{\pi}\right]} \qquad ...(3.5.32)$$

5. Ripple factor (RF) :

- The voltage ripple factor is,

$$RF = (FF^2 - 1)^{1/2} \qquad ...(3.5.33)$$

6. Average output power (P_{Ldc}) :

- The average output power P_{Ldc} is given by,

$$P_{Ldc} = V_{Ldc} \times I_{Ldc} \qquad ...(3.5.34)$$

- But due to the resistive nature of the load

$$I_{Ldc} = V_{Ldc} / R \qquad ...(3.5.35)$$

Therefore $P_{Ldc} = V_{Ldc}^2 / R \qquad ...(3.5.36)$

- Where R is the load resistance.

7. RMS output power ($P_{L\,rms}$) :

The rms output power $= P_{L\,rms} = V_{L\,rms} I_{L\,rms} \qquad ...(3.5.37)$

But $I_{L\,rms} = V_{L\,rms} / R \qquad ...(3.5.38)$

$P_{L\,rms} = V_{L\,rms}^2 / R \qquad ...(3.5.39)$

8. Rectifier efficiency (η) :

- The efficiency of rectification as already defined for the HWCR is

$$\eta = \frac{P_{Ldc}}{P_{L\,rms}} = \frac{V_{Ldc}^2 / R}{V_{L\,rms}^2 / R} = \frac{V_{Ldc}^2}{V_{L\,rms}^2} = \frac{1}{FF^2} \quad ...(3.5.40)$$

$$\eta = \frac{V_{Ldc}^2}{V_{L\,rms}^2} = \frac{1}{FF^2} \quad ...(3.5.41)$$

Ex. 3.5.9 : A single phase semiconverter is operated from 120 V, 60 Hz ac supply. The load resistance is 10 Ω. If the average output voltage is 25% of the maximum possible average output voltage calculate :

(a) Delay angle

(b) Rms and average output currents

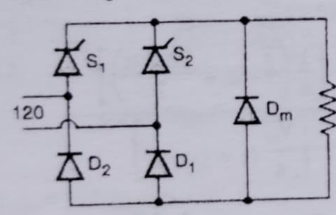
(c) Average and rms thyristor currents.

Dec. 09, May 11, Dec. 11, 6 Marks, Dec. 12, 5 Marks

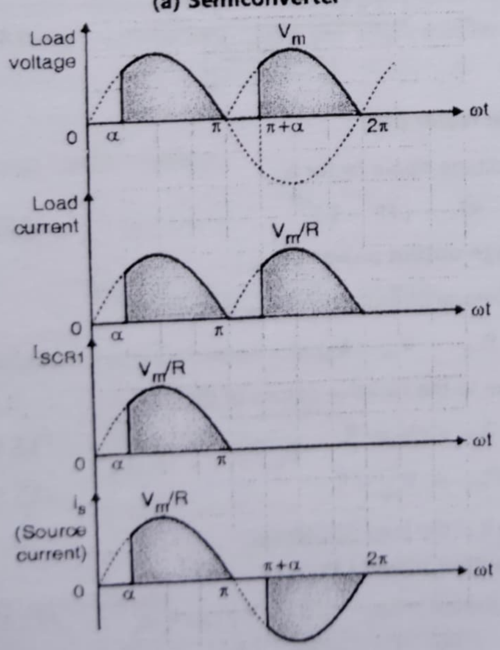
Soln. :

Given : $V_{s\,rms} = 120\ V_{rms}$, $R = 10\ \Omega$, $V_{Ldc} = 0.25\ V_{Ldc(max)}$

- The circuit diagram and waveforms for a semi-converter are shown in Fig. P. 3.5.9.



(a) Semiconverter



(b) Waveforms

(1-176) **Fig. P. 3.5.9**

(a) Average load voltage :

$$V_{Ldc} = 0.25\ V_{Ldc(max)}$$

$$V_{Ldc} = 0.25 \times 2\,V_m / \pi = 0.25 \times \frac{2\sqrt{2} \times 120}{\pi}$$

$$V_{Ldc} = 27 \text{ Volts.}$$

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

$$\therefore \quad 27 = \frac{120\sqrt{2}}{\pi}(1 + \cos\alpha)$$

$$1 + \cos\alpha = 0.5$$

$$\alpha = 120° \quad \text{...Ans.}$$

(b) RMS and average output currents :

$$V_{L\,rms} = \text{Load rms voltage}$$

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

$$= \frac{120\sqrt{2}}{\sqrt{2}}\left[\frac{1}{\pi}\left(\pi - 2\pi/3 + \frac{\sin 4\pi/3}{2}\right)\right]^{1/2}$$

$$= 53 \text{ Volts.} \quad \text{...Ans.}$$

$\therefore$ rms load current $= V_{L\,rms}/R$

$I_{L\,rms} = 5.3$ Amp ...Ans.

Average load current $= V_{Ldc} / R = 27/10$

$\therefore \quad I_{Ldc} = 2.7$ Amp. ...Ans.

(c) Average and rms thyristor currents :

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

(see the waveform for I_{SCR1} shown in Fig. P. 3.5.9(b))

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

$$I_m = V_m / R = 120\sqrt{2} / 10 = 16.97 \text{ Amp}$$

$\therefore$ average thyristor current,

$$I_{TH\,(av)} = \frac{16.97}{2\pi}(1 + \cos 2\pi/3) = 1.35 \text{ Amp.} \quad \text{...Ans.}$$

$$\text{RMS thyristor current, } I_{TH\,rms} = \left\{\frac{1}{2\pi}\int_{\alpha}^{\pi} I_m^2 \sin^2\omega t\, d\omega t\right\}^{1/2}$$

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

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

$$\therefore \text{ RMS thyristor current, } I_{TH\,(rms)} = \frac{I_m}{2}\left[\frac{1}{\pi}\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)\right]^{1/2}$$

$$= \frac{16.97}{2}\left[\frac{1}{\pi}(\pi/3 - 0.433)\right]^{1/2}$$

$$\therefore \quad I_{TH\,(rms)} = 3.75 \text{ Amp.} \quad \text{...Ans.}$$

Ex. 3.5.10 : A single phase semiconverter is operated from 120 V, 50 Hz AC supply. The load is resistive having resistance of 15 Ω. If the average output voltage is 25% of the maximum possible average output voltage, determine the firing angle (α). **Feb. 16, 3 Marks**

Soln. :

Given : $V_{s\,rms} = 120\ V_{rms}$ $R = 15\ \Omega$

$$V_{Ldc} = 0.25 \times 2\ V_m / \pi = 0.25 \times \frac{2\sqrt{2} \times 120}{\pi}$$

$$V_{Ldc} = 27 \text{ Volts.}$$

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

$$\therefore\ 27 = \frac{120\sqrt{2}}{\pi}(1 + \cos \alpha)$$

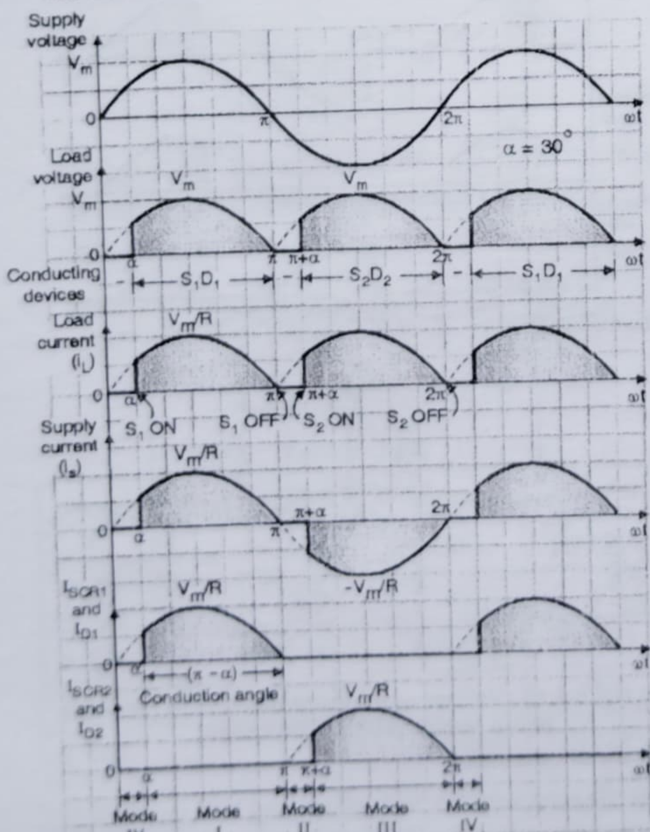
$$1 + \cos \alpha = 0.5$$

$$\alpha = 120^\circ \quad \text{...Ans.}$$

Ex. 3.5.11 : Draw the circuit diagram of a single phase semiconverter with R load. Explain the operation with the help of voltage and current waveforms for α = 30°. **May 11, 8 Marks**

Soln. :

- Refer section 3.5 for the circuit diagram and operation. The waveforms are as shown in Fig. P. 3.5.11.



(I-2090) **Fig. P. 3.5.11 : Waveforms of a semiconverter with R load at α = 30°**

3.5.9 Comparison of Semiconverter Configurations :

SPPU : Dec. 06, Dec. 11, Dec. 13

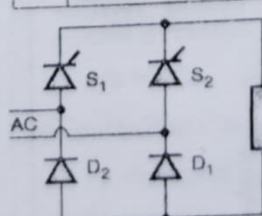
University Questions

Q. 1 Compare the following : Symmetrical and Asymmetrical configurations. **(Dec. 06, 3 Marks)**

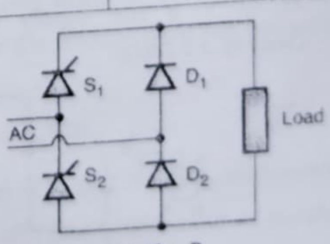
Q. 2 Compare symmetrical and asymmetrical configurations of single phase semi-converters with R-L load. **(Dec. 11, Dec. 13, 4 Marks)**

Table 3.5.1 : Comparison of semiconverter configurations

Sr. No.	Parameter	Symmetrical configuration	Asymmetrical configuration
1.	Configuration	Fig. A	Fig. B
2.	Freewheeling	Through S_1D_2 or S_2D_1	Through D_1D_2
3.	Conduction angle of SCRs	π radians or 180°	(π – α) radians
4.	Triggering pulses for the two SCRs	Need not be isolated from each other due to the common cathode connection	Needs to be isolated from each other as the cathodes are at different potentials.
5.	Average output voltage	$V_{Ldc} = \frac{V_m}{p}(1 + \cos a)$	$V_{Ldc} = \frac{V_m}{p}(1 + \cos a)$
6.	Quadrant of operation	First	First
7.	Freewheeling action	Inherent	Inherent
8.	External freewheeling diode	Not required	Not required



(I-177) **Fig. A**



(I-178) **Fig. B**

3.5.10 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 α / 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.

3.5.11 Disadvantages of Semiconverters :

- Some of the disadvantages of a semiconverter are :
  1. It can operate only in one quadrant.
  2. Energy feedback from load to source is not possible.
  3. Not suitable for the regenerative braking of DC motors.

3.5.12 Application :

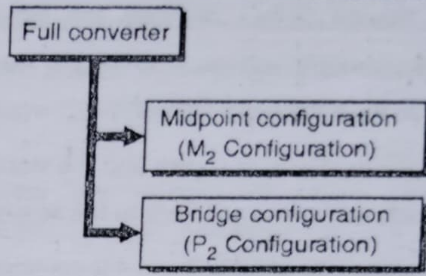
- Semiconverters are popularly used in the unidirectional DC motor controllers.

3.6 Full Converters :

- The semiconverter configuration discussed earlier is a single quadrant converter. The next logical step is a full wave controlled converter which can operate in two quadrants.
- In full converters the polarity of average load voltage can be positive or negative depending on the value of α (whereas, in semiconverter the average load voltage was always positive.).
- The possibility of polarity reversal of average load voltage will enable the full converter to operate either as Rectifier or as Inverter.
- Rectifier mode of operation is defined as the mode of operation in which the net flow of power is from ac to dc side that is from source to load.
- Whereas in the inverter mode of operation the net flow of power is from dc to ac side that is from load to source.
- As the full converter circuit can operate in any of these two modes, the power flow in the full converter can be bi-directional.
- It is unidirectional, only from source to load in case of semiconverters.

Configurations of full converter :

- There are two important configuration of the full converter :
  1. The mid-point configuration (M_2 configuration)
  2. The bridge configuration (P_2 configuration).



(I-179) **Fig. 3.6.1 : Classification of full converters**

- The operation, with different types of loads and the performance parameters for both these configurations has been discussed in this section.

3.7 Full Converter (Bridge Configuration) :

SPPU : Dec. 07, Dec. 15, Feb. 16, May 16

University Questions

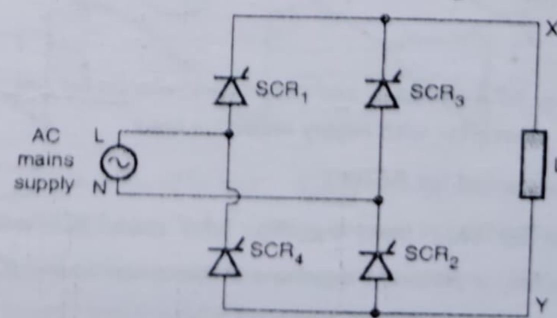
Q. 1 With the help of circuit diagram and waveforms, explain working of single phase full wave converter with inductive load. **(Dec. 07, 4 Marks)**

Q. 2 Explain with circuit diagram and waveforms working of 1ϕ full controlled converter with RL load ? Justify what is Inversion and Rectification mode with waveforms. **(Dec. 15, 7 Marks)**

Q. 3 Draw and explain single phase fully controlled bridge converter for R-L load with various output voltage waveforms. **(Feb. 16, 7 Marks)**

Q. 4 What are phase controlled converters ? Explain with circuit diagram and waveforms working of 1ϕ full controlled converter with suitable load. Comment on rectification, inversion mode and power factor. **(May 16, 10 Marks)**

- If the two diodes in the semi converter circuit are replaced by two SCRs, then we obtain the full bridge converter configuration as shown in Fig. 3.7.1.



(I-189) **Fig. 3.7.1 : Full bridge converter**

- Note that the freewheeling diode has been removed.
- The full converter configuration consists of four SCRs. At any given instant two SCRs (1 and 2 or 3 and 4) conduct simultaneously to connect the load across the input ac supply.

3.7.1 Operation of Full Converter with RL Load :

SPPU : May 13, Dec. 13, May 15, Dec. 15, Feb. 16, May 16, May 17, May 18

University Questions

Q. 1 Draw and explain single phase fully controlled bridge converter for R-L load with all waveforms. Also derive expressions for average output voltage and rms output voltage. **(May 13, 10 Marks)**

Q. 2 Describe the working of single-phase fully controlled bridge converter for R-L load for different modes with all waveforms. Also derive an expression for its rms output voltage. **(Dec. 13, 8 Marks)**

Q. 3 Draw and explain single phase fully controlled rectifier (full converter) for R-L load with various output voltage waveforms. **(May 15, Feb. 16, 7 Marks)**

Q. 4 Explain with circuit diagram and waveforms working of 1ϕ full controlled converter with RL load ? Justify what is Inversion and Rectification mode with waveforms. **(Dec. 15, 7 Marks)**

Q. 5 What are phase controlled converters ? Explain with circuit diagram and waveforms working of 1ϕ full controlled converter with suitable load. Comment on rectification, inversion mode and power factor. **(May 16, 10 Marks)**

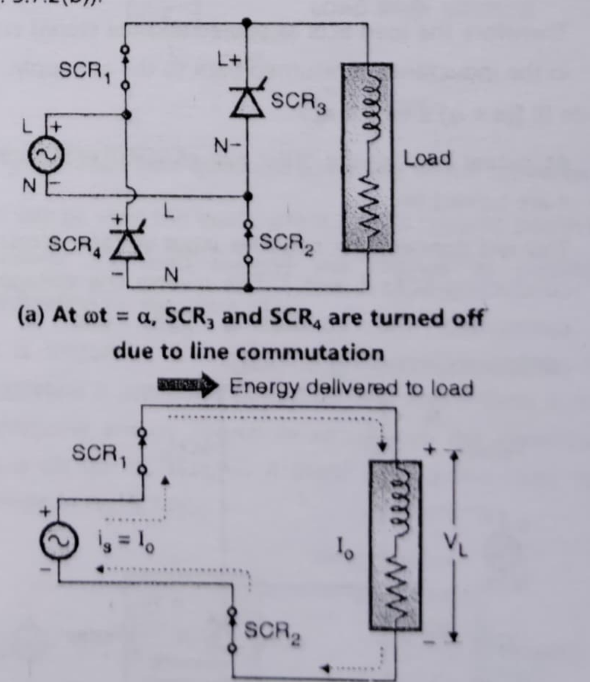
Q. 6 Draw the circuit diagram of single phase Full Controlled Bridge rectifier with RL load. Explain its operation. Draw the waveform of output voltage and current. **(May 17, 7 Marks)**

Q. 7 Draw and explain single phase full converter with highly inductive load with input and output waveforms at 60° and 120° ? **(May 18, 6 Marks)**

- 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 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 :

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

- 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.
- 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. 3.7.2(b)).



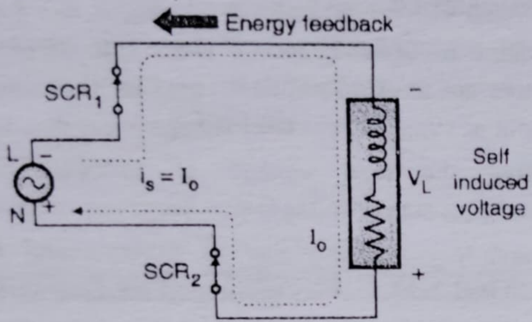
(a) At $\omega t = \alpha$, SCR_3 and SCR_4 are turned off due to line commutation

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

(I-190) Fig. 3.7.2

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. 3.7.2(c).



(I-191) **Fig. 3.7.2(c) : Equivalent circuit for mode II (Energy feedback)**

- This self induced voltage is high enough to maintain the SCRs 1 and 2 forward biased in spite 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.

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

- 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. 3.7.3(a)).

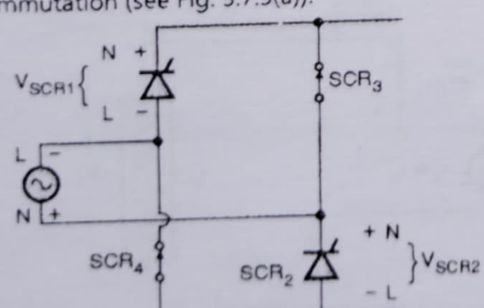
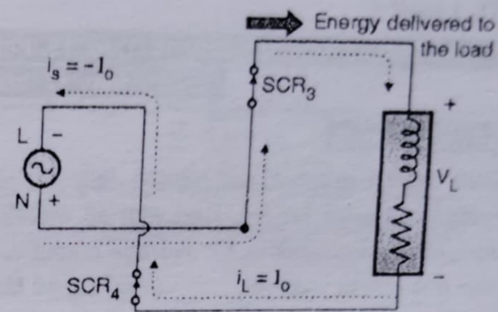


Fig. 3.7.3(a) : Line commutation of SCR_1 and SCR_2 at $\omega t = (\pi + \alpha)$

- 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. 3.7.3(b).

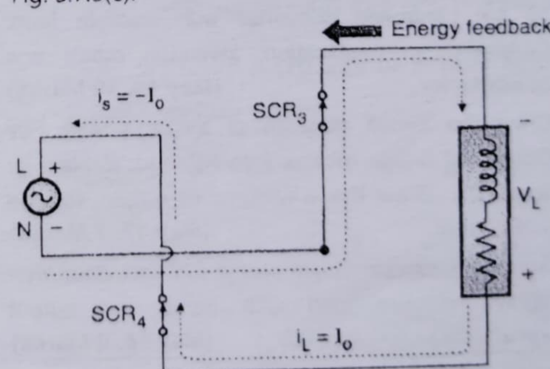


(I-192) **Fig. 3.7.3(b) : Equivalent circuit of mode III [$(\pi + \alpha)$ to 2π]**

- As both the load voltage and current are of same polarity the load stores energy.

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. 3.7.3(c).



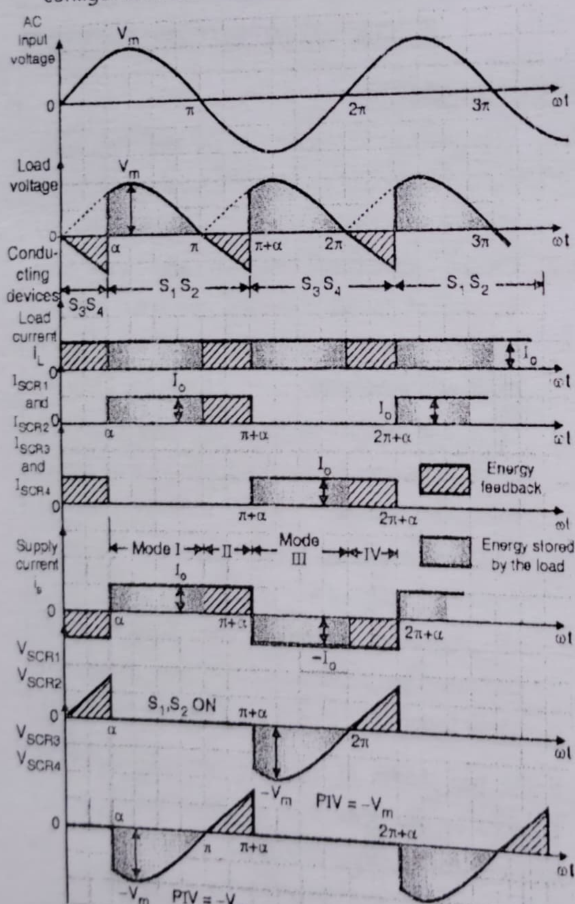
(I-193) **Fig. 3.7.3(c) : Equivalent circuit for mode IV (0 to α) or (2π to $2\pi + \alpha$) energy feedback**

- This maintains the conducting SCRs 3 and 4 forward biased in spite 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. 3.7.2(a).
- The operation then repeats itself.

Waveforms :

- The voltage and current waveforms for the full converter configuration with RL load are as shown in Fig. 3.7.4.



(I-194(a)) **Fig. 3.7.4 : Voltage and current waveforms for full converter with highly inductive load**

Conduction period for SCRs :

- As can be seen from the Fig. 3.7.4 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. 3.7.4.

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. 3.7.4.

3.7.2 Analysis of Full Converter with the RL Load (Output Side) :

SPPU : Dec. 09, May 10, Dec. 11, Dec. 12, May 13, Dec. 13

University Questions

Q. 1 Derive the expression for average output voltage. (Assume level load current) of single phase fully controlled bridge converter.. **(Dec. 09, Dec. 11, 4 Marks)**

Q. 2 Derive the expression for the average output voltage of single phase full converter with RL load. **(May 10, 2 Marks)**

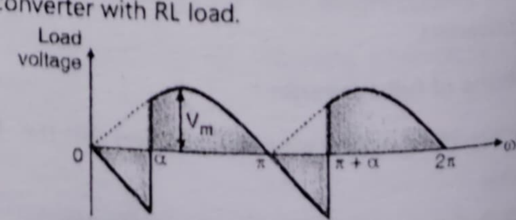
Q. 3 Describe the working of single phase fully controlled bridge converter for R-L load with all waveforms. Also derive an expression for average output voltage (V_o). **(Dec. 12, 8 Marks)**

Q. 4 Draw and explain single phase fully controlled bridge converter for R-L load with all waveforms. Also derive expressions for average output voltage and rms output voltage. **(May 13, 10 Marks)**

Q. 5 Describe the working of single-phase fully controlled bridge converter for R-L load for different modes with all waveforms. Also derive an expression for its rms output voltage. **(Dec. 13, 8 Marks)**

Average load voltage (V_{Ldc}) :

- Fig. 3.7.5 shows the load voltage waveform for a full converter with RL load.



(I-195) **Fig. 3.7.5 : Load voltage with inductive load**

- Referring to Fig. 3.7.5 the average load voltage can be obtained out as follows,

$$V_{Ldc} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin \omega t \, d\omega t \quad ...(3.7.1)$$

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

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

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

$$\therefore \quad V_{Ldc} = \frac{2V_m}{\pi}\cos\alpha \quad ...(3.7.2)$$

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

- Referring to Fig. 3.7.5 the expression for rms load voltage can be obtained as follows,

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

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

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

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

$$= \left\{\frac{V_m^2}{2\pi}\times\pi\right\}^{1/2}$$

$$V_{L\,rms} = V_m/\sqrt{2} \quad ...(3.7.3)$$

Form factor :

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

$$FF = \frac{\pi}{2\sqrt{2}\cos\alpha} \quad ...(3.7.4)$$

Ripple factor :

$$RF = (FF^2 - 1)^{1/2} = \left[\frac{\pi^2}{8\cos^2\alpha} - 1\right]^{1/2} \quad ...(3.7.5)$$

3.7.3 Two Quadrant Operation of Full Converters :

SPPU : Dec. 06, Dec. 07, Dec. 09, Dec. 11, May 12, Dec. 15, May 16

University Questions

Q. 1 Write a short note on : Two quadrant operation of full converter. **(Dec. 06, 6 Marks)**

Q. 2 Explain inverter mode of operation of single phase full wave converter with inductive load. **(Dec. 07, 4 Marks)**

Q. 3 Describe the working of single phase fully controlled bridge converter in the following modes :

1. Rectifying mode 2. Inversion mode.

(Dec. 09, Dec. 11, 4 Marks)

Q. 4 What is inverting and rectifying mode of single phase full wave converter with R-L load ? **(May 12, 8 Marks)**

Q. 5 Explain with circuit diagram and waveforms working of 1ϕ full controlled converter with RL load ? Justify what is Inversion and Rectification mode with waveforms. **(Dec. 15, 7 Marks)**

Q. 6 What are phase controlled converters ? Explain with circuit diagram and waveforms working of 1ϕ full controlled converter with suitable load. Comment on rectification, inversion mode and power factor. **(May 16, 10 Marks)**

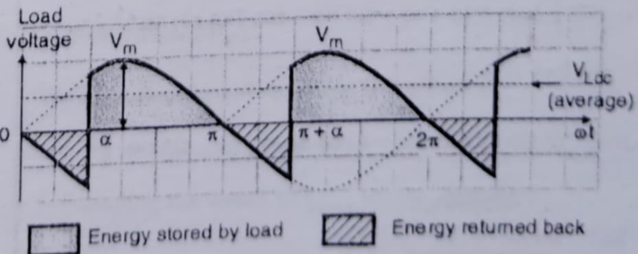
- With highly inductive load, a full converter can operate in one of the following two different possible operating modes :

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

- The load voltage waveforms for different values of α are as shown in Figs. 3.7.6(a), (b) and (c).

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

- The load voltage waveform is as shown in Fig. 3.7.6(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.



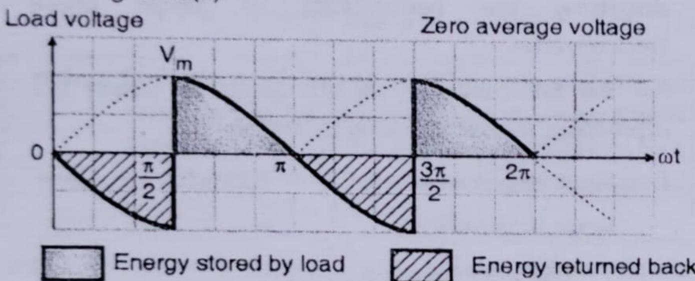
(1-196) **Fig. 3.7.6(a) : Load voltage for $\alpha < 90°$ (Rectification)**

- 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**".

2. Operation for $\alpha = 90°$:

- The load voltage waveform for $\alpha = 90°$ is as shown in Fig. 3.7.6(b).

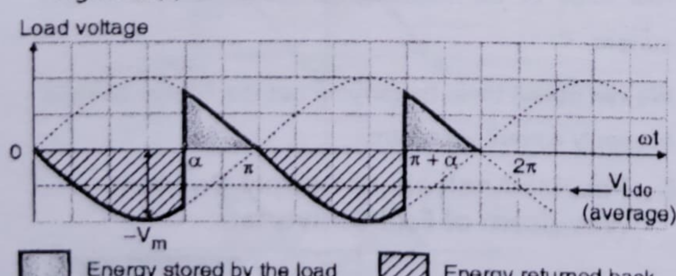


(I-197) **Fig. 3.7.6(b) : Load voltage for $\alpha = 90°$**

- As can be seen clearly, the areas 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.

3. Operation for $\alpha > 90°$ (Inversion) :

- The load voltage waveform for $\alpha > 90°$ is as shown in Fig. 3.7.6(c).



(I-198) **Fig. 3.7.6(c) : Load voltage for $\alpha > 90°$**

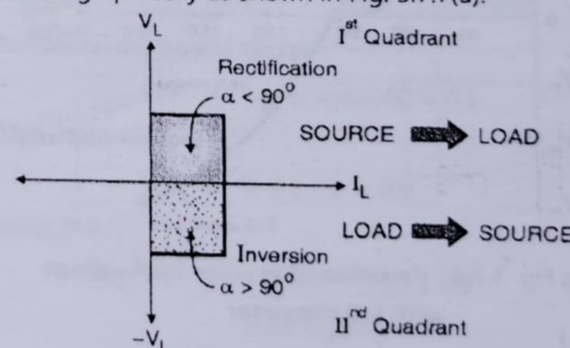
- According to the equation for average load voltage $V_{Ldc} = (2V_m/\pi) \cos \alpha$, the value of $\cos \alpha$ for $\alpha > 90°$ is negative, therefore the average output voltage is negative for $\alpha > 90°$.
- It is seen clearly from Fig. 3.7.6(c) that the area under the negative half is greater 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**.

Conclusions :

1. For $\alpha < 90°$ 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 $\alpha = 90°$ the average load voltage is zero and the net power transferred to the load is zero.
3. For $\alpha > 90°$, 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.

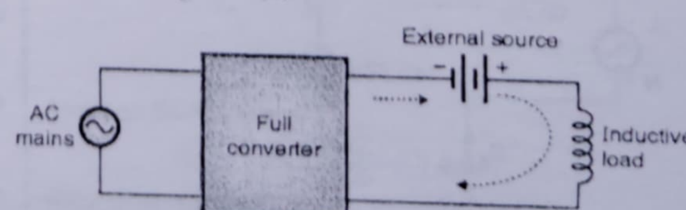
Two quadrant operation of Full Converter :

- The two quadrant operation of the full converter can be shown graphically as shown in Fig. 3.7.7(a).



(I-199**Fig. 3.7.7(a) : Two quadrant operation of full converter**

- 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. 3.7.7(b).



(I-199) **Fig. 3.7.7(b) : Connection of external source for inverter operation**

Variation of average load voltage with firing angle :

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

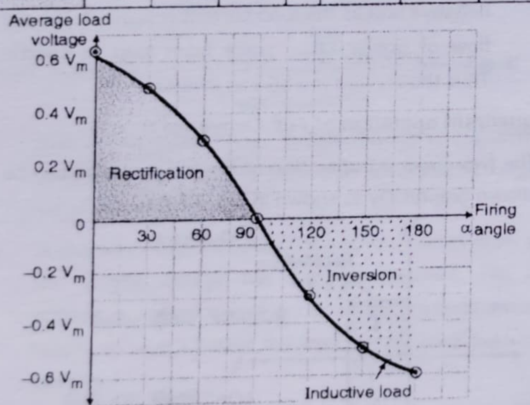
$$V_{Ldc} = \frac{V_m}{\pi}(1 + \cos\alpha) \quad \text{...with R load}$$

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

- The variation in firing angle is from 0° to 180°.
- Table 3.7.1 shows the average load voltage for different values of α and Fig. 3.7.8 shows graphically the variation of average voltage with α.

Table 3.7.1

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

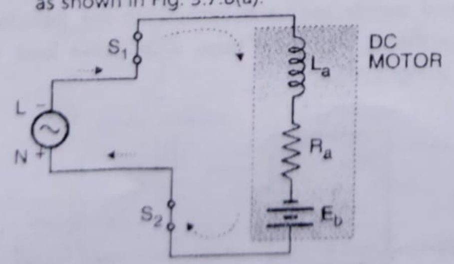


(1-200) **Fig. 3.7.8 : Variation of average load voltage with full converter**

3.7.4 Conditions for Inversion Mode :

- Following are the conditions for inversion mode :

1. The load voltage should be negative.
2. The magnitude of negative load voltage should be higher than the negative supply voltage.
3. The load should be active load like the DC motor as shown in Fig. 3.7.8(a).



(1-2009) **Fig. 3.7.8(a) : Regeneration**

4. The full converter should be used. Semiconverters don't support inversion.
5. Firing angle α should be greater than 90°.

3.7.5 Performance Parameters for Full Converter :

- We have already defined the input performance parameter of a controlled rectifier in section 3.5.7 while discussing the performance of single phase semiconverter.
- For the full converter we are going to obtain the expressions for the following parameters :

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.

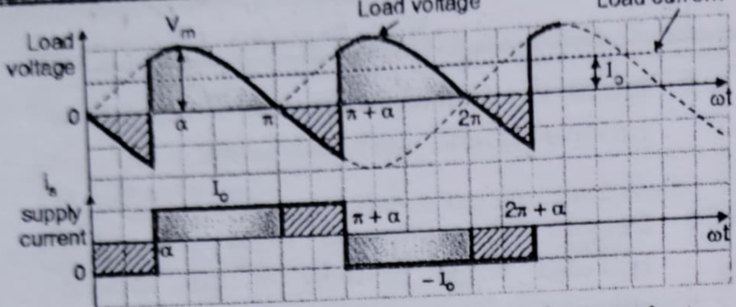
3.7.6 Fourier Analysis of Supply Current Waveform of Full Converter :

SPPU : May 16

University Questions

Q. 1 What are phase controlled converters ? Explain with circuit diagram and waveforms working of 1ϕ full controlled converter with suitable load. Comment on rectification, inversion mode and power factor. **(May 16, 10 Marks)**

- 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 3.7.9.



(1-201) **Fig. 3.7.9 : Load voltage and supply current waveforms for full converter with RL load**

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

$$i_s(t) = \sum_{n=1}^{\infty} (a_n \cos n\omega t + b_n \sin n\omega t) \qquad ...(3.7.6)$$

$$= \sum_{n=1}^{\infty} c_n \sin(n\omega t + \phi_n) \qquad ...(3.7.7)$$

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

and $\phi_n = \tan^{-1}(a_n / b_n) \qquad ...(3.7.8)$

Values of a_n and b_n :

- 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. 3.7.8,

$i_s(t) = +I_o$ ...... for $\alpha \le \omega t \le (\pi + \alpha)$

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

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

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

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

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

But $\cos 2\pi n = 1$

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

But $\sin n\pi = 0$

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

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

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

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

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

$$= \frac{-4I_o}{n\pi}\sin n\alpha.$$

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

and $a_n = 0$ for $n = 2, 4, 6, \qquad ...(3.7.9)$

$$\text{Similarly, } b_n = \frac{1}{\pi}\int_{\alpha}^{2\pi+\alpha} i_s(t)\sin n\omega t\, d\omega t$$

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

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

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

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

But $\sin 2\pi n = 0$

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

But $\cos 2\pi n = 1$

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

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

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

$\therefore b_n = 0$

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

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

$$\therefore b_n = \frac{4I_o}{n\pi}\cos n\alpha$$

For $n = 1, 3, 5, ... \qquad ...(3.7.10)$

and $b_n = 0$ for $n = 2, 4, 6, ...$

Values of c_n and ϕ_n :

- 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 (3.7.9) and (3.7.10) we get,

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

$$c_n = \frac{4\, I_o}{n\, \pi} \quad \text{...(3.7.11)}$$

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

$$\phi_n = -n\alpha \quad \text{...(3.7.12)}$$

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 :

- The peak value of fundamental current is obtained from Equation (3.7.11) as follows :

$$c_1 = \frac{4\, I_o}{\pi} \quad \text{...(3.7.13)}$$

and $\phi_1 = -\alpha$ ...(3.7.14)

- 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.

RMS value of fundamental current :

- The RMS value of the fundamental supply current is given by,

$$I_{s1\,rms} = \frac{c_1}{\sqrt{2}} = \frac{4\, I_o}{\sqrt{2}\,\pi} \quad \text{...(3.7.15)}$$

$$I_{s1\,rms} = \frac{2\sqrt{2}\, I_o}{\pi} \quad \text{...(3.7.16)}$$

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

$$I_{s\,rms} = I_o \quad \text{...(3.7.17)}$$

$\therefore$ RMS value of fundamental component,

$$I_{s1\,rms} = \frac{2\sqrt{2}\, I_o}{\pi}$$

RMS value of supply current,

$$I_{s\,rms} = I_o$$

- Displacement angle for fundamental component,

$$\phi_1 = -\alpha$$

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

3.7.7 Performance Parameters :

- The performance parameters of a full converter are same as those of a semi-converter.
- They are as follows :

1. Input Displacement Factor :

$$DSF = \cos \phi_1 = \cos (-\alpha) = \cos \alpha \quad \text{...(3.7.18)}$$

2. 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

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

$$\therefore \quad PF = \frac{2\sqrt{2}}{\pi} \cos \alpha = 0.9 \cos \alpha \quad \text{...(3.7.19)}$$

3. Input Current Distortion Factor : (CDF)

$$CDF = \frac{I_{s1\,rms}}{I_{s\,rms}} = \frac{2\sqrt{2}\, I_o}{\pi\, I_o} = \frac{2\sqrt{2}}{\pi} = 0.9 \quad \text{...(3.7.20)}$$

4. Input Harmonic Factor :

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

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

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

$$\therefore \quad HF = \left[\frac{\pi^2}{8} - 1\right]^{1/2} = 0.4834 \quad \text{...(3.7.21)}$$

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

$$\therefore \quad P_A = \frac{2\, V_m\, I_o}{\pi} \cos \alpha \quad \text{...(3.7.22)}$$

6. **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 $\sqrt{2}\, V_{s1\,rms} = V_m$

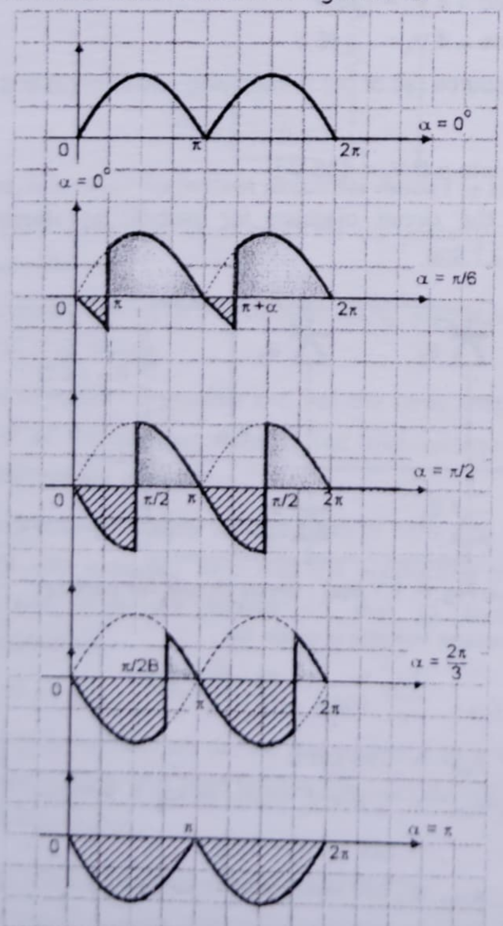
$$\therefore \quad P_R = \frac{2\, V_m\, I_o}{\pi} \sin \alpha \qquad ...(3.7.23)$$

> **Note :** Comparing Equations (3.5.24) and (3.7.23) we conclude that the reactive power drawn by a semi converter is 50% of the reactive power drawn by a full converter. The semi-conductor is thus superior to full converter in this respect.

Ex. 3.7.1 : With the help of circuit diagram and waveforms, explain working of single phase full wave converter with inductive load. Draw output voltage waveforms for the variation in 'α' from '0 to π'. Also explain its inverter mode of operation.

Soln. :

– The output voltage wave forms for different values of α from 0 to π are as shown in Fig. P. 3.7.1.



(I-730) **Fig. P. 3.7.1 : Output voltage waveforms for a full converter at different values of π**

Ex. 3.7.2 : A 1 ϕ full converter supplies an inductive load. Assuming that the output current is continuous and ripple free to equal 15 amp. determine the following :

1. Average output voltage
2. Supply rms current
3. Fundamental power factor
4. Distortion factor
5. Input power factor
6. Harmonic factor
7. Active and reactive power
8. Average and RMS values of thyristor current

(Supply voltage is 230 Volts and $\alpha = 60°$)

May 07, 8 Marks

Soln. :

$$V_m = V_{s\,rms} \times \sqrt{2} = 230 \times \sqrt{2} = 325.26 \text{ Volts}$$

1. **Average output voltage :**

$$V_{Ldc} = \frac{2\, V_m}{\pi} \cos \alpha = 103.53 \text{ Volts}$$

2. **Supply rms current :**

$$I_{srms} = I_{dc} = 15 \text{ amp.}$$

3. **Fundamental power factor :**

$$FPF = \cos \alpha = \cos 60 = 0.5$$

4. **Distortion factor :**

$$DF = 2\sqrt{2} / \pi = 0.9$$

5. **Input P.F. :**

$$\text{Input P.F.} = FPF \times DF = 0.5 \times 0.9$$

$$= 0.45 \text{ lagging}$$

6. **Harmonic factor :**

$$HF = \left[\frac{\pi^2}{8} - 1\right]^{1/2} = 0.4834$$

7. **Active and reactive Power :**

$$P_A = V_{s1}\, I_{s1} \cos \alpha$$

$$P_A = 230 \times \frac{2\sqrt{2} \times 15}{\pi} \cos 60 = 1553 \text{ W.}$$

$$\text{Reactive Power } P_R = V_{s1}\, I_{s1} \sin \alpha$$

$$P_R = 230 \times \frac{2\sqrt{2} \times 15}{\pi} \sin 60$$

$$= 2689.95 \text{ Var}$$

8. **Average SCR current :**

$$I_{TH\,(av)} = I_{dc} / 2 = 7.5 \text{ Amp.}$$

9. **RMS SCR current :**

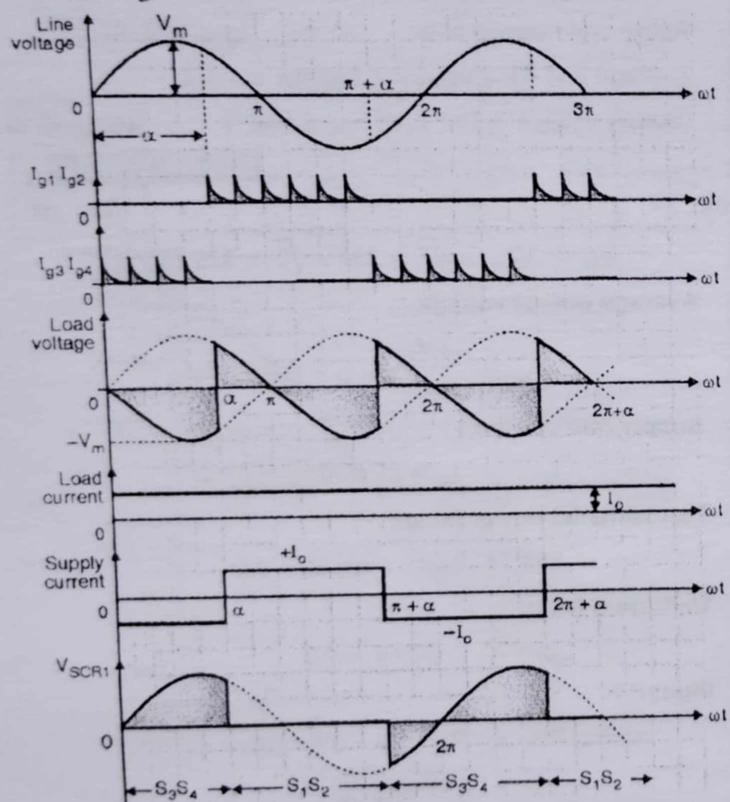
$$I_{THrms} = I_{dc} / \sqrt{2} = 10.6 \text{ Amp.}$$

Ex. 3.7.3 : A single phase fully controlled bridge is operated as a line commutated inverter. Draw the circuit diagram and waveforms. (assume the load to be highly inductive).

1. Line voltage
2. SCR triggering pulses
3. Load voltage
4. Load current
5. Supply current 6. SCR voltage

Soln. :

– See Fig. P. 3.7.3.



(I-219) **Fig. P. 3.7.3 : Waveforms for inverter operation**

Ex. 3.7.4 : A single phase fully controlled bridge converter feeds R-L load from a 230 V ac supply at α = 30°. Assume constant load current of 10 A. Find average output voltage, RMS output voltage, Form factor and ripple factor.

Soln. :

Given : V_{srms} = 230 V, α = 30°, I_{dc} = 10 A

To find : 1. Average output voltage

2. RMS output voltage

3. Form factor 4. Ripple factor.

Step 1 : Find average output voltage :

$$V_{Ldc} = \frac{2V_m}{\pi}\cos\alpha = \frac{2\sqrt{2}\times 230}{\pi}\cos 30^\circ$$

$$= 179.33 \text{ Volts}$$ ...Ans.

Step 2 : Find RMS output voltage :

$$V_{Lrms} = V_m/\sqrt{2} = \frac{\sqrt{2}\times 230}{\sqrt{2}}$$

$$= 230 \text{ V}$$ ...Ans.

Step 3 : Find form factor :

$$FF = \frac{\pi}{2\sqrt{2}\cos\alpha} = \frac{\pi}{2\sqrt{2}\cos 30^\circ}$$

$$= 1.282$$ ...Ans.

Step 4 : Find ripple factor :

$$RF = \left[\frac{\pi^2}{8\cos^2\alpha} - 1\right]^{1/2} = \left[\frac{\pi^2}{8\cos^2 30^\circ} - 1\right]^{1/2}$$

$$= 0.803$$ ...Ans.

Ex. 3.7.5 : A single phase fully controlled thyristor bridge converter supplies a load consisting of R, L and V_c, the inductance L in the circuit is so large that the output current may be considered to be virtually constant. Assume the thyristors to be ideal and take the following data.

RMS supply voltage = 220 V, load resistance = 0.5 Ω, output current I_o = 10 A,

(a) Calculate α if V_c = 135 V

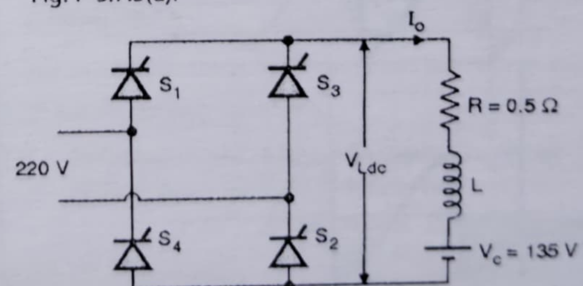
(b) Calculate α if V_c = – 145 V

(c) Which source (ac or dc) is supplying power in (a) and (b)

Soln. :

(a) Calculate α if V_c = 135 V :

– Draw the circuit diagram for part-(a) as shown in Fig. P 3.7.5(a).



(I-214) **Fig. P. 3.7.5(a) : Given circuit for part-(a)**

– The average voltage is given by,

$$V_{Ldc} = \frac{2V_m}{\pi}\cos\alpha = \frac{2\times\sqrt{2}\times 220}{\pi}\cos\alpha$$

$$V_{Ldc} = 198\cos\alpha \quad ...(1)$$

$$\text{also } V_{Ldc} = I_o R + V_c \text{ [Refer to Fig. P. 3.7.5(a)]} \quad ...(2)$$

$$= (10 \times 0.5) + 135$$

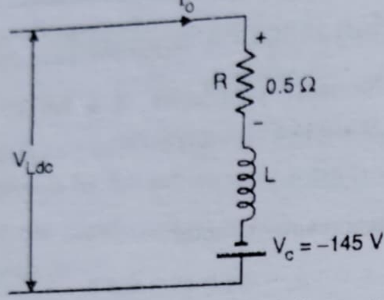
$$\therefore V_{Ldc} = 140 \text{ Volts, substituting in Equation (1)}$$

$$\therefore 140 = 198\cos\alpha$$

$$\therefore \alpha = 45^\circ \text{ or } \pi/4^\circ$$ ...Ans.

(b) Calculate α if $V_c = -145$ V :

- Draw the circuit diagram for part-(a) as shown in Fig. P 3.7.5(b).



(1-214) **Fig. P. 3.7.5(b) : Given circuit for part-(b)**

- From the Fig. P. 3.7.5(b), the average load voltage is given by,

$$V_{Ldc} = I_oR - V_c = (10 \times 0.5) - 145$$

$$\therefore V_{Ldc} = -140 \text{ Volts}$$

$$\therefore -140 = \frac{2V_m}{\pi} \cos\alpha$$

$$= \frac{2\sqrt{2} \times 220}{\pi} \cos\alpha$$

$$\therefore \quad \alpha = 135° \text{ or } 3\pi/4°$$ ...Ans.

(c) Who is supplying power ?

- Power flows from ac source to the load, as the converter works as rectifier in circuit (a). The flow of power changes its direction as it flows from dc to ac in circuit (b) as the converter works as inverter.

Ex. 3.7.6 : A single phase fully controlled bridge operates with 230 V, 50 Hz ac input and supplies continuous ripple free output current of 5 amp. if bridge is operated at firing angle of 45°. Find :

1. Average output voltage
2. RMS supply current
3. Harmonic factor
4. RMS value of 3rd harmonic of input current.

May 08, 6 Marks

Soln. :

Given : $V_{srms} = 230$ V, $I_o = 5$A, $\alpha = 45°$

1. Average output voltage :

$$V_{Ldc} = \frac{2V_m}{\pi} \cos\pi = \frac{2 \times 230\sqrt{2}}{\pi} \cos 45°$$

$$\therefore V_{Ldc} = 146.42 \text{ V}$$ ...Ans.

2. RMS supply current :

$$I_{srms} = I_o = 5 \text{ mA}$$ ...Ans.

3. Harmonic factor :

$$HF = \frac{\left[I_{s\,rms}^2 - I_{s1}^2\right]^{1/2}}{I_{s1}}$$

$$I_{s1} = \frac{2\sqrt{2}\,I_o}{\pi} = \frac{2 \times \sqrt{2} \times 5}{\pi} = 4.501 \text{ A}$$

$$\therefore HF = \frac{[(5)^2 - (4.501)^2]^{1/2}}{4.501}$$

$$= 0.4834$$ ...Ans.

4. RMS value of third harmonic current :

$$I_{3\,rms} = C_{3\,rms} = \frac{4\,I_o}{\sqrt{2} \times 3\pi} = \frac{4 \times 5}{\sqrt{2} \times 3\pi}$$

$$\therefore I_{3\,rms} = 1.5 \text{ A}$$ ...Ans.

Ex. 3.7.7 : A single phase fully controlled bridge rectifier is given 230 V, 50 Hz supply $\alpha = 45°$ load is highly inductive. Calculate

1. Average output voltage
2. Voltage ripple factor
3. Power factor
4. Form factor.

Dec. 11, 6 Marks

Soln. :

Given : $V_{s\,rms} = 230$ V, $\alpha = 45°$

1. Average output voltage :

$$V_{Ldc} = \frac{2V_m}{\pi} \cos\alpha = \frac{2\sqrt{2} \times 230}{\pi} \cos 45°$$

$$V_{Ldc} = 146.42 \text{ Volts}$$ ...Ans.

2. Voltage ripple factor :

$$RF = \left[\frac{\pi^2}{8\cos^2\alpha} - 1\right]^{1/2}$$

$$= \left[\frac{\pi^2}{8\cos^2 45} - 1\right]^{1/2} = 1.21$$

$$\therefore RF = 1.21 \text{ or } 121\%$$ ...Ans.

3. Power factor :

$$PF = \frac{2\sqrt{2}}{\pi} \cos\alpha = \frac{2\sqrt{2}}{\pi} \times \cos 45°$$

$$\therefore PF = 0.6366 \text{ ..... lagging}$$ ...Ans.

4. Form factor :

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

$$\therefore FF = 230 / 146.42$$

$$= 1.57 \text{ or } 157\%$$ ...Ans.

Ex. 3.7.8 : A single-phase fully controlled bridge rectifier is given as 230 V, 50 Hz supply. The firing angle is 30° and load is highly inductive. Determine :

1. Average output voltage
2. Power factor
3. Average output voltage if a freewheeling diode is connected across load. **Dec. 12, Dec. 13, 6 Marks**

Soln. :

Given : Single phase fully controlled converter, $\alpha = 30°$,

$V = 230$ Volts, $f = 50$ Hz, Load highly inductive

To find :

1. V_{Ldc} 2. PF
3. Average output voltage if a freewheeling diode is connected across load.

1. **Average output voltage :**

$$V_{Ldc} = \frac{2V_m}{\pi}\cos\alpha = \frac{2\sqrt{2}\times 230}{\pi}\cos 30°$$

$$\therefore V_{Ldc} = 179.33 \text{ V} \quad \text{...Ans.}$$

2. **Power factor :**

$$PF = \frac{2\sqrt{2}}{\pi}\cos\alpha = \frac{2\sqrt{2}}{\pi}\cos 30°$$

$$\therefore PF = 0.7796 \text{ (Lagging)} \quad \text{...Ans.}$$

3. **Load Voltage with freewheeling diode :**

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

$$\therefore V_{Ldc} = \frac{230\sqrt{2}}{\pi}(1+\cos 30)$$

$$= 193.2 \text{ V} \quad \text{...Ans.}$$

Ex. 3.7.9 : A single phase fully controlled bridge rectifier is given 230 V, 50 Hz supply. The firing angle is 90° and load is highly inductive. If load current is continuous of 10 A, determine :

1. Average and rms output voltage.
2. Active power. 3. Reactive power. **May 13, 6 Marks**

Soln. :

Given : $V_{srms} = 230$ V, $f = 50$ Hz, $\alpha = 90° = \frac{\pi}{2}$, $I_{dc} = 10$A

To find : 1. Average and rms output voltage

2. Active power 3. Reactive power

Step 1 : Calculate average and rms output voltage :

$$\text{Average output voltage} = \frac{2V_m}{\pi}\cos\alpha = \frac{2\sqrt{2}\times 230}{\pi}\cos 90°$$

$$\therefore V_{Ldc} = 0 \text{ Volts}$$

$$\text{RMS output voltage } V_{srms} = 230 \text{ Volts} \quad \text{...Ans.}$$

Step 2 : Calculate active and reactive power :

$$P_A = V_{srms} I_{srms}\cos\alpha$$

$$= 230\times\frac{2\sqrt{2}\times 10}{\pi}\cos 90° = 0 \text{ W} \quad \text{...Ans.}$$

$$P_R = V_{srms} I_{srms}\sin\alpha$$

$$= 230\times\frac{2\sqrt{2}\times 10}{\pi}\sin 90° = 207.07 \text{ VAR} \quad \text{...Ans.}$$

Ex. 3.7.10 : In a single phase full converter with highly inductive load is feed from 120 V RMS ac mains & fired at $\alpha = 45$ deg., Calculate :

1. Average load voltage.
2. RMS load voltage.
3. Power factor. **Dec. 18, 8 Marks**

Soln. : $V_{srms} = 120$ V, $\alpha = 45°$, 1 ϕ full converter

To find : 1. Average load voltage 2. RMS load voltage

3. Power factor.

Step 1 : Calculate average load voltage (V_{Ldc}) :

$$V_{Ldc} = \frac{2V_m}{\pi}\cos\alpha = \frac{2\sqrt{2}\times 120}{\pi}\cos 45° = 76.39 \text{ V} \quad \text{...Ans.}$$

Step 2 : Calculate RMS load voltage (V_{srms}) :

$$(V_{srms}) = 120 \text{ V} \quad \text{...Ans.}$$

Step 3 : Calculate power factor :

$$PF = \frac{2\sqrt{2}}{\pi}\cos\alpha = \frac{2\sqrt{2}}{\pi}\times\cos 45° = 0.636 \text{ (Lagging)} \quad \text{...Ans.}$$

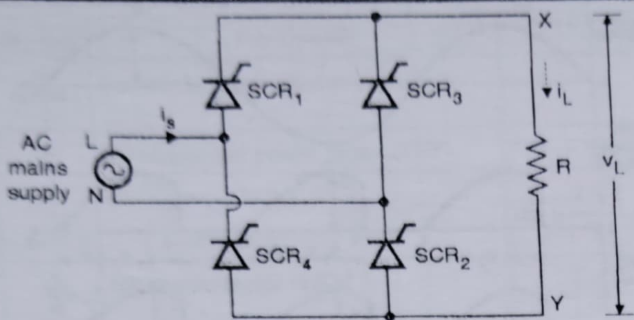
3.7.8 Operation of Full Converter with Resistive Load : SPPU : Dec. 12, March 19

University Questions

Q. 1 Draw and explain single-phase full wave AC voltage controller for R load with waveforms. Derive an expression for its output voltage. **(Dec. 12, 7 Marks)**

Q. 2 Draw and explain working of single phase fully controlled rectifier for R load. Draw input output voltage waveforms. State equation for average output voltage. **(March 19, 7 Marks)**

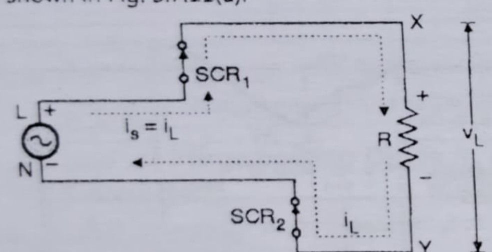
- The single phase full converter consists of four thyristors SCR_1 to SCR_4 connected in the bridge configuration driving a resistive load as shown in Fig. 3.7.10.
- These four thyristors can be divided into two groups each consisting of two SCRs.
- The full converter circuit is being operated on single phase ac mains as shown in Fig. 3.7.10.



(1-202) **Fig. 3.7.10 : Single phase full converter with resistive load**

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. 3.7.11(a).



(1-203) **Fig. 3.7.11(a) : Equivalent circuit for mode I (α to π)**

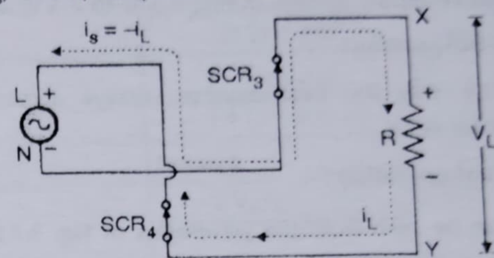
- The load voltage is thus equal to the instantaneous supply voltage.
- The current flows from L through SCR_1, load R, SCR_2 back to N as shown.
- The load current is positive and has the same shape as that of ac mains input voltage. The load voltage and load current are in phase.
- At instant π, the 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 $\pi + \alpha$) :

- All the SCRs remain off during the period π to $\pi + \alpha$. The load voltage and load current are zero during this mode of operation.

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

- 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. 3.7.11(b). The current now flows from N through SCR_3, load R, SCR_4 back to L as shown in Fig. 3.7.11(b).



(1-203) **Fig. 3.7.11(b) : Equivalent circuit for mode III ($\pi + \alpha$) to 2π**

- 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 ($0 \le \omega t \le \alpha$) :

- 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. 3.7.13.

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. 3.7.13.

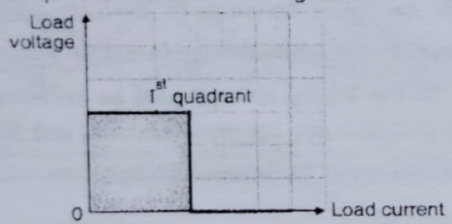
Thyristor voltage :

- 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 non-conducting they offer infinite (∞) impedance.
- The voltage waveform for SCR_1 is as shown in Fig. 3.7.13.

- 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. 3.7.12 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. 3.7.12.



(I-204) **Fig. 3.7.12 : Quadrant of operation for full converter with resistive load**

3.7.9 Analysis of Full Converter with Resistive Load :

Average load voltage :

- Referring to the load voltage waveform shown in Fig. 3.7.13 the average load voltage is given by,

$$V_{Ldc} = \frac{1}{\pi} \int_{\alpha}^{\pi} V_m \sin \omega t \, d\omega t \quad ...(3.7.24)$$

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

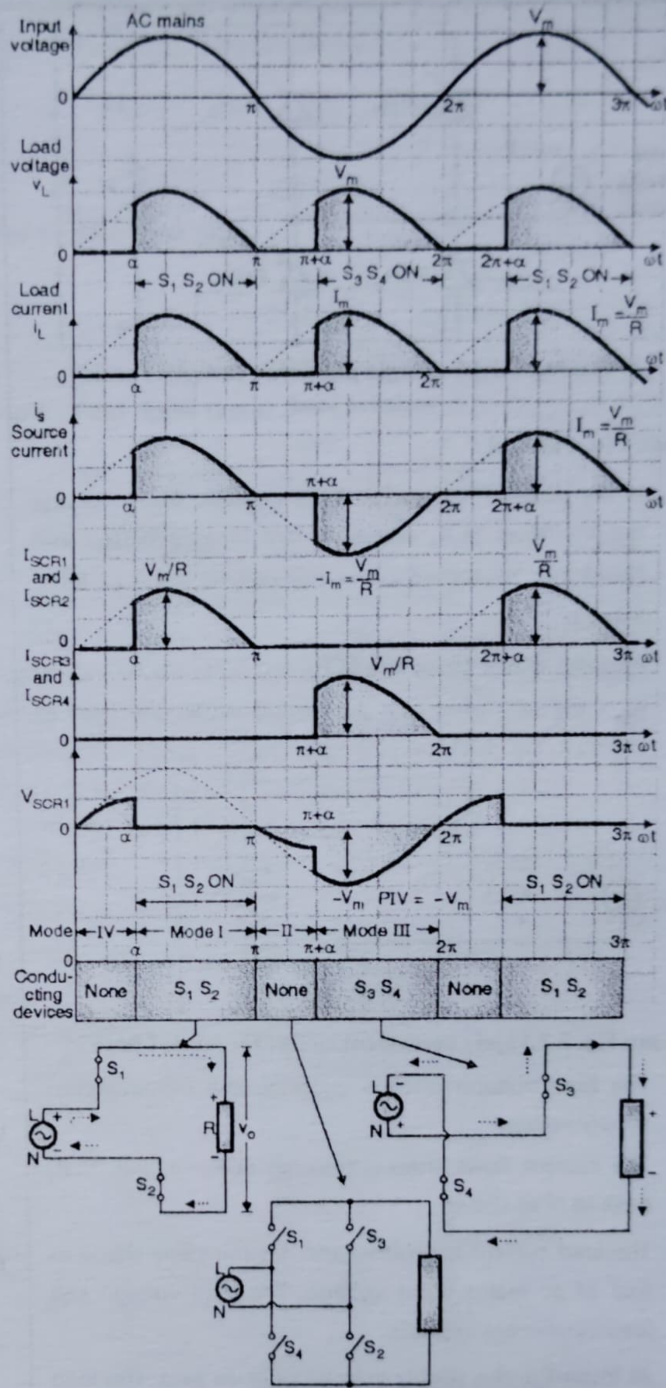
$$V_{Ldc} = \frac{V_m}{\pi} [1 + \cos \alpha] \quad ...(3.7.25)$$

Average load current :

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

Average load current $I_{L\,dc} = V_{L\,dc} / R$ ...(3.7.26)

$$I_{L\,dc} = \frac{V_m}{\pi R} [1 + \cos \alpha] \quad ...(3.7.27)$$



(I-205) **Fig. 3.7.13 : Waveforms for single phase line commutated full converter with resistive load**

RMS load voltage :

- Referring to the load voltage waveform of Fig. 3.7.13 we get,

$$V_{L\,rms} = \left\{ \frac{1}{\pi} \int_{\alpha}^{\pi} V_m^2 \sin^2 \omega t \, d\omega t \right\}^{1/2} \quad ...(3.7.28)$$

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

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

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

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

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

$$V_{L\,rms} = \frac{V_m}{\sqrt{2}}\left\{\frac{(\pi-\alpha) + \frac{1}{2}\sin 2\alpha}{\pi}\right\}^{1/2} \quad \text{...(3.7.29)}$$

Form factor and ripple factor :

– As defined earlier,

$$FF = \frac{V_{L\,rms}}{V_{Ldc}}$$

$$\text{and} \quad RF = [FF^2 - 1]^{1/2}$$

Thyristor currents :

– Referring to the waveform for the current through SCR_1 we get,

1. **Average thyristor current :**

$$I_{TH\,(av)} = \frac{1}{2\pi}\int_{\alpha}^{\pi} I_m \sin \omega t \, d\omega t \quad \text{...(3.7.30)}$$

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

$$= \frac{-I_m}{2\pi}(\cos \pi - \cos \alpha) = \frac{I_m}{2\pi}(1 + \cos \alpha)$$

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

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

– Refer to Equation (3.7.27)

$$I_{Ldc} = \frac{V_m}{2\pi R}(1 + \cos \alpha)$$

$$\therefore \quad I_{TH\,(av)} = \frac{I_{Ldc}}{2} \quad \text{...(3.7.31)}$$

2. **RMS thyristor current ($I_{TH\,(rms)}$) :**

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

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

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

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

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

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

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

– Refer to Equation (3.7.29)

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

$$\therefore \quad I_{TH(rms)} = \frac{I_{L\,rms}}{\sqrt{2}} \quad \text{...(3.7.32)}$$

3. **Peak thyristor current :**

$$I_{TH\,(peak)} = V_m / R \quad \text{...(3.7.33)}$$

Ex. 3.7.11 : For a single phase fully controlled bridge converter with R load

1. Draw circuit diagram.
2. Draw output voltage waveform at firing angle 60°.
3. Write formula for average DC voltage.

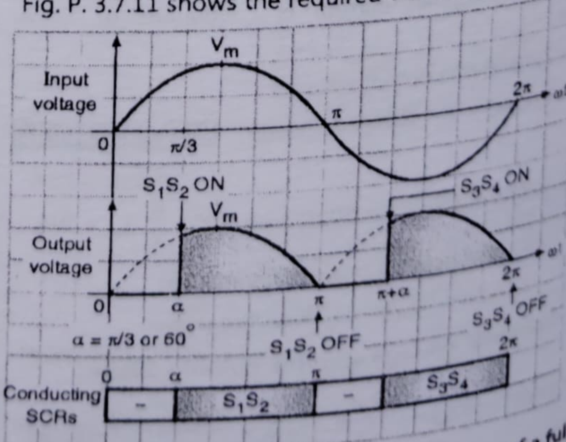
Soln. :

– Refer sections 3.7.8 and 3.7.9 for circuit diagram and formula of average dc voltages.

2. **Output voltage waveform :**

Given : Load R type, $\alpha = 60°$

– Fig. P. 3.7.11 shows the required waveform.



(I-2071) **Fig. P. 3.7.11 : Output voltage waveform of a full converter with R load**

Ex. 3.7.12 : A single phase full controlled converter is fed from 230 V, 50 Hz supply. The load is highly inductive. Find the average load voltage and current if the load resistance is 10 Ω and firing angle α = 45°. **May 16, 8 Marks**

Soln. :

Given : $V_{S\,rms} = 230$ V, $\alpha = 45°$, $R = 10\ \Omega$, 1ϕ full converter.

To find : 1. V_{Ldc} 2. I_{Ldc}

1. **Average load voltage :**

$$V_{Ldc} = \frac{2V_m}{\pi}\cos\alpha = \frac{2\sqrt{2}\times 230}{\pi}\times\cos 45$$

$$= 146.42 \text{ Volts} \qquad \text{...Ans.}$$

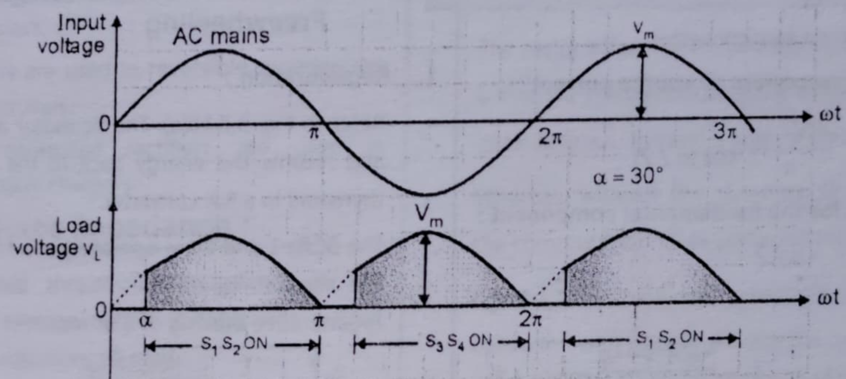
2. **Average load current :**

$$I_{Ldc} = \frac{V_{Ldc}}{R} = \frac{146.42}{10} = 14.64 \text{ Amps.} \qquad \text{...Ans.}$$

Ex. 3.7.13 : With the help of neat circuit diagram and waveforms, explain the operation of 1ϕ full-converter for α = 30 deg. and α = 60 deg. with R load. **March 19, 5 Marks**

Soln. :

- Refer section 3.7 for operation of full converter.
- Refer Fig. 3.7.4 for waveforms at α = 60°. Refer Fig. P. 3.7.13 for waveforms at α = 30°.



(I-2164) **Fig. P. 3.7.13 : Waveforms for single phase line commutated full converter with resistive load (α = 30°)**

3.7.10 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 3.7.2.

Table 3.7.2 : Comparison of semi converter and full converter

Sr. No.	Parameter	Full converter	Semiconverter
1.	Average load voltage (RL load)	$V_{Ldc} = \frac{2V_m}{\pi}\cos\alpha$	$V_{Ldc} = \frac{V_m}{\pi}(1+\cos\alpha)$
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	$\eta = \frac{8\cos^2\alpha}{\pi^2}$	$\eta = \frac{1}{FF^2}$
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	$I_{s1\,rms} = \frac{2\sqrt{2}\,I_o}{\pi}$	$I_{s1\,rms} = \frac{2\sqrt{2}\,I_o}{\pi}\cos\left[\frac{n\alpha}{2}\right]$

Sr. No.	Parameter	Full converter	Semiconverter
9.	Fundamental displacement angle	$\phi_1 = -\alpha$	$\phi_1 = -\frac{\alpha}{2}$
10.	Fundamental power factor (FPF)	FPF = cos α	FPF = cos (α / 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

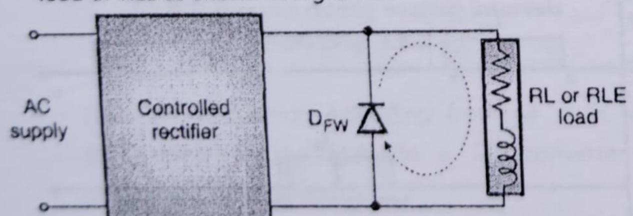
Note : The reactive power input to the semiconverter is half of the reactive power input to the full converter.

3.7.11 Use of Freewheeling Diode in AC-DC Converter : SPPU : Feb. 16

University Questions

Q. 1 Explain the significance of freewheeling diode in controlled rectifiers. **(Feb. 16, 3 Marks)**

- Freewheeling diode is connected across an inductive load or RLE as shown in Fig. 3.7.14.



(I-206) **Fig. 3.7.14 : Connection of D_{FW}**

- When all the devices connected in the converter circuit turn off, the current through RL load is abruptly interrupted and there is a negative self induced voltage across the load which turns on the freewheeling diode.
- This diode will dissipate the stored energy in the RL load.
- It also ensures that the load voltage is unipolar, because it does not allow the load voltage to become negative. D_{FW} can be used to convert a full converter into a semi-converter.
- If D_{FW} is used for converting a full converter to semi-converter, then the power factor improvement will take.
- Another use of D_{FW} is that it helps to make the load current continuous. In applications such as DC motor speed control, a continuous armature current improves the performance.

3.7.12 Effect of Freewheeling Diode on Full Converter : SPPU : Dec. 12, Dec. 13

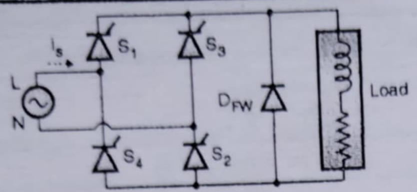
University Questions

Q. 1 What are the effects of freewheeling diode in full converter for R-L load ? **(Dec. 12, 3 Marks, Dec. 13, 4 Marks)**

- The expression for the input power factor of a fully controlled converter is

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

- This equation indicates that the power factor depends on the value of firing angle α.
- As α increases PF decreases. Ideally PF = 1 but practically we get maximum value of PF at α = 0 and $PF_{max} = \frac{2\sqrt{2}}{\pi}$ i.e. 0.9.
- The reduction in PF with increase in α will reduce the share of active power and increase the reactive power.
- One of the ways to improve the input power factor and reduce the reactive input power is to use a freewheeling diode in the full converter circuit as shown in Fig. 3.7.15(a).



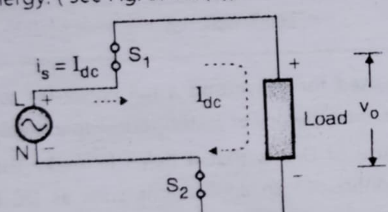
(1-207) **Fig. 3.7.15(a) : Full converter with freewheeling diode**

Operation with highly inductive load :

- It is assumed that the load is highly inductive and the load current is continuous and ripple free equal to I_{dc}.
- The operation in one cycle of input is divided into four modes. The voltage and current waveforms are as shown in Fig. 3.7.15(f).

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

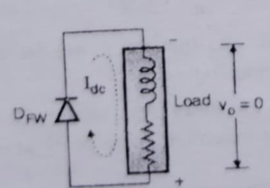
- S_1 and S_2 are turned on at α. Load voltage is positive and equal to instantaneous supply voltage. Load stores the energy. (see Fig. 3.7.15(b)).



(1-207) **Fig. 3.7.15(b) : Mode I equivalent circuit**

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

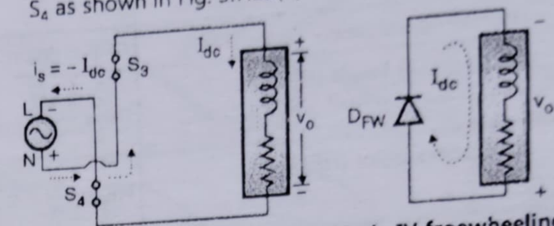
- At $\omega t = \pi$ the supply voltage goes to 0. The load current tries to decrease.
- To maintain it constant there is self induced voltage across the load. This voltage forward biases the freewheeling diode D_{FW}.
- SCRs 1 and 2 are turned off at π. The load voltage during freewheeling interval is 0. The source current $i_s = 0$.



(1-208) **Fig. 3.7.15(c) : Mode II freewheeling (π to $\pi + \alpha$)**

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

- At $\omega t = (\pi + \alpha)$, the SCRs S_3 and S_4 are turned on. Due to this the instantaneous input supply voltage is applied across the freewheeling diode.
- Due to the reverse voltage applied D_{FW} is turned off at $\omega t = (\pi + \alpha)$. The conduction continues through S_3 and S_4 as shown in Fig. 3.7.15(d).



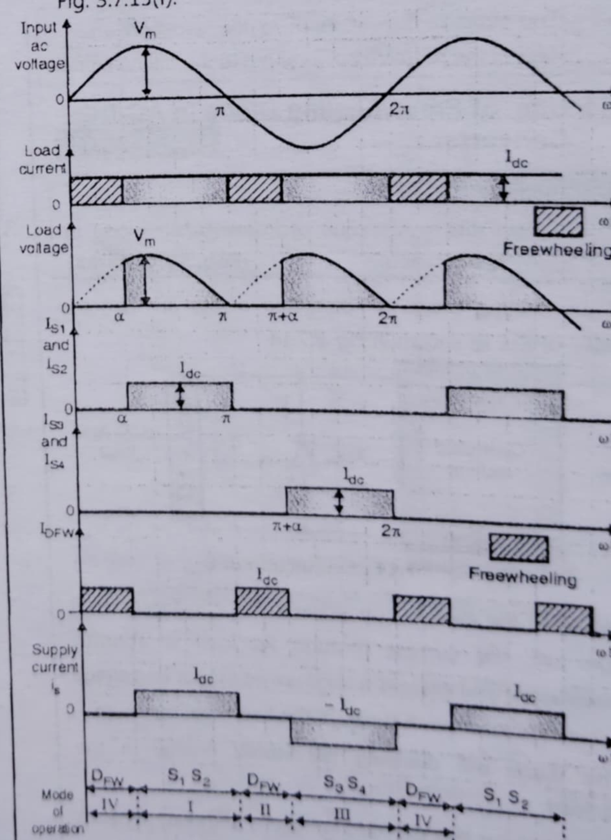
(d) Mode III **(e) Mode IV freewheeling**

(1-208) **Fig. 3.7.15**

- Load voltage is positive and equal to instantaneous supply voltage. The load stores energy. The supply current $i_s = - I_{dc}$.

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

- This mode is identical to mode II. The freewheeling starts at ωt = 0 to 2π when D_{FW} is forward biased. S_3 and S_4 are turned off. The load voltage is 0. The source current $i_s = 0$.
- The voltage and current waveforms are as shown in Fig. 3.7.15(f).



(1-209) **Fig. 3.7.15(f) : Voltage and current waveforms with FWD in the fully controlled bridge circuit**

Analysis :

- If the waveforms in the Fig. 3.7.15(f) are carefully observed, then the load voltage and source current (i_s) waveforms are identical to those for the semiconverter.
- Therefore we can directly use the following equations which were derived for the semiconverter.

1. **Average load voltage :**

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

- This is same as that for a semiconverter.

2. **RMS load voltage :**

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

- This is same as that for a semiconverter.

3. **RMS fundamental component of source current :**

$$I_{s1\,rms} = \frac{2\sqrt{2}\,I_{dc}}{\pi}\cos(\alpha/2)$$

4. **Displacement angle for the fundamental component :**

$$\phi_1 = -\alpha/2$$

5. **The active power :**

$$P_A = V_{s1} I_{s1}\cos\phi_1 = \frac{V_{s1}\,2\sqrt{2}\,I_{dc}}{\pi}\cos(\alpha/2)$$

$$= \frac{2\sqrt{2}}{\pi}V_{s1} I_{dc}\cos^2(\alpha/2)$$

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

$$P_A = \frac{2V_m}{\pi}I_{dc}\cos^2(\alpha/2) \quad ...(3.7.34)$$

6. **The reactive power :**

$$P_R = V_{s1} I_{s1}\sin\phi_1 = \frac{V_{s1}\,2\sqrt{2}\,I_{dc}}{\pi}\cos(\alpha/2)\sin(\alpha/2)$$

$$\text{with FWD } P_R = \frac{V_m I_{dc}}{\pi}\sin\alpha \quad ...(3.7.35)$$

without FWD the reactive power

$$P_R = V_1 \times \frac{2\sqrt{2}\,I_{dc}}{\pi}\sin\alpha = \frac{2V_m I_{dc}}{\pi}\sin\alpha \quad ...(3.7.36)$$

- Comparing the Equations (3.7.35) and (3.7.36) it is clearly seen that the reactive power is reduced to 50 % with the use of FWD in the circuit for the same values of I_{dc} and α.
- The active power input also increases.

7. **Power factor :**

1. With FWD the PF $= \dfrac{\sqrt{2}(1+\cos\alpha)}{[\pi(\pi-\alpha)]^{1/2}}$ ...(3.7.37)

(The power factor of semiconverter).

2. Without FWD, PF $= \dfrac{2\sqrt{2}}{\pi}\cos\alpha$ ...(3.7.38)

- Comparing these two equations for the same value of α it will be found that PF with FWD is closer to unity than that without FWD. Thus PF is also improved.

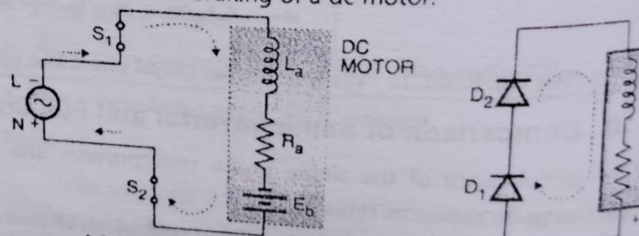
Drawback :

- Due to the freewheeling action, the load voltage is always positive. The full converter with FWD therefore becomes a single quadrant converter. It can operate only as rectifier and it cannot work as inverter.

3.7.13 Difference between Regeneration and Freewheeling :

1. **Regeneration :**

- Refer to Fig. 3.7.16(a). The dc motor acts as a generator and returns the energy back to the ac supply via the thyristors in a full converter.
- The SCRs 1 and 2 are operating at a firing angle $\alpha > 90°$, i.e. inverter operation. This is also known as the regenerative braking of a dc motor.



(a) Regeneration (b) Freewheeling

(I-727) Fig. 3.7.16

2. **Freewheeling :**

- As shown in Fig. 3.7.16(b), in the asymmetric configuration of the semiconverter, due to the stored energy by the inductive load, the diodes D_1 and D_2 are forward biased at $\omega t = \pi$ or 2π and freewheeling takes place through them.
- The stored energy is dissipated in the resistance of inductance and the diodes, in the form of heat.

3.7.14 Advantages of Full Converter :

- Following are some of the advantages of a full converter :

1. It can operate in the rectification as well as inversion modes.
2. Load stored energy can be returned back to source for reutilization.

3. Regeneration is possible. So in dc motor control, it is possible to incorporate the regenerative braking.

3.7.15 Disadvantages of Full Converter :

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

3.7.16 Application :

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

3.7.17 Applications of Controlled Rectifiers :

1. Semiconverters are used in unidirectional DC motor controllers.
2. Full converters are used in reversible regenerative dc motor controllers.
3. Half wave controlled rectifiers are used in automatic battery chargers

3.8 Effect of Source Impedance :

- We have neglected the source impedance in the derivation of the average output voltage, rms output voltage and other equations till now.
- It was assumed that the source is perfect with no source impedance.
- Due to this assumption the transfer of current from the outgoing SCR to the incoming SCR was assumed to be instantaneous.

3.8.1 Effect of Resistive Source Impedance :

- If the source impedance is resistive then there will be a voltage drop across this resistance and the average output voltage of the converter will reduce by an amount which is equivalent to the average drop across this resistance.
- Since the source resistance is normally small, it does not have any effect on the time taken for the transfer of current from outgoing SCR to the incoming SCR.
- But in practice the source resistance is small as compared with the source reactance.
- Therefore in the following discussion only the source inductance has been considered while analysing the converter performance.

3.8.2 Effect of Source Inductance :

- The effect of source inductance on the performance of converter performance has been discussed on the basis of following assumptions.

Assumptions :

1. The source resistance is negligible as compared to the source reactance.
2. The load inductance is infinitely large therefore the output current is virtually constant.

3.8.3 Single Phase with Source Inductance :

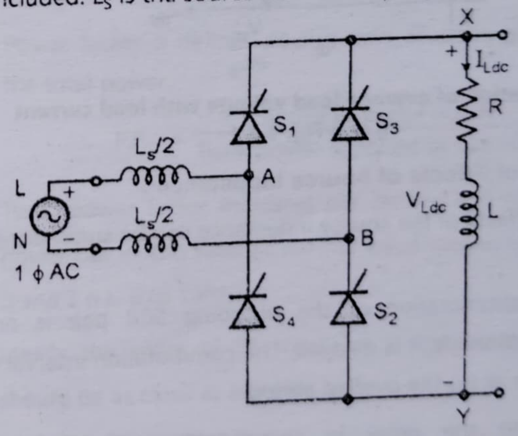
SPPU : Dec. 18

University Questions

Q. 1 Explain effect of source impedance on the performance of 1 ϕ full converter. Derive the expression for average output voltage.

(Dec. 18, 6 Marks)

- The major effect of source inductance in a full converter is that the commutation of the outgoing SCR pair is not instantaneous. Instead it takes a finite time.
- Whereas, without the presence of source inductance, the commutation takes place instantaneous.
- Fig. 3.8.1(a) shows the schematic diagram of the full converter with source inductance L_S . and Fig. 3.8.1(b) shows its equivalent circuit with source inductance included. L_S is the source inductance per phase.

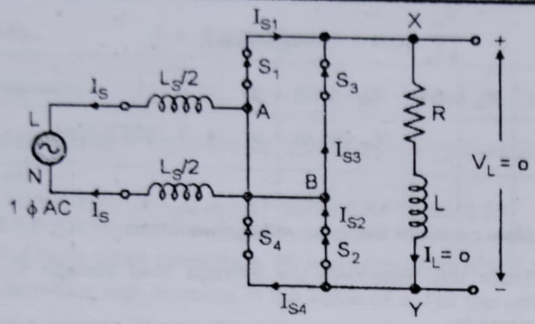


(a) Full converter configuration with source inductance

(I-2451) Fig. 3.8.1

Operation at ωt = (π + α) :

- To understand the effect of source inductance, let us consider the equivalent circuit at the instant ωt = (π + α) as shown in Fig. 3.8.1(b).
- At this instant the pair S_1 S_2 is already conducting and the other pair S_3 S_4 is turned on. This marks the beginning of commutation of the pair S_1 S_2.

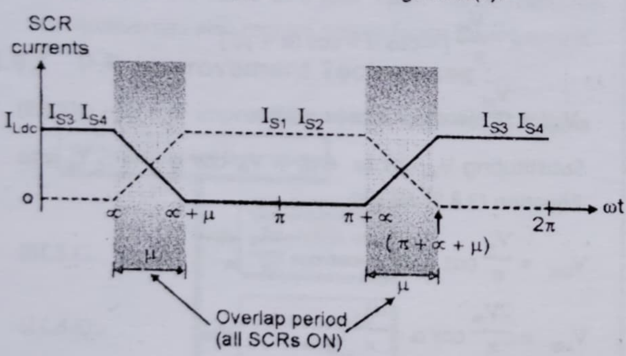


(b) Equivalent circuit during $\omega t = (\pi + \alpha)$ to $(\pi + \alpha + \mu)$

(I-2452) **Fig. 3.8.1**

Operation during $\omega t = (\pi + \alpha)$ and $\omega t = (\pi + \alpha + \mu)$:

- Because of the presence of source inductance L_S in series with each source, the current I_{s3} I_{s4} through the incoming SCRs S_3 S_4 builds up gradually from 0 to I_{dc}, while the current I_{s1} I_{s2} through the outgoing SCRs gradually reduces from I_{dc} to 0, during the interval $(\pi + \alpha)$ to $(\pi + \alpha + \mu)$ as shown in Fig. 3.8.1(c).



(c) SCR currents during overlap intervals

(I-2453) **Fig. 3.8.1**

- Thus, for a duration extending from $\omega t = (\pi + \alpha)$ to $(\pi + \alpha + \mu)$ all the SCRs in a full converter are conducting simultaneously.
- At instant $\omega t = (\pi + \alpha + \mu)$ the current through S_3 and S_4 reaches I_{dc}, while that through S_1 and S_2 goes to zero and commutation of the pair S_1 S_2 is complete.
- The entire load current now starts flowing through the pair S_3 S_4.

Overlap duration / Overlap angle (μ) :

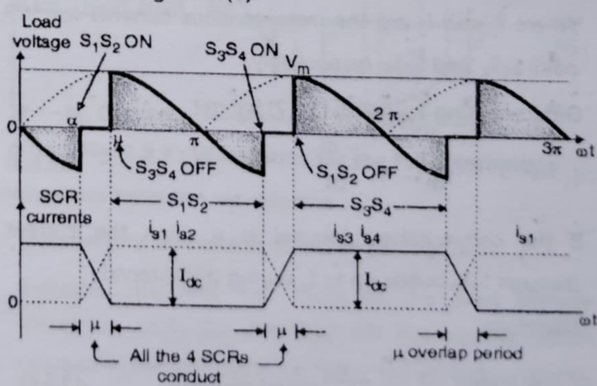
- The finite time duration corresponding to the commutation of the outgoing pair of SCRs is known as overlap period or commutation period or overlap angle which is denoted by (μ).
- During one cycle of input voltage there are two overlap durations for a full converter. One is from $\omega t = \alpha$ to $\omega t = (\alpha + \mu)$ and the other extending from $\omega t = (\pi + \alpha)$ to $(\pi + \alpha + \mu)$.

Effects of overlap :

- The effects of overlap i.e. source inductance are as given below:
  1. The commutation of the outgoing SCR pair is not instantaneous, it is delayed. The commutation interval is known as (μ) the overlap period.
  2. Due to the delay in commutation, all the SCRs (incoming and outgoing) conduct simultaneously during the commutation interval (μ).
  3. The instantaneous load voltage during the overlap period is zero because all SCRs in a full converter are conducting simultaneously which short circuits the load.
  4. The instantaneous load current during the overlap period is also zero and the source current only circulates among the SCRs.

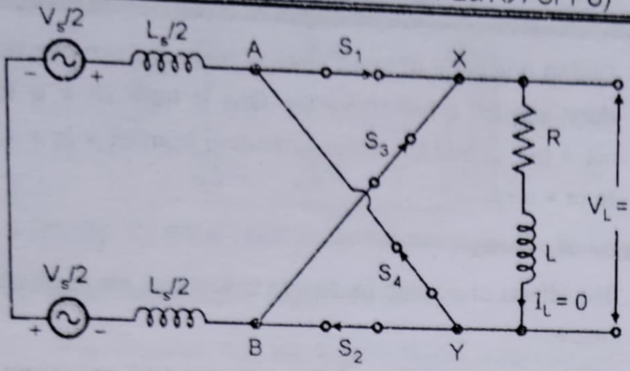
Waveforms :

- The load voltage and SCR current waveforms are as shown in Fig. 3.8.1(d).



(I-225) **Fig. 3.8.1(d) : Voltage and current waveforms, for a full converter with the source inductance**

- The Equivalent circuit of a full converter with the source inductance during overlap intervals is as shown in Fig. 3.8.1(e).
- Note that due to all SCRs conducting, points A,B,X and Y are short circuited to each other, effectively short circuiting the load.



(1-2454) **Fig. 3.8.1(e) : Equivalent circuit for a full converter with the source inductance during overlap interval**

3.8.4 Analysis of Effect of Source Inductance :

SPPU : Dec. 18

University Questions

Q. 1 Explain effect of source impedance on the performance of 1 ϕ full converter. Derive the expression for average output voltage.

(Dec. 18, 6 Marks)

- Refer to Fig. 3.8.1(d) and (e).
- Apply KVL to the loop comprising $V_s/2$, S_1, S_3 and $V_s/2$ during the overlap interval to get,

$$\frac{L_s}{2}\left(\frac{di_1}{dt} - \frac{di_2}{dt}\right) = V_m \sin \omega t \quad ...(3.8.1)$$

- With a constant load current I_o.

$$i_1 + i_2 = I_o \quad ...(3.8.2)$$

- Where i_1 and i_2 are the instantaneous currents for SCR pairs S_1S_2 and S_3S_4 respectively.
- Differentiating Equation (3.8.2) we get,

$$\frac{di_1}{dt} = \frac{-di_2}{dt} \quad ...(3.8.3)$$

- If the commutation interval is μ, then the current through S_3S_4 builds up to I_o during this interval.
- Therefore,

$$I_2 = \frac{2}{\omega L_s} \int_{\pi+\alpha}^{\pi+\alpha+\mu} \frac{-V_m}{2} \sin \omega t \, d\omega t = I_o \quad ...(3.8.4)$$

$$\therefore \quad I_2 = \frac{1}{\omega L_s} \int_{\pi+\alpha}^{\pi+\alpha+\mu} -V_m \sin \omega t \, d(\omega t) = I_o \quad ...(3.8.5)$$

- Integrating the Equation (3.8.5) we get,

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

$$\therefore \quad \frac{V_m}{\omega L_s} [\cos \pi \cos(\alpha + \mu) - \cos \pi \cos \alpha] = I_o$$

$$\therefore \quad \frac{V_m}{\omega L_s} [\cos \alpha - \cos(\alpha + \mu)] = I_o \quad ...(3.8.6)$$

$$\therefore \quad V_m \cos \alpha - V_m \cos(\alpha + \mu) = \omega L_s I_o$$

$$\therefore \quad V_m \cos(\alpha + \mu) = V_m \cos \alpha - \omega L_s I_o \quad ...(3.8.7)$$

- Now consider the load voltage waveform of Fig. 3.8.1(d). From this waveform the average load voltage V_{Ldc} is given by,

$$V_{Ldc} = \frac{1}{\pi} \int_{\alpha+\mu}^{\pi+\alpha} V_m \sin \omega t \, d(\omega t) \quad ...(3.8.8)$$

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

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

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

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

$$V_{Ldc} = \frac{V_m}{\pi} [\cos \alpha + \cos(\alpha + \mu)] \quad ...(3.8.9)$$

- Substituting $V_m \cos(\alpha + \mu) = V_m \cos \alpha - \omega L_s I_{dc}$ into Equation (3.8.9) we get,

$$V_{Ldc} = \frac{V_m}{\pi} \cos \alpha + \frac{V_m}{\pi} \cos \alpha - \frac{\omega L_s}{\pi} I_{dc} \quad ...(3.8.10)$$

$$V_{Ldc} = \frac{2V_m}{\pi} \cos \alpha - \frac{\omega L_s}{\pi} I_{dc} \quad ...(3.8.11)$$

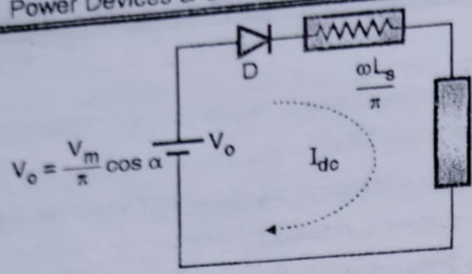
- In this equation $\frac{2V_m}{\pi} \cos \alpha$ is the average load voltage without source inductance.

$$\text{Let} \quad \frac{2V_m}{\pi} \cos \alpha = V_0$$

$$\therefore \quad V_{Ldc} = V_o - \frac{\omega L_s}{\pi} I_{dc} \quad ...(3.8.12)$$

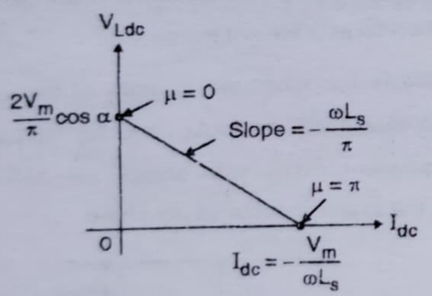
DC Equivalent Circuit :

- Equation (3.8.12) can be used to represent the DC equivalent circuit of a two pulse converter as shown in Fig. 3.8.1(f).
- Diode D is inserted in the circuit to indicate that the current is unidirectional. The effect of source inductance is that it presents an equivalent resistance $\omega L_s / \pi$.
- With the load current equal to I_{dc} the voltage drop is equal to $\frac{\omega L_s}{\pi} I_{dc}$.



(1-224) **Fig. 3.8.1(f) : DC equivalent circuit**

- Thus the reduction in average load voltage due to presence of source inductance is $\frac{\omega L_s}{\pi} I_{dc}$.
- From the Equation (3.8.12) we conclude that the average load voltage is dependent on :
  1. The source inductance L_s and
  2. The load current I_{dc}
- If any one or both the quantities increase the average output voltage will reduce.
- The variation of V_{Ldc} with I_{dc} is as shown in Fig. 3.8.1(g).



(g) Variation of average load voltage with load current
(1-224) **Fig. 3.8.1**

Summary of Effects of Source Inductance :

- The effects of the source inductance can be summarized as :

1. The commutation of the outgoing SCR pair is not instantaneous, it is delayed. The commutation interval is known as (μ) the overlap period.
2. Due to the delay in commutation, all the SCRs (incoming and outgoing) conduct simultaneously during the commutation interval (μ).
3. The instantaneous load voltage is zero during the overlap period.
4. There is reduction in the average load voltage. The drop in average load voltage is given by $\frac{\omega L_s}{\pi} I_{dc}$, thus indicating that the reduction in voltage is proportional to L_s and I_{dc}.

Ex. 3.8.1 : A single phase full converter is supplied from 230 V, 50 Hz supply. The load current is continuous and ripple free. If the average current I_{dc} = 150 Amp and the source inductance L_s = 0.1 mH determine the overlap angle at :

(a) $\alpha = 10°$ (b) $\alpha = 30°$ (c) $\alpha = 60°$.

Soln. :

Given : I_{dc} = 150 Amp, L_s = 0.1 mH.

(a) Overlap angle at $\alpha = 10°$:

- The equation for average output voltage with source inductance L_s is

$$V_{Ldc} = \frac{2V_m}{\pi}\cos\alpha - \frac{\omega L_s}{\pi} I_{dc} \quad ...(1)$$

- Substituting the values

$$V_{Ldc} = \frac{2\sqrt{2}\times 230}{\pi}\cos 10° - \frac{2\pi\times 50\times 0.1\times 10^{-3}}{\pi}\times 150$$

$$= 202.4 \text{ Volts} \quad ...\text{Ans.}$$

- The same V_{Ldc} can be expressed as follows,

$$V_{Ldc} = \frac{V_m}{\pi}[\cos\alpha + (\alpha+\mu)] \quad ...(2)$$

- Substituting the values we get,

$$202.4 = \frac{325.2}{\pi}[\cos 10 + \cos(\mu + 10)]$$

$$\mu = 3.95° \quad ...\text{Ans.}$$

- Similarly the value for the overlap angle μ can be calculated for $\alpha = 30°$ and $\alpha = 60°$.

(b) for $\alpha = 30°$ $\mu = 1.58°$ ...Ans.

(c) for $\alpha = 60°$ $\mu = 0.94°$ ...Ans.

Note : As the delay angle α increases, the overlap μ will decrease.

Ex. 3.8.2 : In a single phase full converter the reduction in the output voltage due to the effect of source inductance is 3 Volts. The load current I_{dc} is continuous and ripple free equal to 100 Amp. Find the value of source inductance L_s and overlap angle μ if supply voltage is 230 V 50 Hz. and $\alpha = \pi/6$.

Soln. :

Given : $\alpha = \pi/6 = 30°$, supply voltage 230 V, 50 Hz,
I_{dc} = 100 A, Voltage drop= 3 V

To find : L_s and μ

1. **Find source Inductance :**

- Reduction in output average voltage due to source inductance $= \frac{\omega L_s}{\pi} I_{dc}$. It is given that this voltage = 3 V

$$\therefore \frac{\omega L_s}{\pi} I_{dc} = 3 \text{ Volts.}$$

$$\text{But } \omega = 2\pi f$$

$$\therefore \frac{2\pi \times 50 \times L_s}{\pi} \times 100 = 3$$

$$\therefore L_s = 0.3 \text{ mH.} \qquad \text{...Ans.}$$

2. **Find overlap angle :**

- Average output voltage,

$$V_{Ldc} = \frac{2V_m}{\pi} \cos \alpha - \frac{\omega L_s}{\pi} I_{dc} \qquad \text{...(1)}$$

$$= \frac{2\sqrt{2} \times 230}{\pi} \cos \pi/6 - 3$$

$$= 176.3 \text{ Volts} \qquad \text{...Ans.}$$

$$\text{Also } V_{Ldc} = \frac{V_m}{\pi} [\cos \alpha + \cos (\alpha + \mu)] \qquad \text{...(2)}$$

$$\therefore 176.3 = \frac{\sqrt{2} \times 230}{\pi} [\cos 30 + \cos (\mu + 30)]$$

$$\therefore \mu = 3.1° \qquad \text{...Ans.}$$

Ex. 3.8.3 : A single phase bridge full converter is connected to an ac supply of 330 sin 314 ωt and 50 Hz. It operates at $\alpha = \pi/4$. The load current is maintained at 5 Amp. and load voltage is 140 Volts. Calculate the source inductance, angle of overlap and load resistance.

Soln. :

Given : $V_m = 330$ V, f = 50 Hz, $\alpha = \pi/4$,

$I_{dc} = 5$A, $V_{Ldc} = 140$ Volts.

To find : L_S and μ and R_L

(a) **Load resistance :**

$$R_L = V_{Ldc}/I_{dc} = 140 / 5 = 28\ \Omega \qquad \text{...Ans.}$$

(b) **Overlap angle :**

$$V_{Ldc} = \frac{V_m}{\pi} [\cos \alpha + \cos (\alpha + \mu)]$$

$$140 = \left[\frac{330}{\pi} (\cos \pi/4) + \cos (\mu + \pi/4)\right]$$

$$\therefore \mu = 6.26° \qquad \text{...Ans.}$$

(c) **Source inductance:**

$$V_{Ldc} = \frac{2 V_m}{\pi} \cos \alpha - \frac{\omega L_s}{\pi} I_{dc}$$

$$\therefore 140 = \frac{2 \times 330}{\pi} \cos (\pi / 4) - \frac{2\pi \times 50}{\pi} L_s \times 5$$

$$\therefore L_s = 17.1 \text{ mH} \qquad \text{...Ans.}$$

Ex. 3.8.4 : For a 1 ϕ full converter with large inductive load, if the source inductance L_s is considered, find the average output voltage and reduction in the output voltage due to overlap if $\alpha = 30°$ and $\mu = 2°$ with supply voltage of 230 Volts.

Soln. :

1. Average output voltage with source inductance

$$V_{Ldc} = \frac{V_m}{\pi} [\cos (\alpha + \mu) + \cos \alpha]$$

$$\therefore V_{Ldc} = \frac{\sqrt{2} \times 230}{\pi} [\cos (32) + \cos 30]$$

$$= 177.46 \text{ Volts} \qquad \text{...Ans.}$$

2. Average output voltage without considering source inductance.

$$V_{o(av)} = \frac{2V_m}{\pi} \cos \alpha = \frac{2\sqrt{2} \times 230}{\pi} \cos 30$$

$$= 179.46 \text{ Volts.}$$

3. Reduction in average output voltage

$$= V_{o(av)} - V_{Ldc}$$

$$= 179.46 - 177.46$$

$$= 2 \text{ Volts} \qquad \text{...Ans.}$$

3.9 Need of Power Factor Improvement :

Definition :

- In ac circuits, out of the total power supplied by the source, only a fraction is useful which is known as active power and the remaining part is not useful which is known as reactive power.
- Power factor is defined as the ratio of active power to the total power.

$$\therefore \text{P.F.} = \frac{\text{Active or useful power}}{\text{Total power supplied by the source}}$$

- Thus, power factor indicates the percentage of useful power out of the total power. Its value ranges between 0 and 1 (i.e. 0 to 100%).
- Ideally the value of PF must be 1 and practically it should be as close as possible to 1.

PF of AC- DC Converters :

- The PF of a full converter is given by,

$$\text{P.F.} = 0.9 \cos \alpha \qquad \text{...(3.9.1)}$$

- Whereas, PF of a semiconverter is given by,

$$\text{P.F.} = \frac{\sqrt{2}\,(1 + \cos \alpha)}{[\pi (\pi - \alpha)]^{1/2}} \qquad \text{...(3.9.2)}$$

- These equations indicate that the PF of both full and semi-converters varies with the value of firing angle α as shown in Table 3.9.1

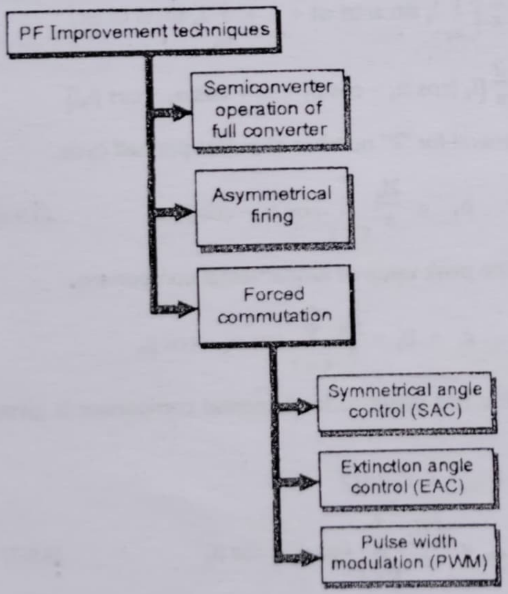
Table 3.9.1

α (degrees)	0	15	30	45	60	75	90
Semiconverter P.F.	0.9	0.92	0.92	0.887	0.83	0.74	0.64
Full converter P.F.	0.9	0.87	0.78	0.64	0.45	0.23	0

- For both these converters, PF is maximum at $\alpha = 0$ and decreases with increase in the value of α. For the values of α close to 90o the PF of these converters is very poor.
- This is why; we need the power factor of AC-DC converters to be improved.
- Equations 3.9.1 and 3.9.2 show that, for any value of α except 0°, the PF of a semiconverter is higher and therefore better than that of a full converter.
- Therefore whenever PF improvement is thought of, we will have prefer a semiconverter over a full converter.
- However for semiconverters also, the PF decreases with increases in the value of α (see Table 3.8.1). Therefore, semiconverters also require power factor improvement.

3.9.1 P.F. Improvement Techniques :

- Some of the PF improvement techniques are as follows :

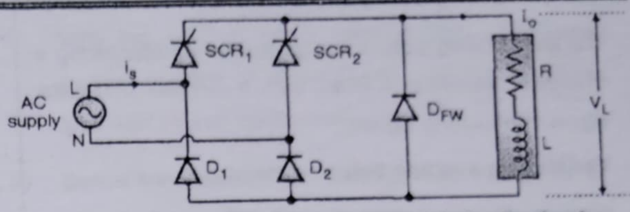


(I-1412) **Fig. 3.9.1 : P.F. Improvement techniques**

3.9.2 PWM Technique for PF Improvement :

Circuit used :

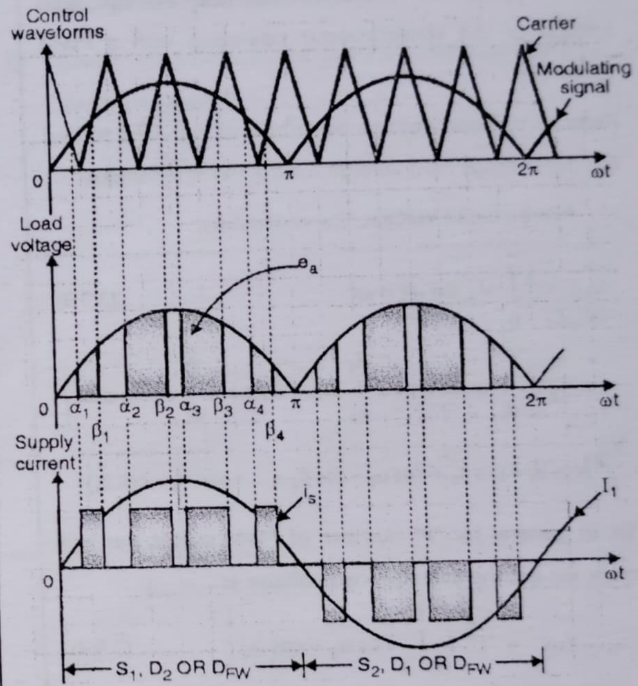
- As semiconverters have a higher PF than that of a full converter, we will use the single phase semiconverter with forced commutation circuits with the PWM technique of PF improvement.



(I-153) **Fig. 3.9.2 : Semiconverter with inductive load**

Waveforms :

- The SCRs in a semiconverter are turned on and off several times per half cycle of the ac supply. The voltage and current waveforms are as shown in Fig. 3.9.3.



(I-1423) **Fig. 3.9.3 : Waveforms for the PWM technique**

Conclusions from the waveforms :

1. **Conducting devices in positive half cycle :**
   - Consider the first half cycle of the load voltage waveform. SCR_1 D_2 and D_{FW} are the devices which conduct in this half cycle. i.e. from "α_1" to "β_2", S_1 and D_2 conduct simultaneously.
   - At "β_1", SCR_1 is turned off and D_{FW} will start conducting making the load voltage zero. At "α_2" again SCR_1 is turned on, S_1 D_2 will conduct and D_{FW} is turned off.
2. **Conducting devices in negative half cycle :**
   - Similarly we get a PWM waveform across the load in the next half cycle also. In this half cycle SCR_2, D_1 and D_{FW} conduct.

3. **Generation of gate signals :**

- The gate driving signals are generated by comparing a triangular waveform (carrier) with a rectified sinusoidal signal (modulating signal).

4. **Variation in average output voltage :**

- We can vary the average output voltage of circuit by varying the modulation index of PWM.

Analysis of PWM Technique :

1. **Expression for average load voltage :**

- Let us derive the expression for the average load voltage of the semiconverter operating with a PWM technique.
- Refer to the load voltage waveform of Fig. 3.9.3 to find out the average load voltage for the PWM technique.

$\therefore$ Average load voltage V_{Ldc} is given by,

$$V_{Ldc} = \frac{1}{\pi}\int_0^{\pi} V_m \sin \omega t \, d\omega t \qquad ...(3.9.3)$$

$$= \frac{V_m}{\pi}\left\{\int_{\alpha_1}^{\beta_1} \sin \omega t \, d\omega t + \int_{\alpha_2}^{\beta_2} \sin \omega t \, d\omega t + ... \int_{\alpha_4}^{\beta_4} \sin \omega t \, d\omega t\right\}$$

$$= \frac{V_m}{\pi}\{\cos\alpha_1 - \cos\beta_1 + \cos\alpha_2 - \cos\beta_2 + ... + \cos\alpha_4 - \cos\beta_4\}$$

- So, in general for "P" number of PWM pulses per half cycle, we get the average load voltage as

$$V_{Ldc} = \frac{V_m}{\pi}\left\{\sum_{K=1}^{P} \cos\alpha_k - \cos\beta_k\right\} \qquad ...(3.9.4)$$

- This is the equation for the average load voltage.

2. **RMS value of supply current ($I_{s\,rms}$)**

- A semiconverter is operating with a PWM technique. The load is highly inductive with the load current equal to "I_a" which is continuous and ripple free.
- Let us obtain the expression for the rms value of supply current.
- Consider the supply current waveform of Fig. 3.9.3 i.e. $i_s(t)$. This waveform has an odd symmetry, a half wave symmetry and quarter wave symmetry.
- Considering its half wave symmetry we can write,

$$I_{s\,rms} = \left[\frac{1}{\pi}\int_0^{\pi} i_s^2(t)\, d\omega t\right]^{1/2}$$

$$I_{s\,rms} = \left[\frac{1}{\pi}\left\{\int_{\alpha_1}^{\beta_1} I_a^2 \, d\omega t + \int_{\alpha_2}^{\beta_2} I_a^2 \, d\omega t + ... + \int_{\alpha_4}^{\beta_4} I_a^2 \, d\omega t\right\}\right]^{1/2}$$

$$= \left[\frac{I_a^2}{\pi}(\beta_1 - \alpha_1 + \beta_2 - \alpha_1 + ... + \beta_4 - \alpha_4)\right]^{1/2}$$

- For "P" number of pulses per half cycles we can write,

$$I_{s\,rms} = I_a\left[\frac{1}{\pi}\sum_{k=1}^{p} \beta_k - \alpha_k\right]^{1/2} \qquad ...(3.9.5)$$

3. **Rms value of fundamental component ($I_{1\,rms}$) :**

- Let us now obtain the expression for the rms value of fundamental component of supply current.
- Due to quarter wave symmetry,

$$a_n = 0 \text{ ... for all values of n.}$$

$$b_n = 0 \text{ ... for even values of n.}$$

$$\therefore \quad \phi_1 = 0$$

$$\therefore \quad b_1 = \frac{2}{\pi}\int_0^{\pi} i_s(t) \cdot \sin\omega \, d\omega t$$

- Note that we have used the equation for "b_1" by keeping in our mind the half wave symmetry of the waveform.

$$\therefore \quad b_1 = \frac{2}{\pi}\left\{\int_{\alpha_1}^{\beta_1} I_a \sin\omega t d\omega t + ... + \int_{\alpha_4}^{\beta_4} I_a \sin\omega t d\omega t\right\}$$

$$= \frac{2}{\pi}\{I_a[\cos\alpha_1 - \cos\beta_1 + ... + \cos\alpha_4 - \cos\beta_4]\}$$

- In general for "P" number of pulses per half cycle,

$$\therefore \quad b_1 = \frac{2I_a}{\pi}\sum_{K=1}^{p} \cos\alpha_k - \cos\beta_k \, p \qquad ...(3.9.6)$$

- The peak value of fundamental component,

$$c_1 = b_1 = \frac{2I_a}{\pi}\sum_{K=1}^{p} \cos\alpha_k - \cos\beta_k$$

- $\therefore$ The rms value of fundamental component is given by,

$$I_{1\,rms} = c_1 / \sqrt{2}$$

$$\therefore \quad I_{1\,rms} = \frac{\sqrt{2}I_a}{\pi}\sum_{K=1}^{p} \cos\alpha_k - \cos\beta_k \qquad ...(3.9.7)$$

4. **Power factor :**

- The power factor of this circuit is given by,

$$PF = \frac{I_{1rms}}{I_{s\,rms}}$$

- We can obtain the expression for PF by substituting the expressions of $I_{1\,rms}$ and $I_{s\,rms}$.

Ex. 3.9.1 : A 1 ϕ semiconverter is operated from 230 V, 50 Hz ac supply. The armature current of the motor load is continuous and ripple free equal to 10 amp. Calculate $I_{s\,rms}$, $I_{1\,rms}$, FPF, DF, HF and PF, for a PWM control with three pulses per half cycle and $\alpha_1 = 30^\circ$, $\alpha_2 = 75^\circ$ and $\beta_1 = 60^\circ$. Find the average voltage and the above parameters.

Soln. :

Given :

PWM control, $\alpha_1 = 30^\circ, \alpha_2 = 75^\circ\ \beta_1 = 60^\circ$

$I_a = 10$ amp, supply voltage $V_{s\,rms} = 230$ V.

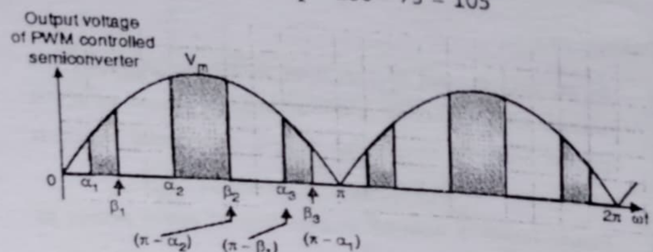
1. Average output voltage ;

$$V_{L\,dc} = \frac{V_m}{\pi} \sum_{K=1}^{p} \cos\alpha_k - \cos\beta_k \quad ...(1)$$

From the data, $\beta_3 = 180 - \alpha_1 = 180 - 30 = 150^\circ$

$$\alpha_3 = 180 - \beta_1 = 180 - 60 = 120^\circ \quad ...(2)$$

See Fig. P. 3.9.3, $\beta_2 = 180 - \alpha_2 = 180 - 75 = 105^\circ$



(I-1424) **Fig. P. 3.9.3 : Load voltage with PWM control**

$$\therefore\ V_{L\,dc} = \frac{230\sqrt{2}}{\pi}\,[\cos\alpha_1 - \cos\beta_1 + \cos\alpha_2 - \cos\beta_2 + \cos\alpha_3 - \cos\beta_3]$$

$$= \frac{230\sqrt{2}}{\pi}\,[\cos 30 - \cos 60 + \cos 75 - \cos 105 + \cos 120 - \cos 150]$$

$$\therefore\ V_{L\,dc} = 129.4 \text{ Volts} \quad ...(3)$$

2. Rms value of supply current :

$$I_{s\,rms} = I_a\left[\frac{1}{\pi}\sum_{k=1}^{P} \beta_k - \alpha_k\right]^{1/2}$$

$$\therefore\ I_{s\,rms} = 10\left[\frac{1}{\pi}(\beta_1 - \alpha_1 + \beta_2 - \alpha_2 + \beta_3 - \alpha_3)\right]^{1/2}$$

$$= 10\left[\frac{1}{\pi}(60 - 30 + 105 - 75 + 150 - 120)\right]^{1/2}$$

$$= 10\,[90/180]^{1/2}$$

$$\therefore\ I_{s\,rms} = 7.07 \text{ Amp}$$ ...Ans.

3. Rms value of fundamental component ($I_{1\,rms}$) :

- Rms value of fundamental component of supply current ($I_{1\,rms}$) is given by,

$$I_{1\,rms} = \frac{\sqrt{2}\,I_a}{\pi}\sum_{K=1}^{p} \cos\alpha_k - \cos\beta_k \quad ...(3)$$

$$= \frac{\sqrt{2}\times 10}{\pi}\,[\cos\alpha_1 - \cos\beta_1 + \cos\alpha_2 - \cos\beta_2 + \cos\alpha_3 - \cos\beta_3]$$

$$= 4.5\,[\cos 30 - \cos 60 + \cos 75 - \cos 105 + \cos 120 - \cos 150]$$

$$\therefore\ I_{1\,rms} = 5.62 \text{ amp}$$ ...Ans.

4. $\text{DF} = \frac{I_{1rms}}{I_{s\,rms}} = 0.7954$ ...Ans.

5. $\text{FPF} = \cos\phi_1 = 1$ (unity) ...Ans.

6. $\text{PF} = \text{DF} \times \text{FPF} = 0.7954$ (lagging) ...Ans.

7. $\text{HF} = \left[\frac{1}{\text{DF}^2} - 1\right]^{1/2} = 0.7619$ or 76.19 % ...Ans.

Review Questions

Q. 1 Define commutation.

Q. 2 Explain the terms natural commutation.

Q. 3 Explain the terms line commutation.

Q. 4 Explain the terms forced commutation and define voltage commutation and current commutation.

Q. 5 Define a phase controlled rectifier.

Q. 6 Explain the principle of a phase controlled rectifier.

Q. 7 With the help of neat circuit diagram and waveforms explain the operation of a single phase half wave controlled rectifier with inductive load.

Q. 8 With the help of neat circuit diagram and waveforms explain the operation of a single phase half wave controlled rectifier with resistive load.

Q. 9 With the help of neat circuit diagram and waveforms explain the operation of a single phase semiconverter with inductive load.

Q. 10 With the help of neat circuit diagram and waveforms explain the operation of a single phase semiconverter with resistive load.

Q. 11 Derive the expressions for average load voltage, rms load voltage, form factor and ripple factor for a single phase semiconverter with inductive load.

Q. 12 Define the following :

1. Form factor
2. Ripple factor

Q. 13 Define the following :

1. Displacement factor
2. Power factor
3. Harmonic factor
4. Active power
5. Reactive power

Q. 14 Derive the expressions for the following parameters for a single phase semiconverter with inductive load.

1. Displacement factor
2. Power factor
3. Harmonic factor
4. Active power
5. Reactive power

Q. 15 Why semiconverter is preferred over full converter where regenerative braking is not required ?

Q. 16 Define power factor and displacement factor highlighting the difference.

Q. 17 A single phase semiconverter is operated from 230 V/50 mains supply. It is driving a large inductive load. The load current has a peak value of I_a and is continuous and ripple free. Derive the following equations :

(a) Fourier series for supply current

(b) Rms and fundamental component of supply current

(c) Distortion factor and displacement power factor

(d) Harmonic factor of supply current

(e) Supply power factor

Q. 18 Differentiate between : Symmetrical and asymmetrical configurations of semiconverter.

Q. 19 Explain different configurations of semiconverter and compare them.

Q. 20 With the help of neat circuit diagram and waveforms explain the operation of a single phase full converter with inductive load in the rectifier mode.

Q. 21 With the help of circuit diagram and waveforms of input voltage, input current, fundamental component of input current, output voltage, output current explain working of single phase fully controlled bridge for inductive load. If two SCRs are replaced by two diodes in above circuit to form half controlled bridge then how the performance will be improved ?

Q. 22 Explain the inverting mode of a 1 ϕ fully controlled bridge.

Q. 23 With the help of neat circuit diagram and waveforms explain the operation of a single phase full converter with resistive load.

Q. 24 Compare half and full controlled bridge rectifiers.

Q. 25 Explain the following concepts in LCC :

1. Regeneration
2. Freewheeling.

Draw suitable equivalent circuits.

Q. 26 Derive the expression for the average output voltage of : Single phase full converter.

Assume the load to be highly inductive. Draw the variation of average output voltage with α. Also draw the output voltage waveforms.

Q. 27 A single phase full converter is operated from mains. A freewheeling diode is placed across the load. Draw the following waveforms and give the quadrant in which it operates. How the circuit differs from a full converter ? Derive the output voltage equation.

1. Supply voltage and current.
2. Gate drives and thyristor currents.
3. Output voltage and current.

Assume large inductive load.

Q. 28 For a 1 ϕ full converter with highly inductive load find out following :

1. Displacement factor (DPF)
2. Distortion factor (DF)
3. Supply power factor (PF)
4. Harmonic factor (HF).

Q. 29 With the help of circuit diagram and waveforms explain working of single phase LCC for inductive load with source inductance.

Q. 30 Derive the expression for average load voltage for a single phase LCC for inductive load with source inductance.

Q. 31 With the help of circuit diagram and waveforms explain the two quadrant operation of single phase LCC for inductive load.

Q. 32 Explain the PWM technique for PF improvement of a single phase LCC.

□□□

Unit II

Chapter 4

Three Phase Converter

Syllabus

Three phase full converters using SCR for R load and its performance analysis, Single phase PWM rectifier using IGBT, Three phase controlled rectifier using IGBT, Difference between SCR based conventional rectifiers and IGBT based rectifiers.

Chapter Contents

4.1 Introduction :

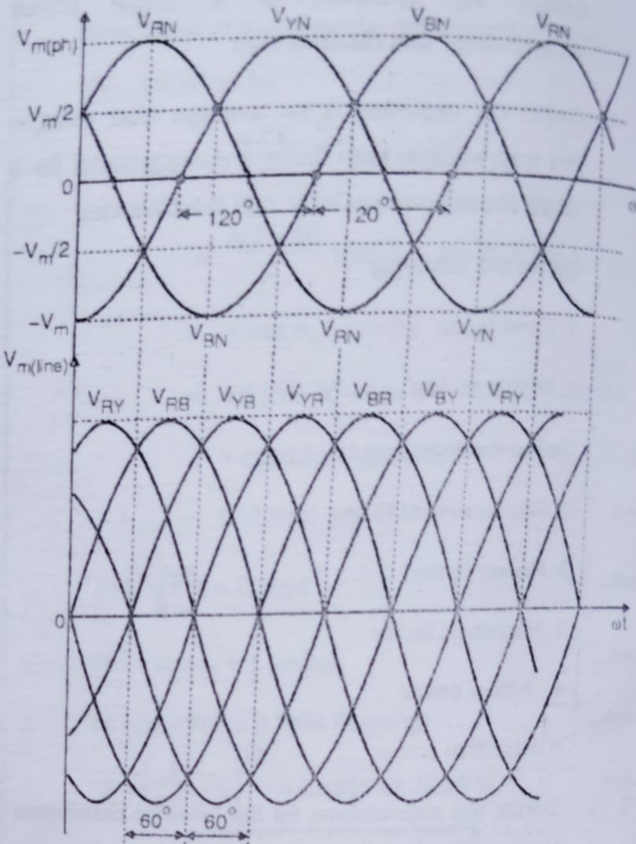
- In the three phase uncontrolled rectifier we use diodes. So there is no control over the voltage across the load or power delivered to the load.
- In order to control the load power, we will have to replace the diodes by SCRs.
- Why to use polyphase rectifiers when the single phase rectifiers are available ? The answer is that the polyphase rectifiers are preferred over the single phase converters for their higher output power, lower ripple contents, higher ripple frequency and low harmonics in the input supply current.
- When the power ratings exceed 5 kW the three phase controlled rectifiers are used in place of the single phase rectifiers.
- Why to use polyphase rectifiers when the single phase rectifiers are available ? The power supplying capacity of polyphase rectifiers is limited (say upto 2 kW).
- If power higher than this is to be delivered to the load, then we have to use the polyphase rectifiers.

4.1.1 3-Phase Transformers :

- For the 3 phase uncontrolled and controlled rectifiers, we need to use a 3 phase transformer on the input side.
- Many configurations of 3 phase transformers, such as star star, delta delta, delta-star, star delta etc are available. But the most widely used configuration is delta-star configuration for many of its advantages.

4.2 Three Phase AC Supply :

- Before we start the discussion about different configurations, certain basic concepts must be very clear in your mind. They are as follows :
- In a four wire three phase ac system, there are three phases namely R, Y and B and the fourth wire is the neutral (N).
- **Phase voltage :** It is the voltage measured between a phase (R, Y or B) and neutral (N). i.e. V_{RN}, V_{YN} and V_{BN}.
- **Line voltage :** It is the voltage measured between any two phases e.g. V_{RY}, V_{RB}, V_{YB} ... etc.
- The phase voltages V_{RN}, V_{YN} and V_{BN} are phase shifted from each other by 120° as shown in Fig. 4.2.1.
- The line voltages are phase shifted from each other by 60° as shown in Fig. 4.2.1.



(I-235) **Fig. 4.2.1 : Phase and line voltage waveforms**

- The peak or maximum phase voltages are denoted by $V_{m\,(ph)}$ whereas the peak line voltages are denoted by $V_{m\,(line)}$. Each line voltage and phase voltage is a sine wave.
- The frequency of each phase voltage and each line voltage is 50 Hz. The sequence of the phase and line voltages is as given in Fig. 4.2.1 and it always remains the same (unchanged).

4.3 Drawing Phase and Line Voltages :

4.3.1 How to Draw the Phase Voltages ?

- Refer to Fig. 4.3.1.

Step 1 : Draw the five equidistant lines 1 to 5. (These can be the lines of your notebook page).

Step 2 : Now place the points A, C and E on line number 2. These are called as the phase crossover points on the positive side.

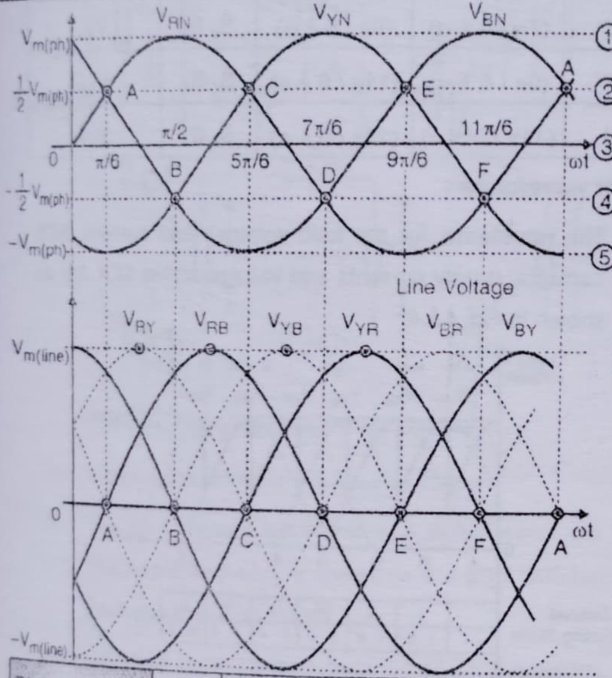
Step 3 : Now place points exactly at the center of these points, on the line number 1. These points are the peak phase voltage points on the positive side.

Step 4 : The peak voltage points on the positive side coincide with the phase crossover points on the negative side.

Therefore project these peak voltage points to line number 4. These points i.e. B, D and F i.e. the phase crossover points on the negative side.

Step 5 : Now place the peak negative voltage points exactly, at the centers of points B, D and F on line number 5.

Step 6 : Now join all these points sinusoidally as shown in Fig. 4.3.1 to complete the phase voltage waveforms.



Phase crossover point	A	B	C	D	E	F
Phase angle w.r.t. zero crossing of V_{RN}	30° or π/6 radians	90° or π/2 radians	150° or 5π/6 radians	210° or 7π/6 radians	270° or 9π/6 radians	330° or 11π/6 radians

(I-237) **Fig. 4.3.1 : How to draw phase and line voltages ?**

4.3.2 How to Draw the Line Voltages ?

Step 1 : Project all the phase crossover points A to F on one more line.

These points correspond to the zero crossing points for the six line voltages that we are going to draw now. (See Fig. 4.3.1).

Step 2 : Consider the points "A" and "D". At these points the phases R and B cross each other. Therefore these points will correspond to zero crossing points for the line voltages V_{RB} and V_{BR}.

Step 3 : Phase R becomes more positive than phase B after the crossover point A. Therefore between the points A and D the line voltage V_{RB} must have a positive half cycle and V_{BR} must have a negative half cycle.

Step 4 : Now mark the peak line voltage points (+ve and –ve) exactly at the center of A and D. And join these points in a sinusoidal way to draw the positive half cycle of and V_{RB} the negative half cycle of V_{BR}.

Step 5 : Using the same principle draw the other line voltages from V_{RY} to V_{BY} as shown in Fig. 4.3.1. Note that $V_{m(line)} = \sqrt{3}\, V_{m(ph)}$

Why does point A correspond to 30° or π/6 radians ?

– Refer Fig. 4.3.1. The voltage at point A is $\frac{V_{m\,(ph)}}{2}$.

– The instantaneous phase voltage $V_{RN} = V_{m(ph)} \sin \omega t$

$$\therefore \quad \text{At point A, } V_{RN} = \frac{V_{m\,(ph)}}{2}$$

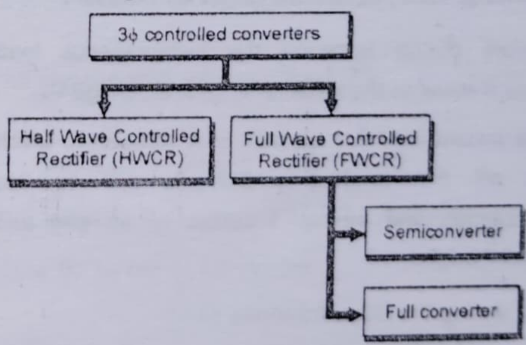
$$\therefore \quad \frac{V_{m\,(ph)}}{2} = V_{m(ph)} \sin \omega t$$

$$\therefore \quad \sin \omega t = 0.5$$

$$\therefore \quad \omega t = 30° \text{ or } \pi/6 \text{ radians.}$$

4.4 Classification of Three Phase Controlled Rectifiers :

– The three phase controlled converters are classified as shown in Fig. 4.4.1.



(I-238) **Fig. 4.4.1 : Classification of 3-ϕ controlled rectifiers**

– The half wave controlled rectifier is the basic building block for the full wave circuits. However, in this chapter we will discuss only the full converter circuit.

4.5 Three Phase Full Converter :

SPPU : May 07, May 08, Dec. 09

University Questions

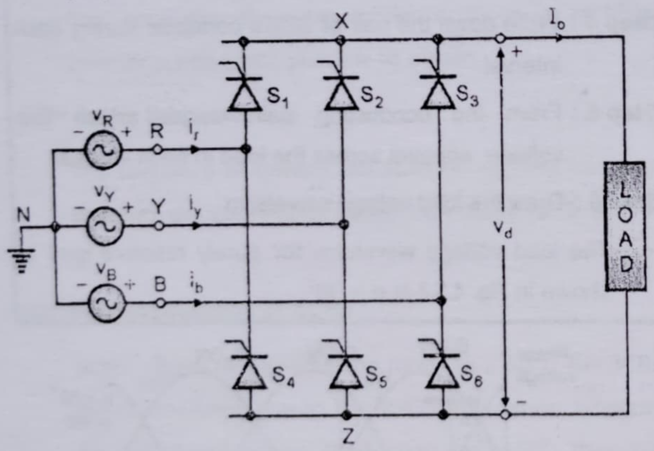
Q. 1 Draw the circuit diagram, voltage and current waveform for α = 30°, resistive load of three phase full bridge converter. **(May 07, 8 Marks)**

Q. 2 Draw the circuit diagram of three phase full converter with a resistive load. Explain its working and draw the load voltage, input supply, load current at $\alpha = \frac{\pi}{6}$. **(May 08, 10 Marks)**

Q. 3 Draw the circuit diagram for three phase fully controlled converter with R load. Draw load current and load voltage waveforms. **(Dec. 09, 2 Marks)**

Circuit diagram :

- The circuit diagram for a 3 phase fully controlled bridge converter or simply a full converter is as shown in Fig. 4.5.1(a).
- There are six SCRs connected in the bridge configuration, as shown in Fig. 4.5.1(a), which can be divided into two groups.
- SCRs S_1, S_2, S_3 form the positive group while SCRs S_4, S_5, S_6 form the negative group.

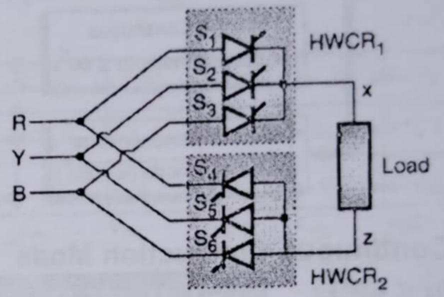


(I-2435) **Fig. 4.5.1(a) : 3 phase full converter**

- The load is connected between common cathode point (X) of the SCRs S_1, S_2, S_3 and the common anode point (Z) of the lower three SCRs S_4, S_5, S_6.
- At any given instant one SCR from S_1, S_2, S_3 and another SCR from S_4, S_5, S_6 will conduct simultaneously. That means two SCRs conduct simultaneously.
- The return path for the load current is through one of the lower three SCRs.
- The load voltage is therefore, equal to any one of the six possible line voltages depending on which pair of SCRs is conducting at the given time.
- The supply neutral is not connected anywhere in the circuit.
- The three phase full converters are used in industrial applications in which two quadrant operation is required.
- The frequency of the output ripple voltage is $6 \times 50 = 300$ Hz and the filtering requirement is less than that of the three phase semi or half wave converters.

Equivalent circuit :

- The three phase full converter circuit can be redrawn as a combination of two half wave controlled converter circuits as shown in Fig. 4.5.1(b).



(I-246) **Fig. 4.5.1(b) : Full converter redrawn as combination of two halfwave converter**

How to measure α ?

- In the single phase AC-DC converters, we measure firing angle with respect to the zero cross over point of the AC supply voltage.
- Now what will be the reference point from which "α" will be measured for a three phase full converter circuit ?
- The answer is the reference points for measurement and adjustment of the firing angle (α) are the "Phase Crossover Points" A, B, C, D, E and F for different SCRs connected in the full converter as listed in Table 4.5.1.

Table 4.5.1

Phase crossover point	A	B	C	D	E	F
Reference for SCR	S_1	S_6	S_2	S_4	S_3	S_5

4.5.1 Full Converter with R Load :

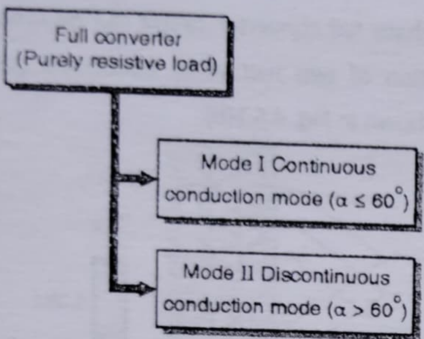
SPPU : Dec. 09

University Questions

Q. 1 Draw the circuit diagram for three phase fully controlled converter with R load. Draw load current and load voltage waveforms. **(Dec. 09, 2 Marks)**

- With a purely resistive load (R) the load current will be in phase with the load voltage. The instantaneous load current will be equal to the instantaneous load voltage divided by the resistance R.

- Naturally, the shape of the load current waveform will be same as that of the load voltage waveform.
- The 3 phase fully controlled converter with a purely resistive load, has two modes of operation depending on the value of α as follows.



(1-261)

4.5.2 Continuous Conduction Mode ($\alpha \le 60°$) : SPPU : May 07, May 08, Dec. 09

University Questions

Q. 1 Draw the circuit diagram, voltage and current waveform for $\alpha = 30°$, resistive load of three phase full bridge converter. **(May 07, 8 Marks)**

Q. 2 Draw the circuit diagram of three phase full converter with a resistive load. Explain its working and draw the load voltage, input supply, load current at $\alpha = \frac{\pi}{6}$. **(May 08, 10 Marks)**

Q. 3 Draw the circuit diagram for three phase fully controlled converter with R load. Draw load current and load voltage waveforms. **(Dec. 09, 2 Marks)**

- The load current in this mode is continuous. The firing angle $\alpha \le 60°$.
- SCRs 1,2 and 3 are turned on at an angle α with respect to the phase cross over points A, C and E respectively with α less than 60°.
- Similarly, SCRs 4, 5 and 6 are turned on at an angle α with respect to the phase cross over points B,D and F respectively.

Load voltage waveform :

Procedure to Draw the Load Voltage Waveform :

- We will follow the procedure given below to draw the load voltage waveform for continuous conduction mode.

Step 1 : Draw the phase and line voltage waveforms.

- Refer Fig. 4.3.1, which shows the phase and line voltage waveforms with phase cross over points.

Step 2 : For the given value of α (in Fig. 4.5.2 $\alpha = 30°$), mark the points at which the six SCRs turn on. The phase cross over points A, B, ...F will be the reference points from which we must measure the firing angle.

- Table 4.5.2 lists the reference points for measuring α for different SCRs.

Table 4.5.2

Phase crossover point	A	B	C	D	E	F
Reference for SCR	S_1	S_6	S_2	S_4	S_3	S_5

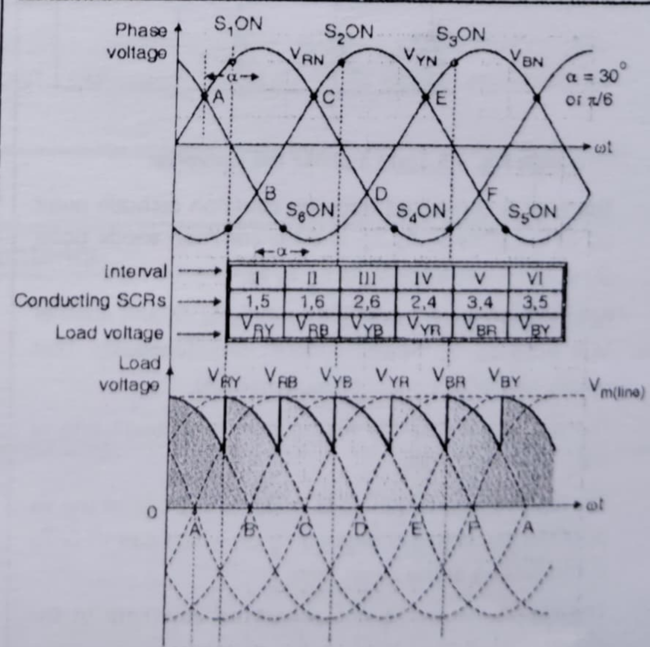
Step 3 : Mark the six intervals from I to VI. Note that an interval corresponds to the time duration between the adjacent SCR turn on points.

Step 4 : Write down the pair of SCRs conducts during each interval.

Step 5 : From the conducting pair, decide which line voltage appears across the load in each interval.

Step 6 : Draw the load voltage waveform.

- The load voltage waveform for purely resistive load is shown in Fig. 4.5.2 at $\alpha = 30°$.



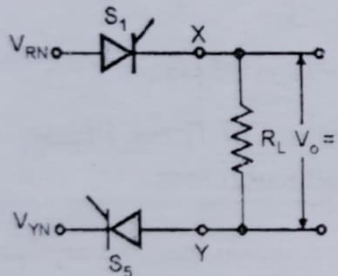
(1-2073(I)) **Fig. 4.5.2 : Load voltage for full converter with $\alpha = 30°$**

SCR turn on sequence :

- The sequence in which SCRs are turned on is 1, 6, 2, 4, 3, 5 with respect to the phase cross over points A, B,C, D, E and F respectively.

Operation during interval - I :

- As shown in Fig. 4.5.2, six different intervals are identified, with the first interval starting at point (α) with respect to A i.e. the point at which SCR S_1 turns on ((π / 6 + α).
- This interval extends from ((π/6 +α) to ((π / 2 + α) where SCR S_6 from the negative group is turned on.
- The conducting SCRs during interval-I are S_1 and S_5 i.e. one each from positive and negative groups of SCRs. Phase voltages R and Y get connected to the load points X and Y respectively as shown in the equivalent circuit of interval I in Fig 4.5.3.



(I-2443) **Fig. 4.5.3 : Equivalent circuit for interval I**

- Therefore during interval-I the instantaneous load voltage is equal to the instantaneous line voltage V_{RY}.
- At the instant ((π / 2 + α), SCR S_6 is turned on, which turns off the conducting SCR S_5 due to line commutation and interval I comes to an end and interval II begins.

Operation during the other intervals :

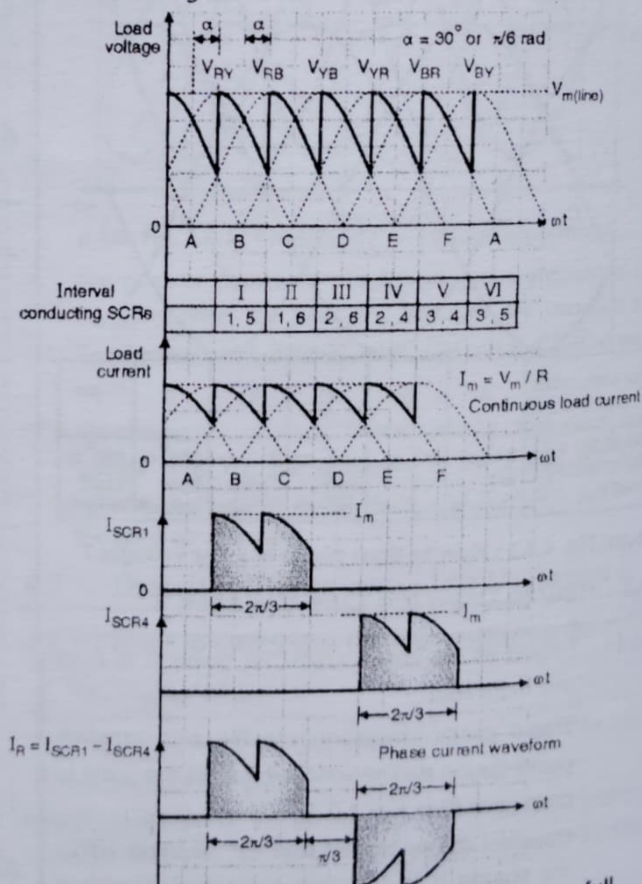
- Similarly we can explain the operation in the remaining five intervals.
- As shown in Fig. 4.5.3, six different intervals are identified, in each interval two SCRs will conduct simultaneously.
- All the intervals in Table 4.5.3 are marked with respect to zero crossing point of the phase voltage V_{RN}.
- Table 4.5.3 shows the starting and end point of the interval.
- Each interval is 60° wide. As seen from the Table 4.5.3 and Fig. 4.5.3, at a time two SCRs conduct.

Table 4.5.3

Interval	From	To	On devices	Line voltages across the load
I	$(\pi/6 + \alpha)$	$(\pi/2 + \alpha)$	$S_1\ S_5$	V_{RY}
II	$(\pi/2 + \alpha)$	$(5\pi/6 + \alpha)$	$S_1\ S_6$	V_{RB}
III	$(5\pi/6 + \alpha)$	$(7\pi/6 + \alpha)$	$S_2\ S_6$	V_{YB}
IV	$(7\pi/6 + \alpha)$	$(9\pi/6 + \alpha)$	$S_2\ S_4$	V_{RY}
V	$(9\pi/6 + \alpha)$	$(11\pi/6 + \alpha)$	$S_3\ S_4$	V_{BR}
VI	$(11\pi/6 + \alpha)$	$(13\pi/6 + \alpha)$	$S_3\ S_5$	V_{BY}

Other waveforms :

- The waveforms for the load voltage, load current, SCR currents, supply currents and voltage across SCR are as shown in Fig. 4.5.4.

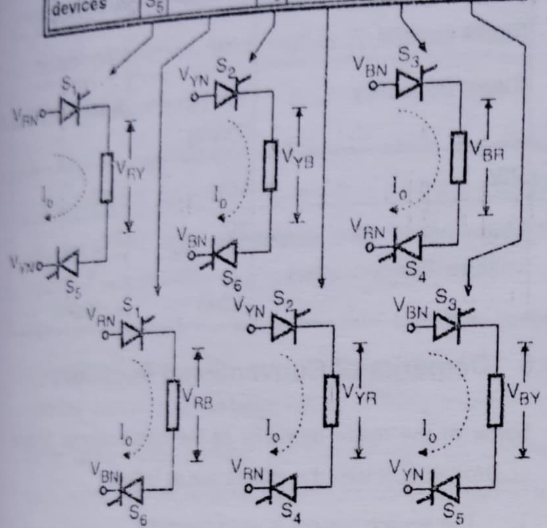


(I-262) **Fig. 4.5.4 : Voltage and current waveforms for a full converter with a resistive load (Continuous conduction mode)**

- The load current is in phase with the load voltage. As the instantaneous load voltage does not go to zero in this mode, the instantaneous load current also won't go to zero, making the load current continuous in nature.

- The equivalent circuits for the 6 different intervals are as shown in Fig. 4.5.5.

Interval	I	II	III	IV	V	IV
Conducting devices	S_1 S_5	S_1 S_6	S_2 S_6	S_2 S_4	S_3 S_4	S_3 S_5



(I-2441) Fig. 4.5.5 : Equivalent circuits

- The observations from Fig. 4.5.5 are as follows :

1. The load voltage waveform is 6 pulse waveform. The ripple frequency is therefore 6 × 50 = 300 Hz. Each pulse is of 60° width.
2. Each SCR conducts for a duration of 2 π / 3 radians or 120°. Each SCR conducts up to the instant where the next SCR from the same group (or half wave rectifier) is turned ON. The type of commutation is line commutation.
3. At any instant, two SCRs conduct simultaneously.
4. The instantaneous load voltage is equal to one of six line voltages, depending on the conducting SCR pair.
5. The maximum (peak) reverse voltage across each SCR is $V_{m\,(line)} = \sqrt{3}\, V_{m\,(ph)}$.
6. The phase current waveform is drawn by subtracting the current waveforms of the two SCRs connected in that phase.

   e.g. $I_R = I_{S1} - I_{S4}$, $I_Y = I_{S2} - I_{S5}$ and $I_B = I_{S3} - I_{S6}$ the supply current I_R is a quasi square waveform as shown in Fig. 4.5.5.

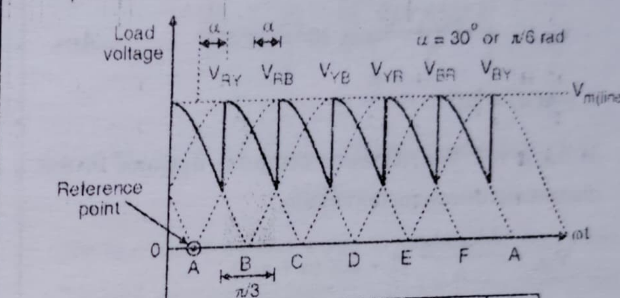
As can be seen in Fig. 4.5.5, the load voltage waveform has 6 pulses, making the ripple frequency = 300 Hz.

- The six line voltages are in the sequence V_{RY}, V_{RB}, V_{YB}, V_{YR}, V_{BR} and V_{BY} appear across the load, for a duration of 60° each.
- Each SCR conducts for a duration of 2π/3 radians or 120°. The peak reverse voltage across each SCR is,

$$V_{m\,(line)} = \sqrt{3}\, V_{m\,(ph)}$$

Expression for average load voltage :

- Refer Fig. 4.5.6. We are going to consider the shaded portion of the waveform for integration.



Interval		I	II	III	IV	V	VI
conducting SCRs		1, 5	1, 6	2, 6	2, 4	3, 4	3, 5

(I-2442) Fig. 4.5.6 : Load voltage for continuous conduction

- The phase crossover point "A" will be treated as a reference point to write down the limits of integration and the expression for V_{RY}.

$$\therefore \text{ The average load voltage} = V_{Ldc} = \frac{1}{\pi/3} \int_{\alpha}^{(\pi/3\,+\,\alpha)} V_{RY}\, d\omega t$$

$$\text{But } V_{RY} = V_{m\,(line)} \cdot \sin(\omega t + \pi/3)$$

- This is because, the line voltage V_{RY} leads our reference point "A" by 60° or π/3 radians.

$$\therefore V_{Ldc} = \frac{3}{\pi} \int_{\alpha}^{(\pi/3\,+\,\alpha)} V_{m\,(line)} \sin(\omega t + \pi/3)\, d\omega t$$

$$= \frac{3\, V_{m\,(line)}}{\pi} [\cos(\alpha + \pi/3) - \cos(2\pi/3 + \alpha)]$$

$$= \frac{3\, V_{m\,(line)}}{\pi} [\cos\alpha \cos(\pi/3) - \cos(2\pi/3) \cos\alpha]$$

$$= \frac{3\, V_{m\,(line)}}{\pi} [\cos\alpha]$$

$$\therefore V_{Ldc} = 3 \frac{V_{m\,(line)}}{\pi} \cos\alpha \qquad \text{...(4.5.1)}$$

Note : The expression for V_{Ldc} in Equation (4.5.1) is valid only for the continuous conduction mode.

Normalized voltage and RMS load voltage :

- The equations for normalized voltage and the rms voltage are also applicable to this mode i.e.

$$V_n = \cos \alpha \quad ...(4.5.2)$$

and $$V_{L\,rms} = V_{m\,(line)} \left[\frac{1}{2} + \frac{3\sqrt{3}}{4\pi} \cos 2\alpha \right]^{1/2} \quad ...(4.5.3)$$

4.5.3 Discontinuous conduction mode ($\alpha \geq 60°$) :

- For $\alpha > 60°$, the load current becomes discontinuous, as the load voltage and load current both reach zero as shown in Fig. 4.5.7. This will turn off the conducting pair of SCRs.
- With the resistive load, the full converter works as a single quadrant converter as the load voltage cannot become negative at all.
- The converter therefore works only as a rectifier. Inverter action is not possible to obtain.

SCR Firing Sequence :

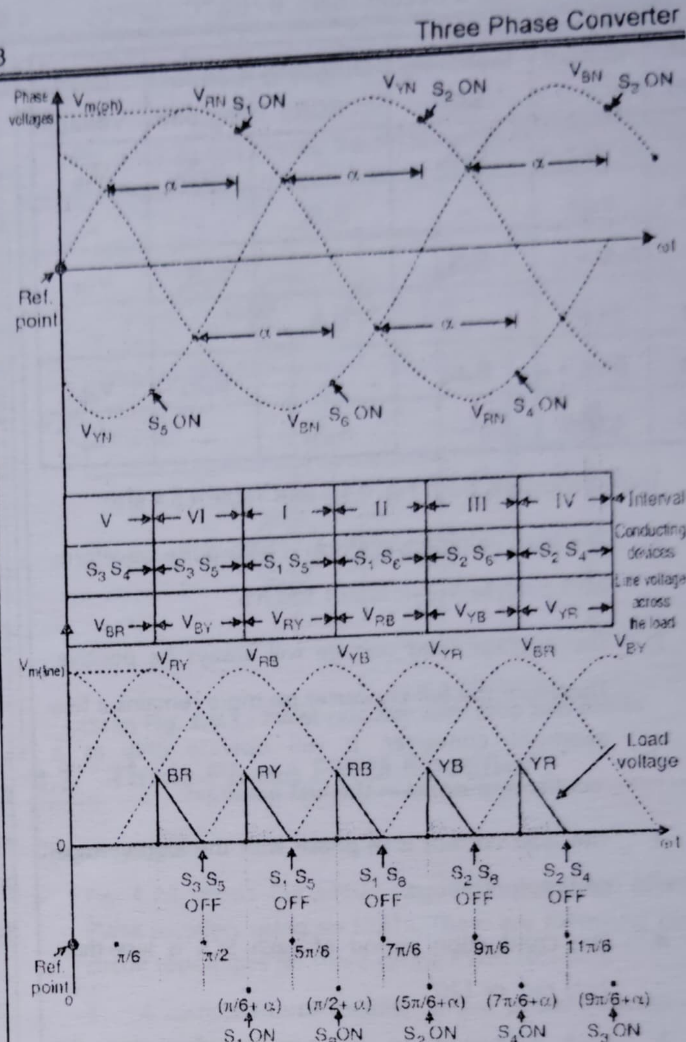
- The sequence of turning the SCRs on remains same as that with the continuous conduction mode i.e. 1, 6, 2, 4, 3, 5.

Natural commutation of SCRs :

- In the continuous conduction mode ($\alpha \leq 60°$), the SCRs are commutated due to the line commutation, whereas for the discontinuous conduction ($\alpha > 60°$) they are commutated due to natural commutation, when the driving line voltage passes through a zero, thereby reducing the SCR current to zero.

Load voltage Waveform :

- For $\alpha > 60°$, the line voltage driving a conducting pair of SCRs goes to zero before the end of their conducting interval. The waveforms for discontinuous conduction are shown in Fig. 4.5.7.
- For example SCR S_1 is turned on at the instant $\omega t = (\pi/6 + \alpha)$. During the interval I, S_1 and S_5 conduct, connecting the instantaneous line voltage V_{RY} across the load.
- The load current is in phase with the load voltage due to the resistive nature of load.



(I-263) **Fig. 4.5.7 : Load voltage for a full converter with a resistive load (discontinuous conduction)**

- At the instant, $5\pi/6$, $V_{RY} = 0$ therefore load current = 0 and the conducting SCRs S_1 and S_5 are turned off due to natural commutation.

Note : The load current is in phase with load voltage hence it also will be discontinuous.

- Table 4.5.4 summarises the operation of a full converter with resistive load in the discontinuous conduction mode.

Table 4.5.4 : Summary of operation with discontinuous mode

Sr. No.	Instant	Incoming SCR	Outgoing SCR	Conducting pair	Load voltage
1.	$\pi/6 + \alpha$	S_1S_5	–	S_1S_5	V_{RY}
2.	$5\pi/6$	–	S_1S_5	–	Zero
3.	$\pi/2 + \alpha$	S_1S_6	–	S_1S_6	V_{RB}
4.	$7\pi/6$	–	S_1S_6	–	–

Sr. No.	Instant	Incoming SCR	Outgoing SCR	Conducting pair	Load voltage
5.	$(5\pi/6 + \alpha$	S_2S_6	–	S_2S_6	V_{YB}
6.	$9\pi/6$	–	S_2S_6	–	–
7.	$7\pi/6 + \alpha$	S_2S_4	–	S_2S_4	V_{YR}
8.	$11\pi/6$	–	S_2S_4	–	–
9.	$9\pi/6 + \alpha$	S_3S_4	–	S_3S_4	V_{BR}
10.	$13\pi/6$	–	S_3S_4	–	–

- The conclusions from Fig. 4.5.7 and Table 4.5.4 are :

1. The load voltage waveform is a six pulse waveform, with a ripple frequency of 300 Hz.
2. The average load voltage will always be positive. Therefore the full converter no more remains a two quadrant converter. It will operate only as a rectifier and works in the first quadrant.
3. The load current is in phase with the load voltage and discontinuous.
4. The conduction period of each SCR is less than $2\pi/3$ rad. or 120°.
5. Each SCR has to be retriggered during its conduction period, therefore the multiple pulse triggering for each SCR is necessary.

Expression for average voltage :

- Refer Fig. 4.5.7. The average load voltage is given by,

$$V_{Ldc} = \frac{1}{\pi/3} \int V_{RY}\, d\omega t$$

$$= \frac{3}{\pi} \int_{\pi/6+\alpha}^{5\pi/6} V_{m\,(line)} \sin(\omega t + \pi/6)\, d\omega t$$

$$= \frac{-3\,V_{m\,(line)}}{\pi} \times \left[\cos(\omega t + \pi/6)\right]_{\pi/6+\alpha}^{5\pi/6}$$

$$= \frac{-3\,V_{m\,(line)}}{\pi} [\cos \pi - \cos(\pi/3 + \alpha)]$$

$$= \frac{-3\,V_{m\,(line)}}{\pi} [-1 - \cos(\alpha + \pi/3)]$$

$$\therefore V_{Ldc} = \frac{3\,V_{m\,(line)}}{\pi} [1 + \cos(\alpha + \pi/3)] \quad ...(4.5.4)$$

- Note that this is different than that for the continuous conduction mode.

4.5.4 Comparison of Continuous and Discontinuous Modes :

Table 4.5.5 : Comparison of continuous and discontinuous modes

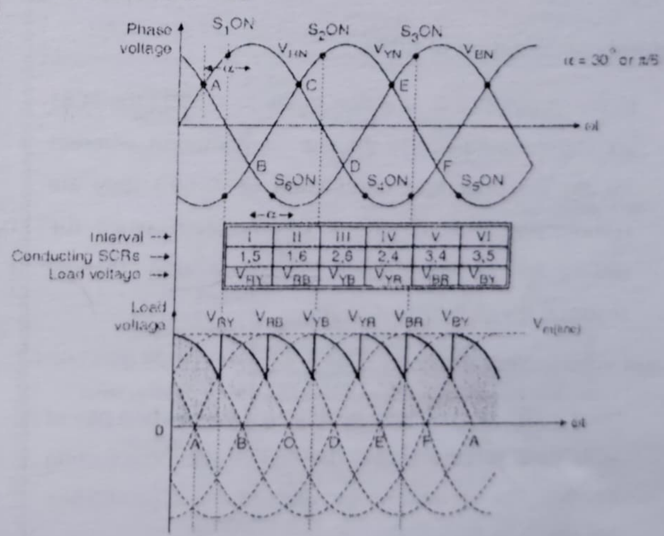
Sr. No.	Parameter	Continuous Mode	Discontinuous Mode
1.	Load current	Never becomes zero	Becomes zero
2.	Firing angle	$< 60^\circ$	$\geq 60^\circ$
3.	Output voltage waveforms	Refer Fig. 4.5.2	Refer Fig. 4.5.7
4.	Commutation	Line	Natural
5.	Average voltage	$3\frac{V_{m\,(line)}}{\pi}\cos\alpha$	$\frac{3\,V_{m\,(line)}}{\pi}[1 + \cos(\alpha + \pi/3)]$

Ex. 4.5.1 : Draw the circuit diagram, voltage and current waveform for $\alpha = 30^\circ$, for the resistive load of three phase full bridge converter. **May 07, 8 Marks**

Soln. :

- Refer section 4.5.1 for circuit diagram. The required waveforms are as shown in Fig. P. 4.5.1.

Waveforms at $\alpha = 30^\circ$:



(1-2073) Fig. P. 4.5.1 : Waveforms at $\alpha = 30^\circ$

Ex. 4.5.2 : A three phase full converter operating from three phase, 415 V, 50 Hz supply with resistive load. Determine average output voltage for $\alpha = 30^\circ$ and $\alpha = 90^\circ$.

Soln. :

Given : 3 phase full converter, R load, $V_{L\,rms} = 415$ V,

$\alpha_1 = 30°$, $\alpha_2 = 90°$.

To find : V_{Ldc}.

1. **V_{Ldc} at $\alpha_1 = 30°$:**

– At $\alpha_1 = 30°$, the full converter operates in the continuous conduction mode.

$$\therefore V_{Ldc} = \frac{3\,V_{m\,(line)}}{\pi}\cos\alpha = \frac{3\sqrt{2}\,V_{L\,rms}}{\pi}\cos\alpha$$

$$\therefore V_{Ldc} = \frac{3\sqrt{2}\times 415}{\pi}\cos 30° = 485.4 \text{ V}$$ ...Ans.

2. **V_{Ldc} at $\alpha_2 = 90°$:**

– At $\alpha_2 = 90°$, the full wave converter operates in the discontinuous conduction mode.

$$V_{Ldc} = \frac{3\,V_{m\,(line)}}{\pi}\,[1 + \cos(\alpha + \pi/3)]$$

$$= \frac{3\sqrt{2}\times 415}{\pi}\,[1 + \cos(150°)]$$

$$\therefore V_{Ldc} = 75 \text{ Volts}$$ ...Ans.

Ex. 4.5.3 : For a 3 phase fully controlled bridge converter feeding resistive load :

1. Draw neat circuit diagram.
2. Draw output voltage and current waveforms at $\alpha = 30°$
3. Write the switching sequence of SCRs clearly.
4. Derive expression for average output voltage

Soln. :

1. Refer Section 4.5, Fig. 4.5.1(a).
2. Refer Section 4.5.2 and Fig. 4.5.4.
3. The switching sequence of SCRs is as follows :
   $S_1, S_6, S_2, S_4, S_3, S_5, ...$
4. Refer Section 4.5.2.

4.5.5 Comparison of 1 ϕ and 3 ϕ Converters :

Table 4.5.6 : Comparison of 1 ϕ and 3 ϕ converters

Sr. No.	Characteristics / Parameter	1 ϕ converter	3 ϕ converter
1.	Number of supply phases	1	3
2.	Number of SCRs	4 (Full converter)	6 (Full converter)
3.	Load power	Up to 2 kW	Above 2 kW
4.	Quality of DC output	Poor	Better
5.	Additional output filter	Necessary	Not necessary
6.	Ripple content	Low	Very low
7.	Ripple frequency	100 Hz (FWR)	300 Hz (FWR)
8.	PIV	Low	High
9.	Magnitude of output voltage (Full converter)	$\frac{2V_m}{\pi}\cos\alpha$ (Low)	$\frac{3V_{m\,(line)}}{\pi}\cos\alpha$ (High)

4.5.6 Demerits of Conventional Rectifiers :

– Some of the major demerits of the conventional phase controlled SCR based rectifiers are as follows:

1. The source current is not sinusoidal
2. Source current has a large percentage of harmonics
3. The power factor varies with firing angle
4. The power factor becomes poor at higher values of firing angle.
5. The inductors and capacitors used for filtering are of large size due to low frequency of operation

4.6 Single Phase PWM Rectifier using IGBT :

Introduction :

– A PWM rectifier is a new member of rectifier family which can overcome the shortcomings of conventional phase controlled rectifiers.

– In all inverter controlled drive applications and in wind power conversions, the use of two stage power conversions i.e power conversion from AC-DC and DC-AC is unavoidable.

– For such applications this PWM rectifier can be used for primary AC-DC conversion and hence it is also called as front end converter.

– We will describe the working and control of PWM rectifier using two and four IGBTs.

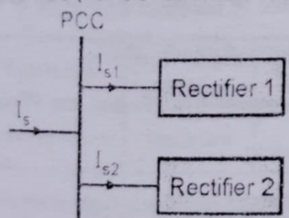
- The base drive circuit for the IGBT incorporates short-circuit protection, control techniques for unity power factor operation and fast current control.
- A pulse width modulated (PWM) rectifier system using insulated gate bipolar transistors (IGBTs) is capable of switching at frequencies as high as 20 kHz.

Need of PWM rectifiers :

- In Present days, we use SCR based phase controlled rectifier for AC-DC conversion which is a simple method as we do not need any closed loop control and the required output voltage can be easily controlled.
- However some of the problems with the SCR based controlled rectifiers are : non sinusoidal source current, and low power factor at large values of firing angle.
- Now, using PWM rectifier we can be able to control both input side AC source current and the output side load voltage.

When to prefer a PWM rectifier ?

Refer Fig. 4.6.1, which consists of two rectifiers connected to PCC (Point of common coupling).

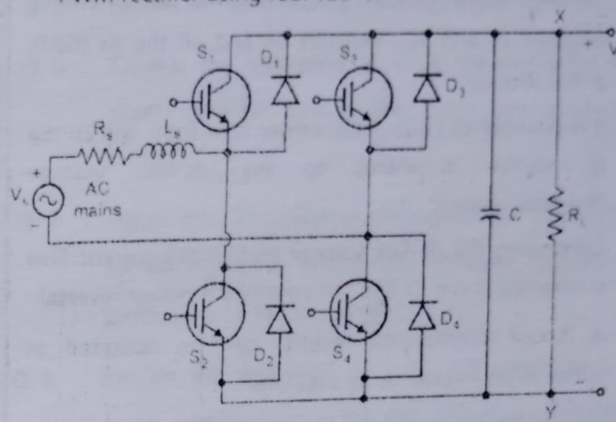


(2446) **Fig. 4.6.1 : Two rectifiers connected to PCC**

- The currents drawn by the rectifier circuit are denoted by I_{s1} and I_{s2} respectively and the total current from PCC is given as I_s.
- Assume that current drawn by rectifier-1 (I_{s1}) is of higher magnitude than I_{s2}, i.e $I_{s1} >> I_{s2}$.
- Let the current drawn by the rectifier-2 (I_{s2}) contains 3rd or 5th harmonics, whose percentage is at the most 30% of the fundamental value of I_{s2}.
- However, I_{s2} itself is very small as compared to the total current drawn at PCC. Therefore, the harmonic currents drawn by rectifier-2 won't affect the performance of the system substantially.
- In this situation we can prefer SCR based conventional phase controlled rectifier for Rectifier-2 circuit. However for the dominating rectifier i.e. rectifier-1 in this case, the PWM rectifier is a better choice.

Circuit diagram :

- Fig. 4.6.2 shows the circuit diagram of a single phase PWM rectifier using four IGBTs.

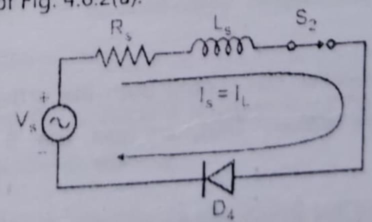


(I-2448) **Fig. 4.6.2 : Single phase PWM rectifier using four IGBTs**

- The four IGBTs are connected in a bridge configuration. The load is connected between the common drain point "X" of the IGBTs S_1, S_3 and the common source point "Y" of the IGBTs S_2, S_4.
- The single phase AC supply with a source resistance R_S and source inductance L_S is connected at the input of the bridge between points A and B.
- Diodes D_1 through D_4 are the feedback diodes connected across the four IGBTs. They are also called as the body diodes as they are present within the devices.

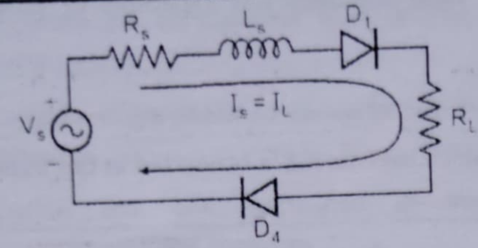
Operation in positive half cycle :

- In the positive half cycle of AC supply voltage IGBTs S_2, S_3 and body diodes D_1, D_4 will get forward biased.
- Now turn on IGBT S_2. The conduction will take place over the path V_S-L-S_2-D_4 as shown in the equivalent circuit of Fig. 4.6.2(a).



(2444) **Fig. 4.6.2(a) : Equivalent circuit when S_2 is ON**

- The AC source is connected to inductor and hence current through the inductor (source current) will rise.
- Now turn off IGBT S_2. Now yconduction will take place over the path V_s-L-D_1-Load-D_4 as shown in the equivalent circuit of Fig. 4.6.2(b) and the source current will fall.



(1-2444) **Fig. 4.6.2(b) : Equivalent circuit when S_2 is OFF**

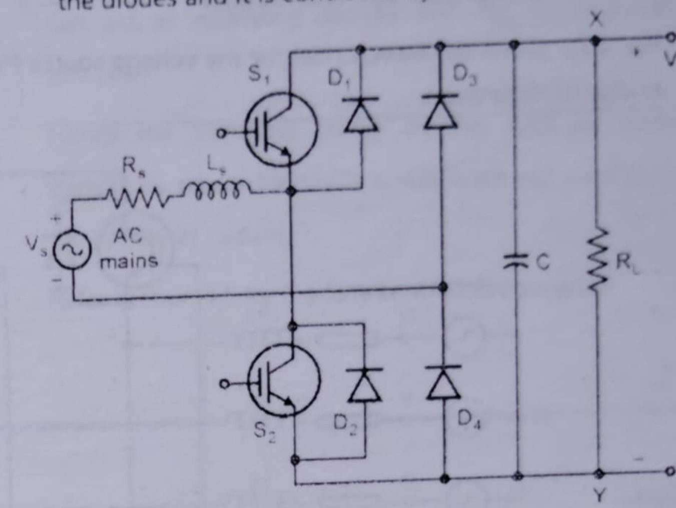
- By turning off IGBT S_2, the source current can decrease only if $L(di/dt) = V_s - V_o$, is negative i.e. $V_s < V_o$.
- Hence, the PWM operation can control current only when the output voltage V_o is greater than the peak value of input voltage. So, it is also called as Boost rectifier. Turning on and off IGBT S_2 can control the source current in the positive half cycle.

Operation in negative half cycle :

- In the negative half cycle of the AC supply, IGBTs S_1, S_4 and body diodes D_2, D_3 will get forward biased.
- We can achieve the current control in negative half cycle with switch S_1. By turning ON and OFF of IGBT S_1 the source current will rise and fall respectively.
- Hence for positive half cycle, turn ON and OFF of IGBT S_2 controls the source current whereas, for negative half cycle, turn ON and OFF of IGBT S_1 controls the source current.

Conclusion :

- From the operation of PWM bridge rectifier, we conclude that for rectification operation, it is enough to use IGBTs S_1 and S_2 and S_3, S_4 are not required to be used.
- The PWM rectifier using only two IGBTs is as shown in Fig. 4.6.3. In this circuit, the rectification is done through the diodes and it is controlled by IGBTs S_1 and S_2.



(2449) **Fig. 4.6.3 : PWM rectifier with only two IGBTs**

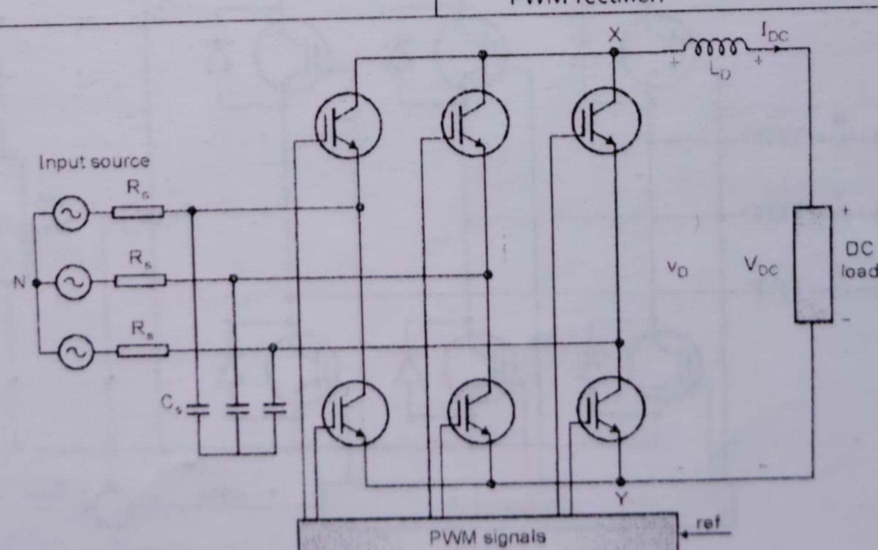
4.7 Three-Phase PWM Rectifier :

Circuit diagram :

- Fig. 4.7.1 shows the circuit diagrams of a three phase PWM rectifiers using six IGBTs. There are following two circuit topologies for three-phase PWM rectifiers:
  1. A current-source rectifier, where power reversal is done by dc voltage reversal; and
  2. A voltage-source rectifier, where power reversal is done by current reversal at the dc link.

Three phase current source PWM rectifier :

- Fig. 4.7.1 shows the basic circuit for the current source PWM rectifier.

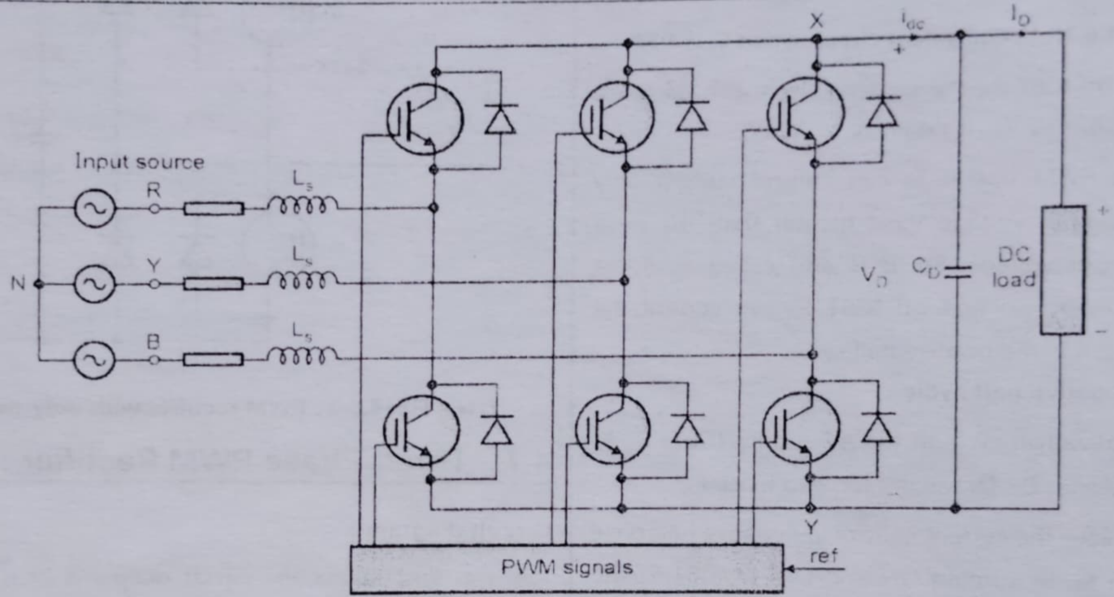


(1-2438) **Fig. 4.7.1 : Three phase current source PWM rectifier**

- Inductor L_D in this circuit maintains a constant current to the load while the input-side capacitors C_S provide low impedance paths for the load current.

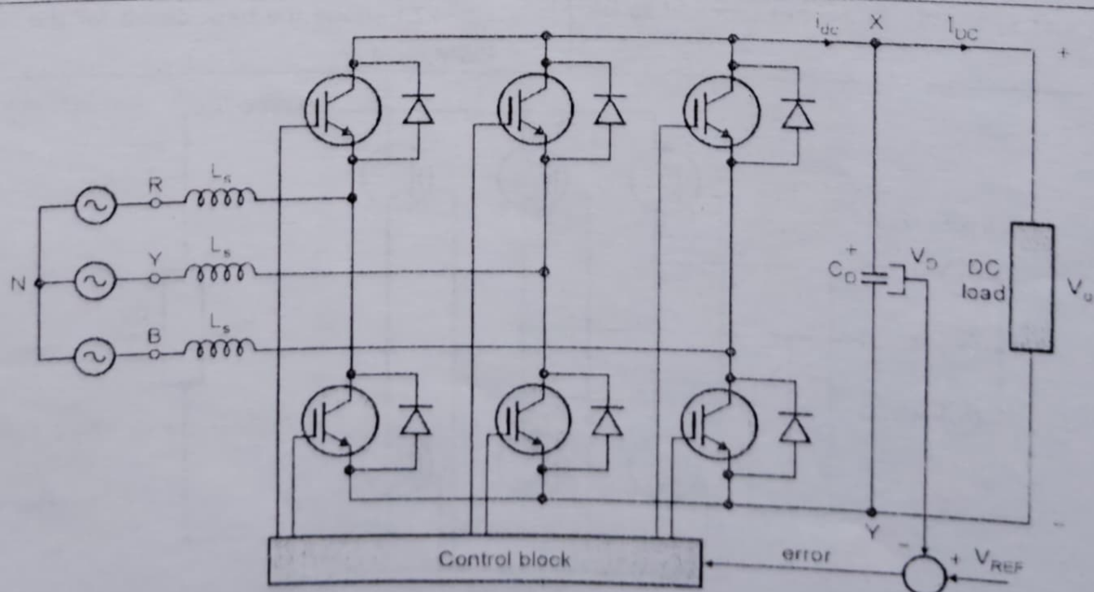
Three phase voltage source PWM rectifier :

- Fig. 4.7.2 shows the basic circuit for the voltage source PWM rectifier which uses six IGBTs connected in the three phase bridge configuration.



(I-2439) **Fig. 4.7.2 : Three phase voltage source PWM rectifier**

- Capacitor C_D in Fig. 4.7.2 ensures a constant load voltage while the input-side inductances L_S ensure that the line currents are continuous.
- They also improve the input power factor of the rectifier.
- A three-phase voltage-source PWM rectifier with a feedback control loop is shown in Fig. 4.7.3.
- The feedback control loop is used for maintaining the dc-link voltage at a desired reference value.



(I-2436) **Fig. 4.7.3 : A three phase force-commutated PWM rectifier**

- The load voltage V_D is sensed using an appropriate sensor and compared with a reference V_{REF}.
- The error signal which is proportional to the difference between V_D and V_{REF} switches on and off the six IGBTs of the rectifier.
- It is possible to control the power flow from and to the ac source according to the dc-link voltage (V_D) requirements.
- Controlling the dc-link voltage so that the current flow is reversed at the dc link can control the power reversal.
- A forced-commutated rectifier can be operated as either as an inverter or as a rectifier.

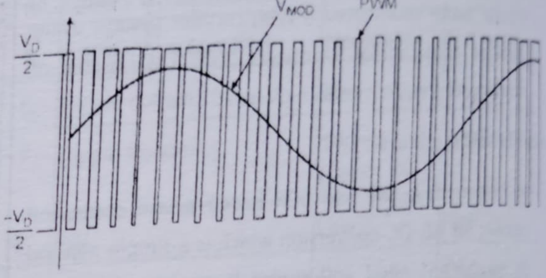
Operation in Rectifier Mode :

- In the rectifier mode of operation, the current I_D is positive which means the load is receiving the power.
- The capacitor C_D is discharged through the dc load, and the error signal is such that the control circuit demands more power from the ac supply.
- The control circuit takes the required amount of extra power from the ac supply by generating the appropriate PWM signals for the switching devices (IGBTs).
- This ensures that more current flows from the ac to the dc side, and the capacitor voltage is recovered to its original value.

Operation in Inverter Mode :

- In the inverter mode of operation I_D becomes negative and the capacitor C_D is overcharged.
- The error signal is such that it demands the control to discharge the capacitor and return power to the ac mains.
- The PWM rectifier can control both the active power and reactive power. Thus, we can use it for PF correction.
- It is also possible to maintain the ac current waveforms almost sinusoidal, which reduces harmonic contamination to the mains supply.
- The PWM turns on and off the switches in a pre established form, which is usually a sinusoidal waveform of voltage or current.

- Fig. 4.7.4 shows as example of pulse width modulation of one phase with amplitude of V_{mod} for the modulating signal.



(I-2437) **Fig. 4.7.4 : PWM pattern and its fundamental modulating voltage.**

- A forced-commutated rectifier can be operated as either an inverter or a rectifier, depending on the control strategy.
- Therefore, it is often called as a converter.

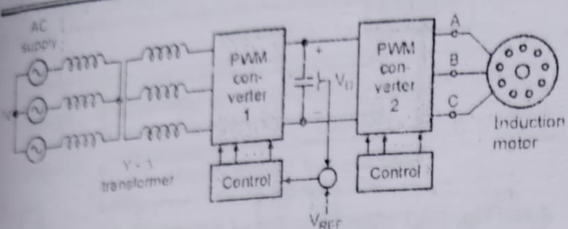
4.7.1 Advantages of PWM Converters :

- Main advantages of a PWM converter include:
  1. It is possible to produce the current or voltage with less harmonic contamination.
  2. We can control the PF, and the PF can even be made leading.
  3. The PF of PWM rectifier is high
  4. We can build the circuit as voltage-source or current-source rectifiers.
  5. It is possible to reverse the PF by reversing the the dc link current.
  6. Thyristor and GTO converters are specially used for high-voltage and high power applications.
  7. Due to higher operating frequency, the size of filter components is small.

4.7.2 Application of PWM Converter :

Block diagram :

- Two three phase PWM converters are cascaded to control power flow from the ac supply to the load and vice versa, as shown in Fig. 4.7.5.



(I-2440) Fig. 4.7.5 : Two forced commutated cascaded PWM converters

Operation :

- The first converter converts ac to a variable dc voltage whereas, the second converter converts dc voltage to a variable ac voltage at a fixed or variable frequency.
- We can use an advanced control technique (e.g., space vector modulation and SPWM) to maintain a near sinusoidal input current from the ac source at unity PF and supply a near sinusoidal output voltage or current to the load.

4.7.3 Difference between SCR Based and IGBT Based Rectifiers :

(I-2450) **Table 4.7.1**

Sr. No	Parameter	SCR based rectifier	IGBT based rectifier
1.	Reactive power	Moderate	Low
2.	Power factor	Moderate	High
3.	Harmonics	Moderate	Low
4.	Power losses	Low	High
5.	Constant DC voltage range	Good	Excellent
6.	Fault current limiting	Yes	No

Review Questions

Q. 1 Why three phase converters are used in high power variable speed drives ?

Q. 2 Give the classification of three phase controlled converters.

Q. 3 Why three phase controlled converters are preferred over single phase converters ?

Q. 4 What are the operating modes of 3 phase full converter with resistive load ?

Q. 5 Define line commutation and natural commutation.

Q. 6 Explain the operation of a 3ϕ full converter with purely resistive load in the continuous conduction mode.

Q. 7 Obtain the expression of average output voltage of a 3ϕ full converter with purely resistive load in the continuous conduction mode.

Q. 8 Explain the operation of a 3ϕ full converter with purely resistive load in the discontinuous conduction mode.

Q. 9 Obtain the expression of average output voltage of a 3ϕ full converter with purely resistive load in the discontinuous conduction mode.

Q. 10 For a 3 ϕ converter operating with resistive load draw the following waveforms :

1. Phase and line voltages
2. Supply current (any one)
3. Thyristor current (any one) for $\alpha = 30°$ and $\alpha = 150°$.

Q. 11 Compare single phase full converter with the 3 ϕ full converter.

Q. 12 Compare the continuous and discontinuous conduction modes of a single phase full converter with a purely resistive load..

Q. 13 State the disadvantages of the conventional SCR based rectifier.

Q. 14 Draw the circuit of a single-phase PWM rectifier and describe its working.

Q. 15 State the advantages of a forced commutated PWM rectifier.

Q. 16 State the disadvantages of a forced commutated PWM rectifier.

Q. 17 Draw the circuit of a three-phase PWM rectifier and describe its working.

Q. 18 Compare the conventional SCR rectifier with the PWM rectifier.

Q. 19 Compare single phase full converter with the 3 ϕ full converter.

Q. 20 Explain any one application of the forced commutated PWM converter.

4.8 University Questions and Answers :

Q. 1 Why generally transistor family devices are not used in converter ? Explain three phase fully controlled converter with necessary circuit and waveforms.

(Dec. 12, 8 Marks)

Ans. :

- For converter circuits we need to use the devices which can act as rectifying devices and not as amplifying devices.
- Hence the transistor family devices such as power transistors, power MOSFETs or IGBTs are not suitable for the converter circuits.
- Refer section 4.5 for 3 ϕ fully controlled converter.

❑❑❑