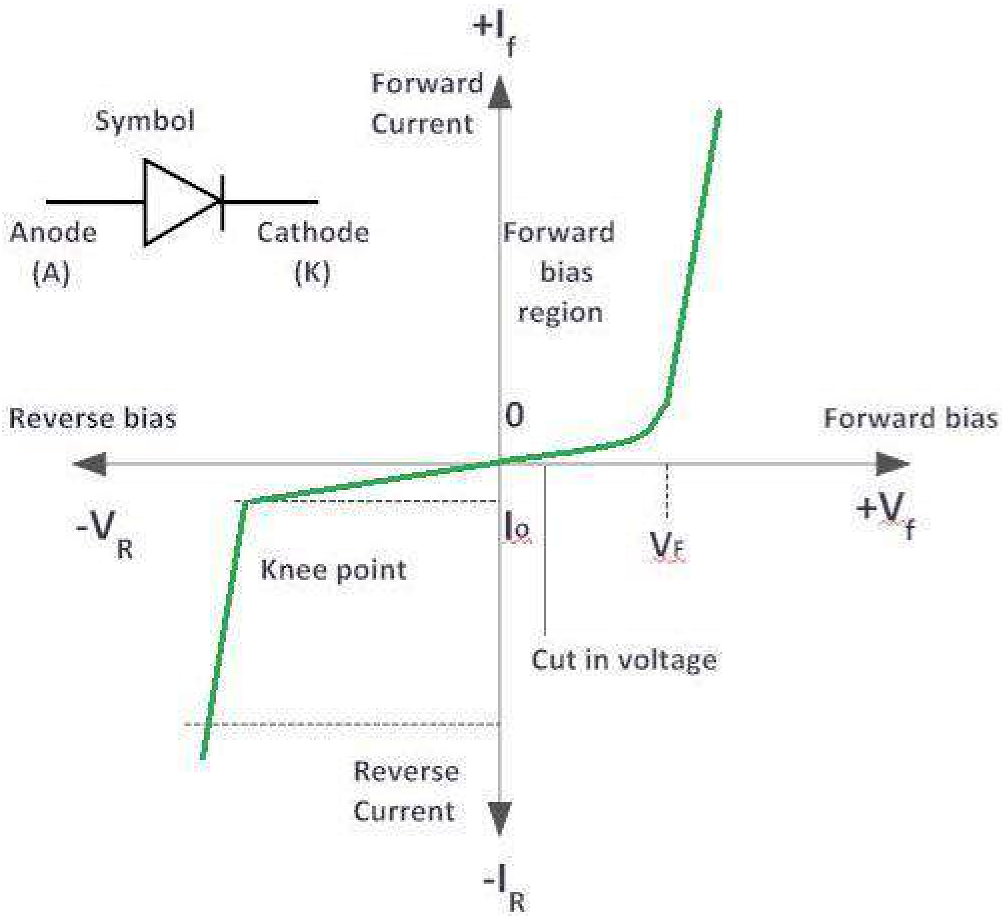
V-I characteristics of diode

The V-I characteristics or voltage-current characteristics of the p-n junction diode is shown in the below figure. The horizontal line in the below figure represents the amount of voltage applied across the p-n junction diode whereas the vertical line represents the amount of current flow in the p-n junction diode.



I_F = Forward Biased Current of diode
V_F = Forward Biased Voltage of diode
I_O = Reverse biased Saturation Current of Diode
I_R = Reverse biased Current of Diode

Forward Bias V-I characteristic of P-N diode.

When anode is positive with respect to cathode , diode is said to be forward biased. with increase of the source voltage V_S from zero value , initially diode current is zero. from $V_S=0$ to cut-in voltage , the forward current is very small .cut-in voltage is also known as ***threshold voltage or turn-on voltage.*** beyond cut-in voltage ,the diode current rises rapidly and diode said to conduct. for silicon diode, the cut-in voltage is around 0.7. when diode conducts, there is a forward voltage drop of the order of 0.8 to 1V

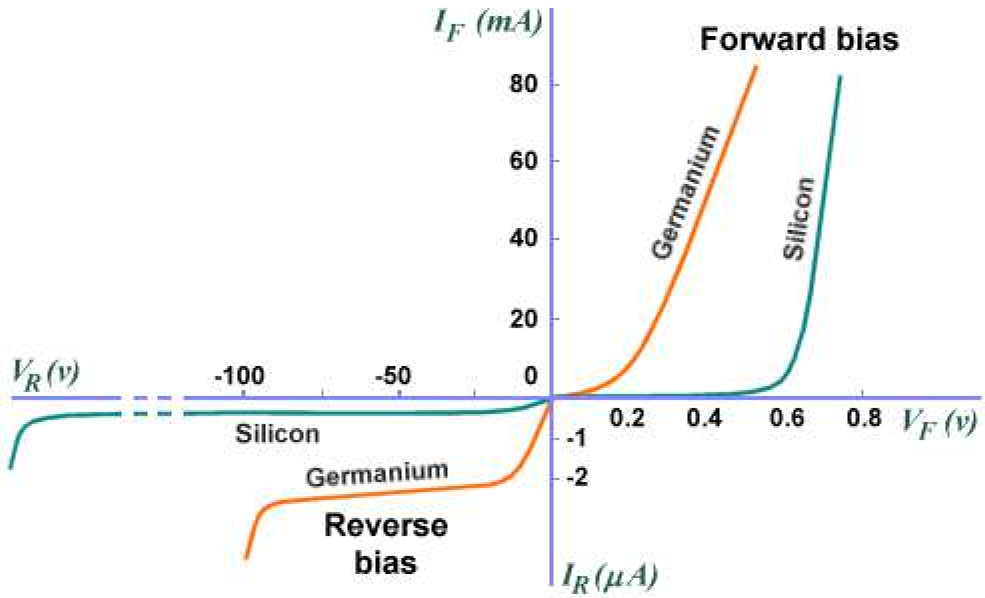
Reverse Bias V-I characteristic of P-N diode.

When cathode is positive with respect to anode the , the diode said to be reverse biased. In the reverse biased condition. a small reverse current leakage current , of the order of microamperes or milli amperes flow . the leakage current is almost independent of the reverse voltage until this voltage reach breakdown voltage at this reverse breakdown, voltage remains almost constant but reverse current becomes quite high limited only by the external circuit resistance . a large reverse break down voltage associated with high reverse current, leads to excessive power loss that may be destroy the diode.

At point a reverse breakdown of the diode occurs and current increase sharply damaging the diode . this point is called **knee** of the reverse characteristics.

V-I Characteristics of typical Ge And Si Diode:

- the cut in voltage voltage for germanium (Ge) diode is about 0.3 while for silicon (Si) diode is as about 0.7 V.
- the potential at which current starts increasing exponentially is called offset potential, threshold potential or firing potential of a diode.



- the reverse saturation current is of order nA for silicon diode while it is of the order of uA for germanium diode.
- Reverse breakdown voltage for Si diode is higher than that of Ge diode of a comparable rating.

If the external reverse voltage applied on the p-n junction diode is increased, the free electrons from the n-type semiconductor and the holes from the p-type semiconductor are moved away from the p-n junction. This increases the width of depletion region.

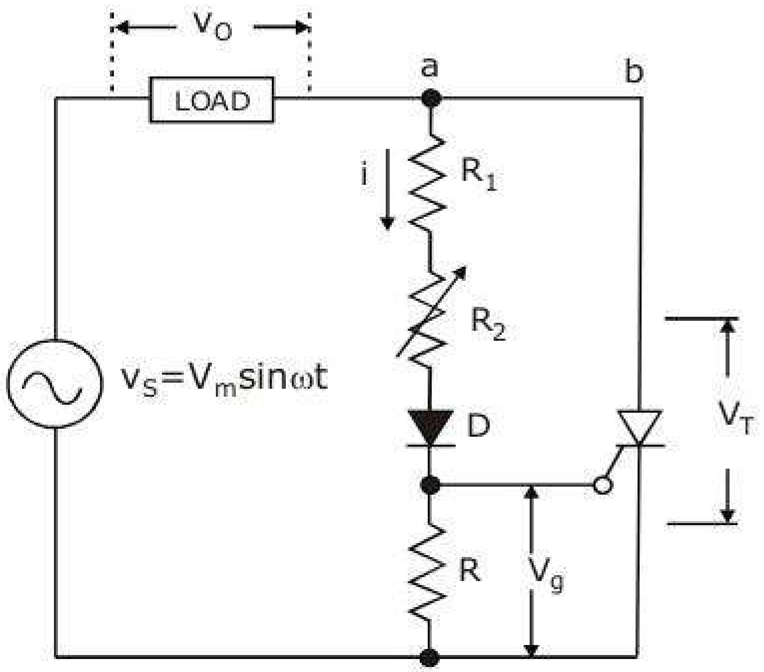
The wide depletion region of reverse biased p-n junction diode completely blocks the majority charge carrier current. However, it allows the minority charge carrier current. The free electrons (minority carriers) in the p-type semiconductor and the holes (minority carriers) in the n-type semiconductor carry the electric current.The electric current, which is carried by the minority charge carriers in the p-n junction diode, is called reverse current.

In n-type and p-type semiconductors, very small number of minority charge carriers is present. Hence, a small voltage applied on the diode pushes all the minority carriers towards the junction. Thus, further increase in the external voltage does not increase the electric current. This electric current is called reverse saturation current. In other words, the voltage or point at which the electric current reaches its maximum level and further increase in voltage does not increase the electric current is called reverse saturation current.

The reverse saturation current is depends on the temperature. If temperature increases the generation of minority charge carriers increases. Hence, the reverse current increases with the increase in temperature. However, the reverse saturation current is independent of the external reverse voltage. Hence, the reverse saturation current remains constant with the increase in voltage. However, if the voltage applied on the diode is increased continuously, the p-n junction diode reaches to a state where junction breakdown occurs and reverse current increases rapidly.

In germanium diodes, a small increase in temperature generates large number of minority charge carriers. The number of minority charge carriers generated in the germanium diodes is greater than the silicon diodes. Hence, the reverse saturation current in the germanium diodes is greater than the silicon diodes.

R - Triggering Circuit



- R_1 is the gate current limiting resistance
- R_2 is used to vary the gate current and hence firing angle

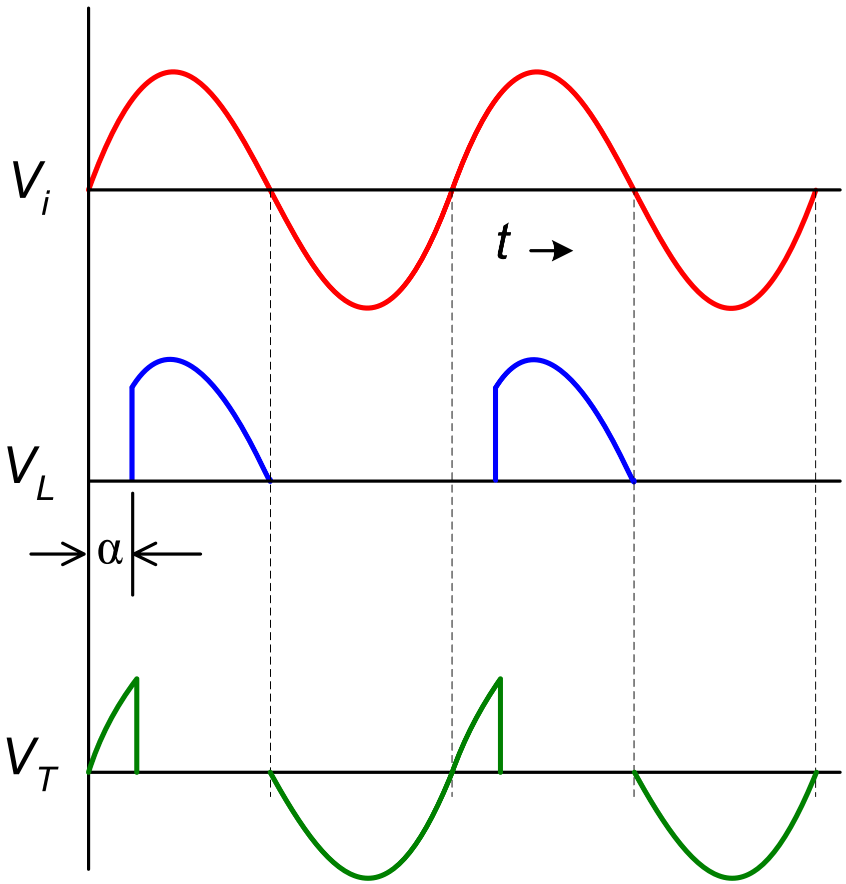
$$I_{g\max} = \frac{V_m}{R_1} \Rightarrow R_1 \geq \frac{V_m}{I_{g\max}}$$

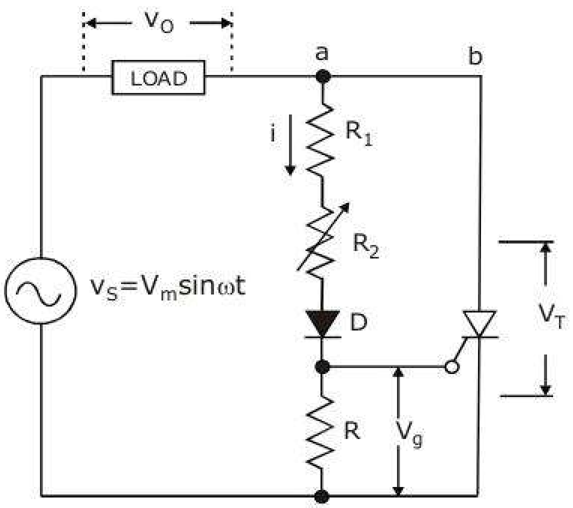
- R limits the voltage at Gate terminal

$$R \leq \frac{V_{g\max} R_1}{V_m - V_{g\max}}$$

- Diode D prevents build-up of negative voltage at Gate terminal

R-Trig Waveforms



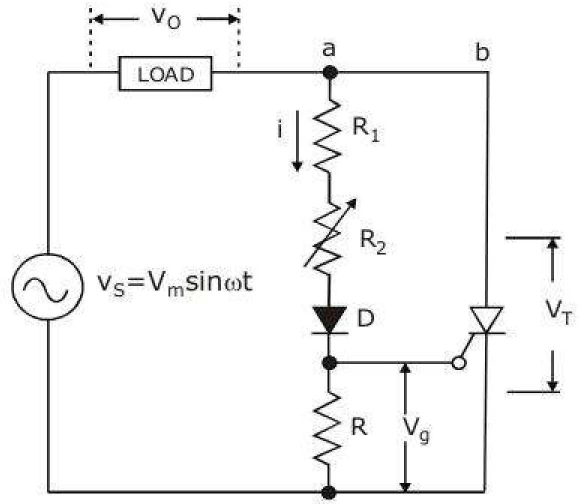


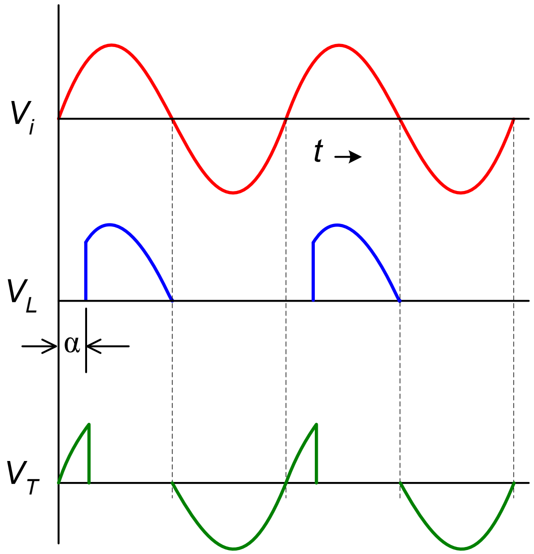
- The phase angle at which the SCR starts conducting is called **firing angle, α**

Features of R-Trig Circuit

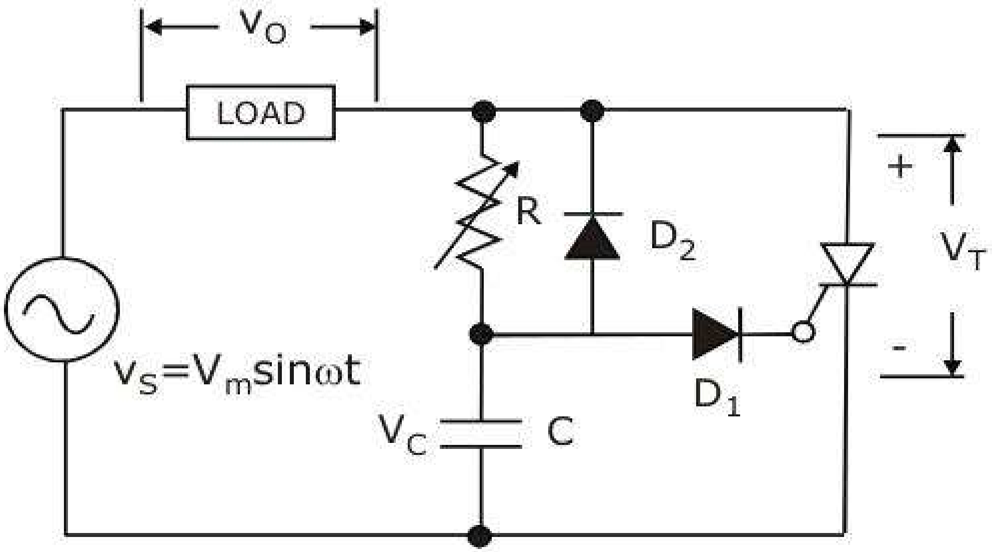
- Simple circuit

- Disadvantages:
  - Performance depends on temperature and SCR characteristics
  - Minimum phase angle is typically 2-4 degrees only (not zero degree)
  - Maximum phase angle is only 90 degrees





RC Triggering Circuit



Advantage over R-triggering Circuit:

Controls upto 180 degrees

$$RC \geq \frac{1.3\,T}{2}$$

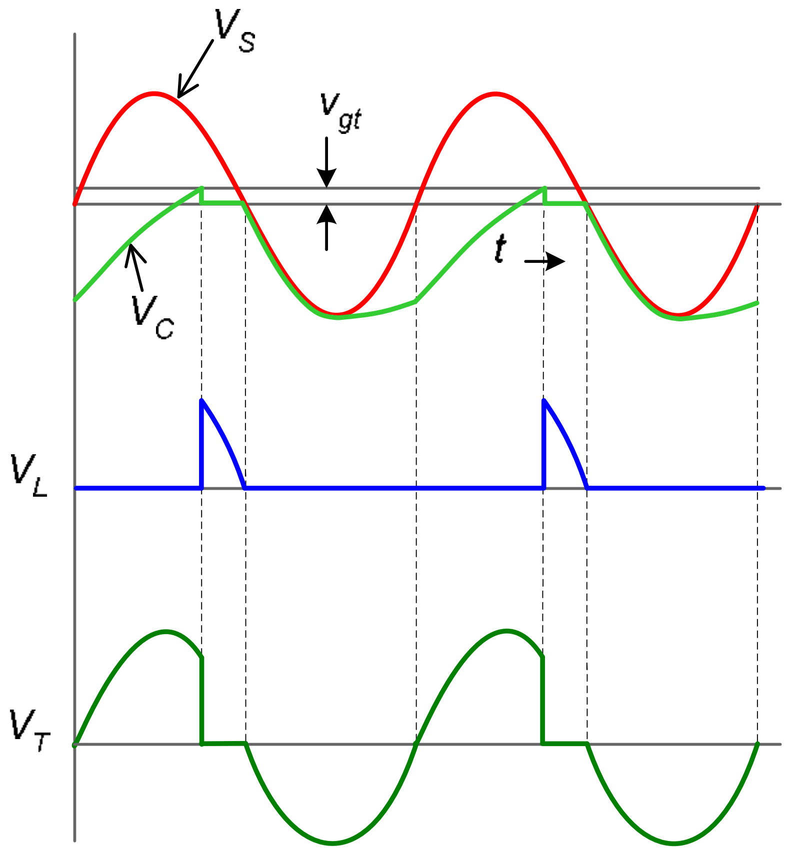
To ensure minimum gate current

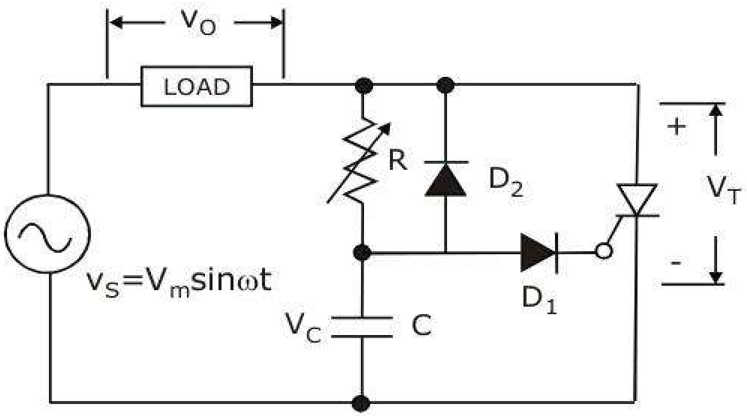
$$v_s \geq R\,I_{g\min} + V_{g\min} + V_{D_1}$$

$$R \leq \frac{v_s - V_{g\min} - V_{D_1}}{I_{g\min}}$$

- Capacitor charges during the negative half cycle through D_2
- When SCR is turned on, capacitor C is suddenly discharged through D_2
- D_1 protects the SCR during negative half cycle

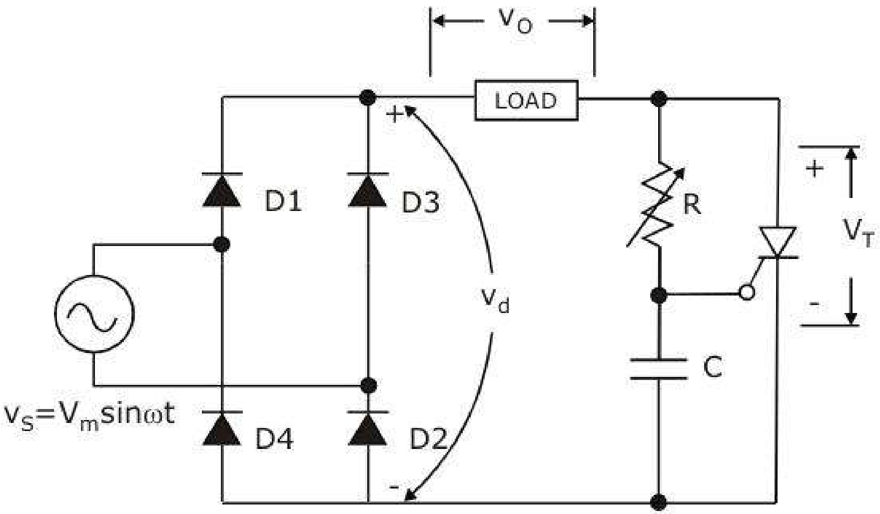
RC Trig Waveforms

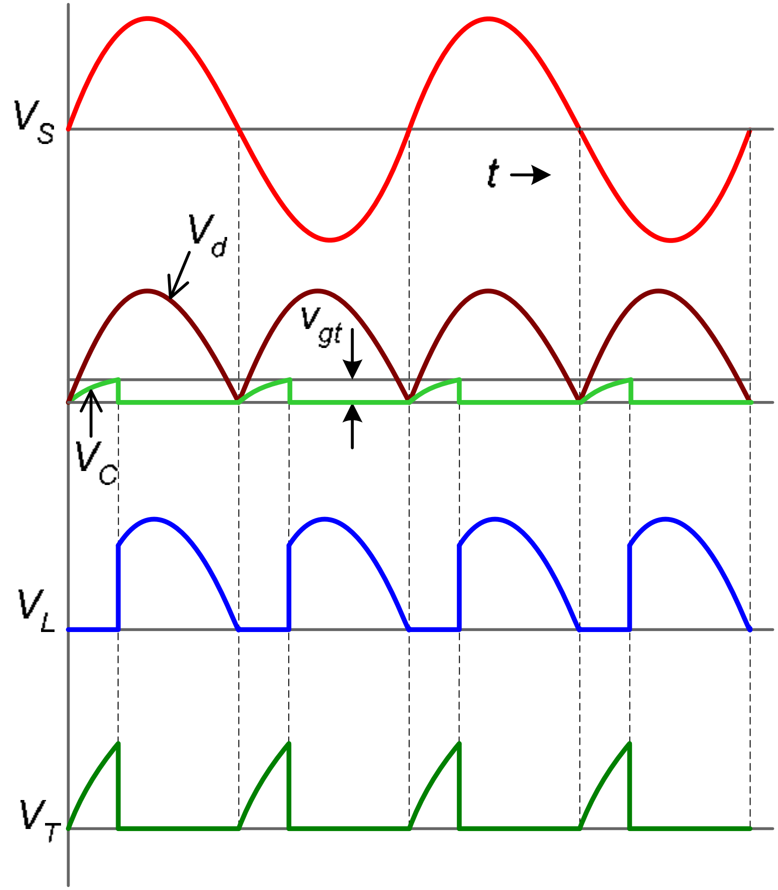




$$RC \geq \frac{1.3\,T}{2}$$

RC Full wave trigger circuit



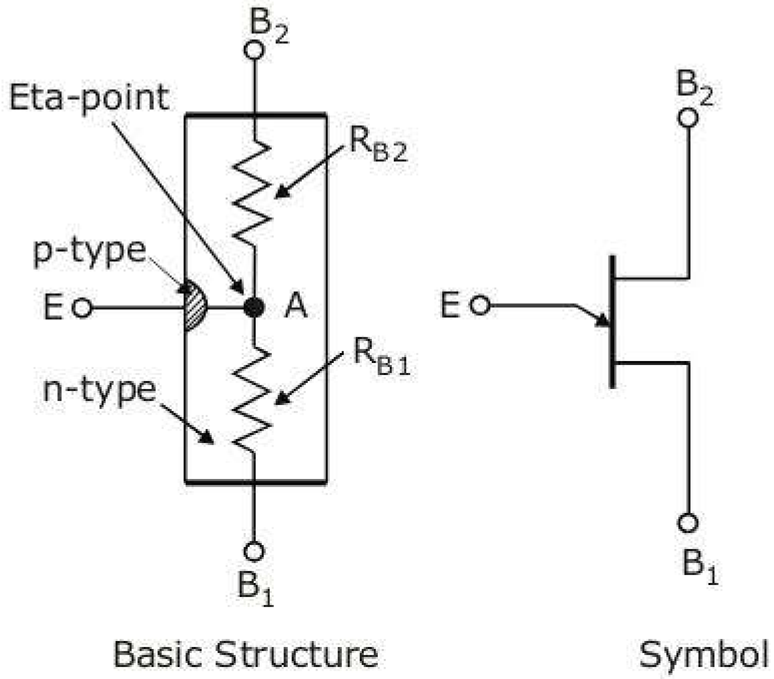


- Initial Capacitor voltage in each half cycle is almost zero

$$RC \geq \frac{50\,T}{2}$$

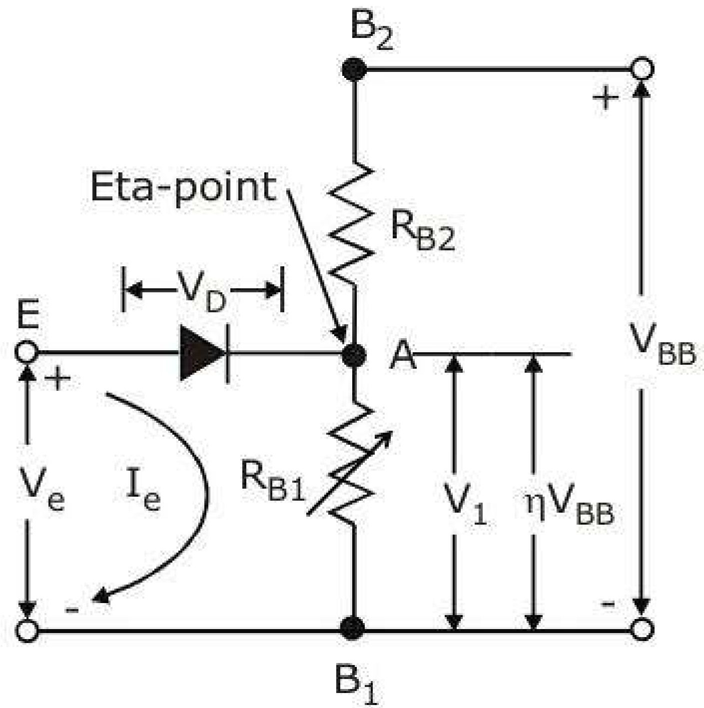
$$R \leq \frac{v_s - V_{g\min}}{I_{g\min}}$$

Unijunction Transistor (UJT)



- Has a lightly doped n-type silicon layer to which a heavily doped p-type emitter is embedded
- The inter-base resistance is in the range of 5 – 10 kΩ
- This device cannot 'amplify'

UJT Equivalent Circuit



$$V_{AB_1} = \frac{R_{B_1}}{R_{B_1} + R_{B_2}} V_{BB} = \eta \, V_{BB}$$

η is called intrinsic standoff ratio

Value of ***η*** varies from 0.5 – 0.8

- When V_e is more than $V_1 + V_D$, then the diode is forward biased and a current flows through R_{B1}
- Number of carriers in R_{B1} increases and the resistance reduces
- V_e decreases with increase in I_e and the therefore the device is said to exhibit negative resistance

Commutation Techniques of Thyristors.

- Commutation is defined as the process of turning-off a thyristor.

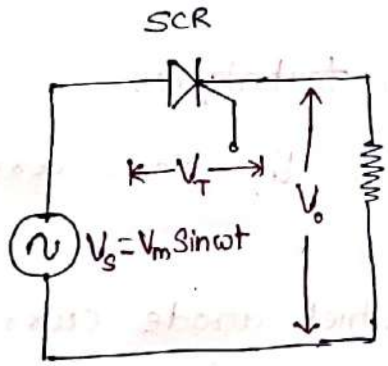
- Turn-off of a thyristor means bringing the device from forward-conduction mode to forward-blocking mode.

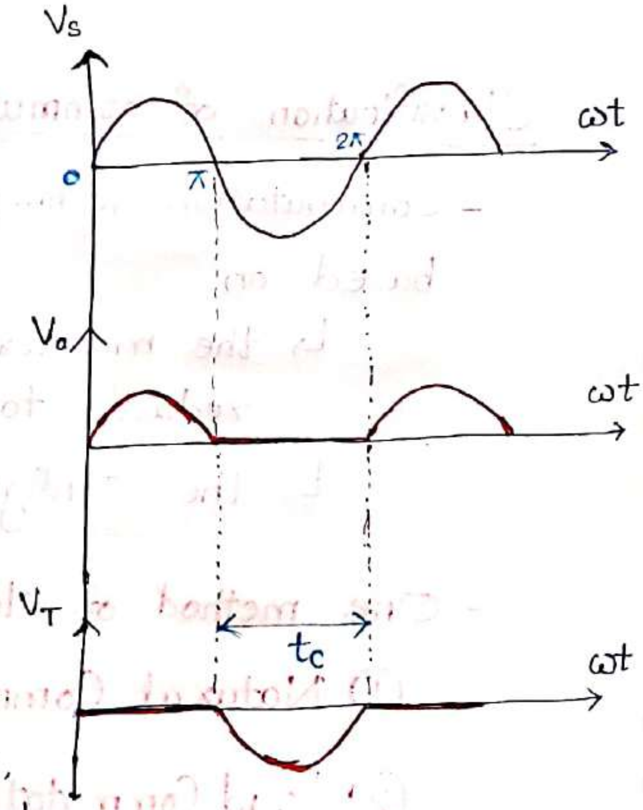
- Turn-off process of thyristor requires
  - ↳ ⓐ Anode current to be reduced below holding current
  - ↳ ⓑ application of a reverse voltage to remove the extra charge carriers and regain its blocking state.

- Classification of commutation techniques.
  - Commutation techniques of thyristors are classified, based on
    - ↳ the manner in which anode current is reduced to zero. and.
    - ↳ the configuration of the commutating circuits.
  - One method of classification is as follows.
    1. Natural Commutation or line Commutation (class F)
    2. Load Commutation or Self commutation (class A)
    3. Forced Commutation.
       - ↳ ⓐ Resonant-Pulse Commutation (class B)
       - ↳ ⓑ Complementary Commutation (class C)
       - ↳ ⓒ Impulse commutation (class D)

① Natural Commutation or Line Commutation (Class F)

- Natural commutation of thyristor occurs only when the supply is ac. Nature of supply automatically takes care of commutation. So, it is known as natural commutation or line commutation.





- When supply is ac, then, the anode current through the thyristor automatically pass through zero at the end of every positive half cycle i.e. at $\omega t = \pi$.

- So. anode current becomes zero after positive half cycle.
- The supply voltage also applies a reverse bias voltage across the SCR in the negative half cycle. This reverse bias ensures that SCR regains its blocking capability.

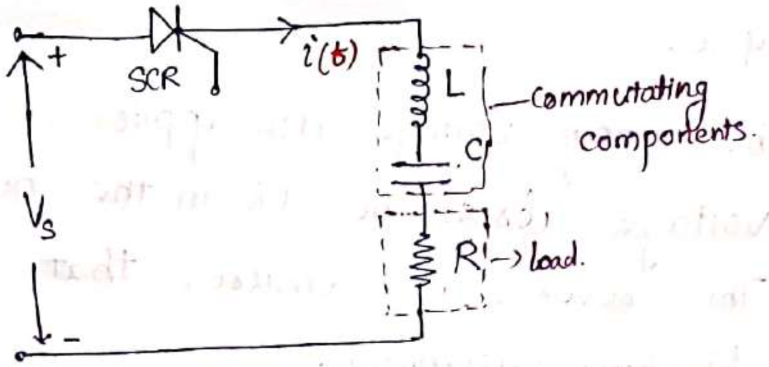
Applications :-
- Phase - controlled converters.
- line - commutated inverters.
- ac - voltage controllers.
- step-down cyclo-converters.

② Load Commutation or Self commutation (Class A).

- Load commutation or class-A commutation is possible in thyristor circuits supplied from dc source. It is not possible in ac circuits.
- For load commutation to occur, the nature of load circuit should be such that, when it is energized from a dc source, the current has a tendency to decay to zero value, due to load.

⇓

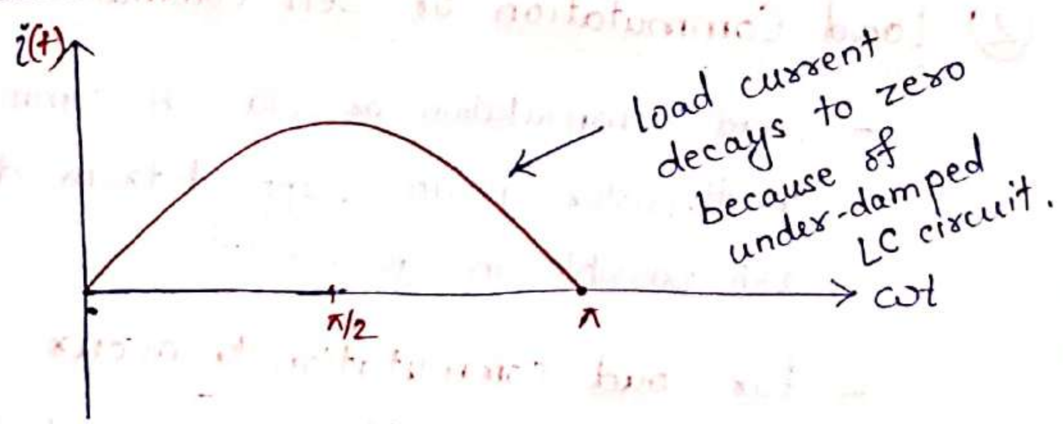
It is possible when load contains R, L and C parameters and satisfy underdamped condition.

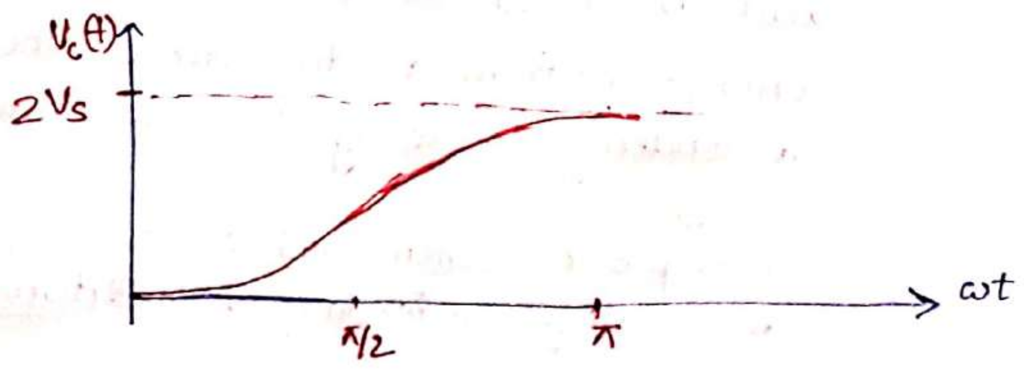


- When the circuit is energised from dc source, the current first rises to maximum value and then decays to zero. So, thyristor gets turned-off. Voltage of capacitor applies a reverse bias across the thyristor after turn-off.
- Load commutation is also known as <u>resonant commutation</u> or <u>self-commutation</u>.

- <u>Application</u> :- Series inverter circuit.

<u>Waveforms</u> :-





- Load current is like charging current of capacitor. So, initially after turning on of thyristor, current $i(t)$ increases, then it reaches maximum value and then decays to zero.

- At $\omega t = \pi$, when thyristor current decays to zero, the voltage stored in capacitor is $2V_s$. So, at $\omega t = \pi$, voltage across thyristor is,

$$V_T = -2V_s + V_s = -V_s$$

So, ~~ca~~ net reverse voltage appears across the thyristor when the thyristor current decays to zero.

→ Conduction angle of thyristor, $\omega_0 t_0 = \pi$.

→ Conduction time of thyristor, $t_0 = \frac{\pi}{\omega_0}$

Here, ω_0 is known as resonant frequency of the LC circuit.

$$\boxed{\omega_0 = \frac{1}{\sqrt{LC}}}$$

→ ∴ Conduction time, $\boxed{t_0 = \frac{\pi}{\omega_0} = \pi\sqrt{LC}}$

→ For satisfying the condition of under-damping.

$$\boxed{\frac{R}{2} < \sqrt{\frac{L}{C}}} \quad \text{or} \quad \boxed{R^2 < \frac{4L}{C}}$$

converter operates in the 'inverter' mode and if the out going SCR fails to turn off it is effectively triggered at $\alpha = 0^0$ which pushes the converter from peak inversion to peak rectification mode. The resulting 'commutation failure' can cause severe short circuits. Thus the trigger angle must be restricted to values, which permit successful commutation of the SCRs.

20.5 Commutation in DC-DC Choppers

DC-DC Choppers have also been categorised on the basis of their commutation process. Three types of commutation are identified: i) Voltage commutation, ii) Current commutation and iii) Load commutation.

20.5.1 Voltage Commutation

In a voltage commutated thyristor circuit a voltage source is impressed across the SCR to be turned off, mostly by an auxiliary SCR. This voltage is comparable in magnitude to the operating voltages. The current in the conducting SCR is immediately quenched, however the reverse-biasing voltage must be maintained for a period greater than that required for the device to turn-off. With a large reverse voltage turning it off, the device offers the fastest turn-off time obtainable from that particular device. It is an exposition of 'hard' turn-off where the reverse biasing stress is maximum.

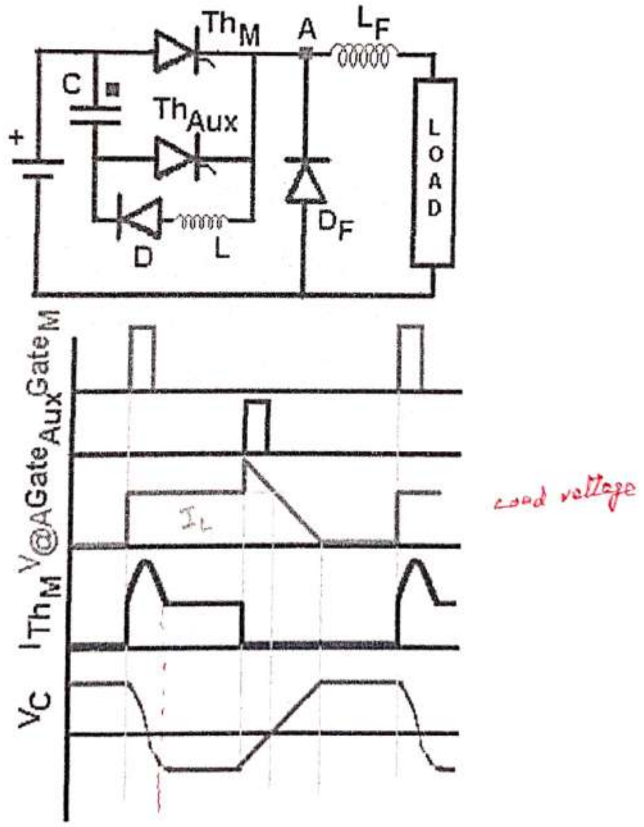


Fig. 20.5 A voltage commutated DC-DC Chopper and most significant waveforms

Fig. 20.5 illustrates voltage commutation. Th_M is the main SCR and Th_{Aux} is the Auxiliary. As a consequence of the previous cycle, Capacitor C is charged with the dot as positive. When the Main SCR is triggered, it carries the load current, which is held practically level by the large filter inductance, L_F and the Free-wheeling diode. Additionally, the charged Capacitor swings half a cycle through Th_M, L and D ending with a negative at the dot. The reverse voltage may be less than its positive value as some energy is lost in the various components in the path. The half cycle capacitor current adds to the load current and is taken by the Main SCR.

With the negative at the dot C-Th_{Aux} is enabled to commutate Th_M. When Th_{Aux} is triggered the negative charge of the capacitor is impressed onto Th_M and it immediately turns off. The SCR does take the reverse recovery current in the process. Thereafter, the level load current charges the capacitor linearly to the supply voltage with the dot again as positive.

The Load voltage peaks by the addition of the capacitor voltage to the supply when Th_{Aux} is triggered. The voltage falls as the capacitor discharges both changes being linear because of the level load current. When the Capacitor voltage returns to zero, the load voltage equals supply voltage. The turn-off time offered by the commutation circuit to the SCR lasts till this stage starting from the triggering of Th_{Aux}. Now the capacitor is progressively positively charged and the load voltage is equally diminished from the supply voltage. Th_{Aux} is naturally commutated when the capacitor is fully charged and a small excess voltage switches on the free wheeling diode. With the positive at the dot the capacitor is again ready for the next cycle. Here Th_{Aux} must be switched before Th_M to charge C to desired polarity.

Voltage commutation may be chosen for comparatively fast switching and it can be identified from the steep fall of the SCR current. There is no overlapping operation between the incoming and the outgoing devices and both currents fall and rise sharply. Stresses on all the three semiconductors can be expected to be high here.

20.5.2 Current commutation

The circuit of Fig. 20.6 can be converted into a current commuted one just by interchanging the positions of the diode and the capacitor. Here the Capacitor is automatically charged through D-L-L_F-Load with the dot as positive. Any of the SCRs can thus be switched on first.

If Th_M is triggered first, it immediately takes the load current turning off D_F. When ThAux is triggered, it takes a half cycle of the ringing current in the L-C circuit and the polarity of the charge across the capacitor reverses. As it swings back, Th_{Aux} is turned off and the path through D-C-L shares the load current which may again be considered to be reasonably level. The Current-share of TH_M is thus reduced in a sinusoidal (damped) manner. Turn-off process is consequently accompanied by an overlap between Th_M and the diode D in the D-C-L path. Once the main SCR is turned off, the capacitor current becomes level and the voltage decreases

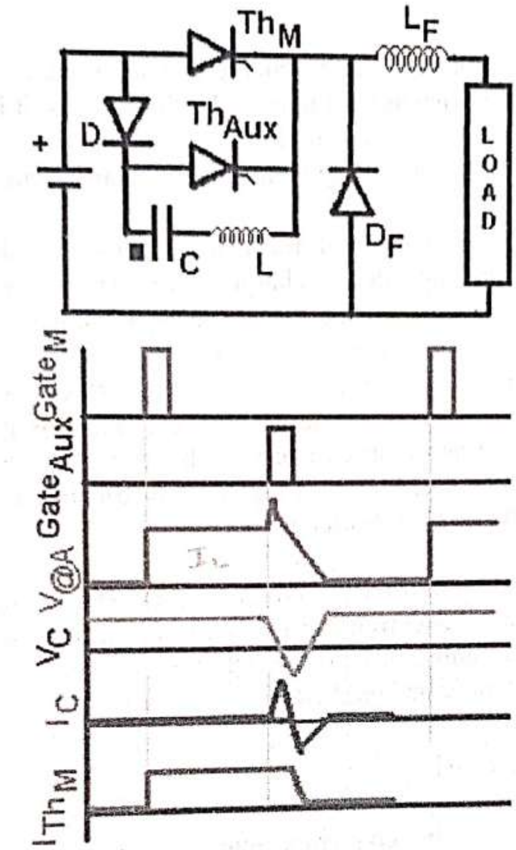


Fig. 20.7 A current commutated DC-DC Chopper and most significant waveforms

linearly. A voltage spike appears across the load when the voltage across the commutating inductance collapses and the capacitance voltage adds to the supply voltage.

The free-wheeling diode also turns on through a overlap with D when the capacitor voltage just exceeds the supply voltage and this extra voltage drives the commutating current through the path D-Supply-D_F-L. Thus there is soft switching of all devices during this period.

Further an additional diode may be connected across the main SCR. It ensures 'soft' turn-off by conducting the excess current in the ringing L-C circuit. The low forward voltage appearing across the SCR causes it to turn-off slowly. Consequently switching frequencies have to be low. *Note that such a diode cannot be connected across the Main SCR in the voltage-commutated circuit.*

Classification of Rectifiers based on Control:

- The converter circuit which converts AC to DC is called a Rectifier.
- The rectifier circuit using diodes only is called an Uncontrolled rectifier circuit.
- All rectifiers are broadly categorized into three sections.

1. Controlled Rectifier - It has only thyristors. NO diodes
2. Half Controlled Rectifier - It has thyristor + diodes
3. Uncontrolled Rectifier - Only diodes

- Control here means controlling when to start rectification and when to stop.

Phase Controlled Rectifiers:

- Unlike diode, an SCR does not become conducting immediately after its voltage has become positive.
- It requires triggering by means of pulse at the gate.
- So it is possible to make the thyristor conduct at any point on the half wave which applies positive voltage to its anode.
- Thus the output voltage is controlled.

Phase Controlled Rectifiers - Applications

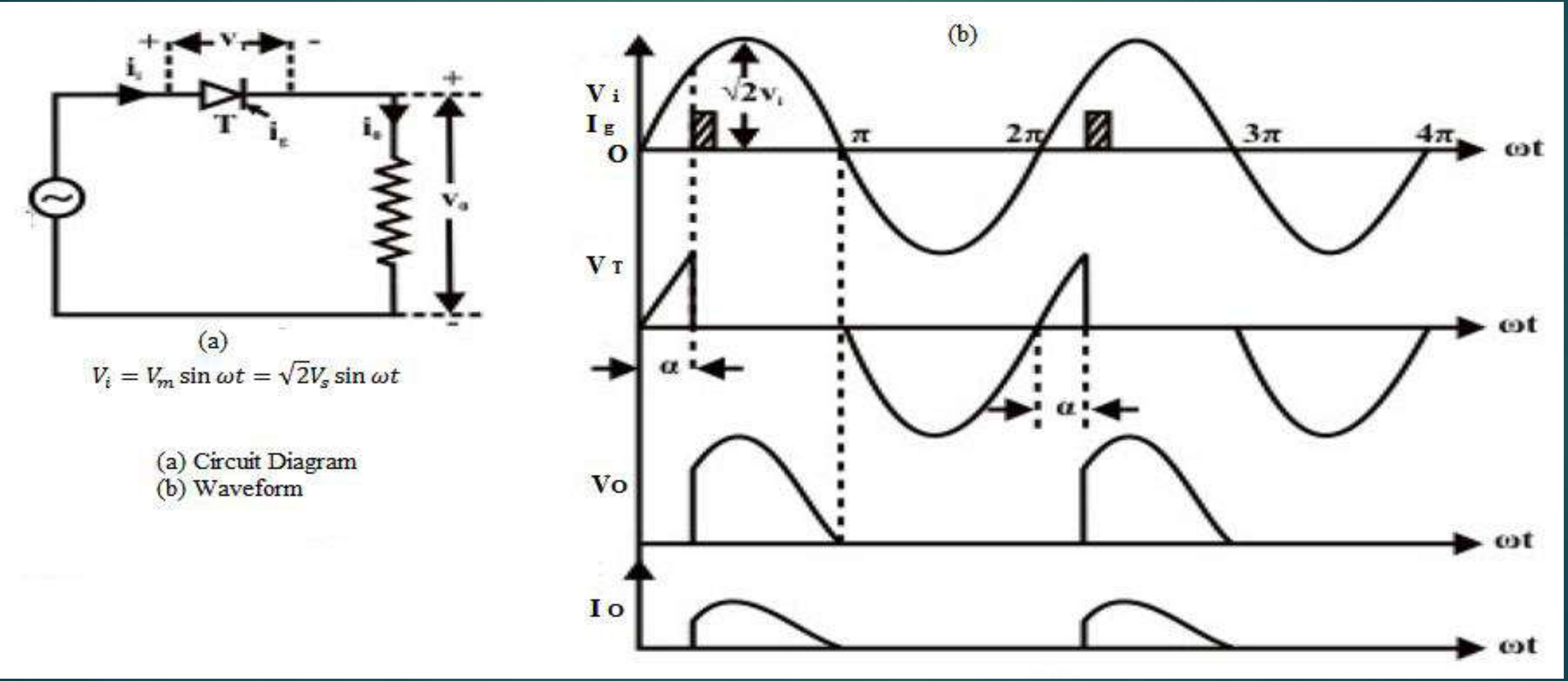
- Steel rolling mills, paper mills, textile mills where controlling of DC motor speed is necessary.
- Electric traction.
- High voltage DC transmissions.
- Electromagnet power supplies.

1 – φ Half Wave Controlled Rectifier (R Load)

- The circuit consists of a thyristor T, a voltage source Vs and a resistive load R.
- During the positive half cycle of the input voltage, the thyristor T is forward biased but it does not conduct until a gate signal is applied to it.
- When a gate pulse is given to the thyristor T at $\omega t = \alpha$, it gets turned ON and begins to conduct.
- When the thyristor is ON, the input voltage is applied to the load.
- During the negative half cycle, the thyristor T gets reverse biased and gets turned OFF.
- So the load receives voltage only during the positive half cycle only.
- The average value of output voltage can be varied by varying the firing angle α.

1 – φ Half Wave Controlled Rectifier (R Load)

- The waveform shows the plot of input voltage, output voltage, gate current, output current and voltage across thyristor.

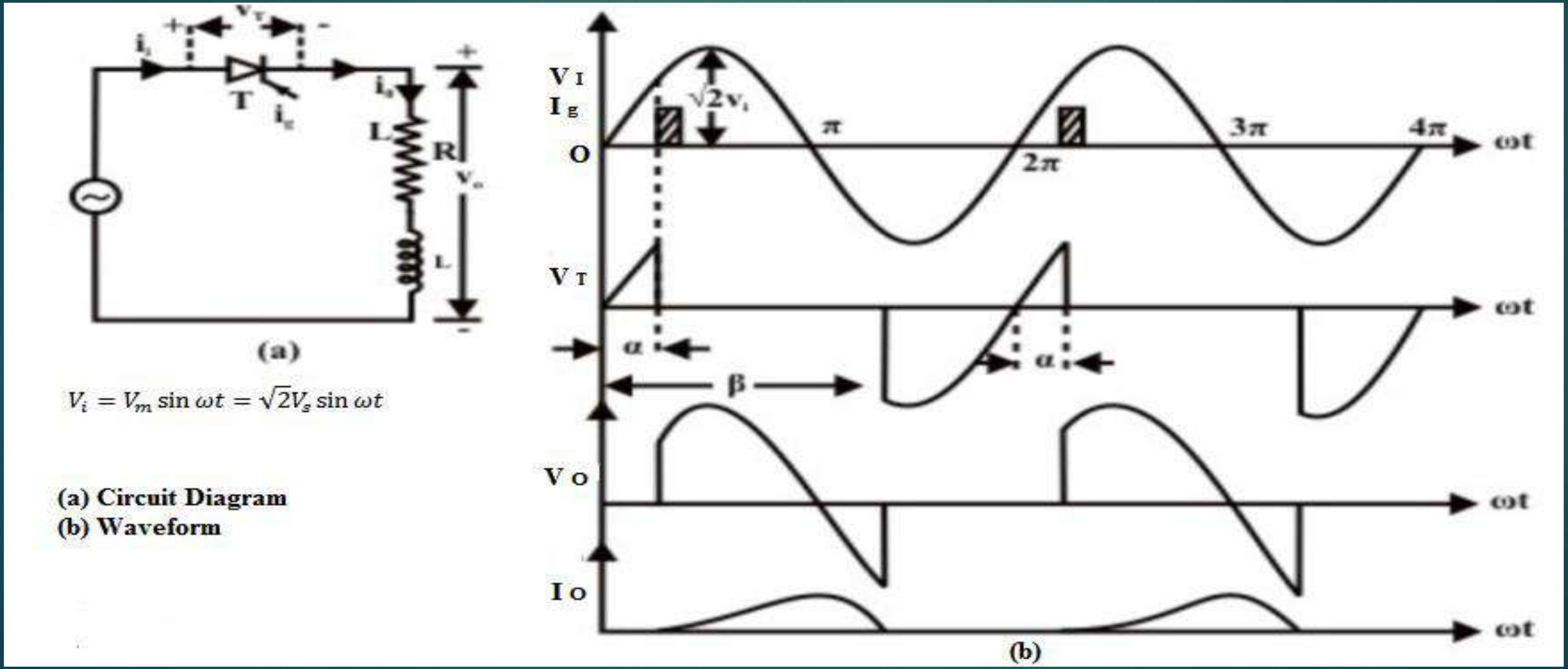


1 – φ Half Wave Controlled Rectifier (RL Load)

- The circuit consist of a thyristor T, a voltage source Vs, an inductive load L and a resistive load R.
- During the positive half cycle of the input voltage, the thyristor T is forward biased but it does not conduct until a gate signal is applied to it.
- When a gate pulse is given to the thyristor T at $\omega t = \alpha$, it gets turned ON and begins to conduct.
- When the thyristor is ON, the input voltage is applied to the load but due to the inductor present in the load, the current through the load builds up slowly.
- During the negative half cycle, the thyristor T gets reverse biased but the current through the thyristors is not zero due to the inductor.

1 – φ Half Wave Controlled Rectifier (RL Load)

- The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.



$V_i = V_m \sin \omega t = \sqrt{2} V_s \sin \omega t$

(a) Circuit Diagram
(b) Waveform

1 – φ Half Wave Controlled Rectifier (RL Load)

- The current through the inductor slowly decays to zero and when the load current (i.e. the current through the thyristor) falls below holding current, it gets turned off.
- So here the thyristor will conduct for a few duration in the negative half cycle and turns off at $\omega t = \beta$. The angle β is called extinction angle.
- The duration from α to β is called conduction angle.
- So the load receives voltage only during the positive half cycle and for a small duration in negative half cycle.
- The average value of output voltage can be varied by varying the firing angle α.

1 – φ Half Wave Controlled Rectifier (RL with FD)

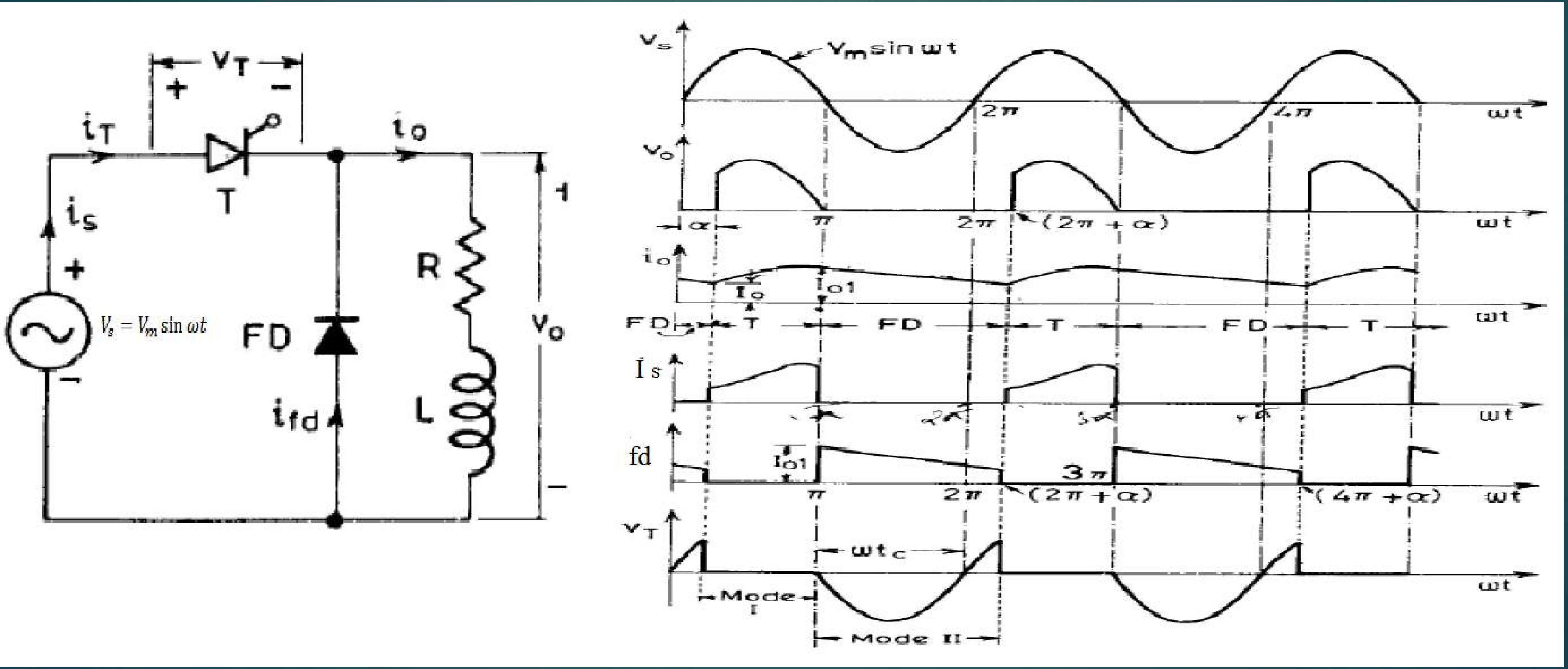
- The circuit consist of a thyristor T, a voltage source Vs, a diode FD across the RL load, an inductive load L and a resistive load R.
- During the positive half cycle of the input voltage, the thyristor T is forward biased but it does not conduct until a gate signal is applied to it.
- When a gate pulse is given to the thyristor T at $\omega t = \alpha$, it gets turned ON and begins to conduct.
- When the thyristor is ON, the input voltage is applied to the load but due to the inductor present in the load, the current through the load builds up slowly.
- During the negative half cycle, the thyristor T gets reverse biased. At this instant i.e at $\omega t = \pi$, the load current shift its path from the thyristor to the freewheeling diode.
- When the current is shifted from thyristor to freewheeling diode, the thyristor turns OFF.

1 – φ Half Wave Controlled Rectifier (RL with FD)

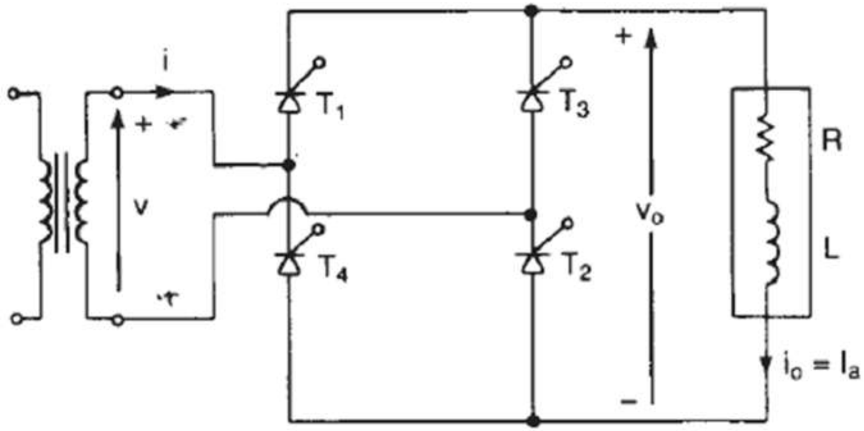
- The current through the inductor slowly decays to zero through the loop R freewheeling diode - L.
- So here the thyristor will not conduct in the negative half cycle and turns off at $\omega t = \pi$.
- So the load receives voltage only during the positive half cycle.
- The average value of output voltage can be varied by varying the firing angle α.
- The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.
- There are two modes in this circuit.
- (a) Conduction Mode (b) Freewheeling Mode.

1 – φ Half Wave Controlled Rectifier (RL with FD)

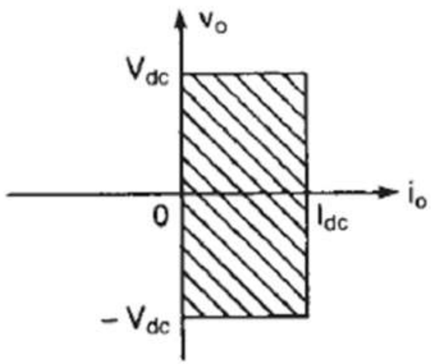
- The waveform shows the plot of input voltage, gate current, output voltage, output current and voltage across thyristor.



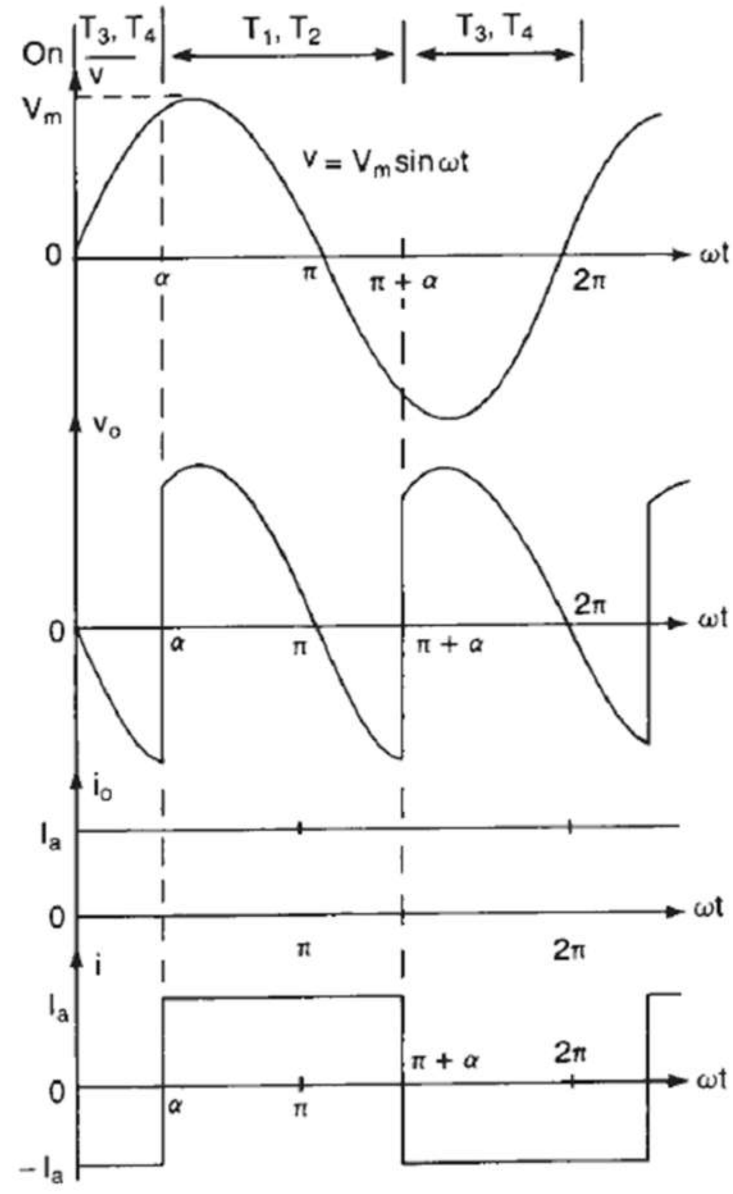
Single-phase full converter (highly inductive load)



(a) Circuit



(b) Quadrant



(c) Waveforms

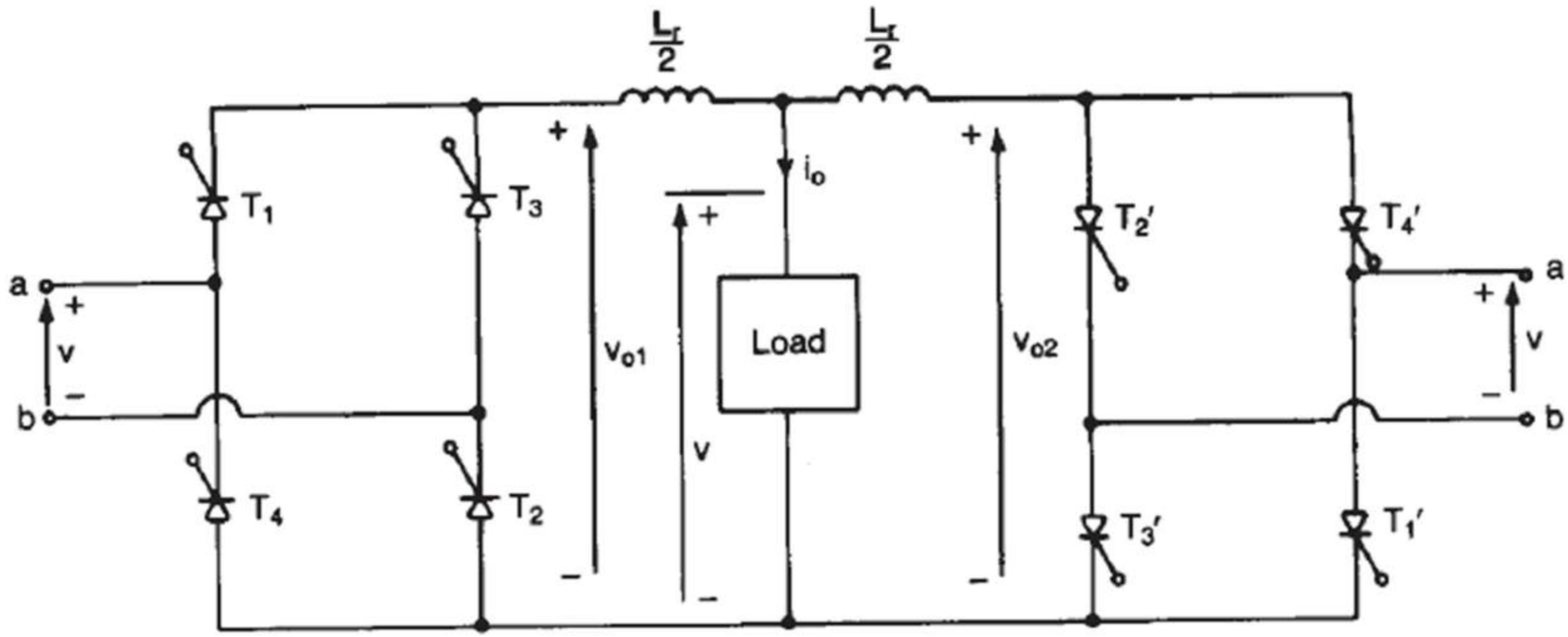
The average value of output voltage

$$V_{dc} = \frac{2}{2\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t\, dt = \frac{2V_m}{\pi}\cos\alpha$$

Therefore, Changing the firing angle from 0 to π/2, the output voltage varies from 2Vm/π to 0. The rms value of output voltage

$$V_{rms} = \sqrt{\frac{2}{2\pi}\int_{\alpha}^{\pi+\alpha} V_m^2\, sin^2\,\omega t\, dt} = \frac{V_m}{\sqrt{2}}$$

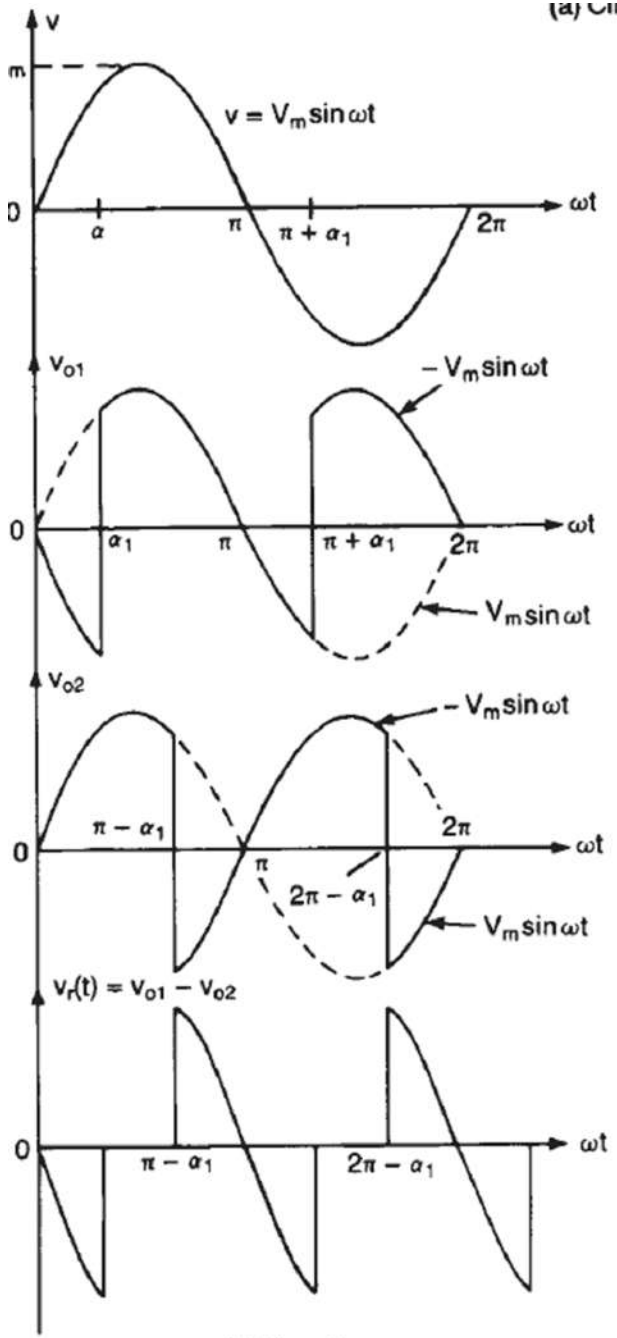
Single-phase dual converter (highly inductive load)



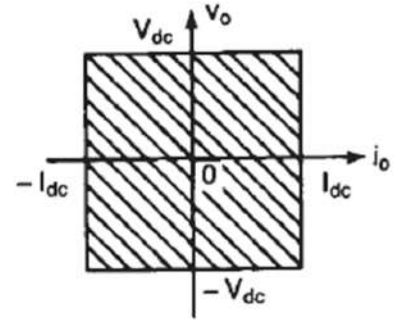
(a) Circuit

Single-phase dual converter consists of two single-phase full converter connected back to back. Thus, both output voltage and load current can be reversed. Therefore, the dual converter can be operated in the four quadrants.

(a) Circuit



(b) Waveforms



(c) Quadrant

$$V_{dc1} = \frac{2V_m}{\pi} \cos \alpha_1$$

$$V_{dc2} = \frac{2V_m}{\pi} \cos \alpha_2$$

$$V_{dc1} = -V_{dc2}$$

$$\cos \alpha_2 = -\cos \alpha_1 = \cos(\pi - \alpha_1)$$

Therefore

$$\alpha_2 = \pi - \alpha_1$$

Full converter (Purely resistive load)

Mode I
Continuous conduction
mode ($\alpha \leq 60^\circ$)

Mode II
Discontinuous conduction
mode ($\alpha > 60^\circ$)

1. **Mode I : Continuous conduction mode :**

The load current in this mode is continuous. The firing angle $\alpha \leq 60^\circ$. The load voltage waveform is identical to that with the inductive load.

2. **Mode II : Discontinuous conduction mode :**

- For $\alpha > 60^\circ$, the load current becomes discontinuous, as the load voltage reaches a zero as shown in Fig. 8.7.9. This will turn off the conducting pair of thyristors.
- With the resistive load, the full converter works as a single quadrant converter as the load voltage can not become negative at all.
- The converter therefore works only as a rectifier. Inverter action is not possible to obtain.
- The sequence of turning the SCRs on remains same as that with the highly inductive load i.e. 1, 6, 2, 4, 3, 5.
- In the continuous conduction mode ($\alpha \leq 60^\circ$), the SCRs are commutated due to the line commutation, whereas for the discontinuous conduction ($\alpha > 60^\circ$) they are commutated due to natural commutation, when the driving line voltage passes through a zero.

8.7.3.1 Operation in Continuous Conduction Mode ($\alpha \leq 60^\circ$) :

- The load voltage and other waveforms are as shown in Fig. 8.7.8. As can be seen 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 $2\pi/3$ radians or 120°.
- The peak reverse voltage across each SCR is,

$$V_{m\,(line)} = \sqrt{3}\; V_{m\,(ph)}$$

- The average load voltage for this mode is,

$$V_{L\,dc} = \frac{3\, V_{m\,(line)}}{\pi} \cos\alpha \qquad ...(8.7.1)$$

- Which is same as that with the highly inductive load. The equations for normalized voltage and the rms voltage are also applicable to this mode i.e.

$$V_n = \cos\alpha \qquad ...(8.7.2)$$

and

$$V_{L\,rms} = V_{m\,(line)} \left[\frac{1}{2} + \frac{3\sqrt{3}}{4\pi} \cos 2\alpha\right]^{1/2} \qquad ...(8.7.3)$$

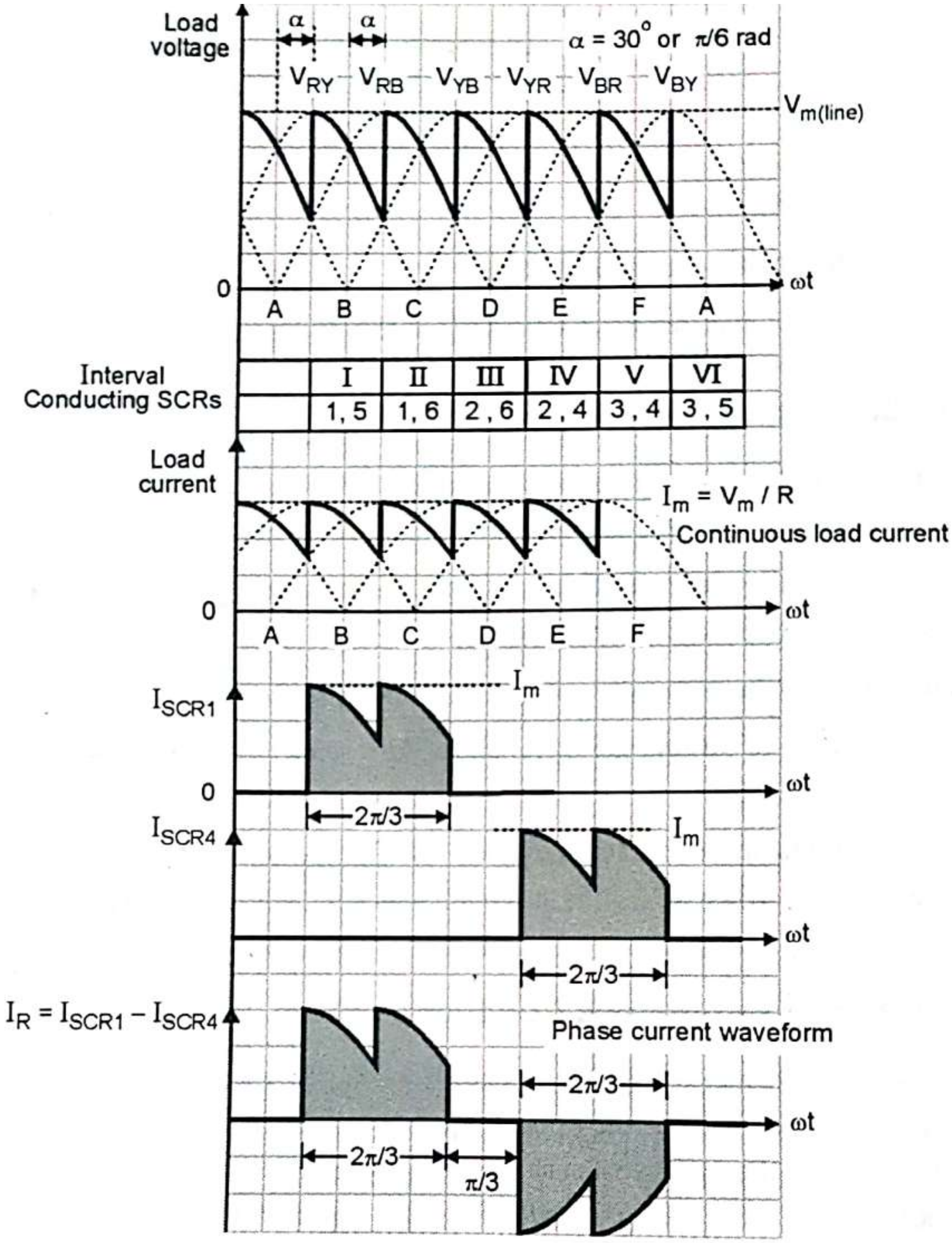


Fig. 8.7.8 : Voltage and current waveforms for a full converter with a resistive load (Continuous conduction mode)

- For example thyristor 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 th load.
- The load current is in phase with the load voltage due to the resistive nature of load.
- At the instant, $5\pi/6$, $V_{RY} = 0$ therefore load current = 0 and the conducting SCRs S_1 and S_5 a turned off due to natural commutation.

Note : The load current is in phase with load voltage hence it also will be discontinuous.

8.7.3.2 Operation in Discontinuous Conduction Mode ($\alpha > 60°$) :

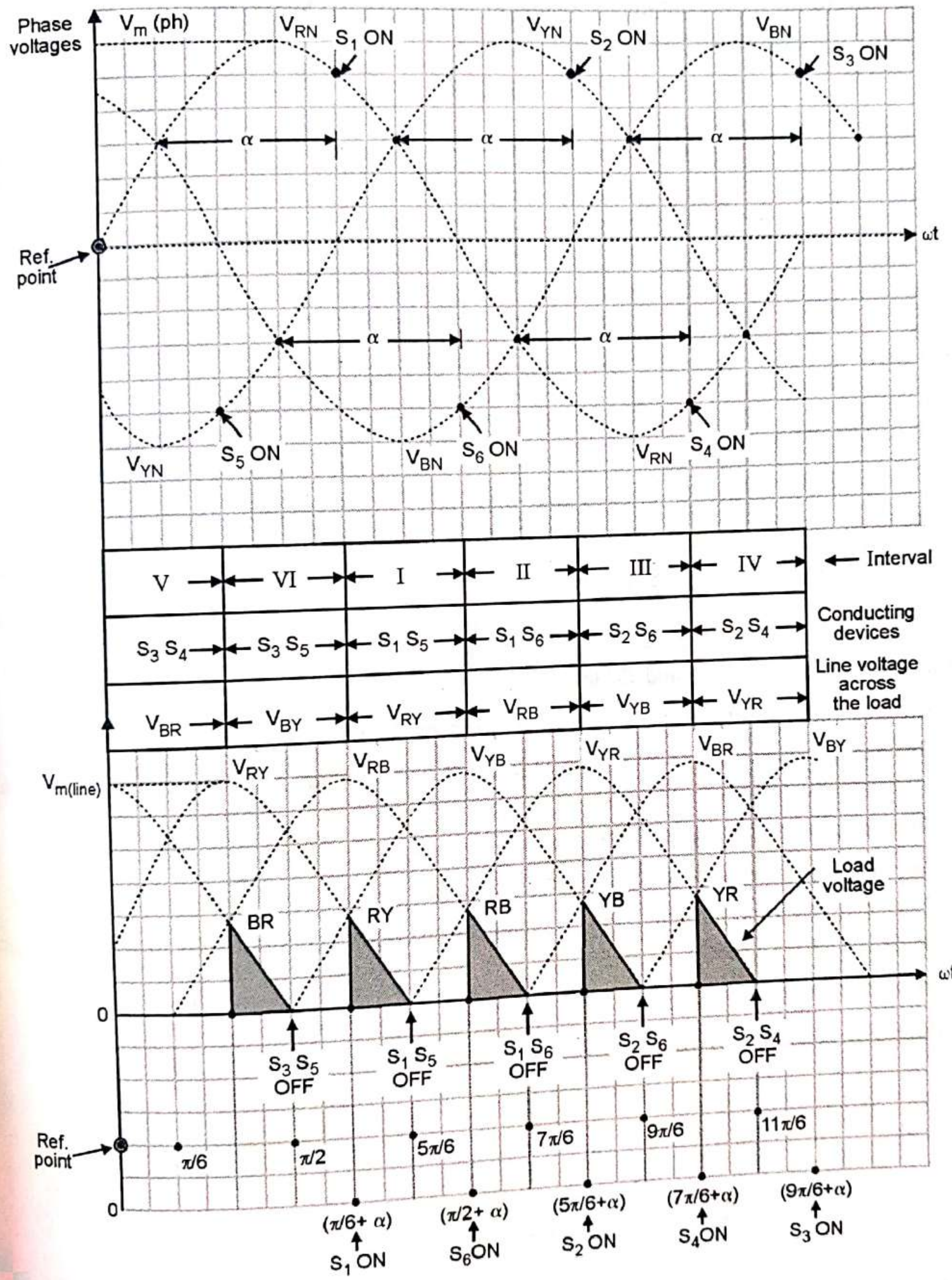


Fig. 8.7.9 : Load voltage for a full converter with a resistive load (discontinuous conduction)

- 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. 8.7.9.

Table 8.7.3 summarises the operation.

Table 8.7.3

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	–	–
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. 8.7.9 and Table 8.7.3 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.
3. The load current is in phase with the load voltage and discontinuous.
4. The conduction period of SCRs is less than $2\pi/3$ rad. or 120°.
5. Each SCR has to be retriggered in its conduction period, therefore the multiple pulse triggering for each SCR is necessary.

Expression for average voltage :

Refer Fig. 8.7.9. The average load voltage is given by,

$$V_{Ldc} = \frac{1}{\pi/3} \int V_{RY}\, d\omega t = \frac{3}{\pi} \int_{\pi/6+\alpha}^{5\pi/6} V_{m\,(line)} \sin(\omega t + \pi/6)\, d\omega t$$

$$= \frac{-3\, V_{m\,(line)}}{\pi} \times \left[\cos(\omega t + \pi/6)\right]_{\pi/6+\alpha}^{5\pi/6}$$

$$= \frac{-3\, V_{m\,(line)}}{\pi} \left[\cos n\pi - \cos(\pi/3 + \alpha)\right]$$

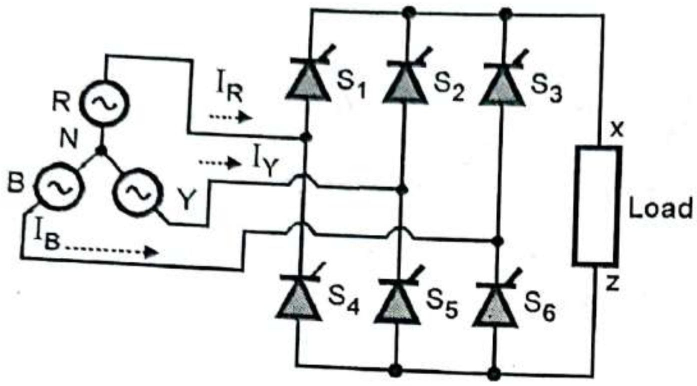
$$\therefore V_{Ldc} = \frac{3 V_{m(line)}}{\pi}\left[1 + \cos(\alpha + \pi/3)\right]$$

Remember this.

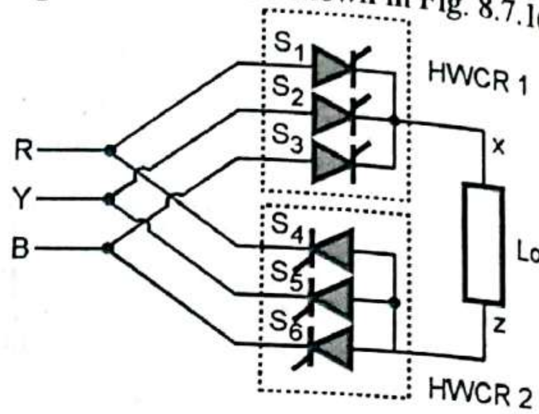
- At any given instant two SCRs, 1 each from upper and lower SCRs conduct simultaneously.
- The frequency of the output ripple voltage is $6 \times 50 = 300$ Hz and the filtering requirement is less than that of the three phase semi or half wave converters.

8.7.1 Operation with Highly Inductive Load :

- The circuit diagram for a 3 phase fully controlled bridge converter is as shown in Fig. 8.7.1(a).



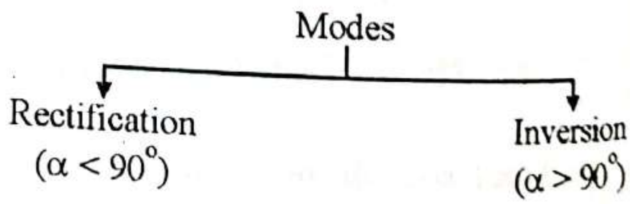
(a) 3 phase full converter



(b) Full converter redrawn as a combination of two halfwave converter

Fig. 8.7.1

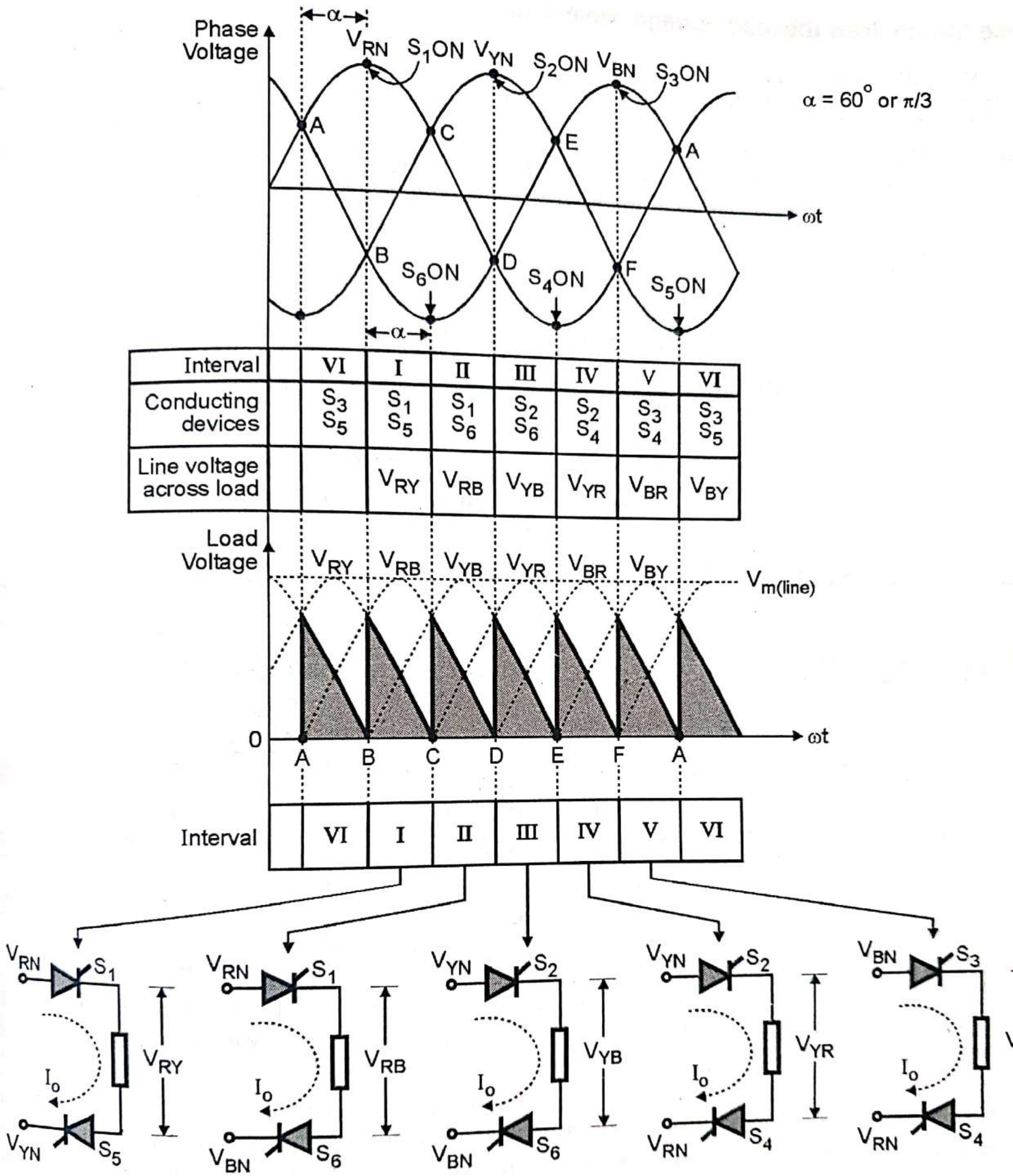
- This circuit can be redrawn as a combination of two half wave controlled converter circuits as shown in Fig. 8.7.1(b).
- At any given instant 2 thyristors will conduct simultaneously one each from the upper and lower half wave converter circuits.
- The load voltage waveform for a full converter with inductive load is as shown in Fig. 8.7.2.
- The load voltage waveform of Fig. 8.7.2 are drawn with the assumption that the load current is ripple free and continuous equal to I_o.
- The full converter operating with a highly inductive load is capable of operating in two different modes.
- It is a two quadrant converter as it is capable of operating in the quadrants I or II of average load voltage load current characteristics.



8.7.1.1 Rectification Mode ($\alpha < 90°$) :

In this mode of operation, the firing angle α is less than 90°.

- The average load voltage is positive and the net power flow will take place from the source to the load, i.e. from ac side to the dc side.
- The load voltage waveforms and the equivalent circuits are as shown in Fig. 8.7.2 and the other waveforms are as shown in Fig. 8.7.3.
- As the load is inductive, the conducting SCR is turned off only when the next SCR from the same group is turned on. The type of commutation is line commutation



Interval		VI	I	II	III	IV	V	VI
Conducting devices		S_3 S_5	S_1 S_5	S_1 S_6	S_2 S_6	S_2 S_4	S_3 S_4	S_3 S_5
Line voltage across load			V_{RY}	V_{RB}	V_{YB}	V_{YR}	V_{BR}	V_{BY}

Fig. 8.7.2 : Load voltage waveform and equivalent circuits (Rectification mode)

...taneously.

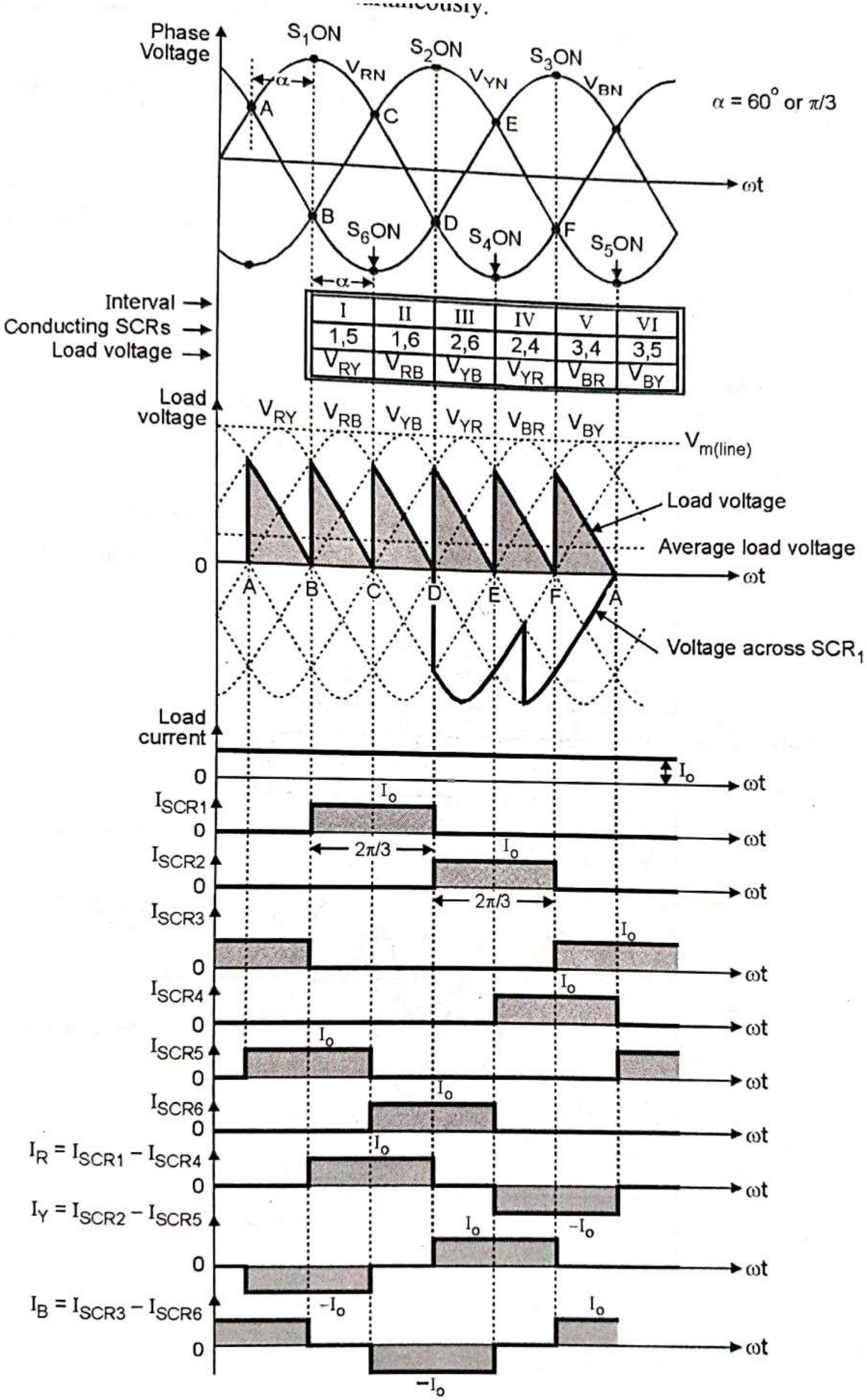


Fig. 8.7.3 : Voltage and current waveforms for full converter in rectifier mode

as shown.

7. The average load voltage for $\alpha \le 90°$ is positive. Therefore the net power flow per cycle of input is from source to load. Therefore for $\alpha \le 90°$, the operation is known as **Rectification**.

Waveforms for $\alpha = 90°$:

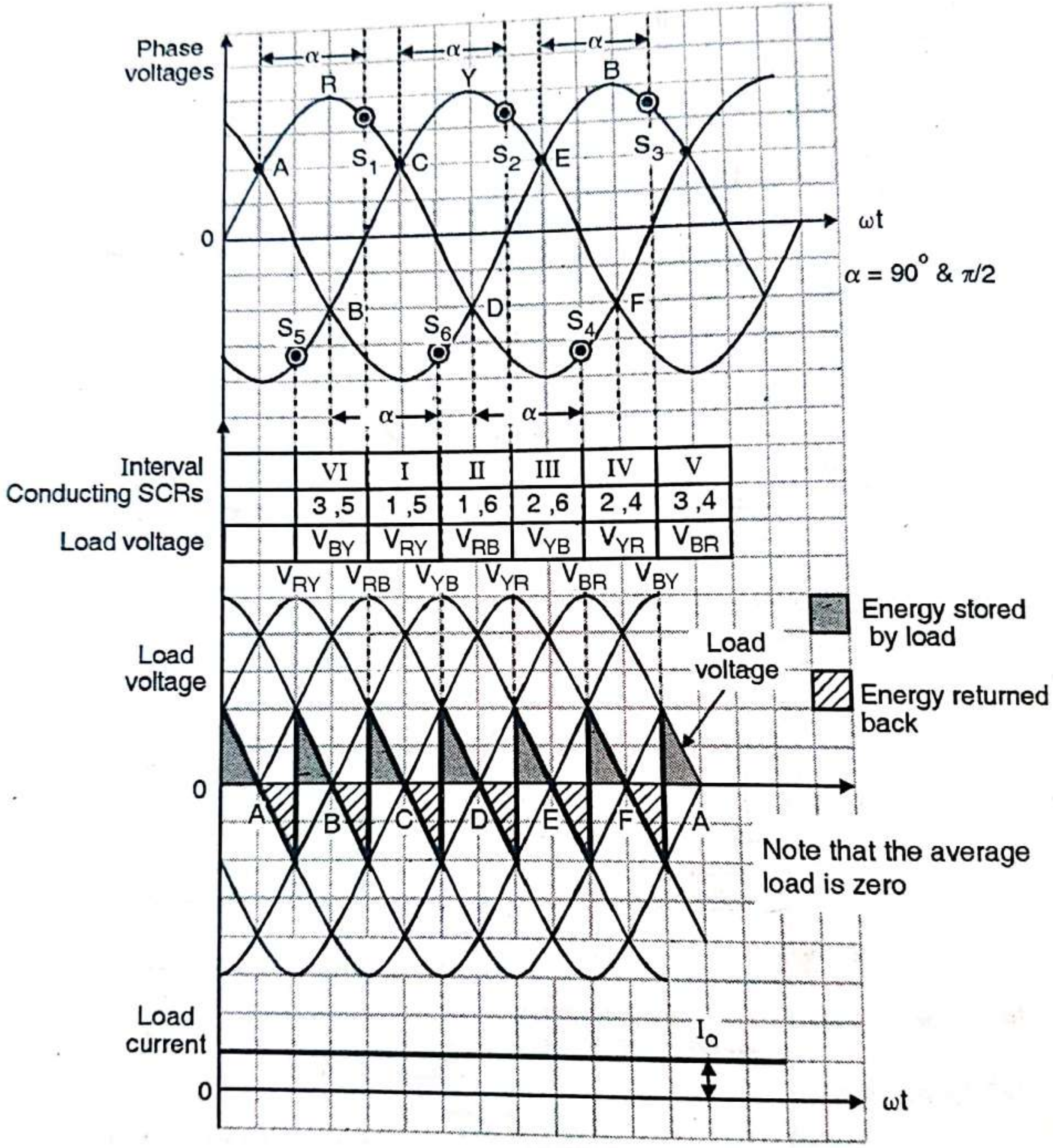


Fig. 8.7.4 : Load voltage waveforms for $\alpha = 90°$

Fig. 8.7.4 shows the load voltage waveforms for $\alpha = 90°$.

As can be seen from the waveforms, the average load voltage is zero because of equal area under the positive and negative halves of the waveform.

In the positive portion, the energy is stored by the load and in the negative portion, it is fed back to the source. As both the positive and negative portions are equal, the net power flow is zero at $\alpha = 90°$.

8.7.2 Inverter Mode of Operation ($\alpha > 90°$) :

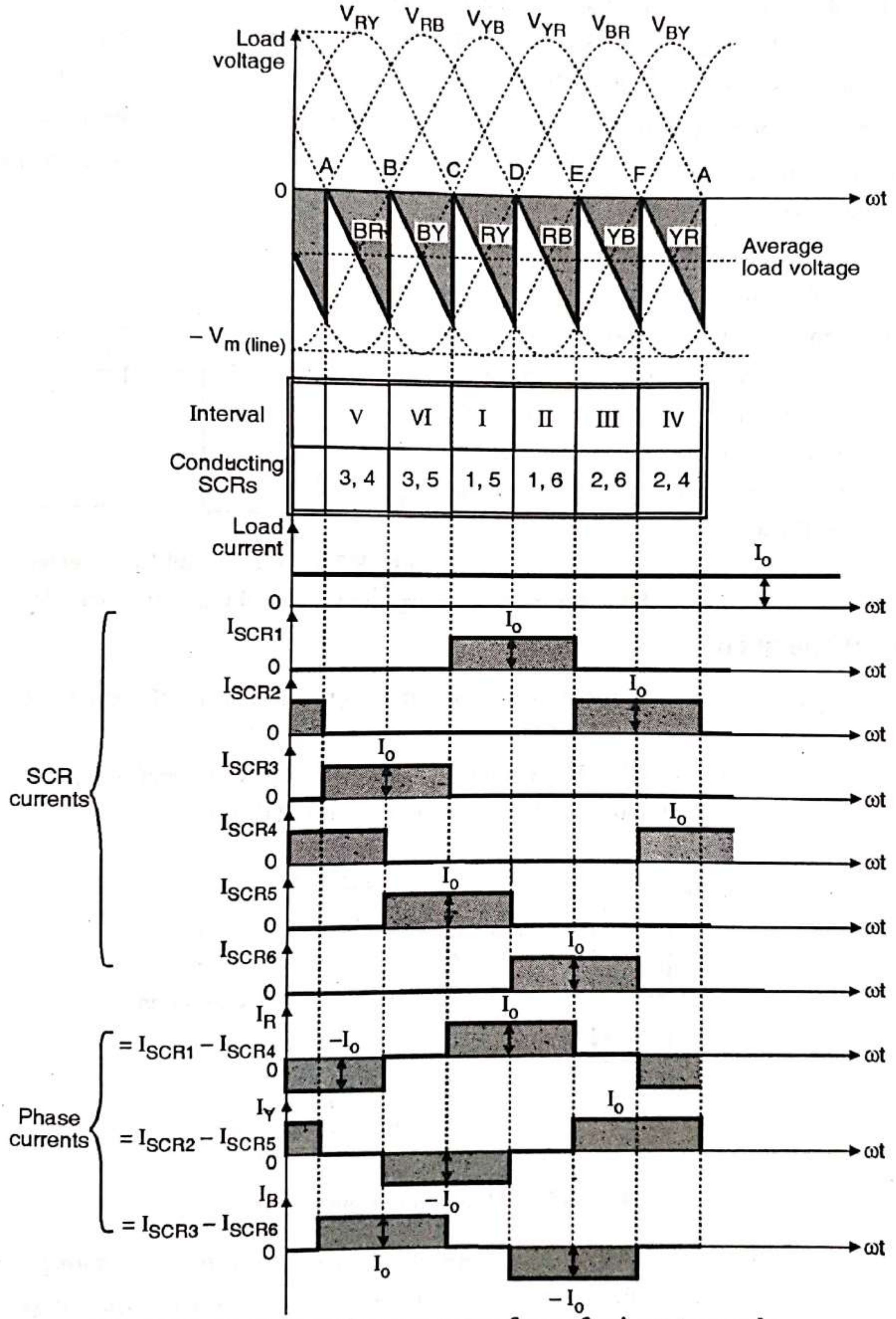


Fig. 8.7.5 : Voltage and current waveforms for inverter mode

Ex. 8.7.1 : Derive the expression for the average load voltage of a 3ϕ full converter operating with an inductive load. The load current is assumed to be continuous and ripple free equal to I_o.

Soln. : Refer to the Fig. P. 8.7.1. We are going to consider the shaded portion of the waveform for integration. 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}.

$$\therefore \text{ The average load voltage } = V_{Ldc} = \frac{1}{\pi/3} \int_{\alpha}^{(\pi/3+\alpha)} V_{RY}\, d\omega t$$

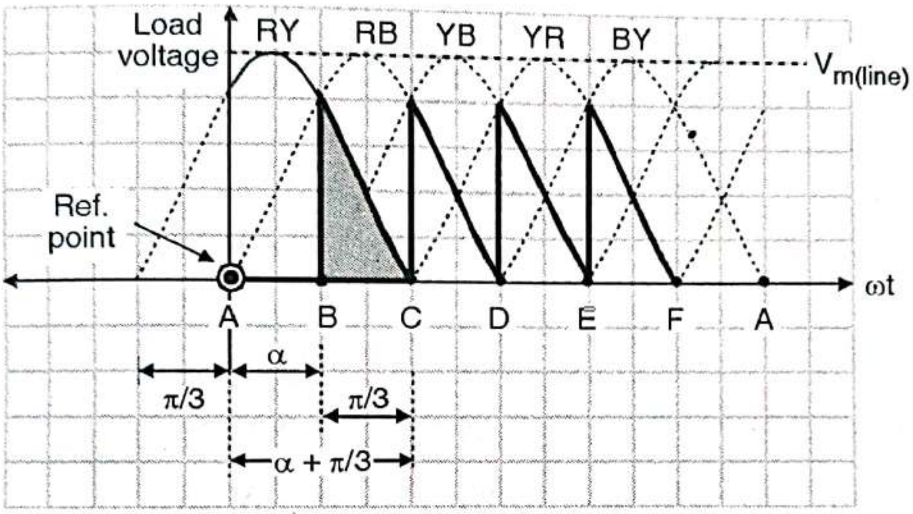


Fig. P. 8.7.1

$$\text{But} \quad V_{RY} = V_{m\,(line)} \cdot \sin(\omega t + \pi/3)$$

This is because, the line voltage V_{RY} leads our reference point "A" by 60° or $\pi/3$ radians.

$$\therefore V_{Ldc} = \frac{3}{\pi} \int_{\alpha}^{(\pi/3+\alpha)} V_{m\,(line)} \sin(\omega t + \pi/3)\, d\omega t$$

$$= \frac{3\,V_{m\,(line)}}{\pi} [\cos(\alpha + \pi/3) - \cos(2\pi/3 + \alpha)]$$

$$= \frac{3\,V_{m\,(line)}}{\pi} [\cos\alpha \cos(\pi/3) - \cos(2\pi/3)\cos\alpha]$$

$$= \frac{3\,V_{m\,(line)}}{\pi} [\cos\alpha]$$

$$\therefore V_{Ldc} = 3\frac{V_{m\,(line)}}{\pi} \cos\alpha \qquad ...(1)$$

In DC-DC converters or choppers, the average output voltage is controlled by varying the alpha (α) value. This is achieved by varying the **Duty Cycle** of the switching pulses. Duty cycle can be varied usually in 2 ways:

1. Time Ratio Control
2. Current Limit Control

In this lecture we shall look upon both the ways of varying the duty cycle.

As all of you know that, **Duty Cycle is the ratio of 'On Time' to 'Time Period of a pulse'.**

<u>Time Ratio Control:</u>

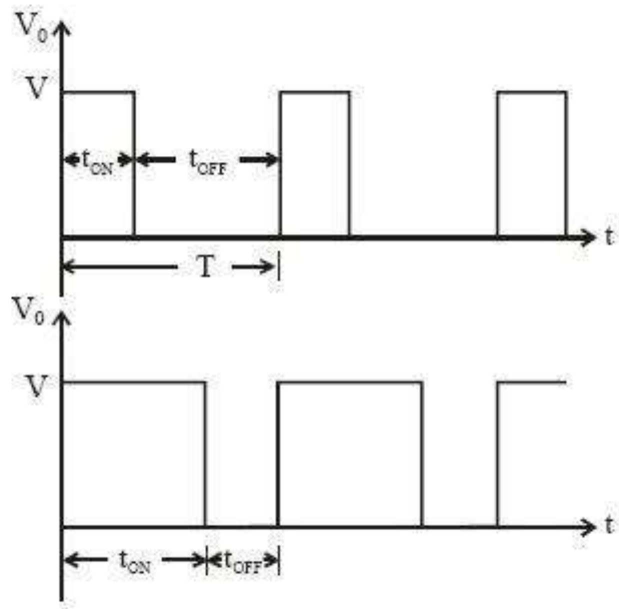
As the name suggest, here the time ratio (i.e. the duty cycle ratio Ton/T) is varied.

This kind of control can be achieved using 2 ways:

- Pulse Width Modulation (PWM)
- Frequency Modulation Control (FMC)

Pulse Width Modulation (PWM):

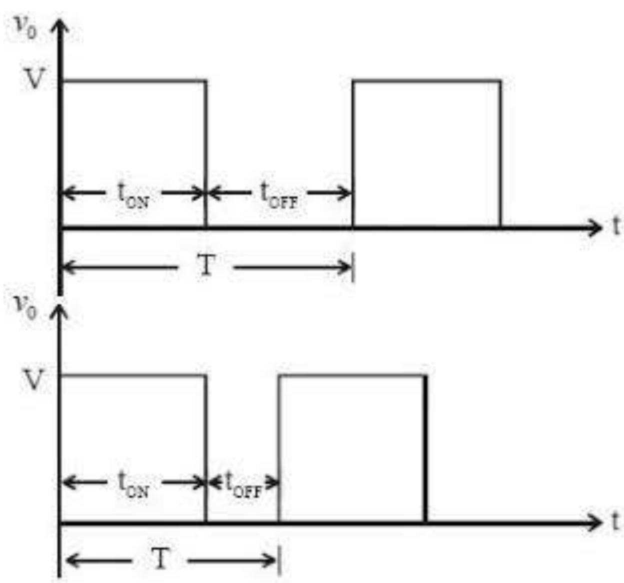
In this technique, the time period is kept constant, but the 'On Time' or the 'OFF Time' is varied. Using this, the duty cycle ratio can be varied. Since the ON time or the 'pulse width' is getting changed in this method, so it is popularly known as Pulse width modulation.



Pulse Width Modulation

Frequency Modulation Control (FMC)

In this control method, the 'Time Period' is varied while keeping either of 'On Time' or 'OFF time' as constant. In this method, since the time period gets changed, so the frequency also changes accordingly, so this method is known as frequency modulation control.



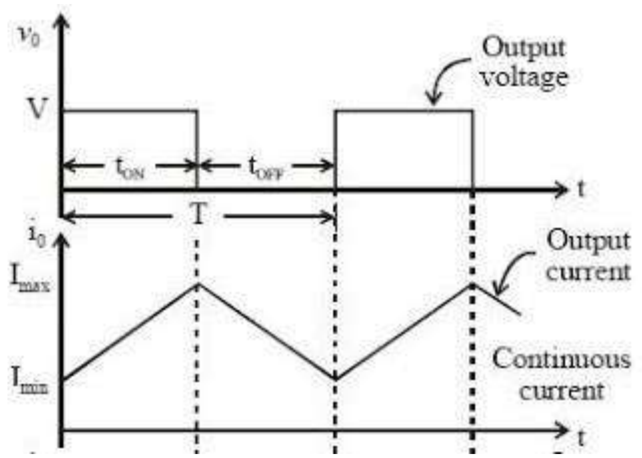
Frequency Modulation Control

Current Limit Control:

As is obvious from its name, in this control strategy, a specific limit is applied on the current variation.

In this method, current is allowed to fluctuate or change only between 2 values i.e. maximum current (I max) and minimum current (I min). When the current is at minimum value, the chopper is switched ON. After this instance, the current starts increasing, and when it reaches up to maximum value, the chopper is switched off allowing the current to fall back to minimum value.

This cycle continues again and again.



Current Limit Control

Important Note:

In nutshell, we can say that load voltage can be controlled by varying duty cycle only.

As load voltage of the chopper is given by-

$$V_L = V_{DC} \cdot \left(\frac{T_{ON}}{T}\right)$$

From the above equation it is clear that the load voltage depends on two factors

1. The supply voltage (Vs)
2. The duty cycle of the chopper (D)

Since the supply voltage is constant, the load voltage is governed by the duty cycle of the chopper.

In other words the load voltage is dependent on two factors TON and TOFF.

So the average load voltage can be controlled by varying the values of the TON and TOFF by above said methods.

The summary is

In chopper circuits,

The average value of the output voltage V_0 can be controlled by opening and closing the semiconductor switch periodically.

In DC-DC converters or choppers, the average output voltage is controlled by varying the alpha (α) value. This is achieved by varying the **Duty Cycle** of the switching pulses. Duty cycle can be varied usually in 2 ways:

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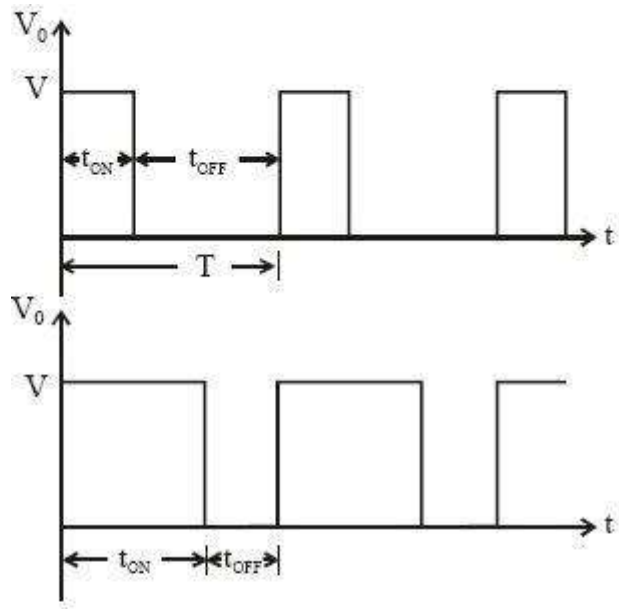
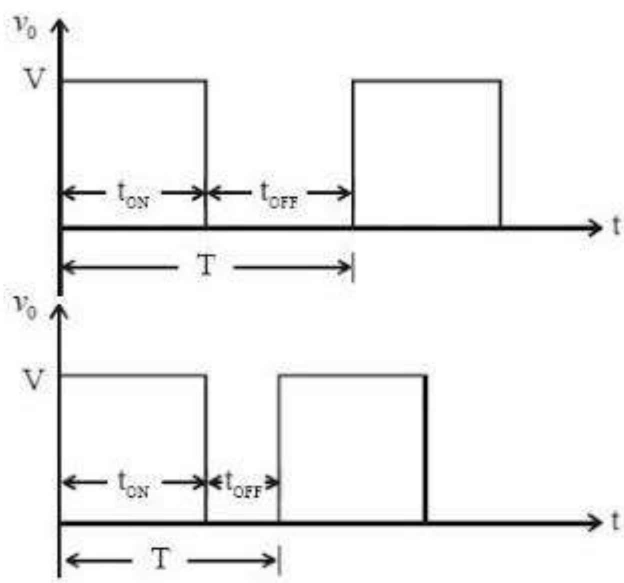


Pulse Width Modulation

Frequency Modulation Control (FMC)

In this control method, the ‘Time Period’ is varied while keeping either of ‘On Time’ or ‘OFF time’ as constant. In this method, since the time period gets changed, so the frequency also changes accordingly, so this method is known as frequency modulation control.



Frequency Modulation Control

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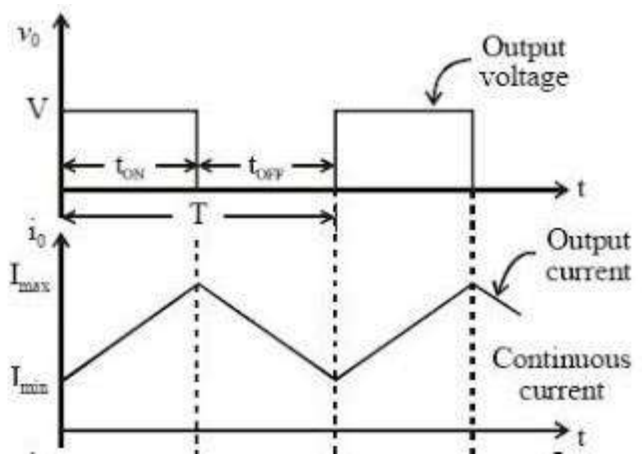
This cycle continues again and again.



Current Limit Control

Important Note:

In nutshell, we can say that load voltage can be controlled by varying duty cycle only.

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$$V_L = V_{DC} \cdot \left(\frac{T_{ON}}{T}\right)$$

From the above equation it is clear that the load voltage depends on two factors

1. The supply voltage (Vs)
2. The duty cycle of the chopper (D)

Since the supply voltage is constant, the load voltage is governed by the duty cycle of the chopper.

In other words the load voltage is dependent on two factors TON and TOFF.

So the average load voltage can be controlled by varying the values of the TON and TOFF by above said methods.

The summary is

In chopper circuits,

The average value of the output voltage V_0 can be controlled by opening and closing the semiconductor switch periodically.

VOLTAGE SOURCE INVERTERS

INTRODUCTION

Inverters are static power converters that produce an AC output waveform from a DC power supply. They are applied in adjustable AC speed drives, Uninterruptible Power Supplies (UPS), shunt active power filter, etc. For sinusoidal AC outputs, the magnitude, frequency, and phase should be controllable. If a DC input is a voltage source, then the inverter is called a Voltage Source Inverter (VSI). Similarly in case of a Current Source Inverter (CSI), the input to the circuit is a current source. The VSI circuit has a capability of controlling AC output voltage, whereas the CSI directly controls AC output current. Sketch of output voltage waveforms by an ideal VSI, should be independent of load connected at the output.

According to a number of phases, inverters are classified into two types

1. Single Phase Voltage Source Inverter
2. Three Phase Voltage Source Inverter

SINGLE PHASE VOLTAGE SOURCE INVERTER

Single phase inverters are basic inverters which produce a square shape AC output with a DC input. These inverters have simple on-off control logic and obviously they operate at much lower frequencies. Due to a capacity of low power, they are widely used in power supplies and single phase UPS .They can be divided into two categories.

3. Half bridge Single Phase Voltage Source Inverter
4. Full bridge Single Phase Voltage Source Inverter.

Half Bridge Voltage Source Inverter

Figure 2.1 shows a circuit topology of a Half-Bridge VSI, where two large capacitors are required to provide a neutral point O, such that each capacitor maintains a constant voltage ($V_1=V_2=V_{dc}/2$). Due to reason that current harmonics produced by the operation of the inverter are low-order harmonics, a set of large capacitors (C_1 and C_2) are required. In this topology, it has a single leg with two power switches Q_1 and Q_2. For bidirectional flow of current, feedback diodes D_1 and D_2 are employed in parallel with switches Q_1 and Q_2.

According to Figure 2.1, it is clear that both switches cannot be ON simultaneously, because both are directly connected across the DC link source. If two switches conduct at the same time, a short circuit across the DC link voltage source V_{dc} would be produced. There are two defined switching states (States 1 and 2) as shown in Table 2.1. In order to avoid the short circuit across the DC bus and the undefined AC output voltage condition, the modulating technique should make sure that at any moment either the top or the bottom switch of the inverter leg is on.

In a half bridge topology, the input DC voltage is split in two equal parts (V_1 and V_2)through an ideal and loss-less capacitive potential divider.

The half bridge topology consists of one leg (one pole) of switches whereas the full bridge topology has two such legs. Each leg of the inverter consists of two series connected power electronic switches
Q_1 and Q_2 as shown in figure 2.1

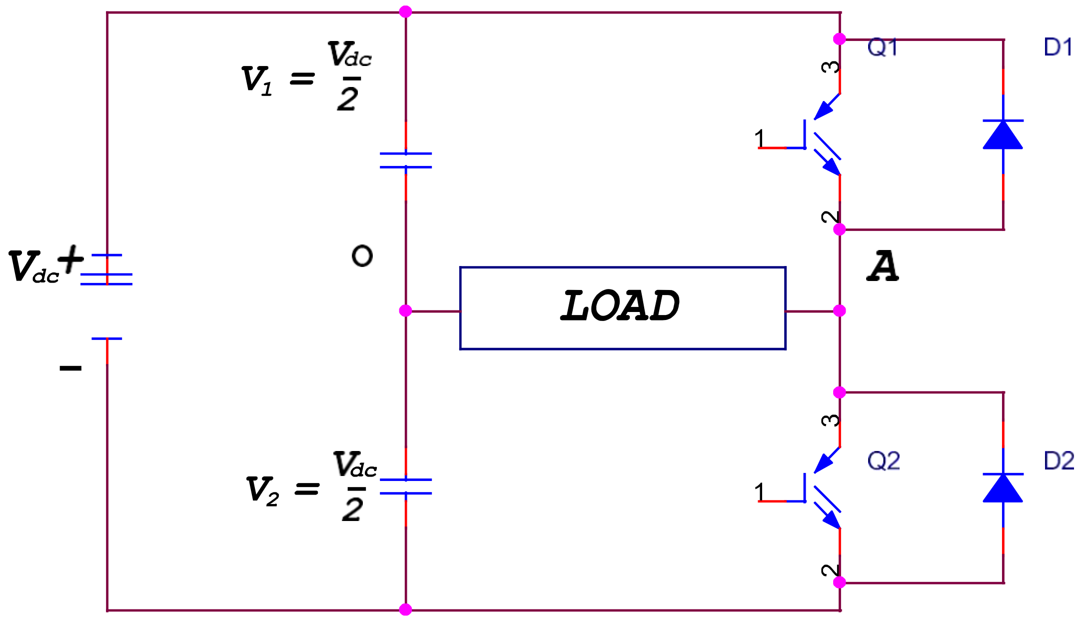

Figure 2.1 Circuit topology of half bridge inverter

Each of these switches consists of an IGBT type controlled switch across which, an uncontrolled diode is put in anti-parallel approach. These switches are capable of conducting bi-directional current, but they have to obstruct only one polarity of voltage. In a half bridge topology, the single- phase load is connected between the mid-point of the input DC supply and the junction point of the two switches. These points are marked as 'O' and 'A' respectively.

2.2.1.1 Principle and operation of half bridge inverter

With refer to the Table 2.1, there are two switching states and the output voltage is obtained or produced on single phase load from either upper half DC voltage ($V_{dc}/2$) or lower half DC voltage. Principle and operation of this inverter with switching states are discussed below.

State 1

In state 1, upper half dc voltage $V_1=V_{dc}/2$ and power switch Q1 are in conducting mode and remaining components are in non-conducting mode. During time period of 0 to T/2, Switch Q_1 is on and upper voltage $\frac{V_{dc}}{2}$ is appeared across a load as an output voltage (V_{AO}). The path of conduction of this state is shown in Figure 2.2.

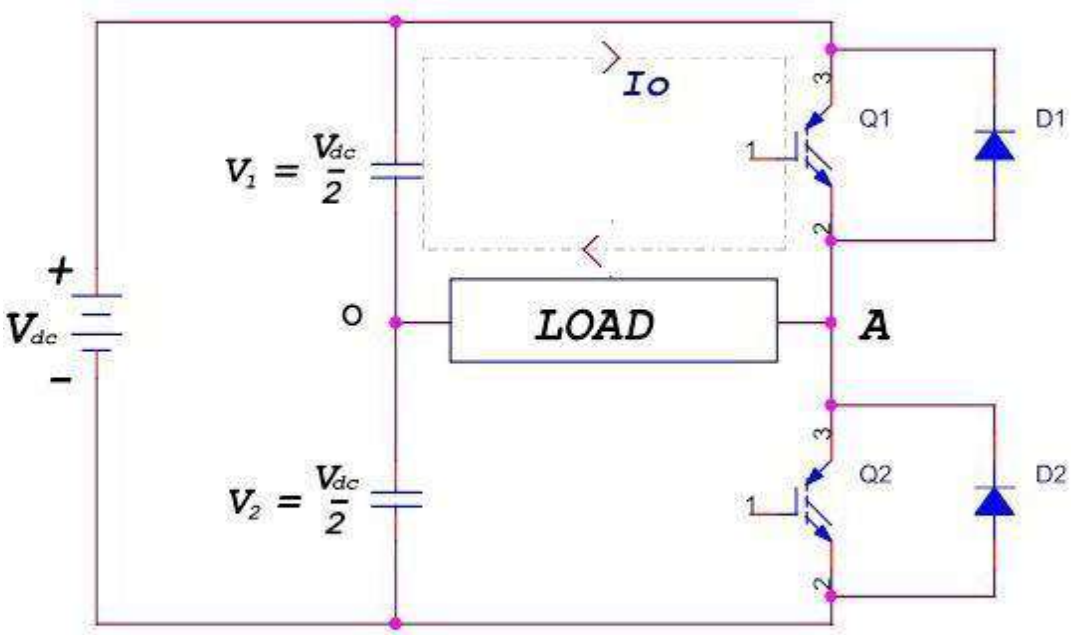

Figure 2.2 Operation of the inverter in State 1

State 2

In state 2, lower half DC voltage($V_2=V_{dc}/2$) and power switch Q_2 are in conduction mode and remaining components are in non-conduction mode.

During time T/2 to T lower switch Q_2 conducts and lower voltage V_2 appears across the load as an output voltage V_{AO}

The path of conduction of this state is shown in Figure 2.3.

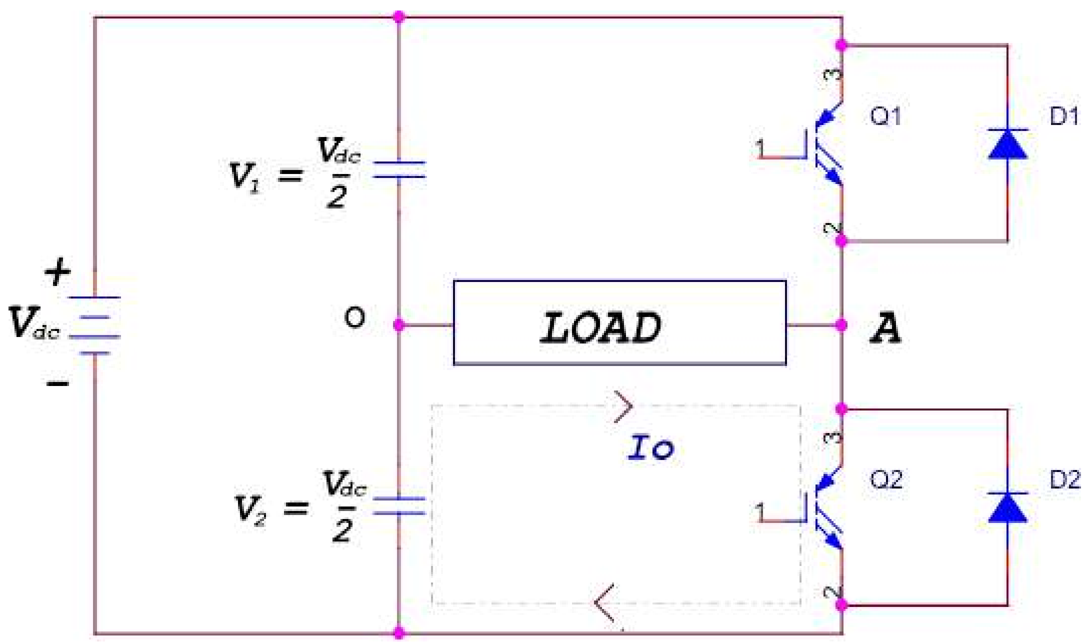

Figure 2.3 Operation of the inverter in State 2

Table 2.1 Switching states of half bridge single phase inverter

State	Switching State	Output Voltage
1	Q_1 is ON and Q_2 is OFF	$\frac{V_{dc}}{2}$
2	Q_1 is OFF and Q_2 is ON	$-\frac{V_{dc}}{2}$

Figure 2.4 shows a typical load voltage waveform output by the half bridge inverter.

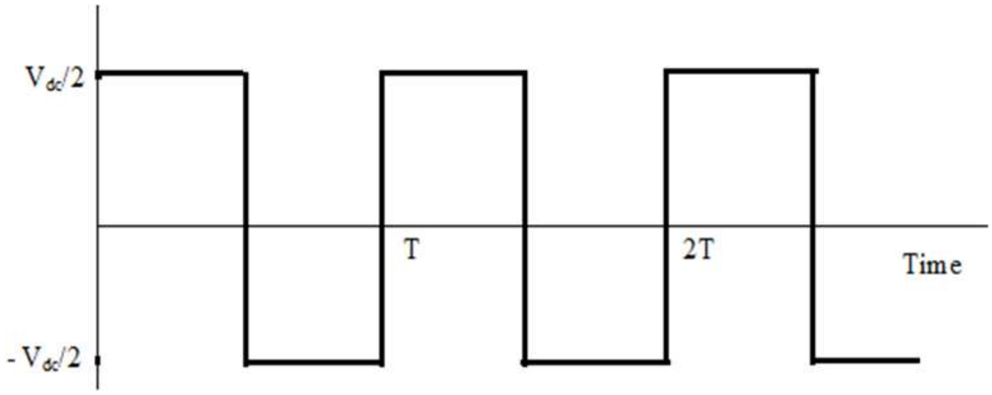

Figure 2.4 Output voltage waveform of half bridge inverter

2.2.2 Full Bridge Voltage Source Inverter

Figure 2.5 shows the power topology of a full bridge VSI. This inverter is similar to the half bridge inverter, however a second leg provides

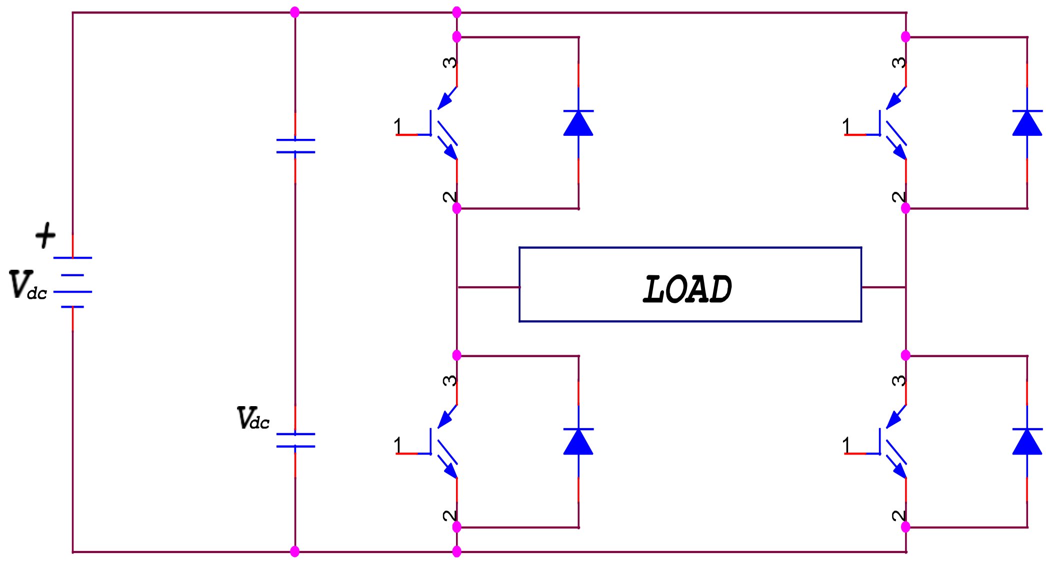

Figure 2.5 Circuit diagram of full bridge voltage source inverter

the neutral point to the load. As in the half bridge inverter, both switches Q_1 and Q_2 or Q_3 and Q_4 in a single leg cannot be on simultaneously because a short circuit across the dc link voltage source V_{dc} would be occurred.

In a full bridge inverter, there are four defined (states 1, 2, 3, and 4) switching states as shown in Table 2.2. The undefined condition should be avoided so as to be always capable of defining the AC output voltage. It can be observed that the AC output voltage can acquire values up to the DC link value V_{dc} which is twice that obtained with half bridge voltage source inverter topologies. Output voltage is denoted as V_{AB} taken from the load.

The single-phase full bridge circuit shown in Figure 2.5 is similar to that of two half bridge circuits sharing the same DC bus. The full bridge circuit has two pole-voltages (V_{AO} and V_{BO}), which are similar to the pole voltage (V_{AO}) of the half bridge circuit. Both (V_{AO}) and (V_{BO}) of the full bridge circuit are square waves but they will have some phase difference. Respective pole voltages are determined by using Thevenin's analysis.

State 1

In this state, the power switches Q_1 and Q_4 are in conduction mode and remaining switches are OFF condition. By using Thevenin's analysis, pole voltages at 'A' and 'B' are (V_{AO} and V_{BO}) measured and the output voltage is obtained as $V_{AB} = V_{AO} - V_{BO} = V_{dc}$. The path for conduction of this state is shown in Figure 2.6.

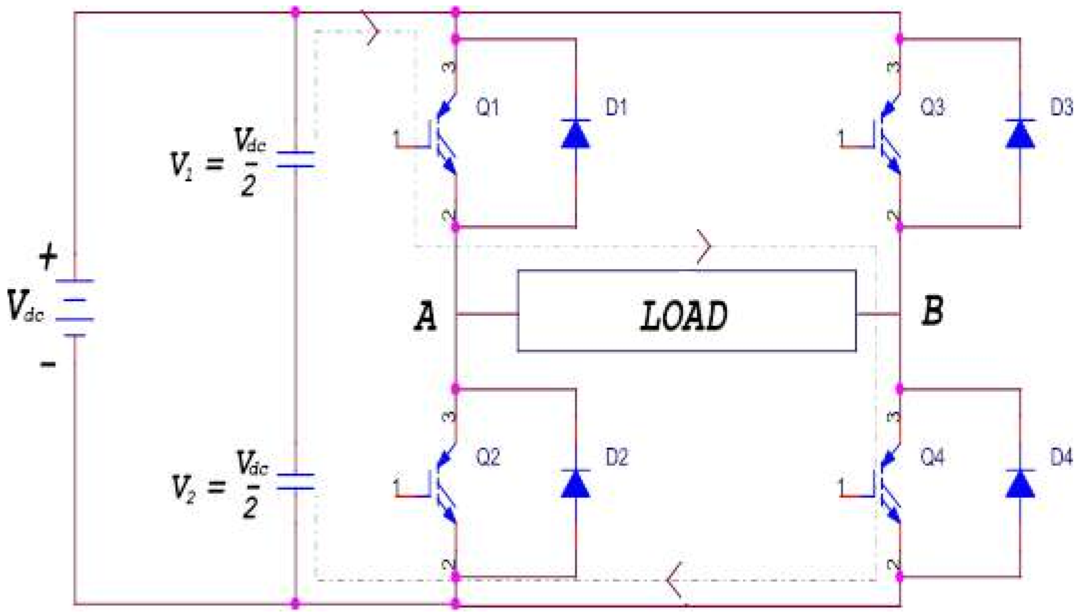

Figure 2.6 Conduction flow of inverter at State 1

State 2

In this state, the power switches Q_2 and Q_3 are in conduction mode and remaining switches are in OFF condition. Pole voltages at ‘A’ and ‘B’ are measured from the load and the output voltage is determined by $V_{AB} = V_{AO} - V_{BO} = -V_{dc}$ as shown in Table 2.2. Topology of this state is shown in Figure 2.7.

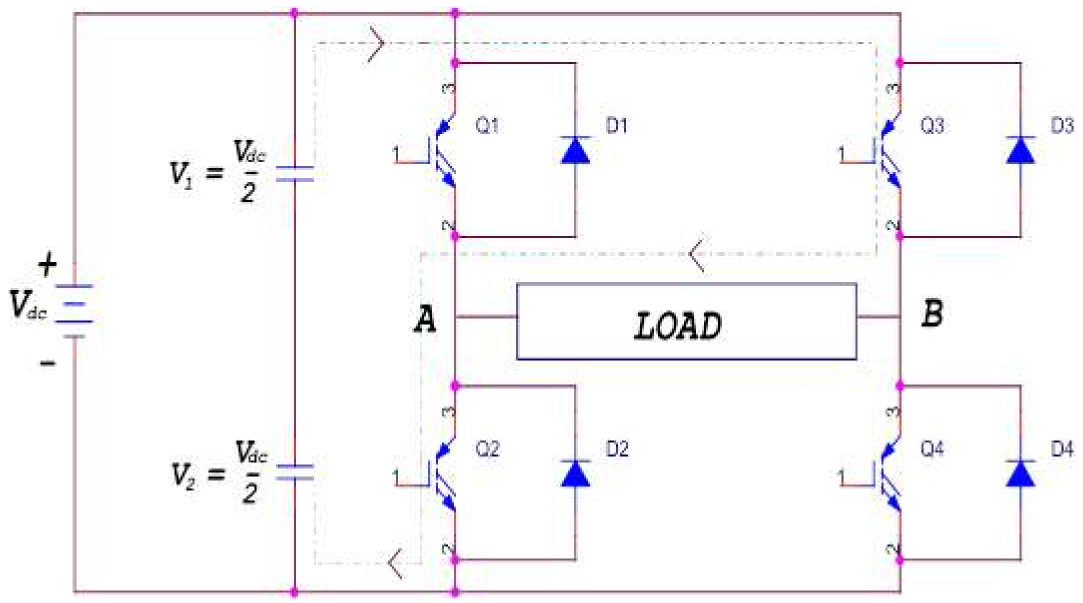

Figure 2.7 Conduction flow of inverter at State 2

State 3

In this state, the power switches Q_1 and Q_3 are in conduction mode and remaining switches are in OFF condition. Voltages at nodes ‘A’ and ‘B’ are measured and the output voltage $V_{AB} = V_{AO} - V_{BO} = 0$. Topology of this state is given in Figure 2.8.

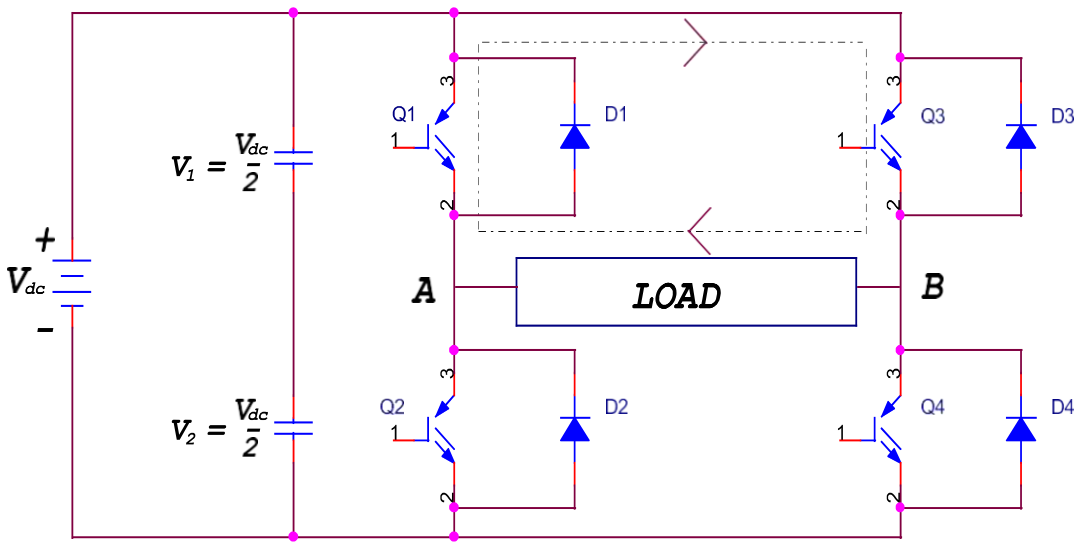

Figure 2.8 Conduction flow of inverter at State 3

State 4

In this state, the power switches Q_2 and Q_4 are in conduction mode and remaining switches are in OFF condition. Pole voltages at 'A' and 'B' are measured and a load voltage is calculated as $V_{AB} = V_{AO} - V_{BO} = 0$. Topology of this state is given in Figure 2.9.

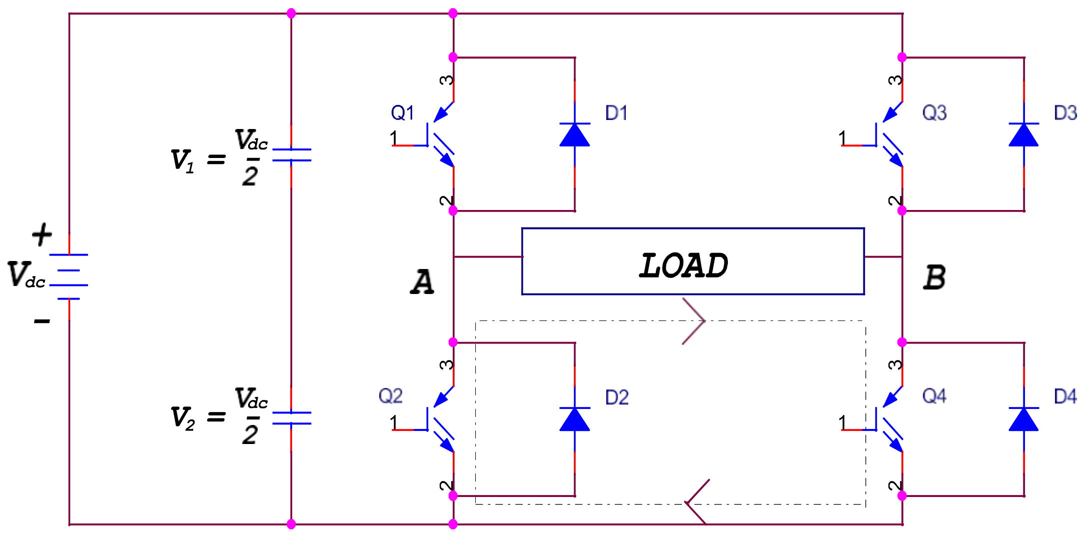

Figure 2.9 Conduction flow of inverter at State 4

Table 2.2 Switching states and output voltage of single phase inverter

State	Switching state	Output voltage		
		V_{AO}	V_{BO}	V_{AB}
1	Q_1 and Q_4 are ON	$\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	V_{dc}
2	Q_2 and Q_3 are ON	$-\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	$-V_{dc}$
3	Q_1 and Q_3 are ON	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	0
4	Q_2 and Q_4 are ON	$-\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	0

Figure 2.10 indicates the representation of two pole voltages and load voltage wave forms of a full bridge single phase inverter. During the time period (0 to t), switches Q_1 and Q_4 are ON, and in which pole voltages are measured as $V_{AO}=V_{dc}/2$ and $V_{BO}=-V_{dc}/2$. So the output voltage V_{AB} is shown as below-

$$V_{AB} = V_{AO} - V_{BO} = \frac{V_{dc}}{2} + \frac{V_{dc}}{2} = V_{dc}$$

Similarly, output voltage can be found for next three intervals.

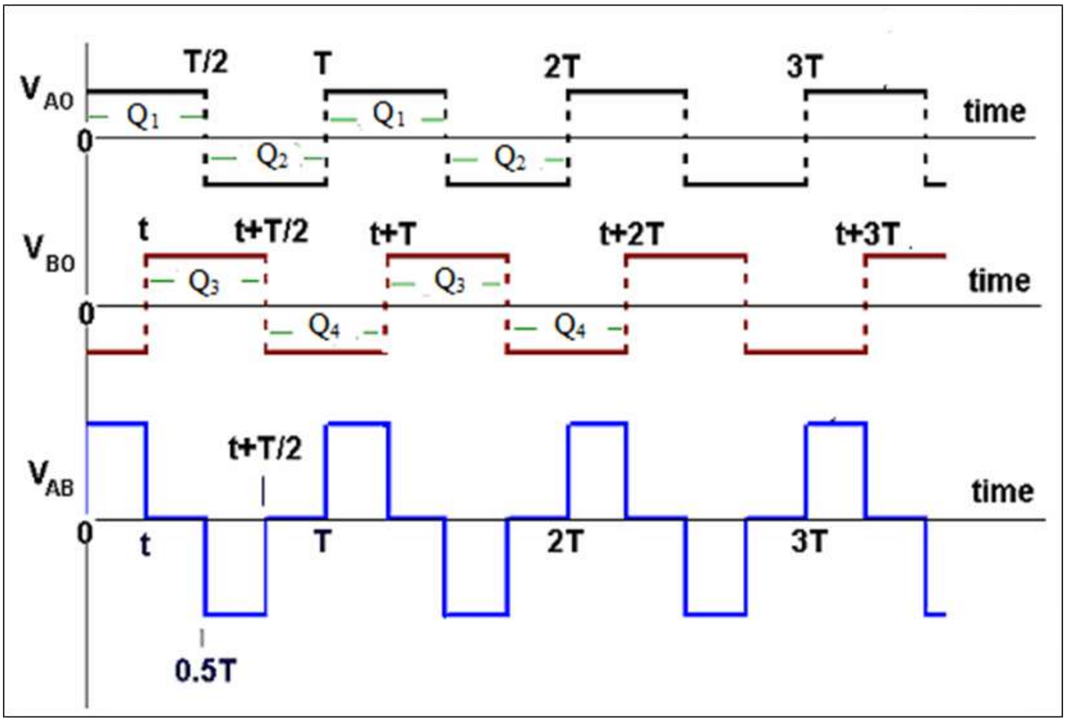

Figure 2.10 Output voltage waveforms of three phase voltage source inverter

IMPORTANT NOTE

Single-phase square wave type voltage source inverter

- produces square shaped output voltage for a single-phase load.
- have very simple control logic
- power switches need to operate at much lower frequencies compared to switches in some other types of inverters.

- The first generation inverters, using thyristor switches, were almost invariably square wave inverters because thyristor switches could be switched on and off only a few hundred times in a second.
- In contrast, the present day switches like IGBTs are much faster and used at switching frequencies of several kilohertz.