

NBKRIST

POWER ELECTRONICS LECTURE NOTES

UNIT-5

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT-V

Inverters: Single phase inverter - basic series inverter- basic parallel inverter - waveform - Mc Murray half bridge inverter - basic operation and wave forms of three phase inverters (120⁰ conduction and 180⁰ conduction)- voltage control techniques for inverters, pulse width modulation techniques- Introduction to CSI- difference between voltage source inverter and current source inverter.

V - INVERTERS

5.0 Introduction

Inverters are those which convert DC to AC power by switching the *DC input voltage (or current)* in a pre-determined sequence so as to generate *AC voltage (or current) output as shown in fig 5.1*. They can have variable output voltage and frequency. The ideal output waveforms should be sinusoidal. However, practical inverters are non-sinusoidal and contain certain harmonics. With the availability of high speed power semiconductor devices, the harmonic contents of the output voltage can be minimized significantly by switching technique.

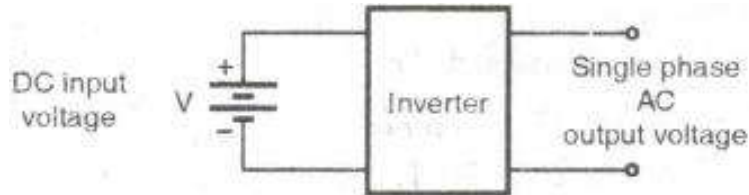


Fig.5.1 Block diagram of an inverter.

5.1 Types of Inverters:

Inverters can be classified into two groups based on nature of the source

- Voltage Source Inverter (VSI): Input to the inverter is constant dc voltage.
 - ❖ Single phase voltage source inverter
 - ✓ Half bridge inverter
 - ✓ Full bridge inverter
 - ❖ Three-phase voltage source inverter
 - ✓ 180° mode
 - ✓ 120° mode
- Current Source Inverter (CSI): Input to the inverter is constant dc current.
 - ❖ Single phase voltage source inverter
 - ❖ Three-phase voltage source inverter

5.2 Single phase half-bridge inverter:

- In half bridge topology the input dc voltage is split in two equal parts through an ideal and loss-less capacitive potential divider. The half bridge topology shown in fig 5.2 consists of one leg (one pole) of switches. Leg of the inverter consists of two series connected electronic switches across which an uncontrolled diode is put in anti-parallel manner. These switches are capable of conducting bi-directional current but they need to block only one polarity of voltage. The junction point of the switches in each leg of the inverter serves as one output point for the load.
- In 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.
- If the switches T1 and T2 are turned on alternately with duty ratio of each switch kept equal to 0.5, the load voltage, V_O will be square wave with a peak-to-peak magnitude equal to input dc voltage, V_{DC} . Figure shows a typical load voltage waveform output by the half bridge inverter. V_O will be $V_{DC}/2$ when T1 is on and the magnitude reverses to $-V_{DC}/2$ when T2 is turned on. The two switches of the inverter leg are turned on in a complementary manner.

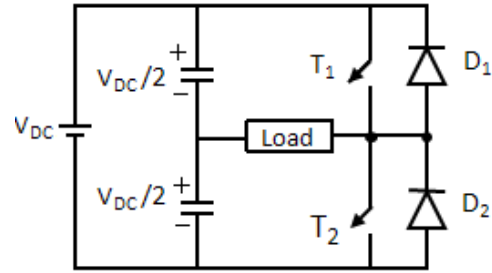


Fig 5.2 single phase halfbridge inverter

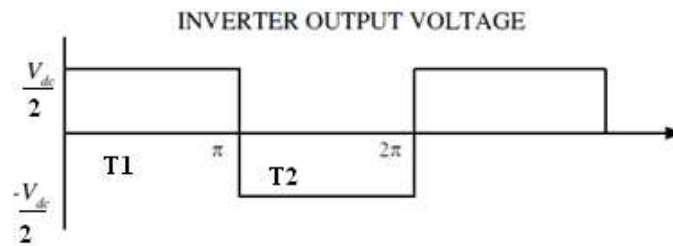


Fig:5.3 output voltage wave form

RMS value of output voltage $V_{orms} = V_{DC}/2$

5.3 Single phase full bridge inverter:

- The circuit arrangement for the full-bridge inverter and its equivalent circuit are shown in figure5.4. If the load is purely resistive, the feedback diodes are not required. S1 and S3 are turned on for the positive half-cycle, S2 and S5 for the negative half-cycle. The load voltage value is twice that of the half-bridge, i.e. for ideal switches the full battery voltage appears across the load. The rms load current is twice that of the half-bridge, and the load power is increased by a factor of 4.

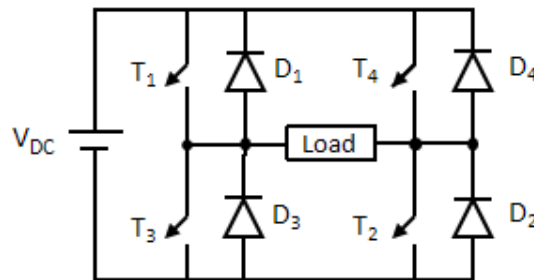


Fig 5.4 single phase fullbridge inverter

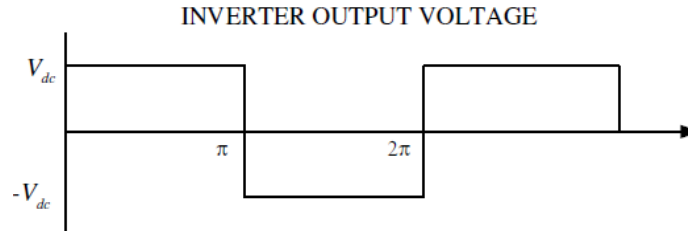


Fig 5.5 output voltage waveforms

RMS of value of the output voltage, $V_{\text{orms}} = V_{\text{dc}}$

5.5 Voltage control of Inverter:

Many inverter applications require a means of output voltage control. In most of these applications this control is usually required in order to provide step-less adjustment of the inverter output voltage.

5.5.1 The methods of control can be group into three categories:

- Control of voltage supplies to the inverter
- Control of voltage delivered by the inverter
- Control of voltage within the inverter
- There are a number of well-known methods of controlling the d.c. voltage supplies to an inverter or the a.c. voltage delivered by an inverter. These include the use of d.c. choppers, magnetic amplifiers, induction regulators, phase-controlled rectifiers and transistor series or shunt regulators. The principal disadvantage of these methods is that the power delivered by the inverter is handed twice, once by the d.c. or a.c. voltage control and once by the inverter. This generally involves more equipment than is required if the voltage control function can be within the inverter itself.
- Control of the inverter output voltage may be achieved by incorporating time-ratio controls within the inverter circuit. It is only employed in applications, which require a small amount of voltage control.

5.5.2 Methods of inverter output voltage control within inverter:

5.5.2.1 Pulse width voltage control:

- A method of controlling the voltage within an inverter involves the use of pulse wide modulation techniques.
- Single pulse width modulation technique: With this technique the inverter output voltage is controlled by varying the duration of the output voltage pulses. Output voltage contains only one pulse in each half cycle i.e. switches are turned on one time in each cycle as shown in figure below. With this method, one selective harmonic can also be eliminated by the proper selection of pulse width.

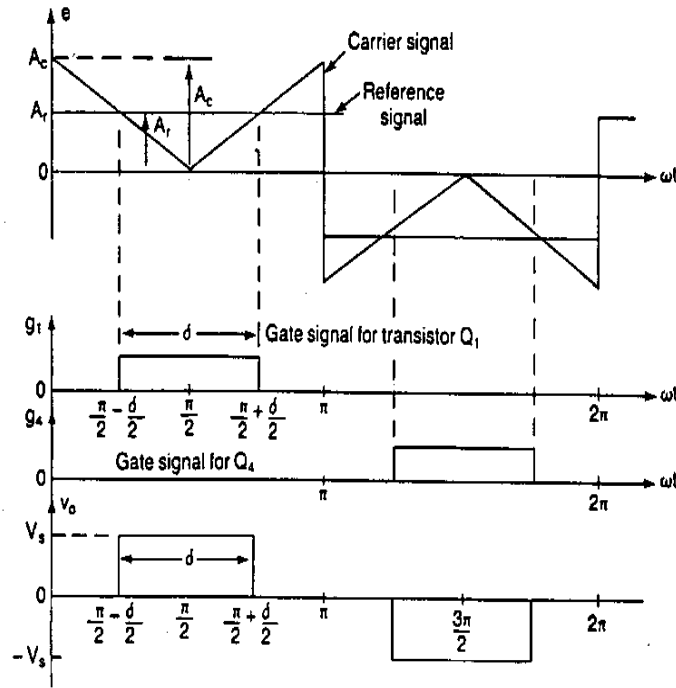


Fig 5.6 single pulse width modulation

- Multiple-pulse-width modulation technique: Output voltage contains many pulses of same width. Output voltage can be varied by changing the pulse width. The large number of harmonics can be reduced by using several pulses in each half-cycle of output voltage.

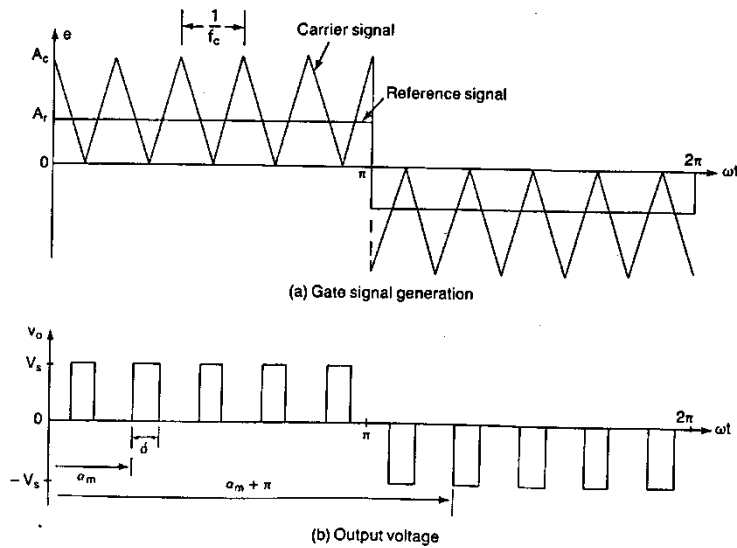


Fig 5.7 multiple pulse width modulation

5.5.2.2 Sinusoidal Pulse-width Modulation:

- Sinusoidal reference wave is used instead of square reference wave which is used in multiple pulse modulation technique. It is commonly used in industry. Harmonic content is significantly reduced, all

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harmonics $\leq 2P - 1$ are eliminated, where $P = (\text{triangular wave frequency}/2 \cdot \text{Sinusoidal wave frequency})$.
 For $P = 5$, the lowest order harmonic is ninth.

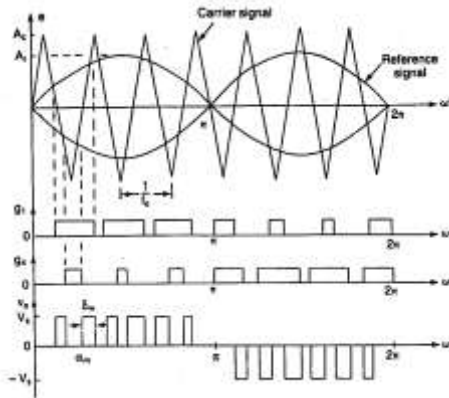


Fig 5.8 sinusoidal pulse width modulation

5.5 Three phase inverters:

Figure 5.9 shows the power circuit of the three-phase inverter. This circuit may be identified as three single-phase half-bridge inverter circuits put across the same dc bus. The individual pole voltages of the 3-phase bridge circuit are identical to the square pole voltages output by single-phase half bridge or full bridge circuits. The three pole voltages of the 3-phase square wave inverter are shifted in time by one third of the output time period. These pole voltages along with some other relevant waveforms have been plotted in figure. In three-phase inverters, two or three switches could be conducting simultaneously. Based on this three-phase inverters can be classified as

5.5.1 180 degree Conduction Mode

180° conduction mode or three switches conduction inverter: In this inverter always three switches are in conduction and each conducts for 180° period in each cycle of output voltage. Output voltage waveforms are shown in figure 5.3. The conducting switches sequence is as follows: S5 S6 S1, S6 S1 S2, S1 S2 S3, S2 S3 S5, S3 S5 S5, S5 S5 S6, S5 S6 S1 and so on. Each combination conducts for 60°. In this mode, all three phases are connected to the input dc supply at every instant.

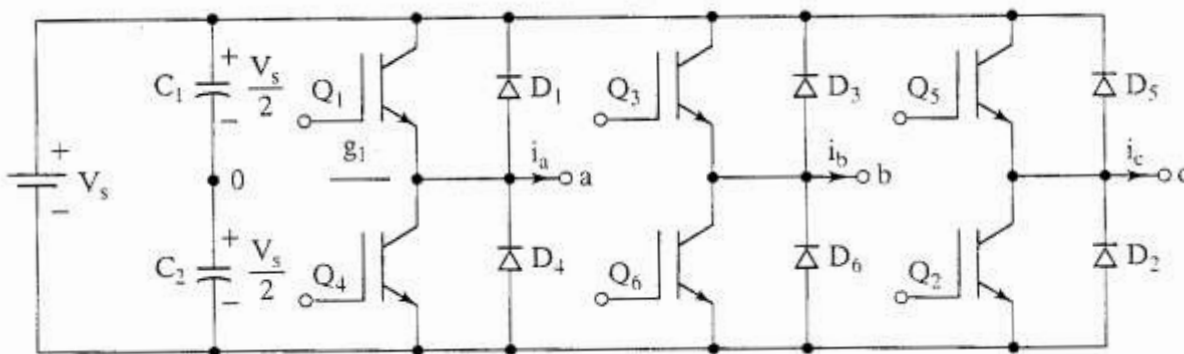


Fig 5.9: three phase bridge inverter 180° Conduction

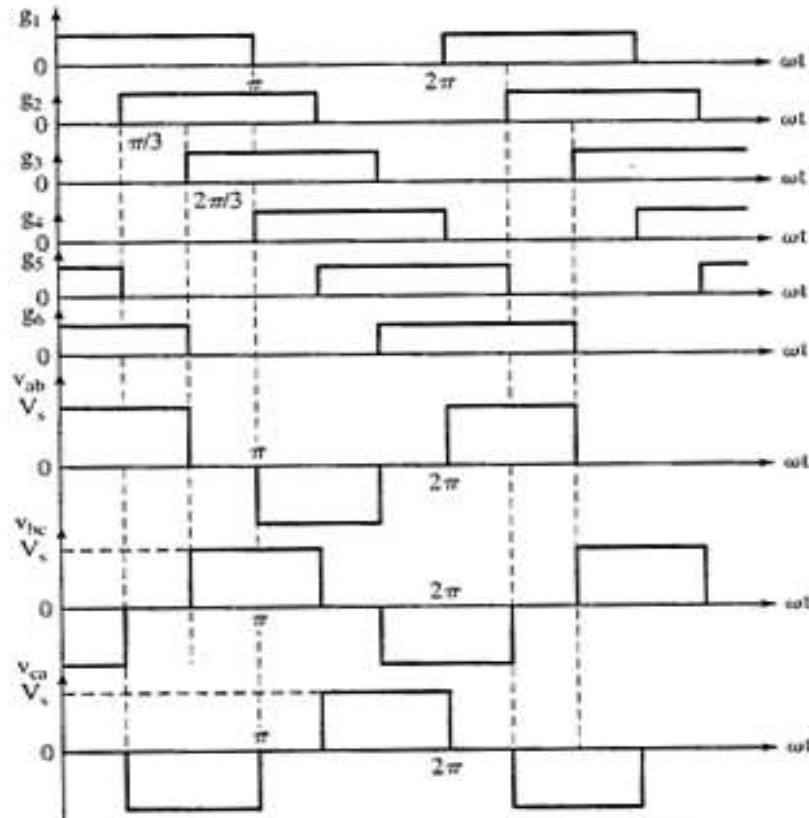


Figure 5.10 : Output voltage waveforms for 180° mode configuration

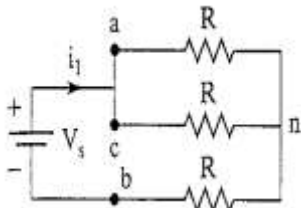
MODE - I Operation:

In this mode of operation Q_6, Q_5, Q_1 are in conducting state

$$0 \leq \omega t \leq \frac{\pi}{3}$$

$$R_{eq} = R + \frac{R}{2} = \frac{3R}{2}$$

$$i_1 = \frac{V_s}{R_{eq}} = \frac{2V_s}{3R}$$

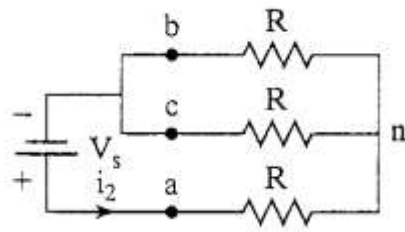


$$v_{an} = v_{cn} = \frac{i_1 R}{2} = \frac{V_s}{3}$$

$$v_{bn} = -i_1 R = \frac{-2V_s}{3}$$

Mode - II Operation

$$\frac{\pi}{3} \leq \omega t \leq \frac{2\pi}{3}$$



$$R_{eq} = R + \frac{R}{2} = \frac{3R}{2}$$

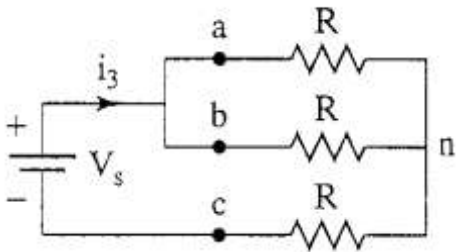
$$i_2 = \frac{V_s}{R_{eq}} = \frac{2V_s}{3R}$$

$$v_{an} = i_2 R = \frac{2V_s}{3}$$

$$v_{bn} = v_{cn} = \frac{-i_2 R}{2} = \frac{-V_s}{3}$$

Mode – III Operation

$$\frac{2\pi}{3} \leq \omega t \leq \pi$$



$$R_{eq} = R + \frac{R}{2} = \frac{3R}{2}$$

$$i_3 = \frac{V_s}{R_{eq}} = \frac{2V_s}{3R}$$

$$v_{an} = v_{bn} = \frac{i_3 R}{2}$$

$$v_{cn} = i_3 R = \frac{2V_s}{3}$$

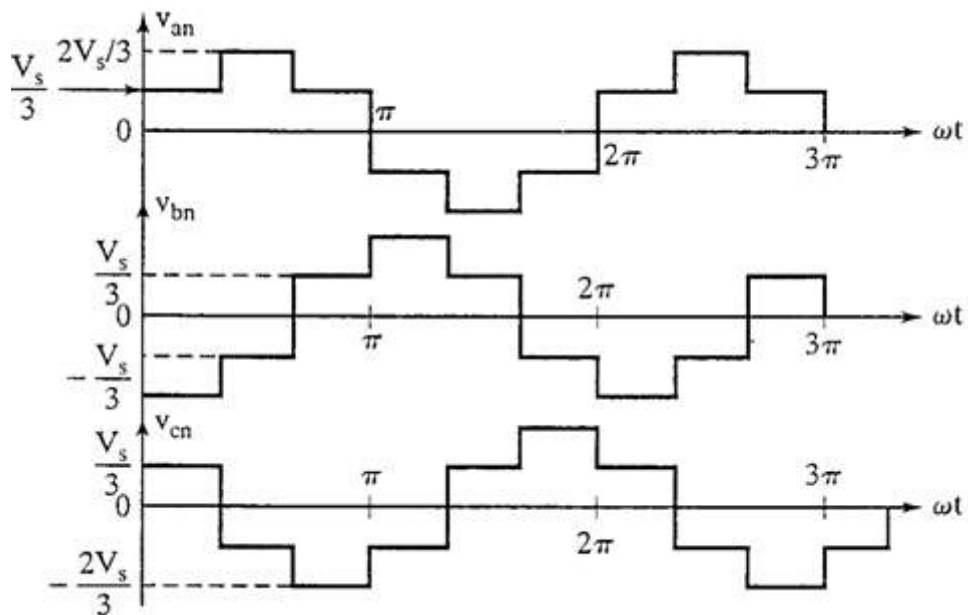


Fig 5.11 : Phase voltages for 180° Conduction Mode

Fourier series for Line to Line Voltages

$$v_{ab} = \frac{a_o}{2} + \sum_{n=1}^{\infty} (a_n \cos(n\omega t) + b_n \sin(n\omega t))$$

$$b_n = \frac{1}{\pi} \left[\int_{-\frac{5\pi}{6}}^{\frac{5\pi}{6}} -V_s d(\omega t) + \int_{\frac{\pi}{6}}^{\frac{5\pi}{6}} V_s d(\omega t) \right]$$

$$b_n = \frac{4V_s}{n\pi} \sin\left(\frac{n\pi}{2}\right) \sin\left(\frac{n\pi}{3}\right)$$

$$v_{ab} = \sum_{n=1,3,5,\dots}^{\infty} \frac{4V_s}{n\pi} \sin \frac{n\pi}{3} \sin n\left(\omega t + \frac{\pi}{6}\right)$$

$$v_{bc} = \sum_{n=1,3,5,\dots}^{\infty} \frac{4V_s}{n\pi} \sin \frac{n\pi}{3} \sin n\left(\omega t - \frac{\pi}{2}\right)$$

$$v_{ca} = \sum_{n=1,3,5,\dots}^{\infty} \frac{4V_s}{n\pi} \sin \frac{n\pi}{3} \sin n\left(\omega t - \frac{7\pi}{6}\right)$$

Line-to-Line RMS Voltage

$$V_L = \left[\frac{2}{2\pi} \int_0^{2\pi} V_s^2 d(\omega t) \right]^{\frac{1}{2}}$$

$$V_L = \sqrt{\frac{2}{3}} V_s = 0.8165 V_s$$

rms value of the nth Component

$$V_{Ln} = \frac{4V_s}{\sqrt{2}n\pi} \sin \frac{n\pi}{3}$$

$n = 1$ Fundamental Component

$$V_{L1} = \frac{4V_s \sin 60^\circ}{\sqrt{2}\pi} = 0.7797 V_s$$

Line to Neutral Voltage

$$V_p = \frac{V_L}{\sqrt{3}} = \frac{\sqrt{2}V_s}{3} = 0.4714 V_s$$

Phase Voltages (Y-connected load)

$$v_{aN} = \sum_{n=1,3,5,\dots}^{\infty} \frac{4V_s}{\sqrt{3n\pi}} \sin\left(\frac{n\pi}{3}\right) \sin(n\omega t)$$

$$v_{bN} = \sum_{n=1,3,5,\dots}^{\infty} \frac{4V_s}{\sqrt{3n\pi}} \sin\left(\frac{n\pi}{3}\right) \sin\left(n\left(\omega t - \frac{2\pi}{3}\right)\right)$$

$$v_{cN} = \sum_{n=1,3,5,\dots}^{\infty} \frac{4V_s}{\sqrt{3n\pi}} \sin\left(\frac{n\pi}{3}\right) \sin\left(n\left(\omega t - \frac{4\pi}{3}\right)\right)$$

Line Current for an RL load

$$i_a = \sum_{n=1,3,5,\dots}^{\infty} \left[\frac{4V_s}{\sqrt{3} \left[n\pi \sqrt{R^2 + (n\omega L)^2} \right]} \sin \frac{n\pi}{3} \right] \sin(n\omega t - \theta_n)$$

$$\theta_n = \tan^{-1} \left(\frac{n\omega L}{R} \right)$$

DC Supply Current

$$v_s i_s = v_{ab}(t) i_a(t) + v_{bc}(t) i_b(t) + v_{ca}(t) i_c(t)$$

....

$$I_s = 3 \frac{V_{o1}}{V_s} I_o \cos(\theta_1)$$

$$I_s = \sqrt{3} \frac{V_{o1}}{V_s} I_L \cos(\theta_1)$$

$I_L = \sqrt{3} I_o$ is the rms load line current

V_{o1} = fundamental rms output line voltage

I_o is the rms load phase current

Θ_1 = the load impedance angle at the fundamental frequency

5.5.2 120 degree Conduction Mode

120° conduction mode or two switches conduction inverter: In this inverter always two switches are in conduction and each conducts for 120° period in each cycle of output voltage. Output voltage waveforms are shown in figure 5.12. The conducting switches sequence is as follows: S6 S1, S1 S2, S2 S3, S3 S5, S5 S5, S5 S6, S6 S1 and so on. Each combination conducts for 60°. In this mode, only two output phases are connected to the input dc supply and other phase is opened at every instant.

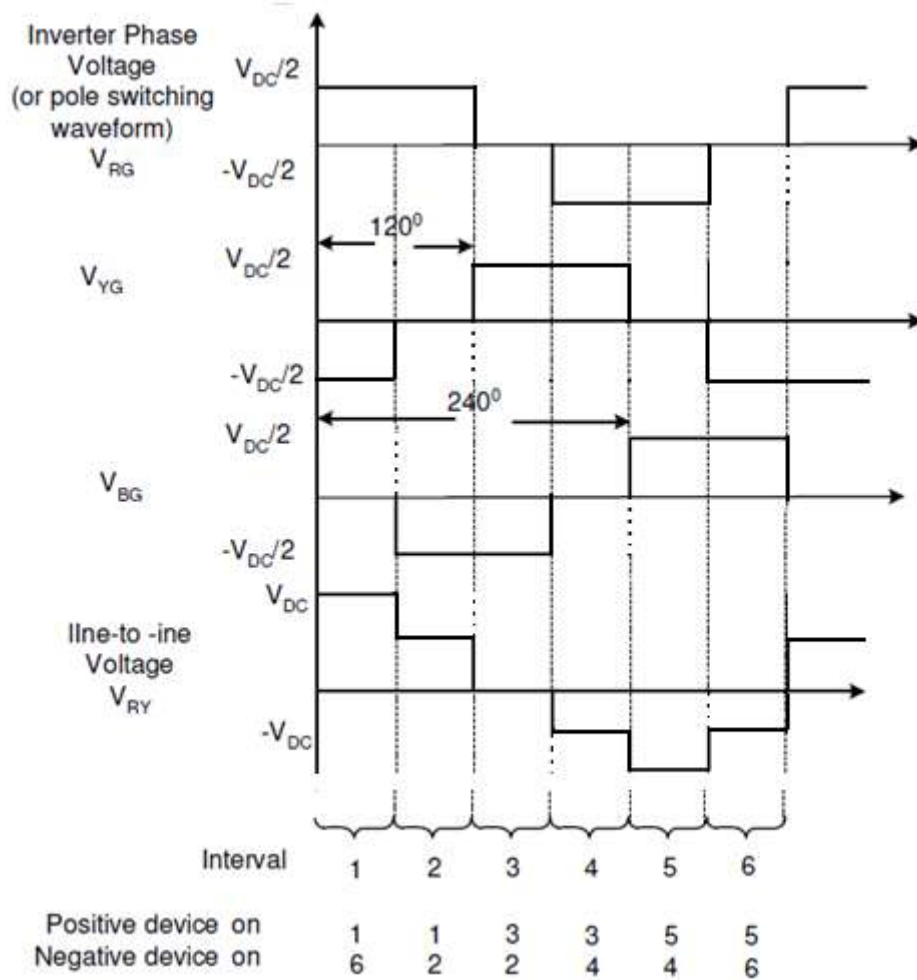


Figure 5.12: Output voltage waveforms for 120° mode configuration

- RMS value of fundamental phase voltage is

$$V_{p1} = 0.3898V_S$$
- RMS Value of phase voltage

$$V_P = 0.5082V_S$$
- RMS Value of Fundamental Line Voltage

$$V_{L1} = 0.6752 V_S = \sqrt{3} V_{p1}$$
- RMS Value of line Voltage

$$V_L = \sqrt{3} V_P = 0.7071 V_S$$

5.6 Current-source Inverter:

Figure 5.13 shows a single-phase current source inverter. For circuit analysis, we assume that all switching devices are ideal. Thyristor is an ideal switch and has zero commutation time. Figure 5.13 shows the current and voltage waveforms of a single-phase current source inverter. In this inverter

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circuit, the current source consists of a dc voltage source V with a large inductance L in series with it. The high impedance reactor is connected in series with voltage source to maintain constant current at the input terminals of current source inverter (CSI) and a constant dc current I is maintained at the input terminals of CSI. When thyristors $T1$ and $T2$, are turned ON, the load current I flows through the load and is positive. When thyristors $T3$ and $T5$ are turned ON, the load current I flow through load and is negative. The output current I_o is a square wave with amplitude of I . The frequency of current I can he controlled by controlling the switching frequency of triggering signals of thyristor pairs $T1$ and $T2$, and $T3$ and $T5$. The amplitude of dc current I is constant and it is always unidirectional, if the average value of input voltage is positive, power flows from current source to load. When average value of input voltage is negative, the power flows from load to source and regenerative action takes place. In ideal case load current waveform is a square wave but practically the load current waveform is not a square wave as the rise and fall of current cannot be instantaneous. Since each switching device (thyristor) has finite commutation time, all practical inverter has finite rise time of current and fall time of current. Current source inverters can be developed by using forced commutation or load commutation. Forced commutation is required for lagging power factor load where as load commutation is possible for leading power factor load.

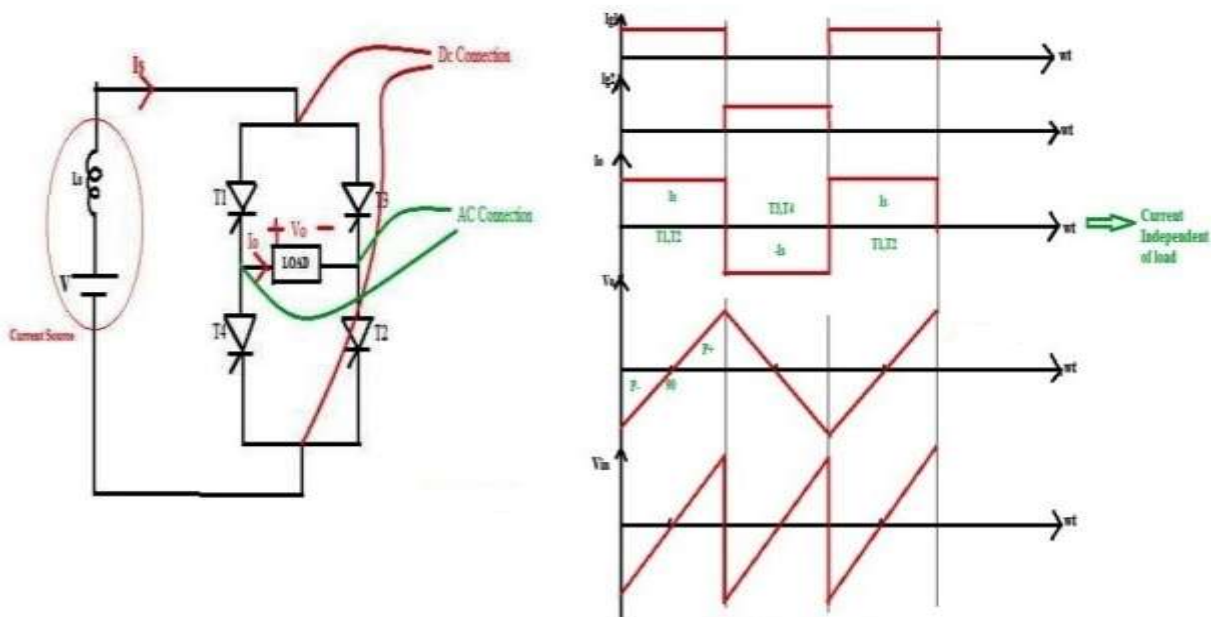


Fig 5.13 current source inverter and its wave forms

5.7 Difference between VSI and CSI

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VSI	CSI
VSI is fed from a DC voltage source having small or negligible impedance.	CSI is fed with adjustable current from a DC voltage source of high impedance.
Input voltage is maintained constant	The input current is constant but adjustable.
Output voltage does not depend on the load	The amplitude of output current is independent of the load.
The waveform of the load current as well as its magnitude depends upon the nature of load impedance.	The magnitude of output voltage and its waveform depends upon the nature of the load impedance.
VSI requires feedback diodes	The CSI does not require any feedback diodes.
The commutation circuit is complicated	Commutation circuit is simple as it contains only capacitors.
Power BJT, Power MOSFET, IGBT, GTO with self commutation can be used in the circuit.	They cannot be used as these devices have to withstand reverse voltage.

5.8 Series inverter

Basic Series Inverter Circuit

Fig.5.15 shows the circuit of a series inverter. The commutating elements L and C are such that R , L and C form an under damped circuit. The capacitor has an initial voltage E_c . Thyristor T_1 is turned on first by an external pulse. Since T_1 is already forward biased (due to dc voltage V), T_1 starts conducting and a current I flows in the circuit through T_1 , C , L and load.

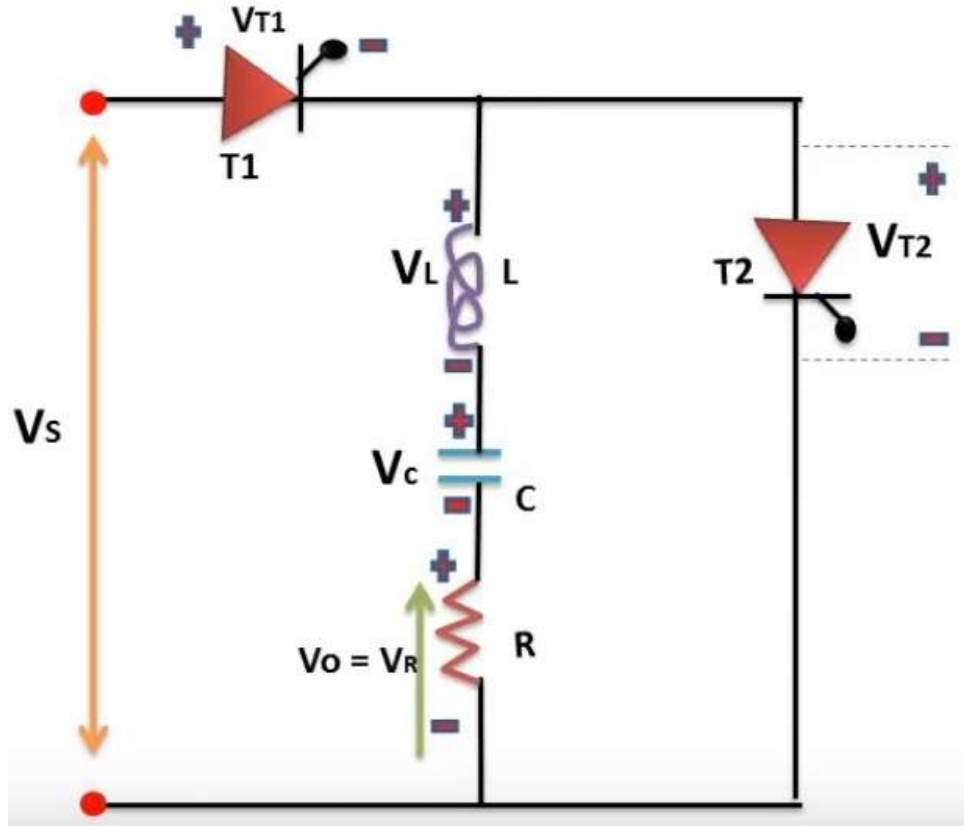


Fig 5.15 basic series inverter

Because of under damped nature of the circuit the current is not constant but has the wave shapes as shown in fig.5.15. It rises to maximum value and then decreases to zero. When the current is at its peak value, the voltage across capacitor is nearly equal to supply voltage V . After this the current starts decreasing but the voltage across the capacitor continues to increase as it is still getting charged. When the current becomes zero the voltage across capacitor is maintained at $V+E_c$. The voltage across L is zero. The time interval ab must be more than time t_{off} of the thyristor. This is necessary to ensure that the stored charges in T_1 are reduced to zero so that at point b T_1 is in completely off state. At point b when T_2 is turned on by an external gate pulse the anode of T_2 is positive (with respect to cathode) due to charge on capacitor T_2 starts conducting. The capacitor discharges and the current I flows through the circuit in the direction opposite to that in the start. The current reaches its negative peak value and then decreases to zero at point c when T_2 is turned off. The above sequence of operation is repeated in the next cycle when T_1 is turned on.

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Where $T/2$ is the time period of oscillation and T_{off} the time gap between turn off of one thyristor and turn on of the second thyristor,

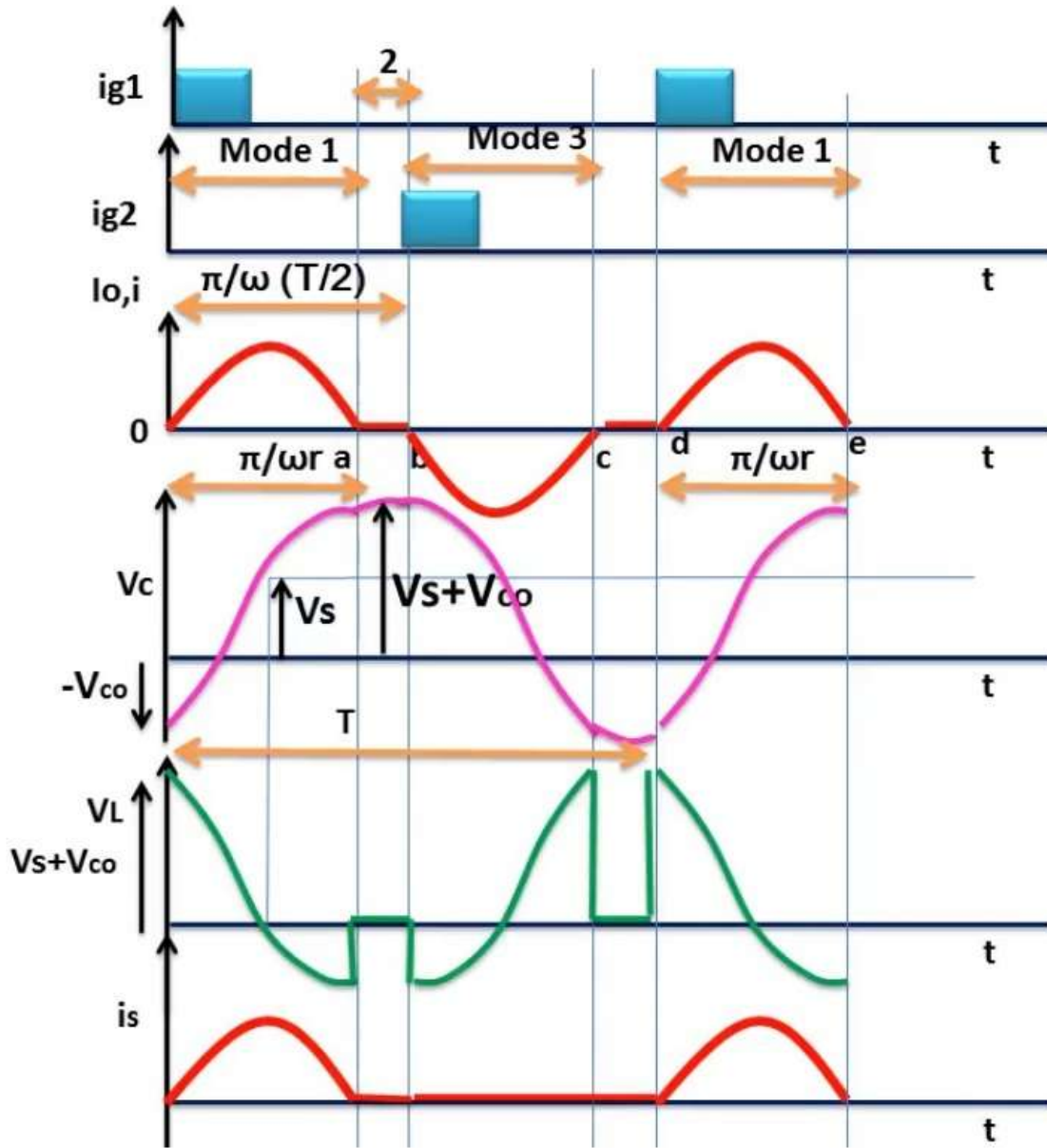
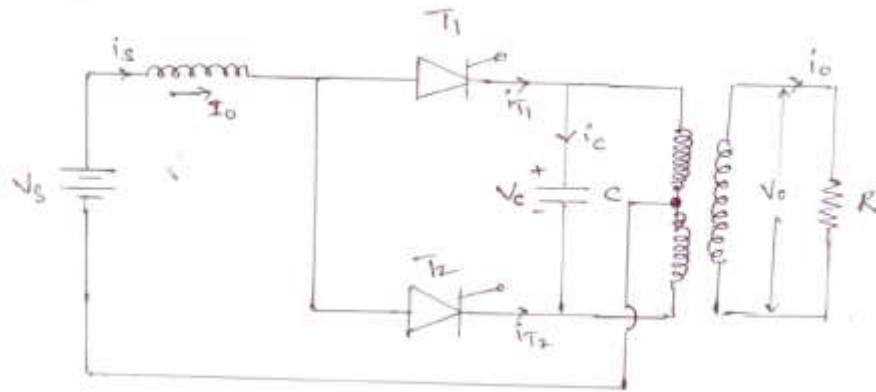


Fig 5.15 wave forms of basic series inverter

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5.9 Parallel inverter:

CIRCUIT DIAGRAM:



WAVE FORMS :

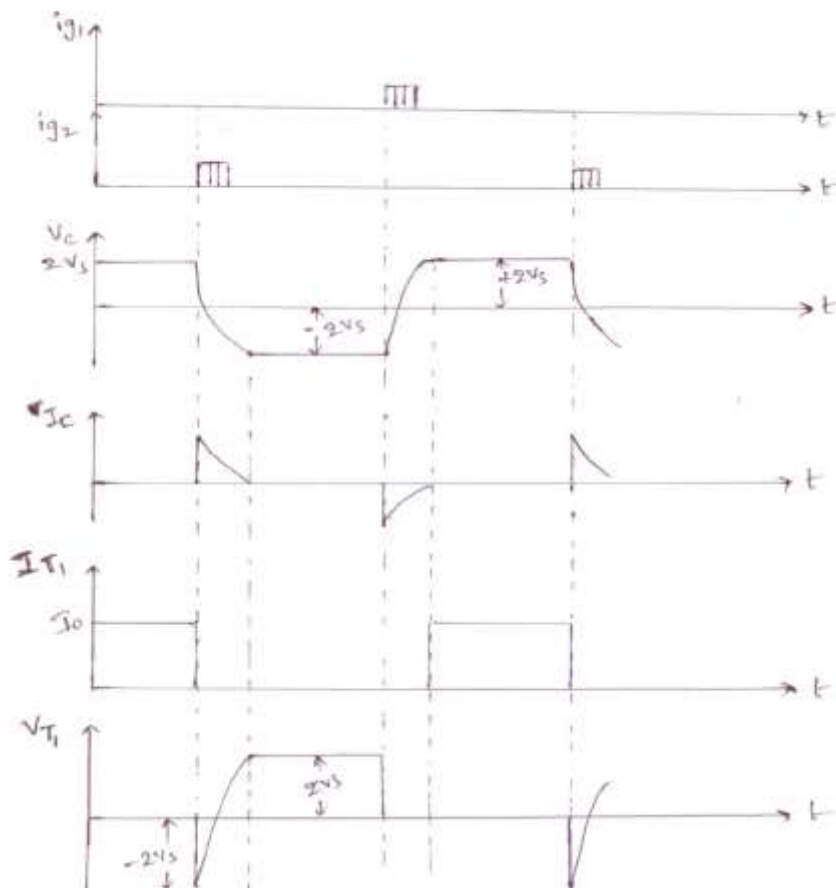


Fig5.16: circuit diagram and wave forms

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The inverter plays a vital role in Uninterrupted Power Supply (UPS). It is used to convert the direct current (DC) to alternating Current (AC) of required voltage.

The basic single phase parallel inverter circuit consists of two SCRs T1 and T2, an inductor L, an output transformer and a commutating capacitor C. The output voltage and current are V_o and I_o respectively. The function of L is to make the source current constant. During the working of this inverter, capacitor C comes in parallel with the load via the transformer. So it is called a parallel inverter. The operation of this inverter can be explained in the following modes.

Mode I

In this mode, SCR T1 is conducting and a current flow in the upper half of primary winding. SCR T2 is OFF. As a result an emf V_s is induced across upper as well as lower half of the primary winding. In other words total voltage across primary winding is $2 V_s$. Now the capacitor C charges to a voltage of $2V_s$ with upper plate as positive.

Mode II

At time t_0 , T2 is turned ON by applying a trigger pulse to its gate. At this time $t=0$, capacitor voltage $2V_s$ appears as a reverse bias across T1, it is therefore turned OFF. A current I_o begins to flow through T2 and lower half of primary winding. Now the capacitor has charged (upper plate as negative) from $+2V_s$ to $-2V_s$ at time $t=t_1$. Load voltage also changes from V_s at $t=0$ to $-V_s$ at $t=t_1$.

Mode III

When capacitor has charged to $-V_s$, T1 may be turned ON at any time. When T1 is triggered, capacitor voltage $2V_s$ applies a reverse bias across T2, it is therefore turned OFF. After T2 is OFF, capacitor starts discharging, and charged to the opposite direction, the upper plate as positive.

5.10 Forced commutated inverters:

For low- and medium-power applications, inverters using transistors, PMOSFETs GTOs and IGBTs are becoming increasingly popular. However, for high-voltage and high-current applications, thyristors are more suitable. In voltage fed inverters, thyristors remain forward biased by the dc supply voltage. This entails the use of forced commutation for inverter circuits using thyristors. As stated earlier, forced commutation requires a precharged capacitor of correct polarity to turn-off an already conducting thyristor. A large variety of forced commutation circuits have been described in the technical

literature. Here popularly used McMurray technique will be described leading to the discussion of two types of force-commutated inverters, viz, modified McMurray inverter and McMurray-Bedford inverter. These are now described in what follows:

5.10.1 Modified McMurray Half-bridge Inverter

Load commutated voltage-source inverter has been discussed in the latter part of the Section. It is shown there that for obtaining load commutation in VSI, the load circuit must be under damped, i.e. capacitive reactance of the load must be more than its inductive reactance. The object of this section is to describe modified McMurray half-bridge inverter which is a current-commutated VSI. Fig.5.18 shows a single-phase modified McMurray half-bridge inverter. It consists of main thyristors T1, T2 and main diodes D1, D2. The commutation circuit consists of auxiliary thyristors TA1, TA2, auxiliary diodes DA1, DA2; damping resistor R_d , inductor L and capacitor C . Three-wire dc supply is required and ac load is connected between A and B as shown in Fig. 5.17. The function of capacitor is to provide the energy.

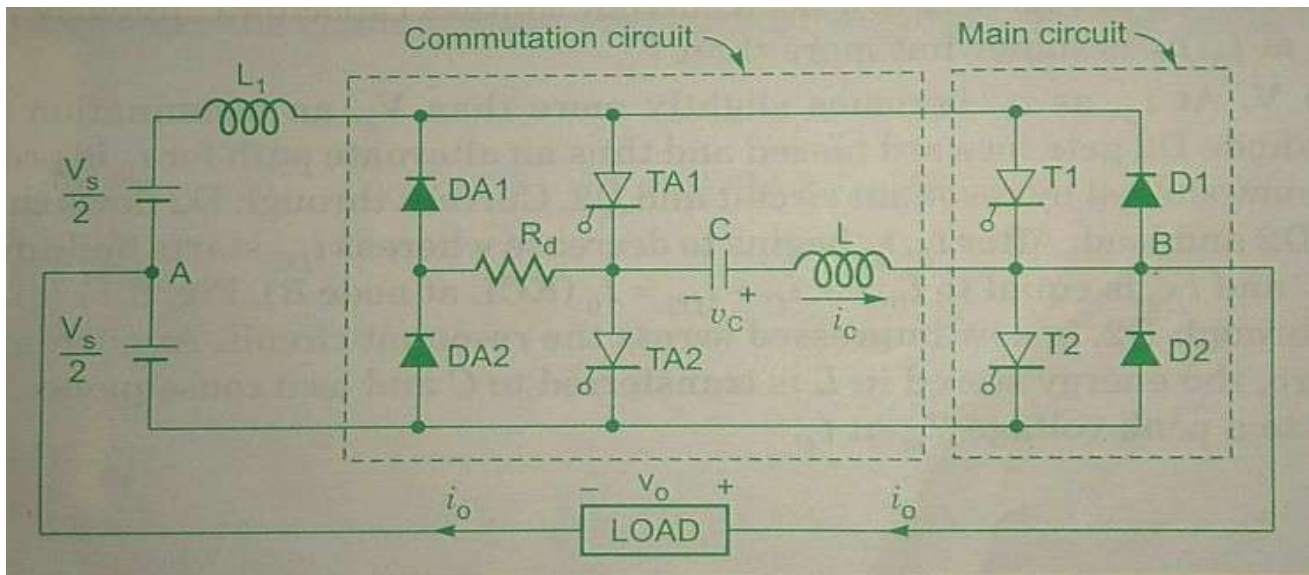


Fig 5.17 Modified McMurray Half-bridge Inverter

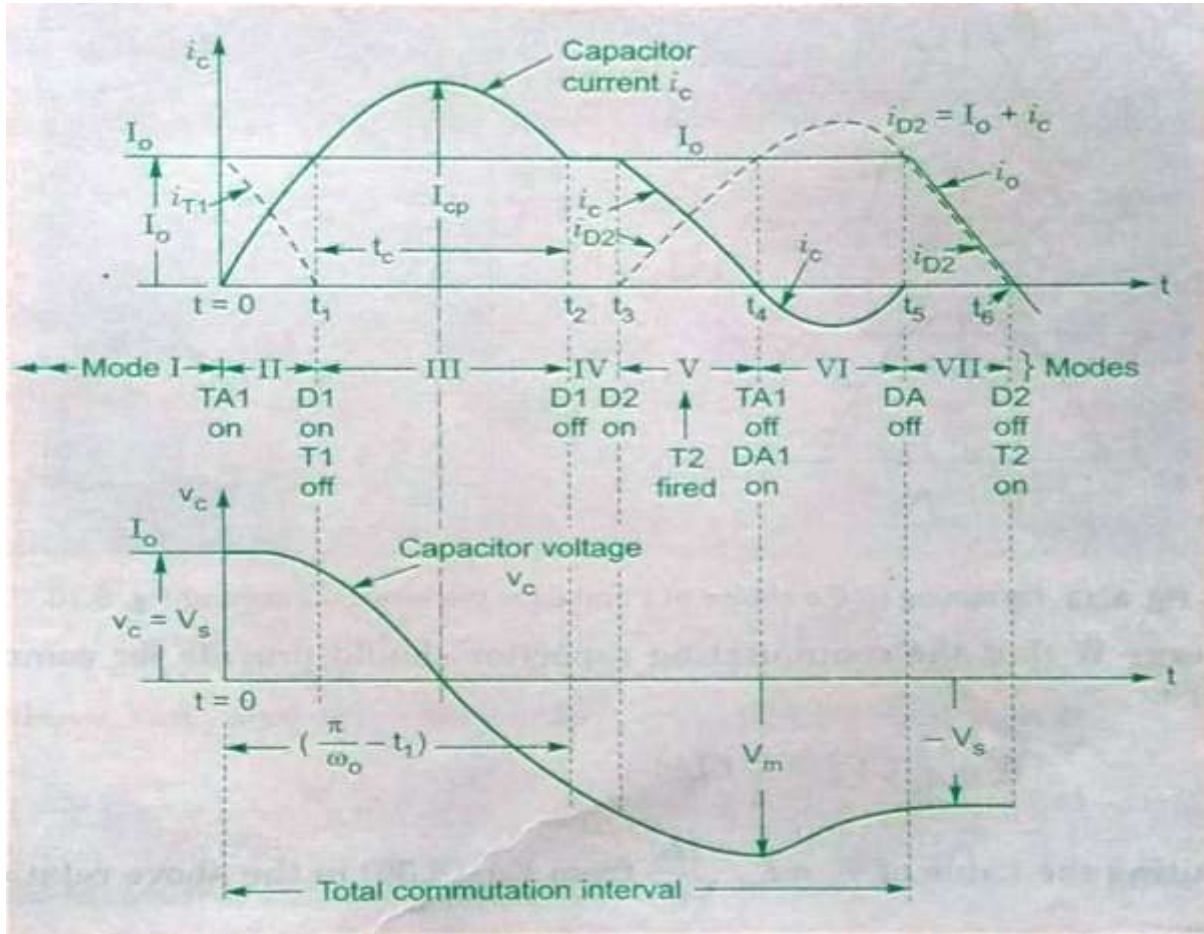


Fig 5.18 Modified McMurray Half-bridge Inverter wave forms