MODULE-5(a)
DC-DC COVERTER

STRUCTURE

5.0 Introduction
5.1 Objectives
5.2 Principle of Step-down Chopper
5.3 Principle of Step-up Chopper
5.4 Classification of Choppers
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5.0 INTRODUCTION

Chopper is a static device.

• A variable dc voltage is obtained from a constant dc voltage source.

• Also known as dc-to-dc converter.

• Widely used for motor control.

• Also used in regenerative braking.

• Thyristor converter offers greater efficiency, faster response, lower maintenance, smaller size and smooth control.

Choppers are of Two Types

- Step-down choppers.
- Step-up choppers.

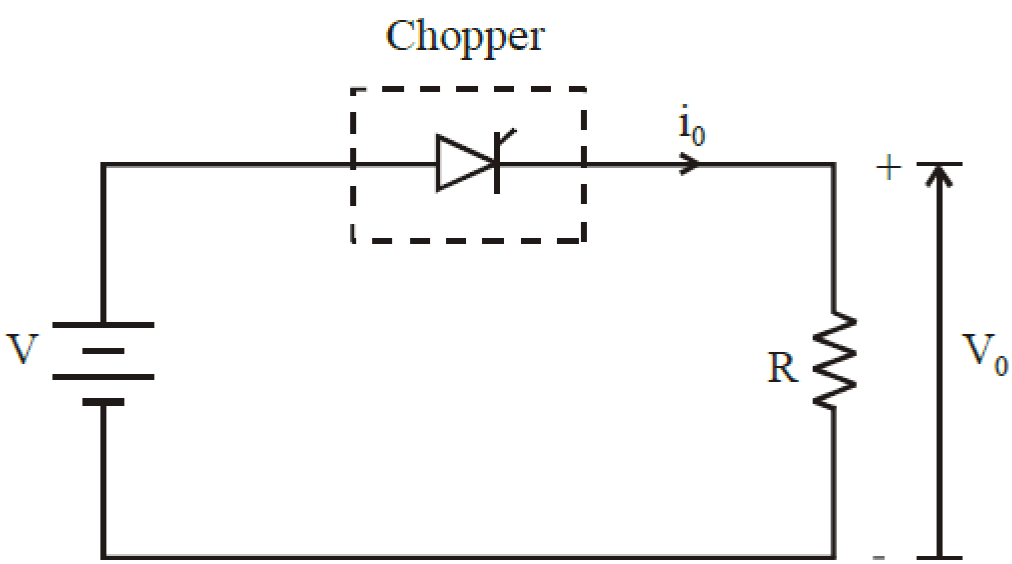
In step down chopper output voltage is less than input voltage.

In step up chopper output voltage is more than input voltage

5.1OBJECTIVES

- ✓ To explain the design, analysis techniques, performance parameters and characteristics of DC-DC converters,operation of various chopper commutation circuits.

5.2 Principle of Step-down Chopper

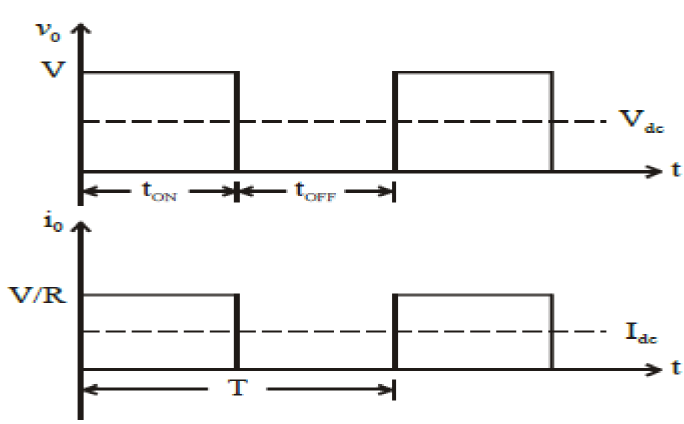


A step-down chopper with resistive load.

• The thyristor in the circuit acts as a switch.

• When thyristor is ON, supply voltage appears across the load

• When thyristor is OFF, the voltage across the load will be zero.



Methods of Control

• The output dc voltage can be varied by the following methods.

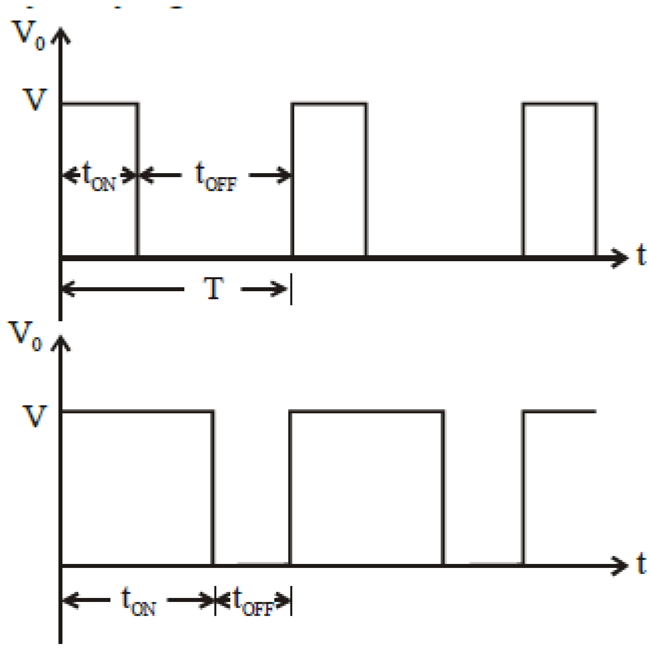
– Pulse width modulation control or constant frequency operation.

– Variable frequency control.

Pulse Width Modulation

• t_{ON} is varied keeping chopping frequency '*f*' & chopping period 'T' constant.

• Output voltage is varied by varying the ON time *tON*

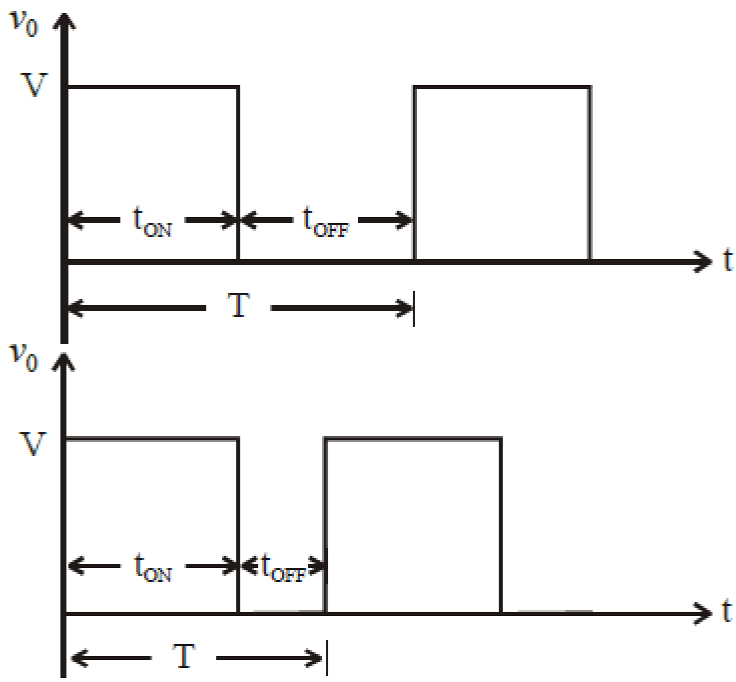


Variable Frequency Control

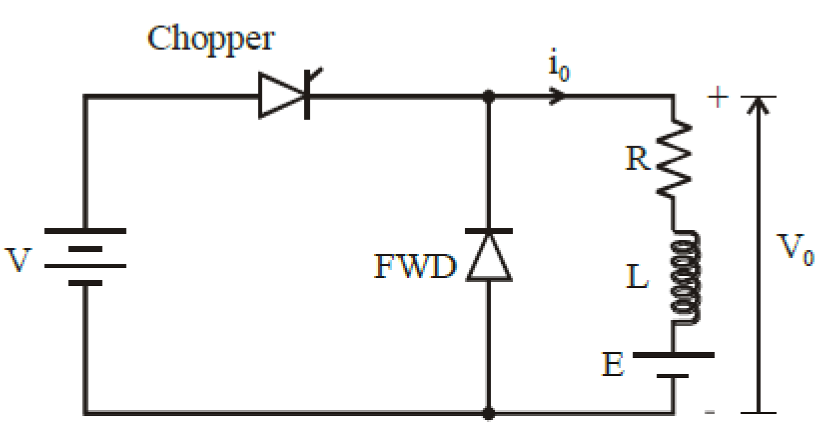
• Chopping frequency '*f*' is varied keeping either *tON* or *tOFF* constant.

• To obtain full output voltage range, frequency has to be varied over a wide range.

• This method produces harmonics in the output and for large *tOFF* load current may become discontinuous



5.2.1 Step-down Chopper with R-L Load



When chopper is ON, supply is connected across load.

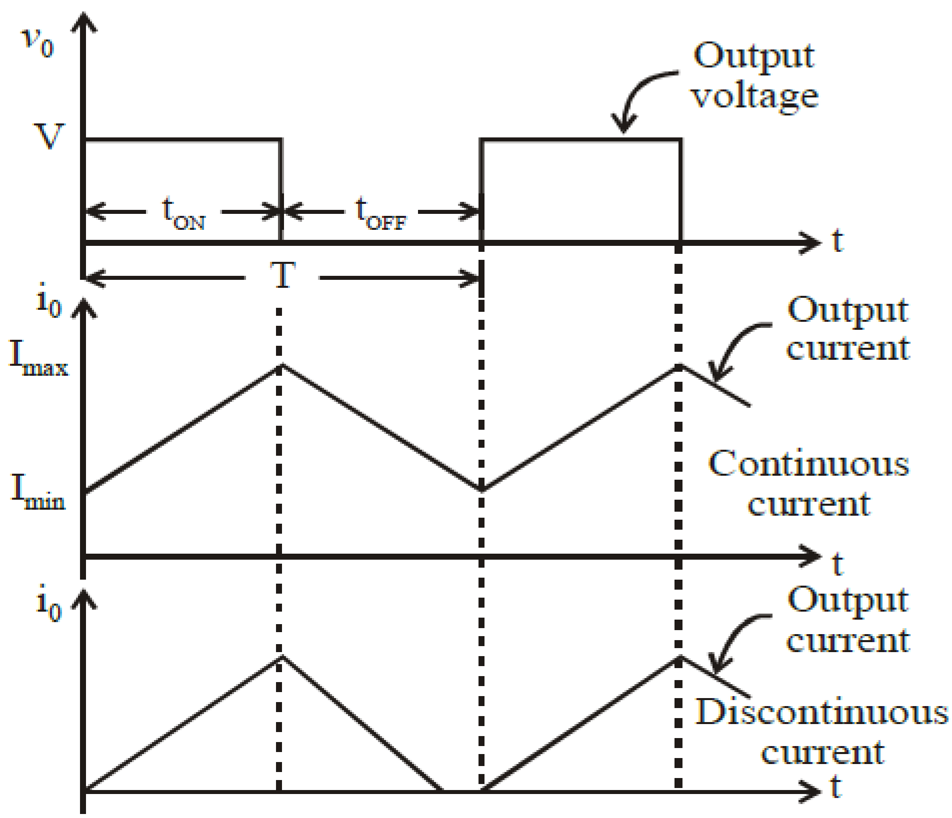
Current flows from supply to load.

When chopper is OFF, load current continues to flow in the same direction through FWD due to energy stored in inductor *'L'*.

Load current can be continuous or discontinuous depending on the values of *'L'* and duty cycle *'d'*

For a continuous current operation, load current varies between two limits *Imax* and *Imin*

When current becomes equal to *Imax* the chopper is turned-off and it is turned-on when current reduces to *Imin*.



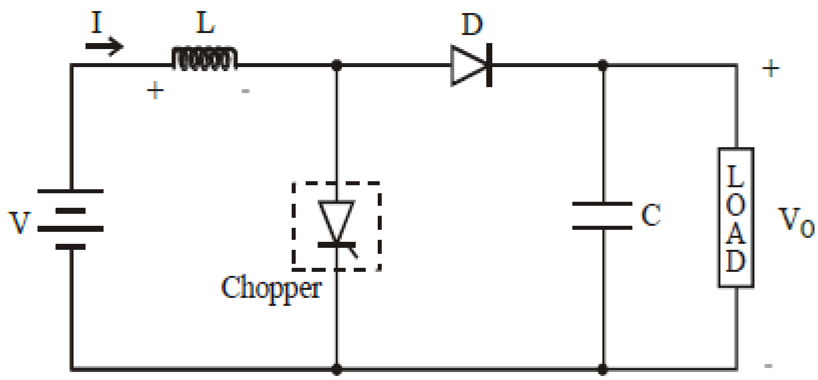
5.3 Principle of Step-up Chopper

Step-up chopper is used to obtain a load voltage higher than the input voltage *V*.

The values of *L* and *C* are chosen depending upon the requirement of output voltage and current.

When the chopper is *ON*, the inductor *L* is connected across the supply.

The inductor current *'I'* rises and the inductor stores energy during the *ON* time of the chopper, *Ton*. When the chopper is off, the inductor current *I* is forced to flow through the diode *D* and load for a period, *tOFF*.



The current tends to decrease resulting in reversing the polarity of induced EMF in *L*.

Therefore voltage across load is given by

A large capacitor 'C' connected across the load, will provide a continuous output voltage.

• Diode *D* prevents any current flow from capacitor to the source.

• Step up choppers are used for regenerative braking of dc motors.

(i) Expression For Output Voltage

$$VIt_{ON} = \ V_O - V \ \ It_{OFF}$$

$$V_O = \frac{V \ \ t_{ON} + t_{OFF}}{t_{OFF}}$$

$$V_O = V\left(\frac{T}{T - t_{ON}}\right)$$

Performance Parameters

• The thyristor requires a certain minimum time to turn *ON* and turn *OFF*.

• Duty cycle *d* can be varied only between a min. & max. value, limiting the min. and max. value of the output voltage.

• Ripple in the load current depends inversely on the chopping frequency, *f*.

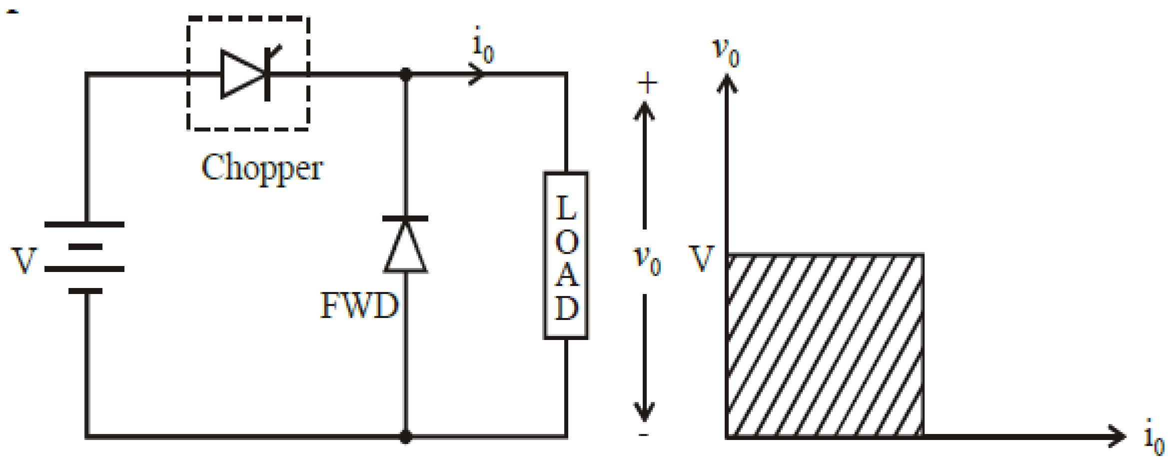
• To reduce the load ripple current, frequency should be as high as possible.

5.4 Classification of Choppers

Choppers are classified as

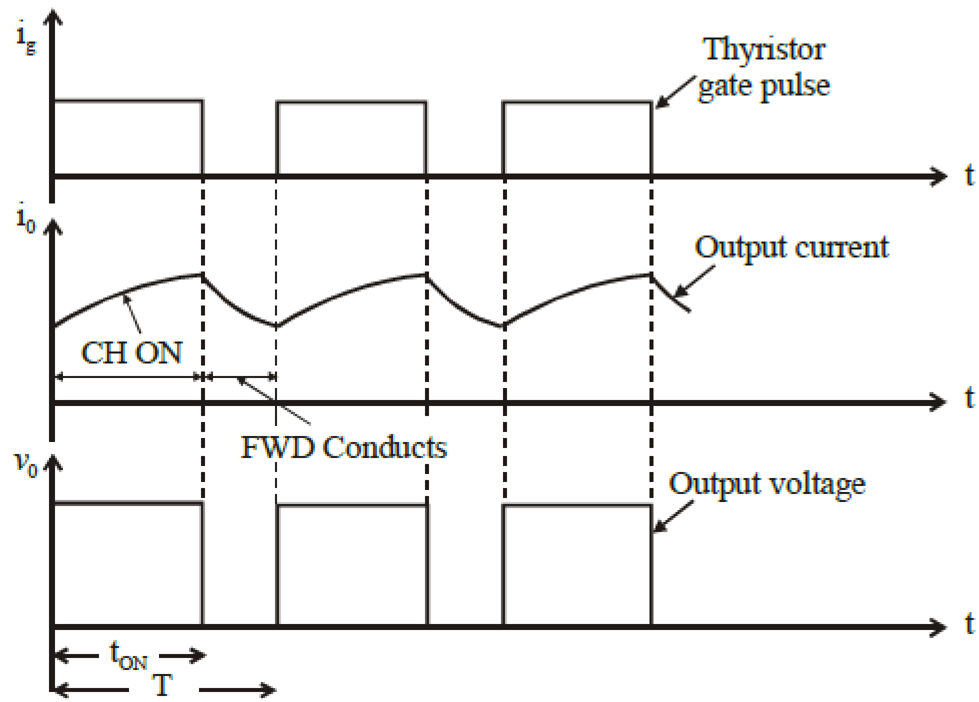
- Class A Chopper
- Class B Chopper
- Class C Chopper
- Class D Chopper
- Class E Chopper

1. Class A Chopper

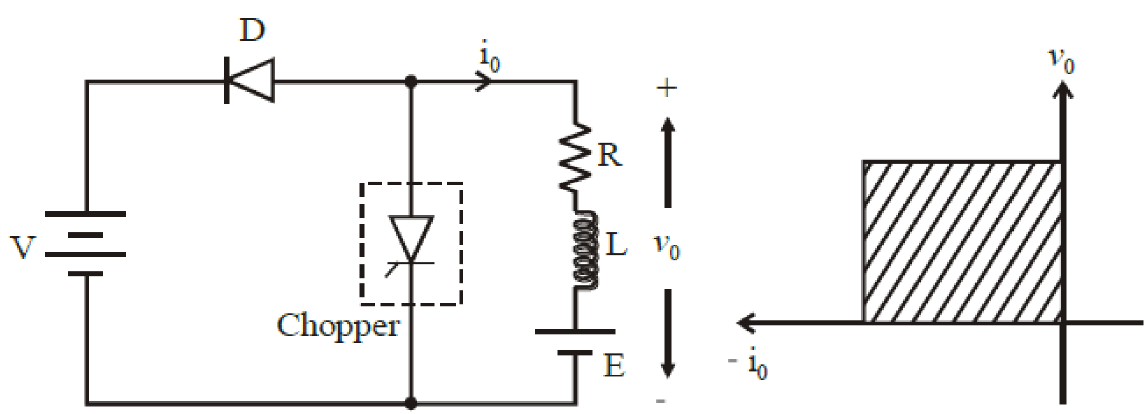


When chopper is *ON*, supply voltage *V* is connected across the load.

- When chopper is OFF, *v*O = 0 and the load current continues to flow in the same direction through the FWD.
- The average values of output voltage and current are always positive.
- *Class A Chopper* is a first quadrant chopper .
- *Class A Chopper* is a step-down chopper in which power always flows form source to load.
- It is used to control the speed of dc motor.
- The output current equations obtained in step down chopper with *R-L* load can be used to study the performance of *Class A Chopper*.



2. Class B Chopper



When chopper is ON, *E* drives a current through *L* and R in a direction opposite to that shown in figure.

• During the ON period of the chopper, the inductance *L* stores energy.

• When Chopper is OFF, diode *D* conducts, and part of the energy stored in inductor *L* is returned to the supply.

• Average output voltage is positive.

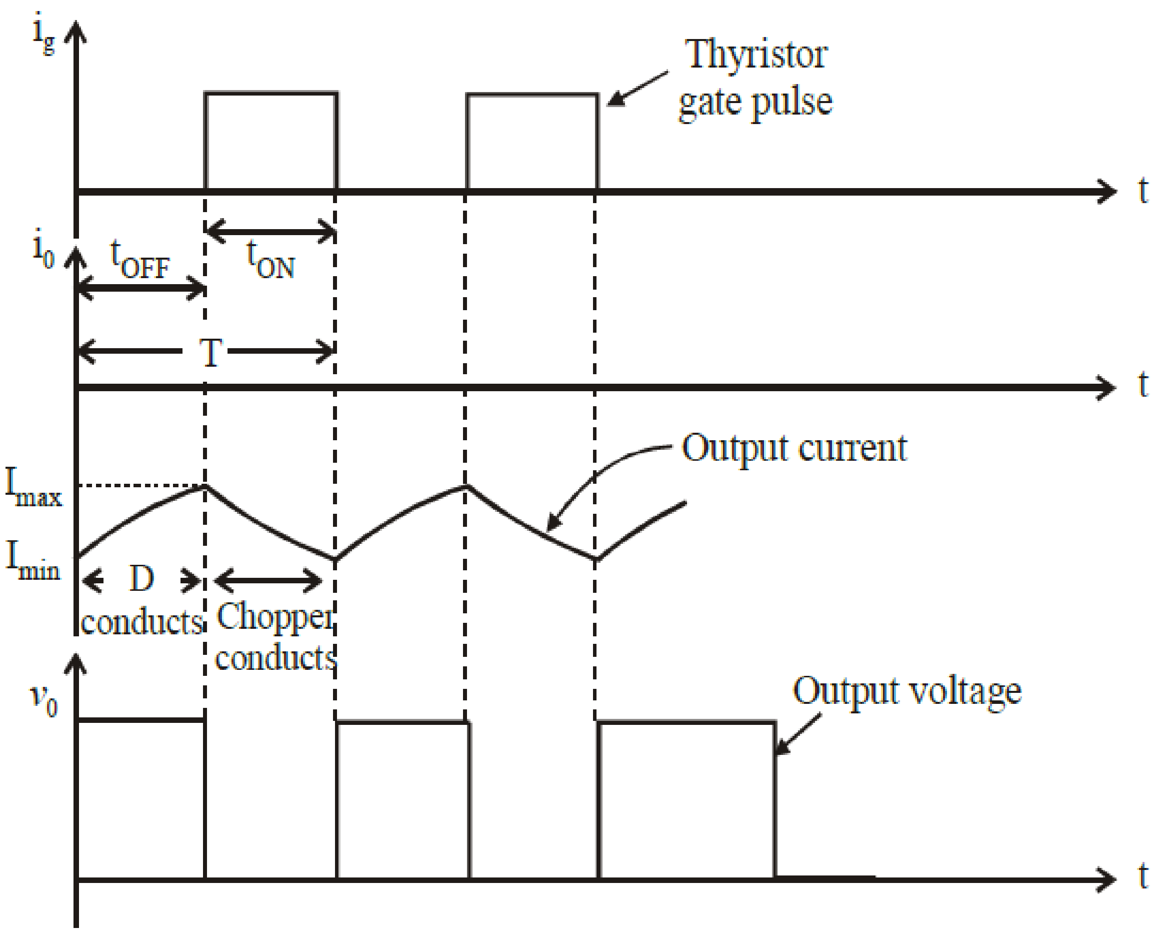
• Average output current is negative.

• Therefore Class B Chopper operates in second quadrant.

• In this chopper, power flows from load to source.

• Class B Chopper is used for regenerative braking of dc motor.

• Class B Chopper is a step-up chopper



(i) Expression for Output Current

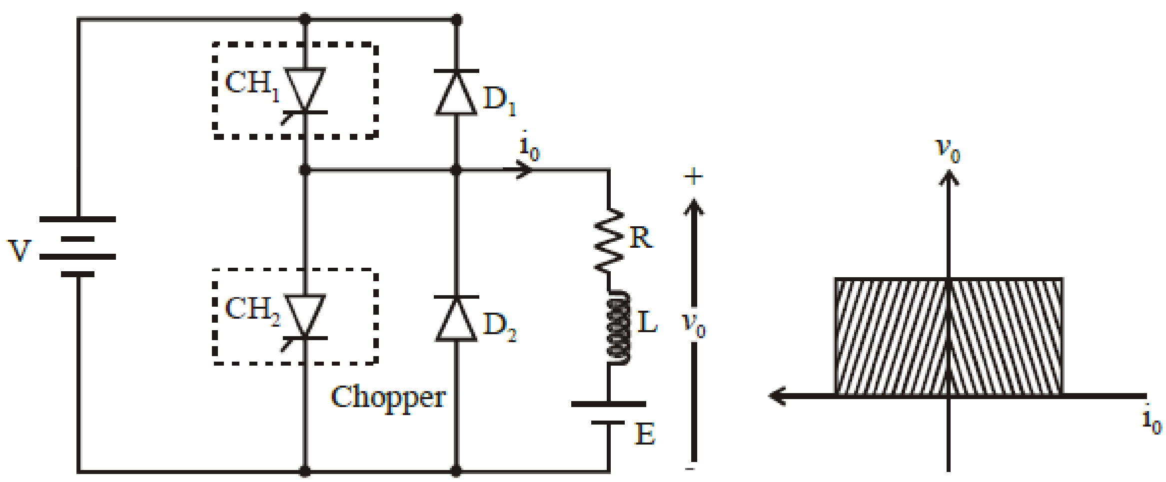
$$\therefore \quad i_O(t) = \frac{V-E}{R}\left(1-e^{-\frac{R}{L}t}\right) + I_{\min} e^{-\frac{R}{L}t} \quad 0 < t < t_{OFF}$$

At $t = t_{OFF}$ $\quad i_O(t) = I_{\max}$

$$I_{\max} = \frac{V-E}{R}\left(1-e^{-\frac{R}{L}t_{OFF}}\right) + I_{\min} e^{-\frac{R}{L}t_{OFF}}$$

$$\therefore \quad I_{\min} = I_{\max} e^{-\frac{R}{L}t_{ON}} - \frac{E}{R}\left(1-e^{-\frac{R}{L}t_{ON}}\right)$$

3. Class C Chopper



Class C Chopper is a combination of Class A and Class B Choppers.

- For first quadrant operation, CH1 is ON or D2 conducts.
- For second quadrant operation, CH2 is ON or D1 conducts.
- When CH1 is ON, the load current is positive.

• The output voltage is equal to ‘V’ & the load receives power from the source.

• When CH1 is turned OFF, energy stored in inductance L forces current to flow through the diode D2 and the output voltage is zero.

• Current continues to flow in positive direction.

• When CH2 is triggered, the voltage E forces current to flow in opposite direction through L and CH2 .

• The output voltage is zero.

• On turning OFF CH2 , the energy stored in the inductance drives current through diode D1 and the supply

• Output voltage is V, the input current becomes negative and power flows from load to source.

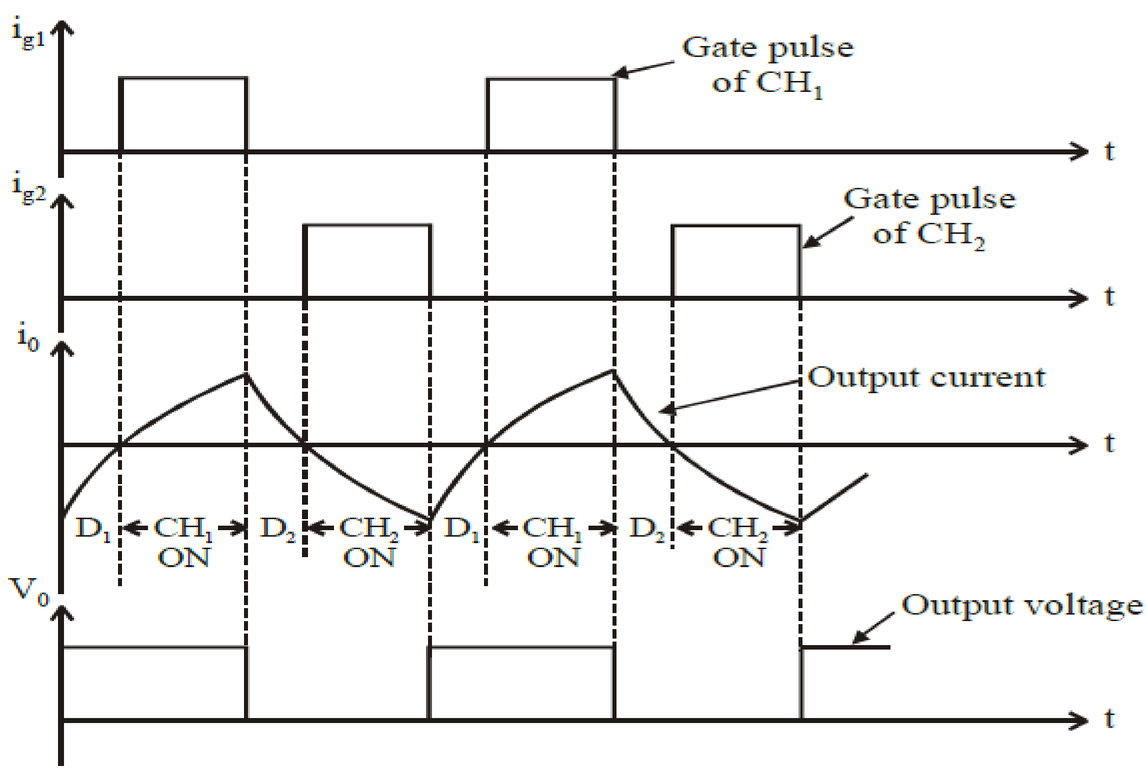
• Average output voltage is positive

• Average output current can take both positive and negative values.

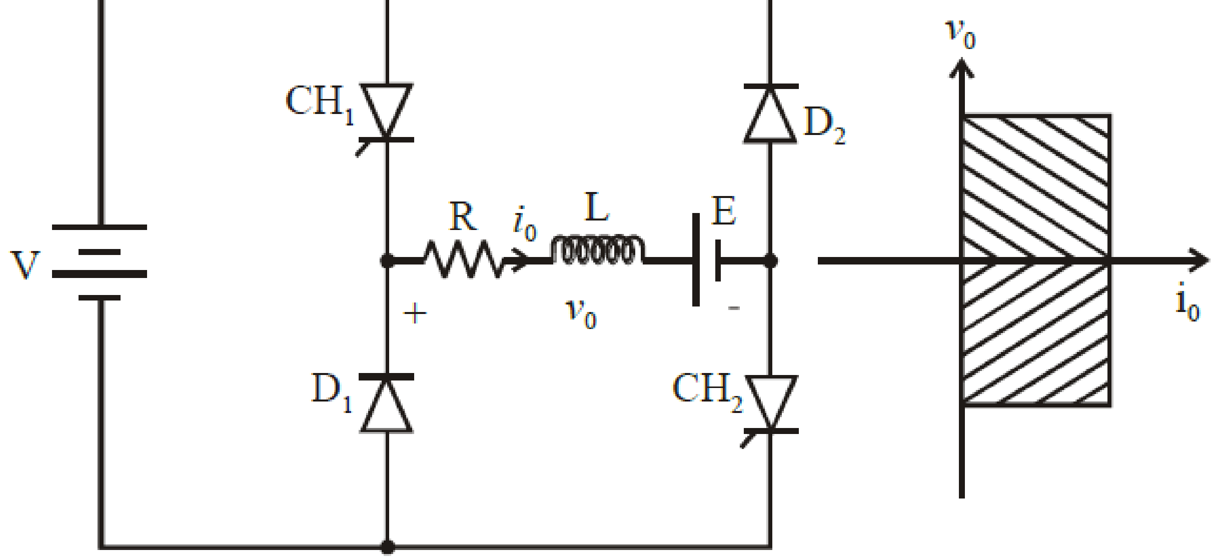
• Choppers CH1 & CH2 should not be turned ON simultaneously as it would result in short circuiting the supply.

• Class C Chopper can be used both for dc motor control and regenerative braking of dc motor.

• Class C Chopper can be used as a step-up or step-down chopper



4. Class D Chopper



Class D is a two quadrant chopper.

• When both CH1 and CH2 are triggered simultaneously, the output voltage vO = V and output current flows through the load.

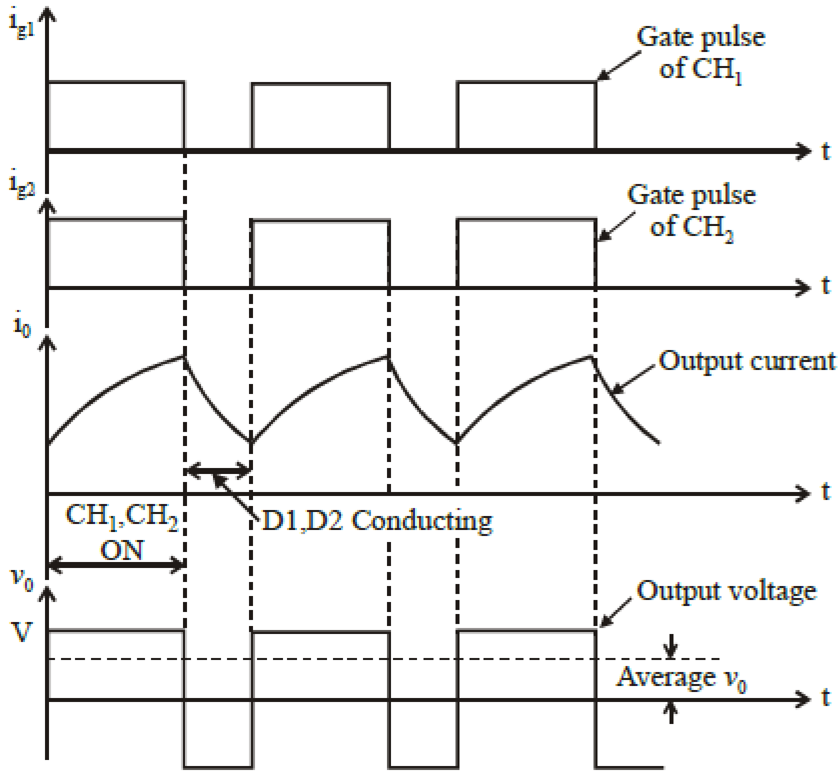
• When CH1 and CH2 are turned OFF, the load current continues to flow in the same direction through load, D1 and D2 , due to the energy stored in the inductor L.

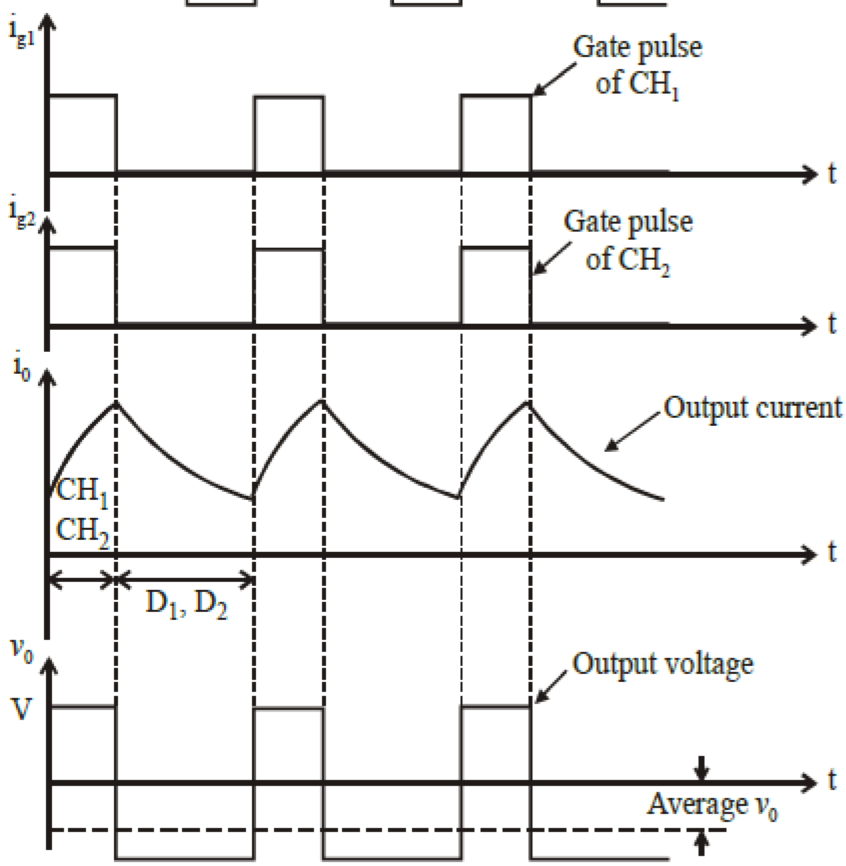
• Output voltage vO = - V .

• Average load voltage is positive if chopper ON time is more than the OFF time

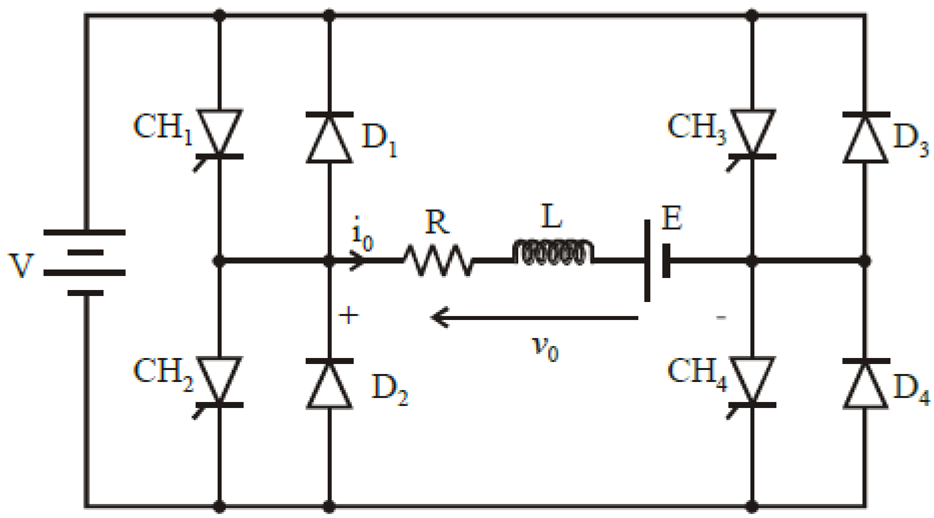
• Average output voltage becomes negative if tON < tOFF .

• Hence the direction of load current is always positive but load voltage can be positive or negative


i_{g1}
Gate pulse of CH_1
t
i_{g2}
Gate pulse of CH_2
t
i_0
Output current
t
CH_1,CH_2 ON
D1,D2 Conducting
v_0
V
Output voltage
Average v_0
t


i_{g1}
Gate pulse of CH_1
t
i_{g2}
Gate pulse of CH_2
t
i_0
Output current
CH_1
CH_2
t
D_1, D_2
v_0
V
Output voltage
t
Average v_0

5. Class E Chopper



Class E is a four quadrant chopper

• When CH1 and CH4 are triggered, output current iO flows in positive direction through CH1 and CH4, and with output voltage vO = V.

• This gives the first quadrant operation.

• When both CH1 and CH4 are OFF, the energy stored in the inductor L drives iO through D2 and D3 in the same direction, but output voltage vO = -V.

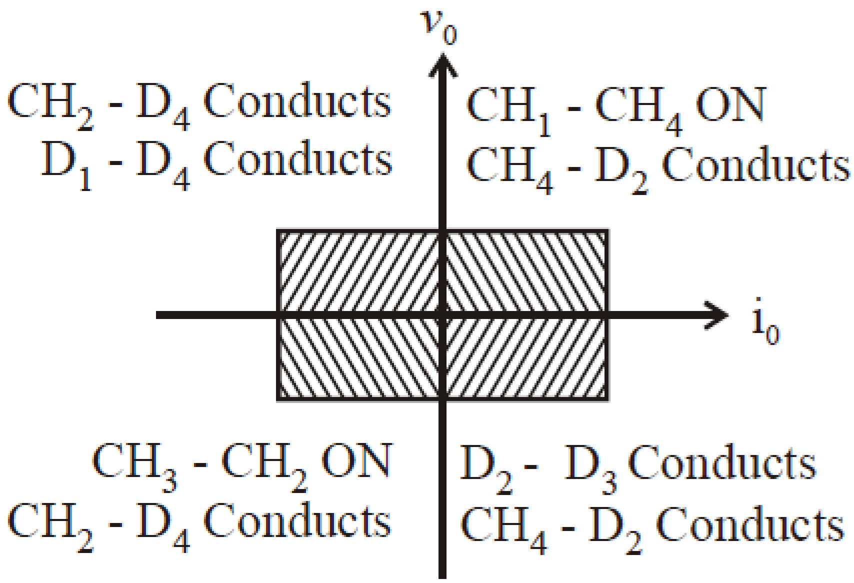
• Therefore the chopper operates in the fourth quadrant.

• When CH2 and CH3 are triggered, the load current iO flows in opposite direction & output voltage vO = -V.

• Since both iO and vO are negative, the chopper operates in third quadrant.

• When both CH2 and CH3 are OFF, the load current iO continues to flow in the same direction D1 and D4 and the output voltage vO = V.

• Therefore the chopper operates in second quadrant as vO is positive but iO is negative.



Effect Of Source & Load Inductance

- The source inductance should be as small as possible to limit the transient voltage.
- Also source inductance may cause commutation problem for the chopper.
- Usually an input filter is used to overcome the problem of source inductance.
- The load ripple current is inversely proportional to load inductance and chopping frequency.
- Peak load current depends on load inductance.
- To limit the load ripple current, a smoothing inductor is connected in series with the load.

5.6 Recommended questions

1. Explain the principle of operation of a chopper. Briefly explain time-ratio control and PWM as applied to chopper

2. Explain the working of step down shopper. Determine its performance factors, VA, Vo rms, efficiency and Ri the effective input resistane

3. Explain the working of step done chopper for RLE load. Obtain the expressions for minimum load current I1max load current I2, peak – peak load ripple current di avg value of load current Ia, the rms load current Io and Ri.

4. Give the classification of stem down converters. Explain with the help of circuit diagram one-quadrant and four quadrant converters.

5. The step down chopper has a resistive load of R=10ohm and the input voltage is Vs=220V. When the converter switch remain ON its voltage drop is Vch=2V and the chopping frequency is 1 KHz. If the duty cycle is 50% determine a) the avg output voltage VA, b) the rms output voltage Vo c) the converter efficiency d) the effective input resistance Ri of the converter.

6. Explain the working of step-up chopper. Determine its performance factors

5.7 Generic Skills / Outcomes

✓ Discuss the principle of operation of single phase and three phase DC –DC converters

5.8 Further Reading

1. **"Power Electronics" -** M. H. Rashid 3rd edition, PHI / Pearson publisher 2004.

2. **"Power Electronics" -** M. D. Singh and Kanchandani K.B. TMH publisher, 2nd Ed. 2007.

3. **"Thyristorized Power Controllers" -** G. K. Dubey S. R. Doradla, A. Joshi and Rmk Sinha New age international (P) ltd reprint 1999.

MODULE- 5(b)
DC-AC CONVERTERS

Structure

5.0 INTRODUCTION

The converters which converts the power into ac power popularly known as the inverters. The application areas for the inverters include the uninterrupted power supply (UPS), the ac motor speed controllers, etc.

The inverters can be classified based on a number of factors like, the nature of output waveform (sine, square, quasi square, PWM etc), the power devices being used (thyristor transistor, MOSFETs IGBTs), the configuration being used, (series. parallel, half bridge, Full bridge), the type of commutation circuit that is being employed and Voltage source and current source inverters.

The Thyristorised inverters use SCRs as power switches. Because the input source of power is pure de in nature, forced commutation circuit is an essential part of Thyristorised inverters. The commutation circuits must be carefully designed to ensure a successful commutation of SCRs. The addition of the commutation circuit makes the Thyristorised inverters bulky and costly. The size and the cost of the circuit can be reduced to some extent if the operating frequency is increased but then the inverter grade thyristors which are special thyristors manufactured to operate at a higher frequency must be used, which are costly.

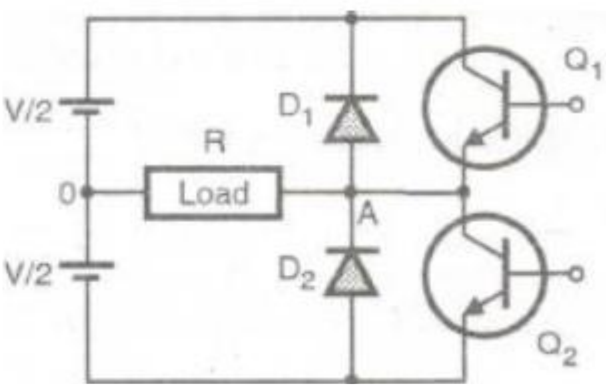
5.1OBJECTIVES:

- ✓ To explain the design, analysis techniques, performance parameters and characteristics of DC-AC converters

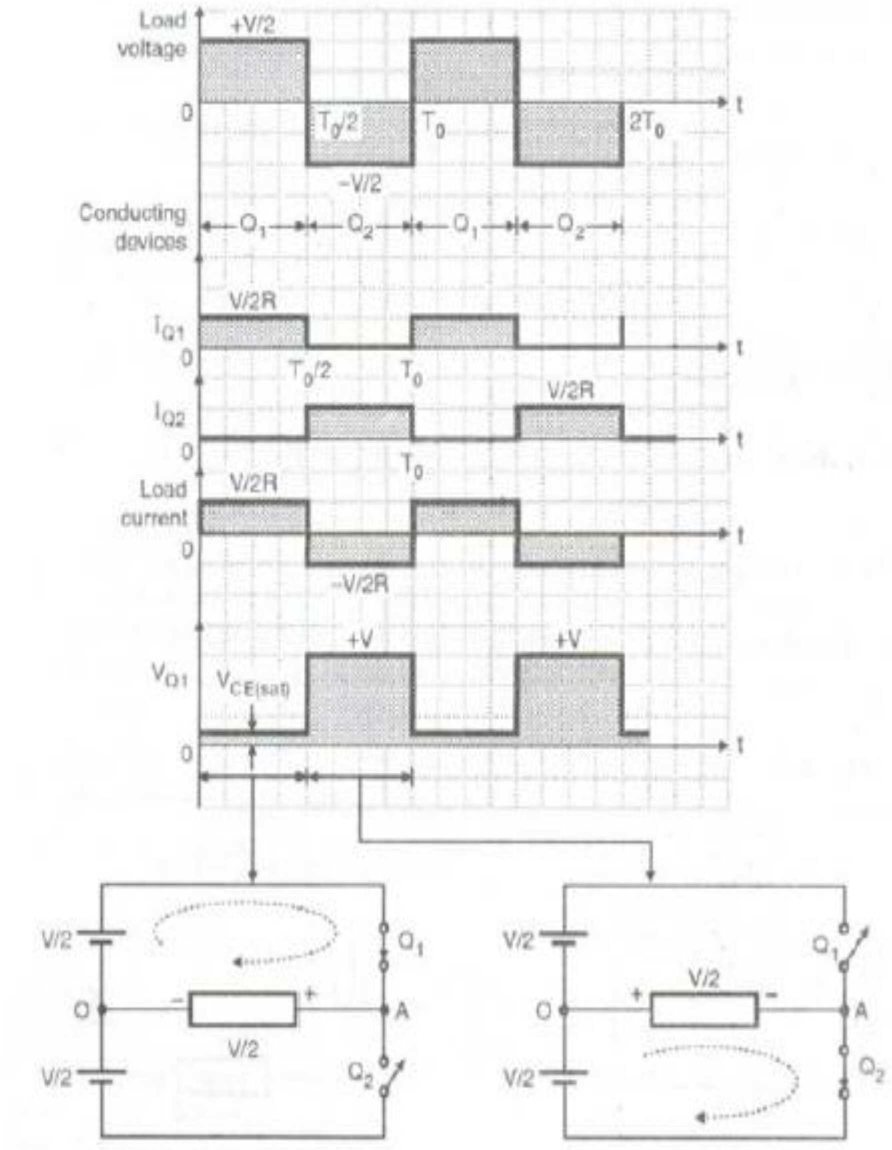
5.2 Classification of Inverters

There are different basis of classification of inverters. Inverters are broadly classified as current source inverter and voltage source inverters. Moreover it can be classified on the basis of devices used (SCR or gate commutation devices), circuit configuration (half bridge or full bridge), nature of output voltage (square, quasi square or sine wave), type of circuit (switched mode PWM or resonant converters) etc.

5.3 Principle of Operation



1. The principle of single phase transistorised inverters can be explained with the help of Fig. The configuration is known as the half bridge configuration**.**
2. The transistor Q1 is turned on for a time T0/2, which makes the instantaneous voltage across the load Vo = V*12*.
3. If transistor Q2 is turned on at the instant T0/2 by turning Q1 off then -V/2 appears across the load.

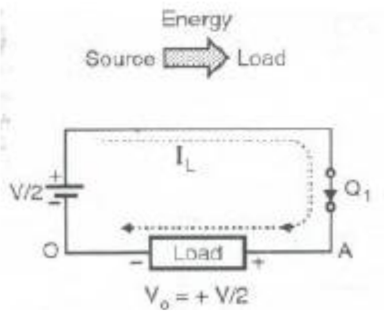


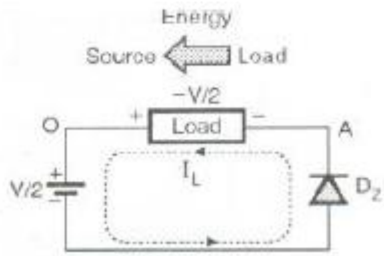
5.4 Half bridge inverter with Inductive load

Operation with inductive load:

Let us divide the operation into four intervals. We start explanation from the second lime interval II to t2 because at the beginning of this interval transistor Q1 will start conducting.

Interval II (tl - t2): Q1 is turned on at instant tl, the load voltage is equal to + V/2 and the positive load current increases gradually. At instant t2 the load current reaches the peak value. The transistor Q1 is turned off at this instant. Due to the same polarity of load voltage and load current the energy is stored by the load. Refer Fig. 8.3(a).

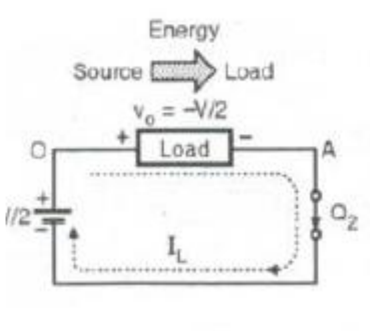




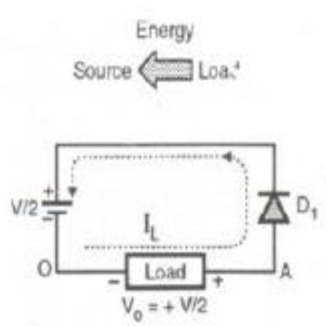
Interval III (t2- t3): Due to inductive load, the load current direction will be maintained same even after Q1 is turned off. The self induced voltage across the load will be negative. The load current flows through lower half of the supply and D2 as shown in Fig. 8.3(b). In this interval the stored energy in load is fed back to the lower half of the source and the load voltage is clamped to -V/2.

Interval IV (t3 - t4):

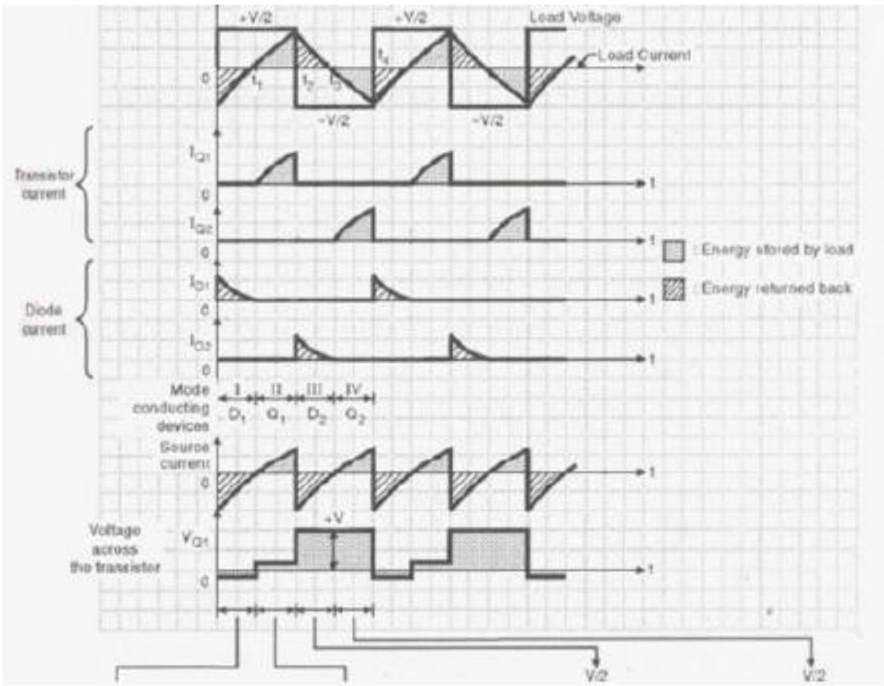
At the instant t3, the load current goes to zero, indicating that all the stored energy has been returned back to the lower half of supply. At instant t3 ' Q2 ‘is turned on. This will produce a negative load voltage v0 = - V/2 and a negative load current. Load current reaches a negative peak at the end of this interval. (See Fig. 8.4(a)).



(a) Interval IV $(t_3 - t_4)$



(b) Interval I $(t_0 - t_1)$



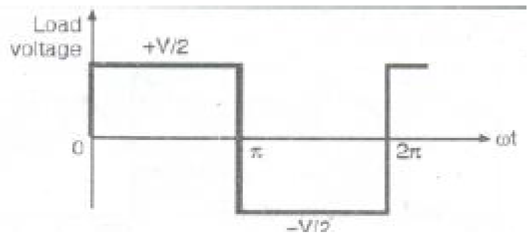
Interval I (t4 to t5) or (t0 to t1)

Conduction period of the transistors depends upon the load power, factor. For purely inductive load, a transistor conducts only for T0/2 or 90 o. Depending on the load power factor, that conduction period of the transistor will vary between 90 to 1800 (1800 for purely resistive load).

5.5 Fourier analysis of the Load Voltage Waveform of a Half Bridge Inverter

Assumptions:

• The load voltage waveform is a perfect square wave with a zero average value.
• The load voltage waveform does not depend on the type of load.
• an, bn and cn are the Fourier coefficients.
• ɵn is the displacement angle for the nth harmonic component of output voltage.
• Total dc input voltage to the inverter is V volts.



RMS output voltage

$$V_{o\,rms} = \left\{ \frac{1}{\pi} \int_0^{\pi} (V/2)^2 \, d\omega t \right\}^{1/2}$$

$$= \left\{ \frac{V^2}{4\pi} \times \pi \right\}^{1/2}$$

$$V_{o\,rms} = \frac{V}{2} \text{ volts}$$

RMS value of fundamental component of output voltage

As the fundamental component is a sinewave, its rms value is given by,

$$V_{o1\,rms} = \frac{2V}{\sqrt{2}\,\pi} = \frac{\sqrt{2}\,V}{\pi} = 0.45\ V$$

5.6 Performance parameters of inverters

The output of practical inverters contains harmonics and the quality of an inverter is normally evaluated in terms of following performance parameters:

- Harmonic factor of nth harmonic.
- Total harmonic distortion.
- Distortion factor.
- Lowest order harmonic.

***Harmonic factor of nth harmonics HFn*:**

The harmonic factor is a measure of contribution of indivisual harmonics. It is defined as the ratio of the rms voltage of a particular harmonic component to the rms value of fundamental component.

Total harmonic distortion, THD: It is a measure of closeness in shape between a waveform and its fundamental component (sinusoidal waveform). THD = 0 means sinusoidal wave.

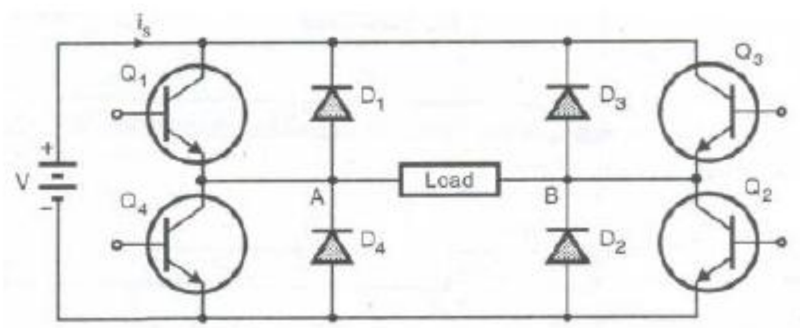
Distortion Factor, DF

DF indicates the amount of HD that remains in a particular waveform after the harmonics of that waveform have been subjected to the second order attenuation (i.e. divided by n2)

Lowest-orderharmonic,LOH

LOH is that harmonic component whose frequency is closest to the fundamental one. Its amplitude is normally > 3% of the fundamental component. High LOH is desired.

5.7 Single Phase Bridge Inverter



A single phase bridge inverter is shown in Fig.8.7. It consists of four transistors. These transistors are turned on and off in pairs of Q1, Q2 and Q3 Q4.

In order to develop a positive voltage + V across the load, the transistors Q1, and O2 are turned on simultaneously whereas to have a negative voltage - V across the load we need to turn on the devices Q3 and Q4.

Diodes D1, D2, D3, and D4 are known as the feedback diodes, because energy feedback takes place through these diodes when the load is inductive.

Operation with resistive load

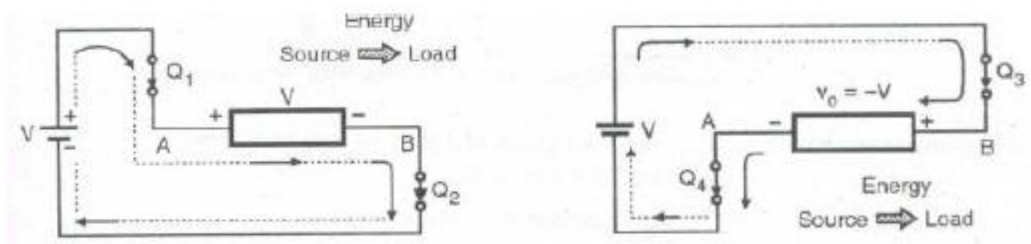
With the purely resistive load the bridge inverter operates in two different intervals In one cycle of the output.

Mode I (0 - T0/2*):*

The transistors 01 and O2 conduct simultaneously in this mode. The load voltage is + V and load current flows from A to B. The equivalent circuit for mode 1 is as shown in Fig. 8.8 (A). At t = To/2 , 0, and Q2 are turned off and Q3 and Q4 are turned on.

At t = T0/2, Q3 and Q4 are turned on and Q1 and Q2 are turned off. The load voltage is –V and load current flows from B to A. The equivalent circuit for mode II is as shown in Fig. 9.5.1(b). At t = To, Q3 and Q4 are turned off and Q1 and Q2 are turned on again.

• As the load is resistive it does not store any energy. Therefore the feedback diodes are not effective here.



(a) Mode I equivalent circuit (b) Mode II equivalent circuit

• The voltage and current waveforms with resistive load are as shown in Fig.

The important observations from the waveforms of Fig as follows:

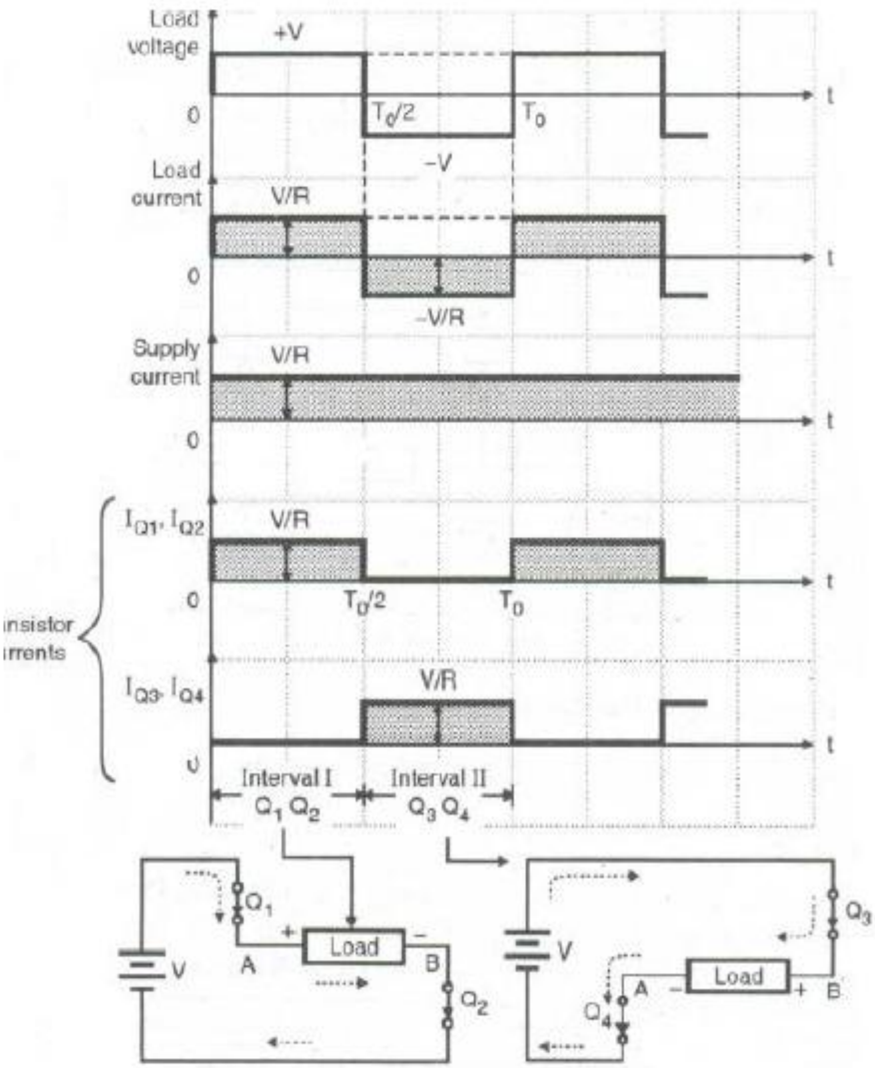
(i) The load current is in phase with the load voltage

(ii) The conduction period for each transistor is 1t radians or 1800

(iii) Peak current through each transistor = V/R.

(iv) Average current through each transistor = V/2R

(v) Peak forward voltage across each transistor = V volts.



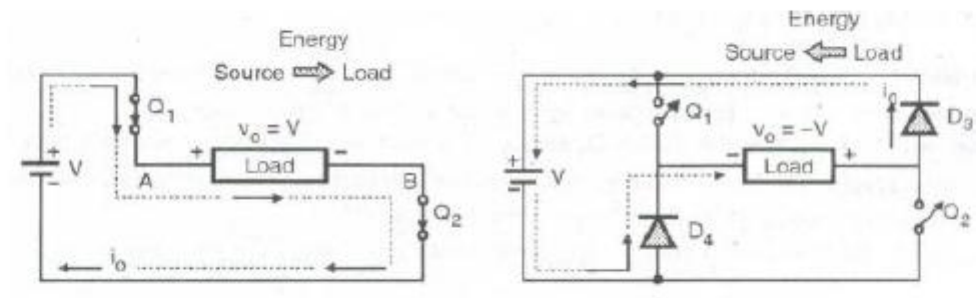
5.8 Single Phase Bridge Inverter with RL Load

The operation of the circuit can be divided into four intervals or modes. The waveforms are as shown in Fig.

Interval I (t1 – t2):

At instant tl, the pair of transistors Q1 and Q2 is turned on. The transistors are assumed to be ideal switches. Therefore point A gets connected to positive point of dc source V through Q, and point B gets connected to negative point of input supply.

The output voltage Vo == + V as shown in Fig 8.11(a). The load current starts increasing exponentially due to the inductive nature of the load.
The instantaneous current through Q1 and Q2 is equal to the instantaneous load current. The energy is stored into the inductive load during this interval of operation.



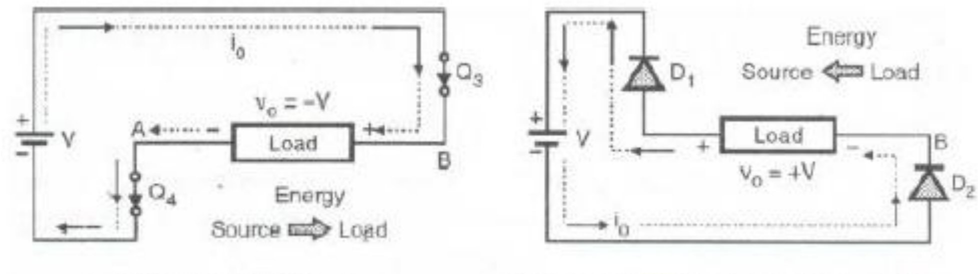
(a) Interval I ($t_1 - t_2$) (b) Interval II ($t_2 - t_3$)

Interval II (t2 - t3) :

• At instant t2 both the transistors Q1 and Q2 are turned off. But the load current does not reduce to 0 instantaneously, due to its inductive nature.
• So in order to maintain the flow of current in the same direction there is a self induced voltage across the load. The polarity of this voltage is exactly opposite to that in the previous mode.
• Thus output voltage becomes negative equal to - V. But the load current continues to now in the same direction, through D3 andD4 as shown in Fig. 8.11(b).
• Thus the stored energy in the load inductance is returned back to the source in this mode. The diodes D1 to D4 are therefore known as the feedback diodes.
• The load current decreases exponentially and goes to 0 at instant t3 when all the energy stored ill the load is returned back to supply. D3 and D4 are turned off at t3·

Interval III (t3 – t4)

• At instant t3 ' Q3 and Q4 are turned on simultaneously. The load voltage remains negative equal to - V but the direction of load current will reverse and become negative.
• The current increases exponentially in the negative direction. And the load again stores energy) in this mode of operation. This is as shown in Fig.



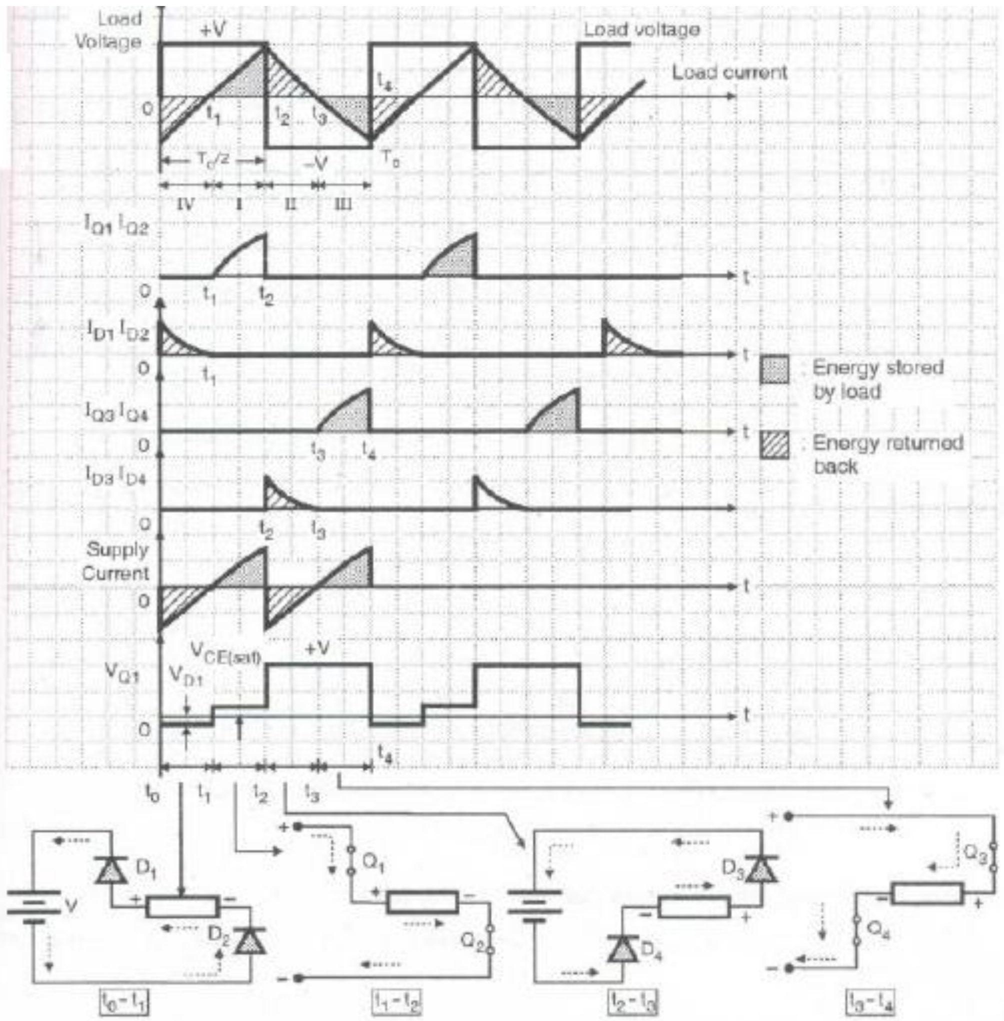
(a) Interval III ($t_3 - t_4$) (b) Interval IV (t_4 to t_5) or ($t_0 - t_1$)

Interval IV (t4 to t5) or (t0 to t1)

• At instant t4 or to the transistors Q3 and Q4 are turned off. The load inductance tries to maintain the load current in the same direction, by inducing a positive load voltage.
• This will forward bias the diodes D) and D2. The load stored energy is returned back to the input dc supply. The load voltage Vo = + V but the load current remains negative and decrease exponentially towards 0. This is as shown in Fig. 8.12(b).
• At t5 or t1 the load current goes to zero and transistors Q1 and Q2 can be turned on again.

Conduction period of devices:

• The conduction period with a very highly inductive load, will be T*01*4 or 90 0 for all the transistors as well as the diodes.
• The conduction period of transistors will increase towards To/2.*or* 1800 with increase in th1 load power factor. (i.e., as the load becomes more and more resistive).

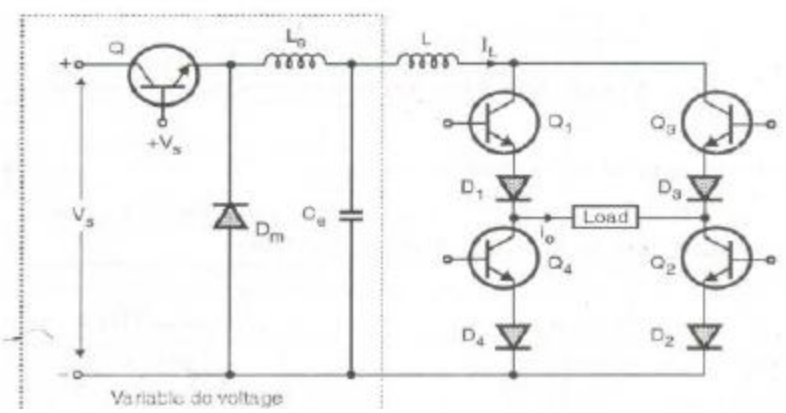


5.9 Comparison of half bridge and full bridge inverters

Sr. No.	Parameter	Half bridge	Full bridge
1	Need of an output transformer	Not needed	Not needed
2	Number of transistors required to be used.	Two	Four
3	Efficiency	High	High
4	Voltage across the nonconducting transistor	V Volts	V Volts
5	Output voltage waveform	Square, Quasi square or PWM	Square, Quasi square or PWM
6	Current rating of power device	Equal to the load current	Equal to the load current
7	Number of devices conducting simultaneously	One	Two
8	Necessity of dead band to avoid cross conduction	Yes	Yes

5.10 Principle of Operation of CSI

The circuit diagram of current source inverter is shown in Fig. The variable dc voltage source is converted into variable current source by using inductance L.

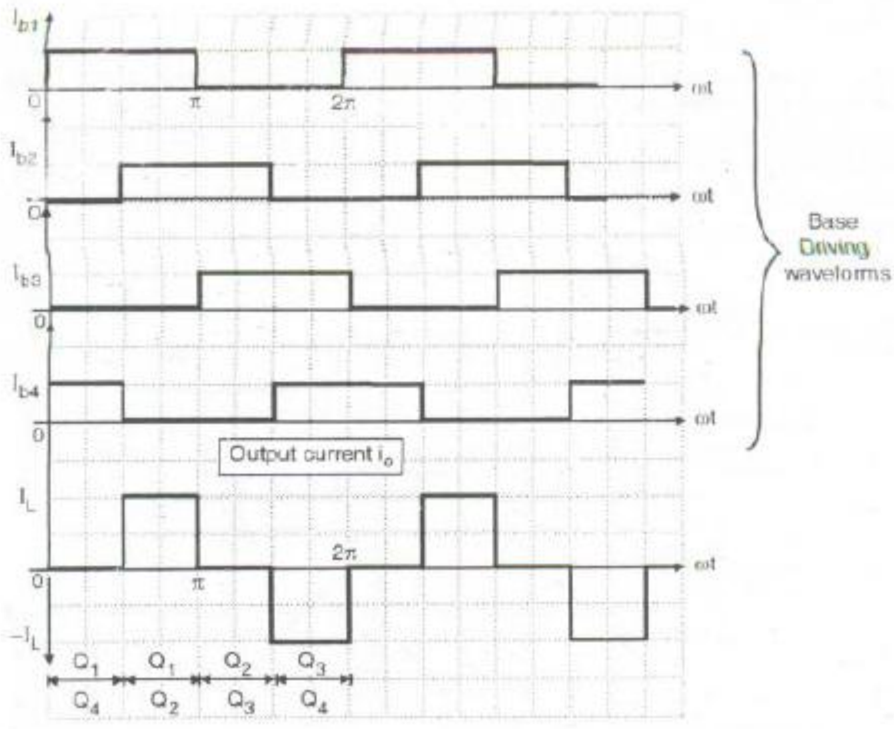


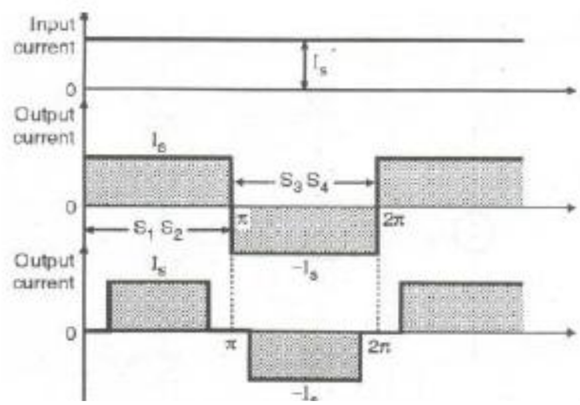
The current IL supplied to the single phase transistorised inverter is adjusted by the combination of variable dc voltage and inductance L.

The waveforms of base currents and output current io are as shown in Fig. 8.15. When transistors Q1 and Q2 conduct simultaneously, the output current is positive and equal to + IL. When transistors Q3 and Q4 conduct simultaneously the output current io = - IL.

But io = 0 when the transistors from same arm i.e. Q(Q4 or Q2 Q3 conduct simultaneously.

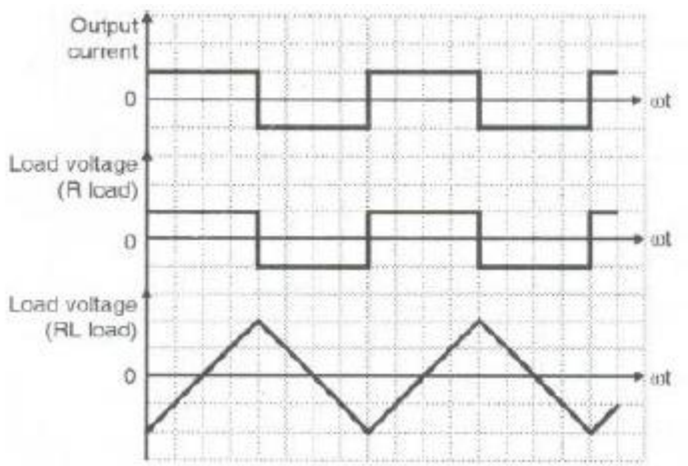
The output current waveform of Fig.is a quasi-square waveform. But it is possible to Obtain a square wave load current by changing the pattern of base driving signals. Such waveforms are shown in Fig.





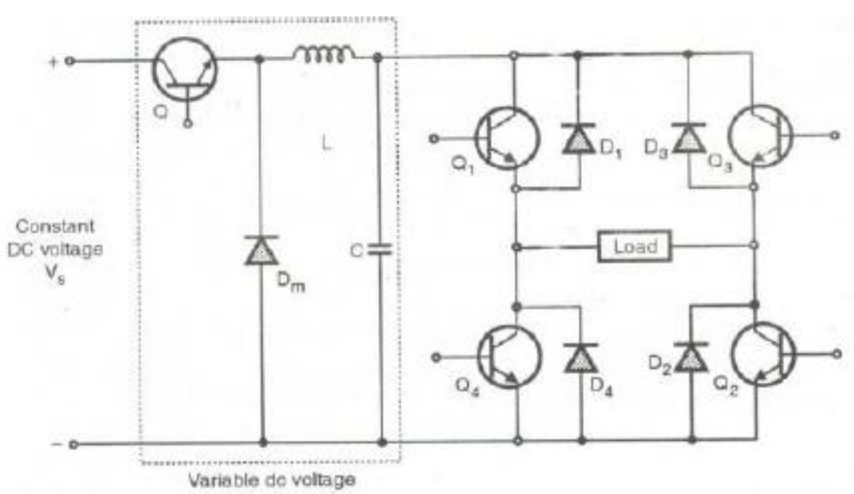
Load Voltage:

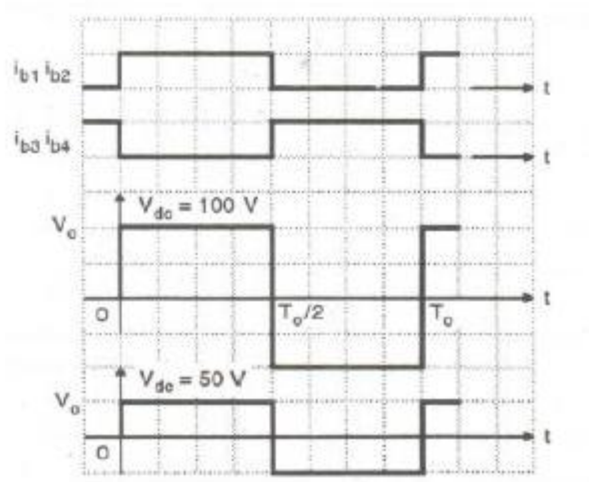
• The load current waveform in CSI has a defined shape, as it is a square waveform in this case. But the load voltage waveform will be dependent entirely on the nature of the load.
• The load voltage with the resistive load will be a square wave, whereas with a highly inductive load it will be a triangular waveform. The load voltage will contain frequency components at the inverter frequency f, equal to l/T and other components at multiples of inverter frequency.
• The load voltage waveforms for different types of loads are shown in Fig.



5.11 Variable DC link Inverter

The circuit diagram of a variable DC-link inverter is shown in Fig. This circuit can be divided into two parts namely a block giving a variable DC voltage and the second part being the bridge inverter itself.





The components Q, Dm, Land C give out a variable DC output. L and C are the filter components. This variable DC voltage acts as the supply voltage for the bridge inverter.

The pulse width (conduction period) of the transistors is maintained constant and the variation in output voltage is obtained by varying the DC voltage.
The output voltage waveforms with a resistive load for different dc input voltages are shown in Fig.
We know that for a square wave inverter, the rms value of output voltage is given by,
V0 (rms) = Vdc volts
Hence by varying Vdc, we can vary V0 (rms)
One important advantage of variable DC link inverters is that it is possible to eliminate or reduce certain harmonic components from the output voltage waveform.
The disadvantage is that an extra converter stage is required to obtain a variable DC voltage from a fixed DC. This converter can be a chopper

Three Phase DC-AC Inverters:

Three Phase DC-AC Converters Three phase inverters are normally used for high power applications. The advantages of a three phase inverter are:

- The frequency of the output voltage waveform depends on the switching rate of the switches and hence can be varied over a wide range.
- The direction of rotation of the motor can be reversed by changing the output phase sequence of the inverter.
- The ac output voltage can be controlled by varying the dc link voltage.

The general configuration of a three phase DC-AC inverter is shown in Figure 1. Two types of control signals can be applied to the switches:

- 180^o conduction

- 120° conduction

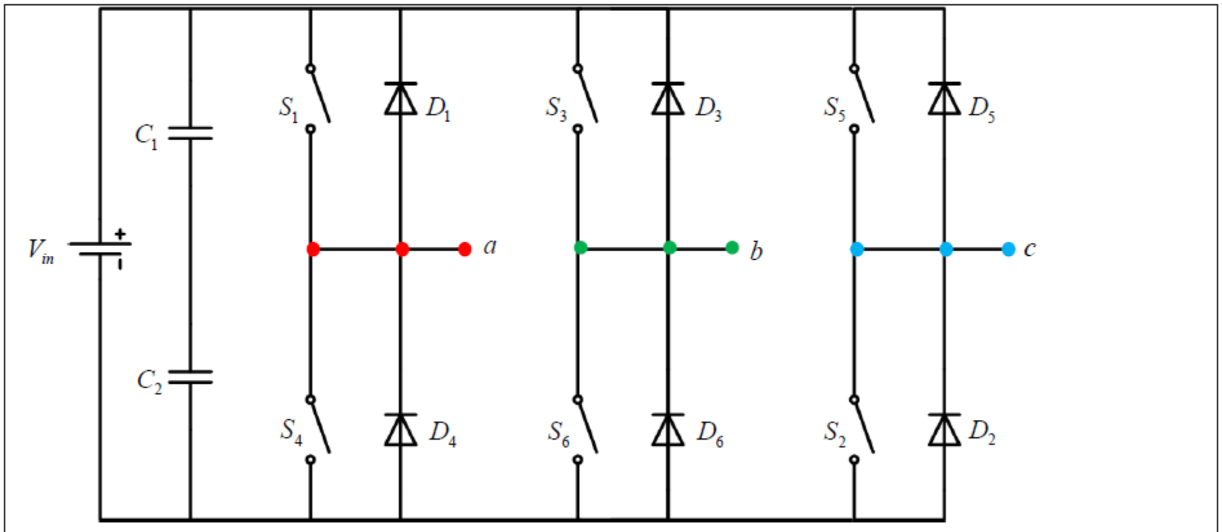


Figure 1: Configuration of a Three-Phase DC-AC Inverter

180-Degree Conduction with Star Connected Resistive Load

The configuration of the three phase inverter with star connected resistive load is shown in **Figure** 2. The following convention is followed:
A current leaving a node point ***a***, ***b*** or ***c*** and entering the neutral point ***n*** is assumed to be positive.
All the three resistances are equal, Ra= Rb= Rc= R

In this mode of operation each switch conducts for 180o. Hence, at any instant of time ***three switches*** remain ***on***. When is S1 ***on***, the terminal ***a*** gets connected to the positive terminal of input DC source. Similarly, when S4 is ***on***, terminal ***a*** gets connected to the negative terminal of input DC source. There are six possible modes of operation in a cycle and each mode is of 60o duration and the explanation of each mode is as follows:

Mode 1*:** In this mode the switches s5,s6 and s1 are turned ***on for time interval 0< ωt< π/3 As a result of this the terminals ***a*** and ***c*** are connected to the positive terminal of the input DC source and the terminal ***b*** is connected to the negative terminal of the DC source. The current flow through Ra,Rb and Rc is shown in **Figure 3a** and the equivalent circuit is shown in **Figure 3b**. The equivalent resistance of the circuit shown in **Figure 3b** is

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

The current delivered by the DC input source is

$$i = \frac{V_{in}}{R_{eq}} = \frac{2}{3}\frac{V_{in}}{R}$$

The currents and are ia and ib

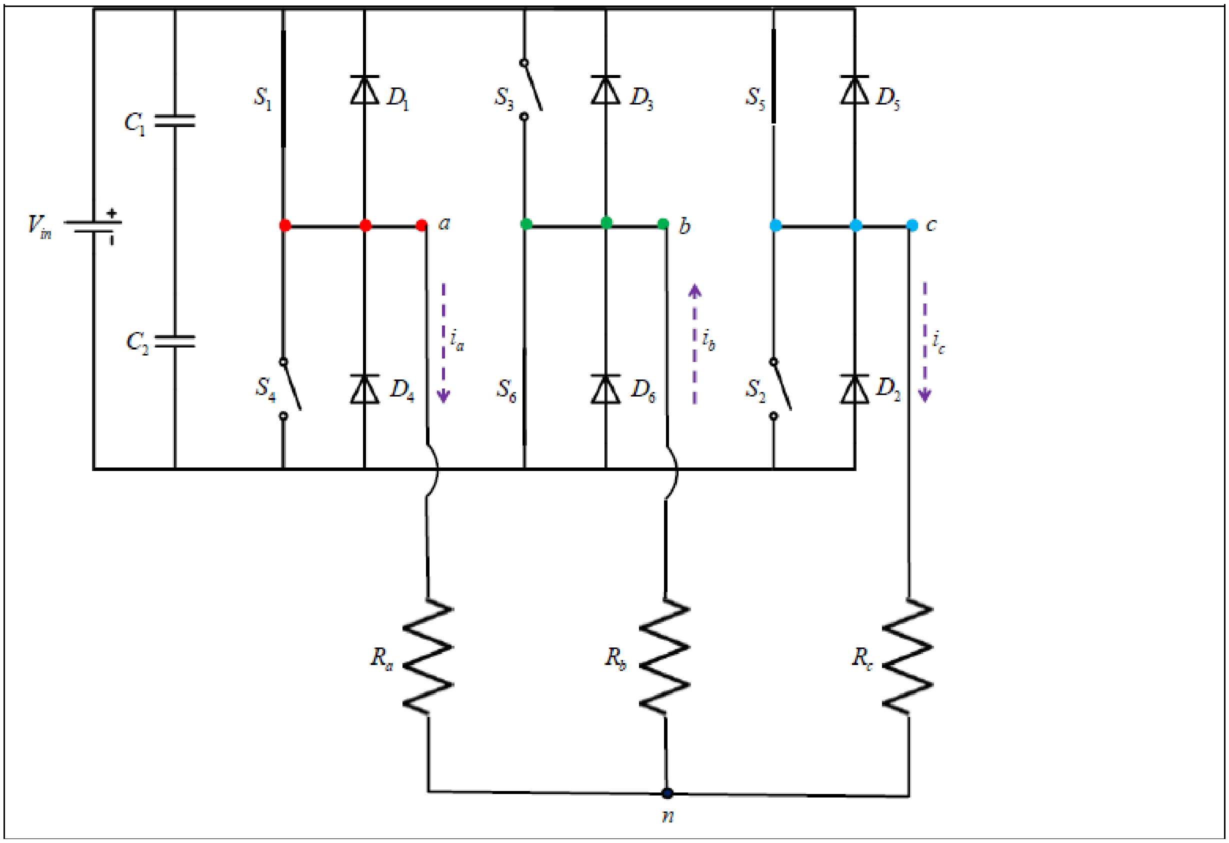
$$i_a = i_c = \frac{1}{3}\frac{V_{in}}{R}$$

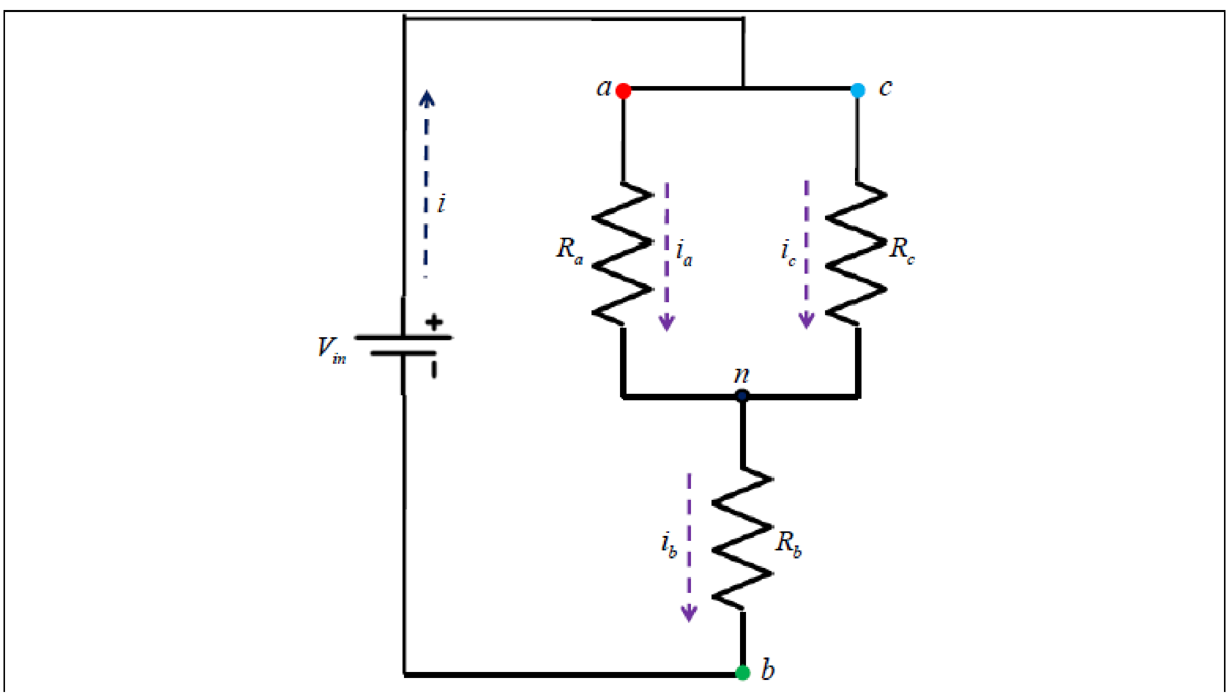
Keeping the current convention in mind, the current is ib

$$i_b = -i = -\frac{2}{3}\frac{V_{in}}{R}$$

Having determined the currents through each branch, the voltage across each branch is

$$v_{an} = v_{cn} = i_a R = \frac{V_{in}}{3};\ v_{bn} = i_b R = -\frac{2V_{in}}{3}$$





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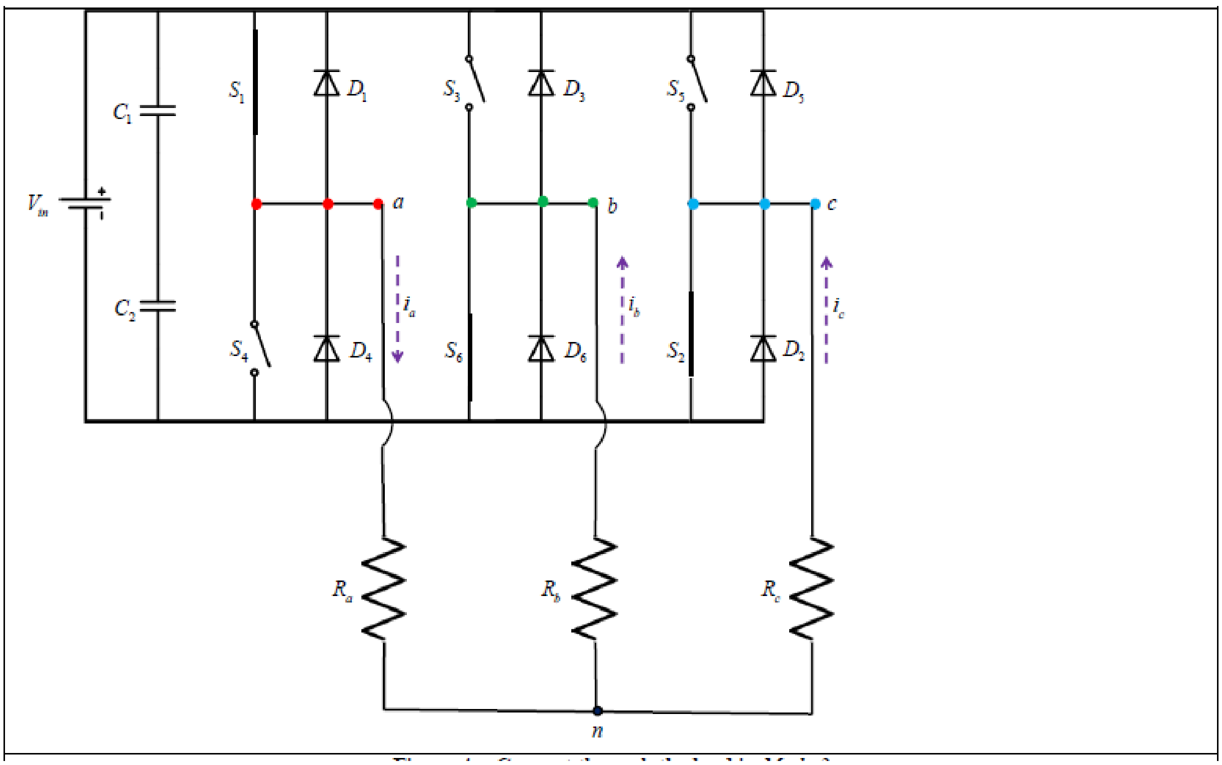
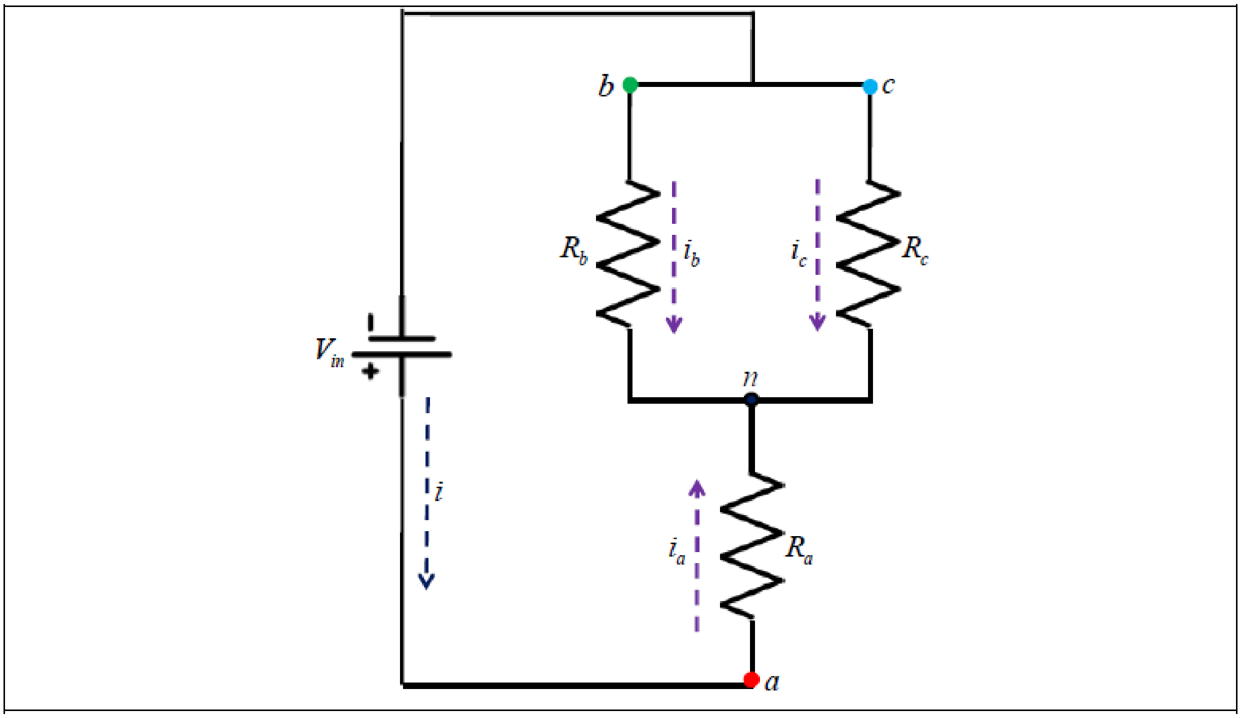
Mode 2*:** In this mode the switches s6,s1 and s2 are turned ***on for time interval π/3< ωt< 2π/3. The current flow and the equivalent circuits are shown in **Figure 4a** and **Figure 4b** respectively. Following the reasoning given for ***mode 1***, the currents through each branch and the voltage drops are given by

$$i_b = i_c = \frac{1}{3}\frac{V_{in}}{R};\ i_a = -\frac{2}{3}\frac{V_{in}}{R}$$

$$v_{bn} = v_{cn} = \frac{V_{in}}{3};\ v_{an} = -\frac{2V_{in}}{3}$$

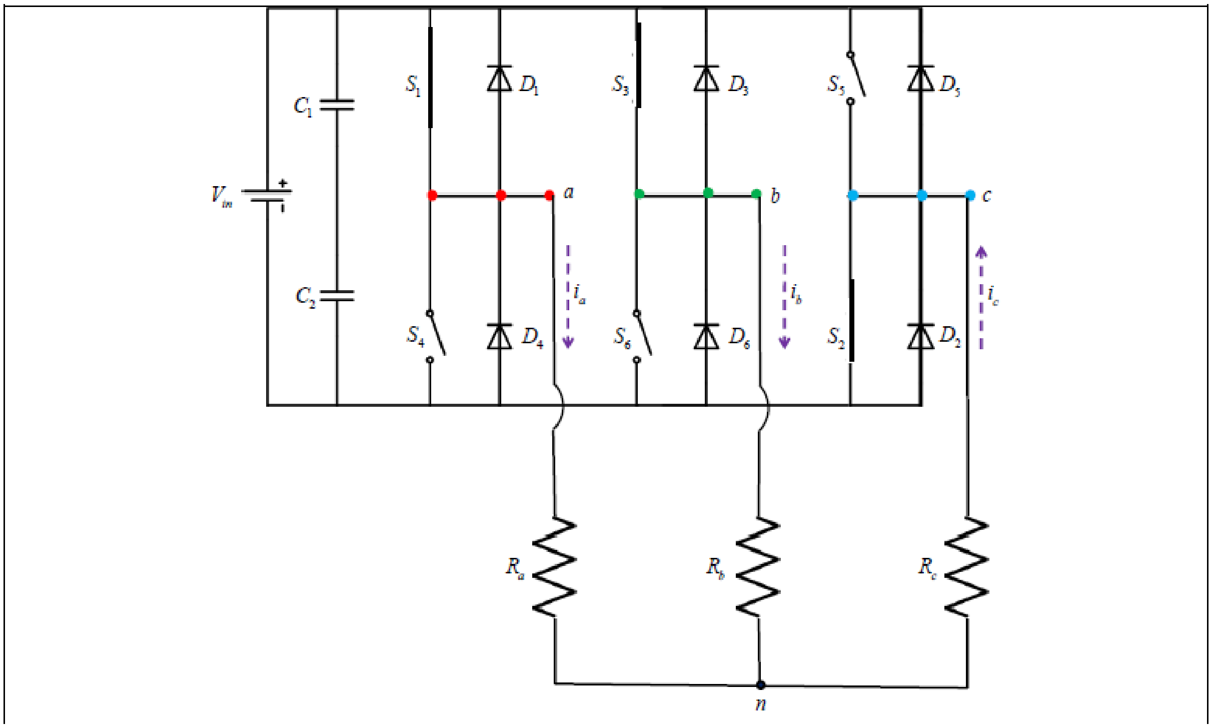


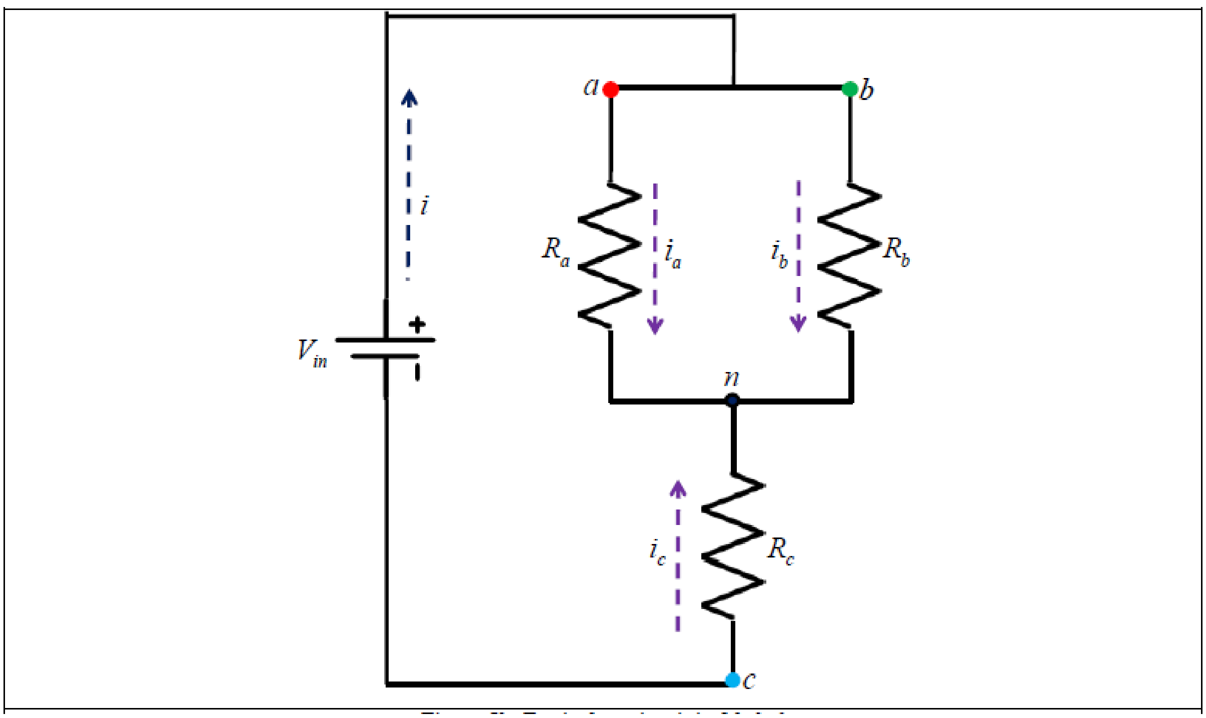


Mode 3**:** In this mode the switches s1,s2 and s3 are turned ***on*** for time interval 2π/3< ωt< π. . The current flow and the equivalent circuits are shown in **Figure 5a** and **figure 5b** respectively. The magnitudes of currents and voltages are:

$$i_a = i_b = \frac{1}{3}\frac{V_{in}}{R};\ i_c = -\frac{2}{3}\frac{V_{in}}{R}$$

$$v_{an} = v_{bn} = \frac{V_{in}}{3};\ v_{cn} = -\frac{2V_{in}}{3}$$





For ***modes 4, 5*** and ***6*** the equivalent circuits will be same as ***modes 1, 2*** and ***3*** respectively. The voltages and currents for each mode are:

$$\left.\begin{aligned} i_a = i_c &= -\frac{1}{3}\frac{V_{in}}{R};\ i_b = \frac{2}{3}\frac{V_{in}}{R} \\ v_{an} = v_{cn} &= -\frac{V_{in}}{3}; V_{bn} = \frac{2V_{in}}{3} \end{aligned}\right\}\text{ for } \textbf{\textit{mode 4}}$$

$$\left.\begin{aligned} i_b = i_c &= -\frac{1}{3}\frac{V_{in}}{R};\ i_a = \frac{2}{3}\frac{V_{in}}{R} \\ v_{bn} = v_{cn} &= -\frac{V_{in}}{3}; V_{an} = \frac{2V_{in}}{3} \end{aligned}\right\}\text{ for } \textbf{\textit{mode5}}$$

$$\left.\begin{aligned} i_a = i_b &= -\frac{1}{3}\frac{V_{in}}{R};\ i_c = \frac{2}{3}\frac{V_{in}}{R} \\ v_{an} = v_{bn} &= -\frac{V_{in}}{3}; V_{cn} = \frac{2V_{in}}{3} \end{aligned}\right\}\text{ for } \textbf{\textit{mode 6}}$$

The plots of the phase voltages (V_{an} ,V_{bn} and V_{cn}) and the currents (I_a , I_b and I_c) are shown in **Figure 6**. Having known the phase voltages, the line voltages can also be determined as:

$$v_{ab} = v_{an} - v_{bn}$$

$$v_{bc} = v_{bn} - v_{cn}$$

$$v_{ca} = v_{cn} - v_{an}$$

The plots of line voltages are also shown in **Figure 6** and the phase and line voltages can be expressed in terms of Fourier series as:

$$v_{an} = \sum_{n=1,3,5,...}^{\infty} \frac{4V_{in}}{3n\pi}\left[1 + \sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin(n\omega t)$$

$$v_{bn} = \sum_{n=1,3,5,...}^{\infty} \frac{4V_{in}}{3n\pi}\left[1 + \sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t - \frac{2n\pi}{3}\right)$$

$$v_{cn} = \sum_{n=1,3,5,...}^{\infty} \frac{4V_{in}}{3n\pi}\left[1 + \sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t - \frac{4n\pi}{3}\right)$$

$$v_{ab} = v_{an} - v_{bn} = \sum_{n=1,3,5,...}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t + \frac{n\pi}{6}\right)$$

$$v_{bc} = v_{bn} - v_{cn} = \sum_{n=1,3,5,...}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t - \frac{n\pi}{2}\right)$$

$$v_{ca} = v_{cn} - v_{an} = \sum_{n=1,3,5,...}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t - \frac{7n\pi}{6}\right)$$

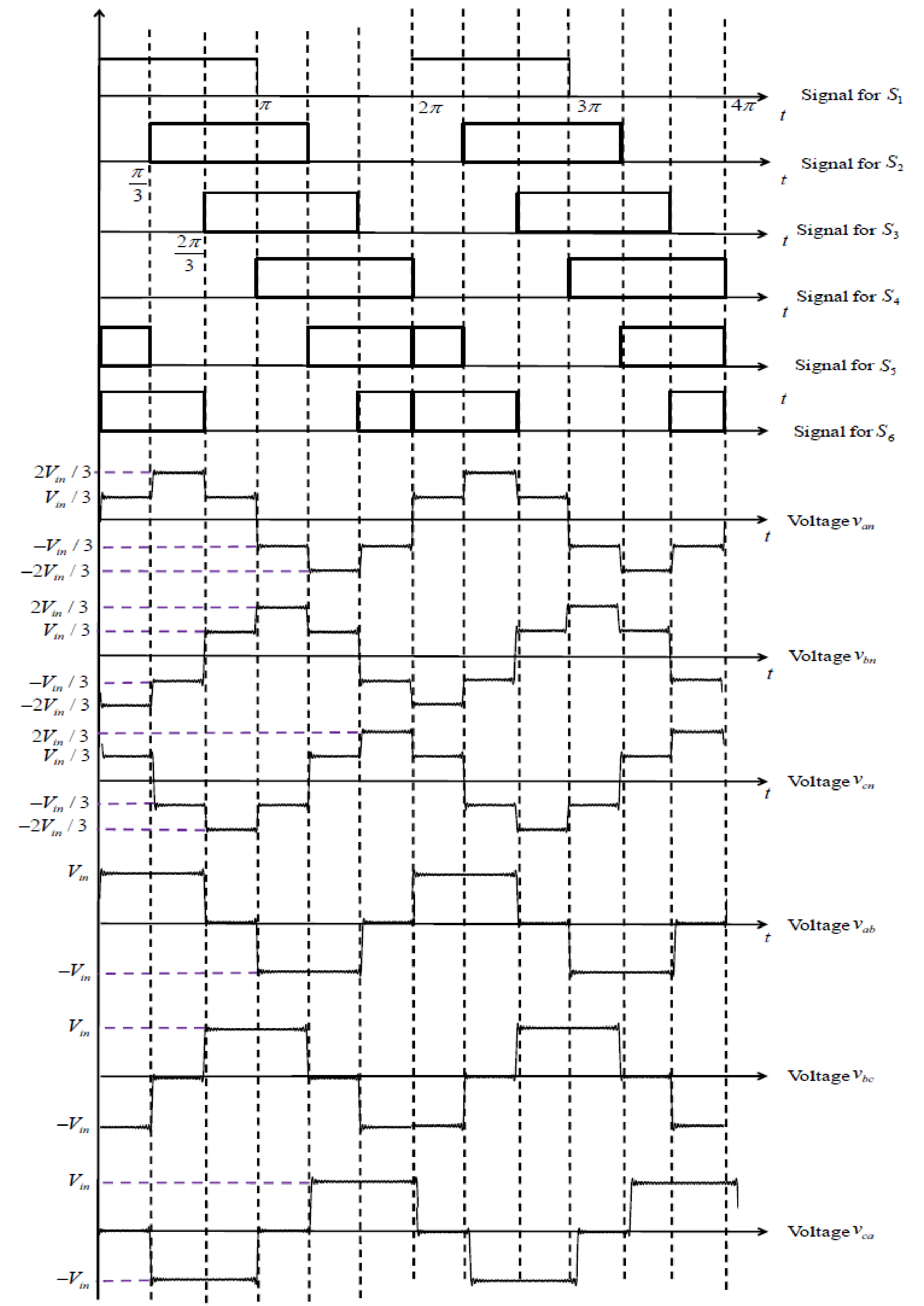


Figure 6: Voltage waveforms for Resistive load for 180°

5.12 Recommended questions

1. What are the differences between half and full bridge inverters?
2. What are the purposes of feedback diodes in inverters?
3. What are the arrangements for obtaining three phase output voltages?
4. What are the methods for voltage control within the inverters?
5. What are the methods of voltage control of I-phase inverters? Explain them briefly.
6. What are the main differences between VSI and CSI?
7. With a neat circuit diagram, explain single phase CSI?
8. The single phase half bridge inverter has a resistive load of R= 2.4 Ω and the dc input voltage is Vs=48V Determine a) the rms output voltage at the fundamental frequency Vo1 b) The output power Po c) the average and peak currents of each transistor d) the peak reverse blocking voltage Vbr of each transistor e) the THD f) the DF g) the HF and DF of the LOH.

5.13 Generic Skills / Outcomes

- ✓ Discuss the principle of operation of single phase and three phase DC –AC converters

5.14 Further Reading

1. **"Power Electronics" -** M. D. Singh and Kanchandani K.B. TMH publisher, 2nd Ed. 2007.

2. **"Thyristorized Power Controllers" -** G. K. Dubey S. R. Doradla, A. Joshi and Rmk Sinha New age international (P) ltd reprint 1999.

3. **"Power Electronics" -** Cynil W. Lander 3rd edition, MGH 2003.