CHAPTER-4

CHOPPER CIRCUIT USING MOSFET OR IGBT

4.1. Introduction :

In AC application, the transformer serves to convert electric power efficiently from one voltage level to another. Static DC to DC converters called as choppers achieve a similar function in DC. The operation of AC transformer is based on an alternating magnetic field. But in chopper the voltage conversion is achieved by power semiconductors, which function as static switches, switching at high repetitive frequency. Choppers are widely used for traction motor control, in electric automobiles, trolley cars, marine hoists, fork lift trucks, and mine haulers. They provide smooth acceleration control, high efficiency, and fast dynamic response. Choppers are also used in DC voltage regulators. The circuit configuration of a chopper converter can be designed either to step down the input voltage level or to step up the input voltage to a higher voltage level. Accordingly the chopper is called as step down or step up chopper. The basic principle of step down chopper is explained in the following.

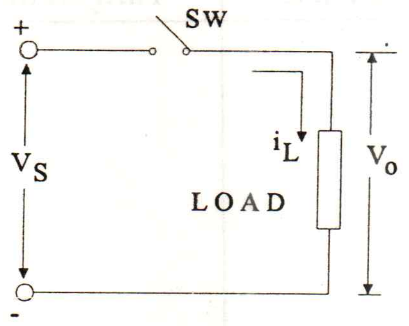


Fig .4.1 Chopper Circuit

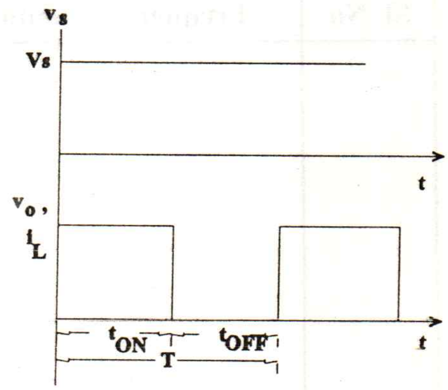


Fig.4.2 Load Voltage and Current Waveform Resistive Load.

4.2 Step Down Chopper:

The principle of operation of the chopper is explained by the circuit of fig 4.1. The switch SW is a semiconductor device. When the switch is ON for a time tON, the input voltage Vs appears across the load. If the switch is OFF for a time tOFF, the voltage across the load is zero. The waveforms of the output voltage and load current for resistive load is shown in fig.4.2.

Neglecting the voltage drop across the switch, the average output voltage Vo is given by

$$V_o = \frac{1}{T}\int_0^{t_{ON}} V_0 . dt = \frac{1}{T}\int_0^{t_{ON}} V_s . dt \qquad (4.1)$$

$$= \frac{t_{ON}}{T} \; V_s \qquad (4.2)$$

$$= f\, T_{ON} \cdot V_s \qquad (4.3)$$

$$= DV_s \qquad (4.4)$$

where,

$$D = \frac{t_{ON}}{T} \text{ - Duty Cycle Ratio} \qquad (4.5)$$

$$T = t_{ON} + t_{OFF} \text{ - Chopping Period} \qquad (4.6)$$

$$f = \frac{1}{T} \text{ - Chopping Frequency} \qquad (4.7)$$

theoretically the duty cycle ratio D can be varied from 0 to 1 by varying t_{ON} and tOFF. Thus the output voltage V_O can be varied from 0 to V_s by controlling D and hence the power flow can be controlled.

When the chopping frequency f is kept constant and the on time t_{ON} is varied, the width of the pulse is varied and the chopper is known as constant frequency chopper. This type of control is known as Pulse Width Modulation (PWM) control.

4.3 Operation with inductive (R-L) Load :

When the load is inductive in nature (R-L), another semiconductor device (a diode - D_f) is to be added to the basic circuit as shown in fig. 4.3. The diode is commonly known as the freewheeling diode.

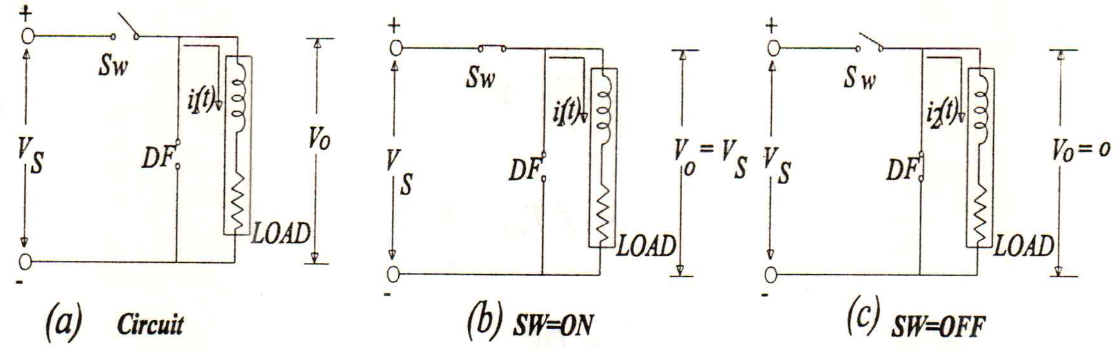


Fig.4.3 Chopper with inductive load.

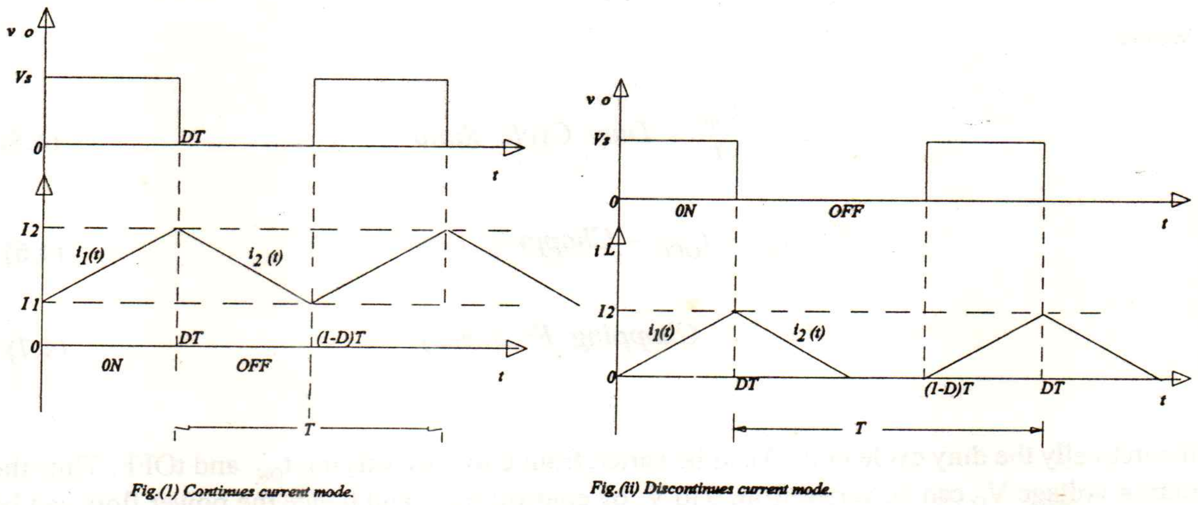


Fig.4.4. Waveform of load voltage and current with inductive load

When the switch SW is turned on for a time t_{ON}, the input voltage V_s appears across the load, The diode D_f is reverse biased. The load current starts building up from the instant when switch is turned on. The growth of the current is exponential because of the inductance L. The waveforms of Load voltage V_0 and current i_1, are shown in fig.4.4, The current $i_1(t)$ when SW is ON is given by

$$i_1(t) = I_1 e^{-\frac{R}{L}t} + \frac{V_s}{R}\left(1 - e^{-\frac{R}{L}t}\right) \qquad \textbf{(4.8)}$$

for $o \leq t \leq T_{on}$ (=DT), At the end of $t = t_{ON}$, the load current becomes

$$i_1\left(t_{ON} = DT\right) = I_2 \qquad \textbf{(4.9)}$$

At the instant when SW is turned off, the current $i_1(t_{ON}) = I_2$, cannot instantly fall to zero, because of the presence of the inductance L. The decay of current causes and induced voltage across the inductance. Because of this voltage, the diode D_F is forward biased and causes the current flow to continue. The term "Free wheeling" is commonly used to describe the flow of current in this manner without being caused by a voltage source, but solely due to the stored energy in the inductance. The purpose of the diode D_F is to provide the freewheeling path when SW is turned off. Therefore the turning OFF of SW automatically causes the turning ON of D_F.

The decay of current I_2 continues as long as SW is off. The current decays exponentially from the initial value of I_2 (When SW is turned OFF) as long as SW remains OFF. The current in this period is given by

$$i_2(t) = I_2 e^{-\frac{R}{L}t} \qquad \textbf{(4.10)}$$

for $0 \le t \le t_{OFF}$ [= (1-D) T]. The values of current at the time instants when SW is turned ON I_1 and turned OFF I_2, are the steady state values after a number of switching cycles have been passed. If the load inductance is very small or the duty cycle ratio is very small the value of I_1 will be zero, as shown in fig 4.4.(a). The chopper is then said to operate in the discontinues current mode.

Chopper with Back-emf (DC Motor) Load :

The chopper with back-emf load such as a DC motor is shown in Fig.4.5. The voltage and current waveforms will be similar to that shown in fig 4.4. The current during SW is on, is given by (Under continuous current mode).

$$i_1(t) = I_1 e^{-\frac{R}{L}t} + \frac{V_s - E}{R}\left(1 - e^{-\frac{R}{L}t}\right) \qquad \textbf{(4.11)}$$

$$for \quad 0 \le t \le t_{ON} \; (= DT)$$

When SW is OFF, and D_F is ON, the current

Where E - the back emf.

$$i_2(t) = I_2 e^{-\frac{R}{L}t} - \frac{E}{R}\left(1 - e^{-\frac{R}{L}t}\right) \qquad (4.12)$$

$$for \quad 0 \le t \le t_{OFF} \; [= (1-D)\,T]$$

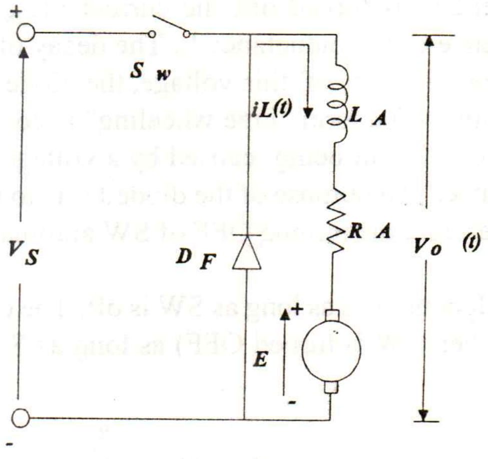


Fig.4.5 Chopper with back-EMF Load.

4.4 Switching Device in the chopper :

The switch SW shown in the chopper circuit can be any one of the following switching power semiconductor devices.

(i) An SCR
(ii) Power Transistor [power BJT]
(iii) Power MOSFET
(iv) IGBT
(v) GTO

When SCR is used as the switching device an additional commutating circuitry must be used to turn off the SCR at the end of t_{on}. This makes the chopper circuits more complicated. The chopping frequency is also limited by the commutating circuit relaxation timings and the larger turn-off time required for the SCRs.

The other semiconductors device listed, can be turned On and OFF through the base or the gate control signals. When these devices are used in chopper circuits no additional commutating circuits are necessary. The switching speeds of these devices are much higher than that of the SCR. Hence chopping frequencies in the order of 1-20 KHz. Can be easily achieved. This enables smooth control of the output voltage and the load current can be continuous even with small value of load inductance.

4.5 Chopper Control Circuit :

The block diagram of the chopper control circuit is shown in fig 4.6. It consists of a ramp or triangular carrier wave generator. The frequency of which can be 1 to 5 KHz. The pulse width modulated signal is obtained by comparing the carrier wave with a control voltage level Vc in a comparator. The pulse width is varied by varying the control voltage level. The output of the comparator is then isolated and amplified before applying to the gate driver circuit. The PWM signal with triangular carrier is shown in fig 4.7.

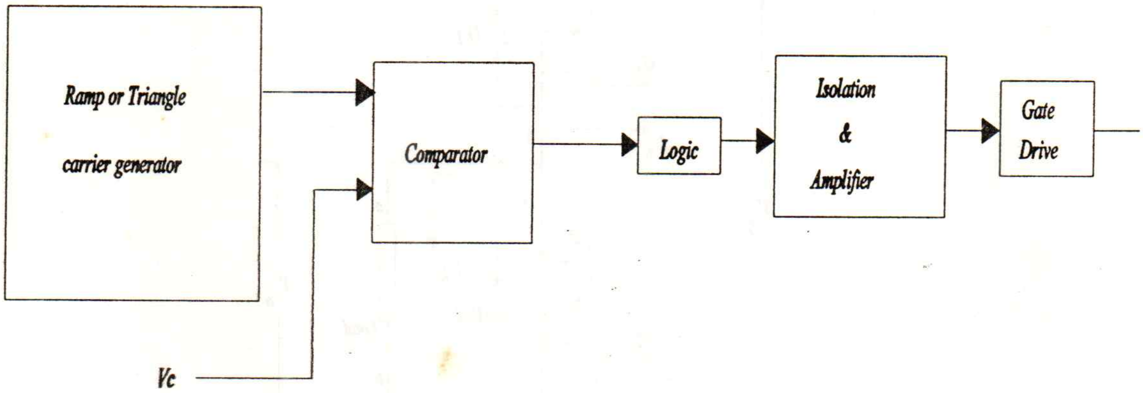


Fig. 4.6. Block Diagram for Chopper Control Circuit

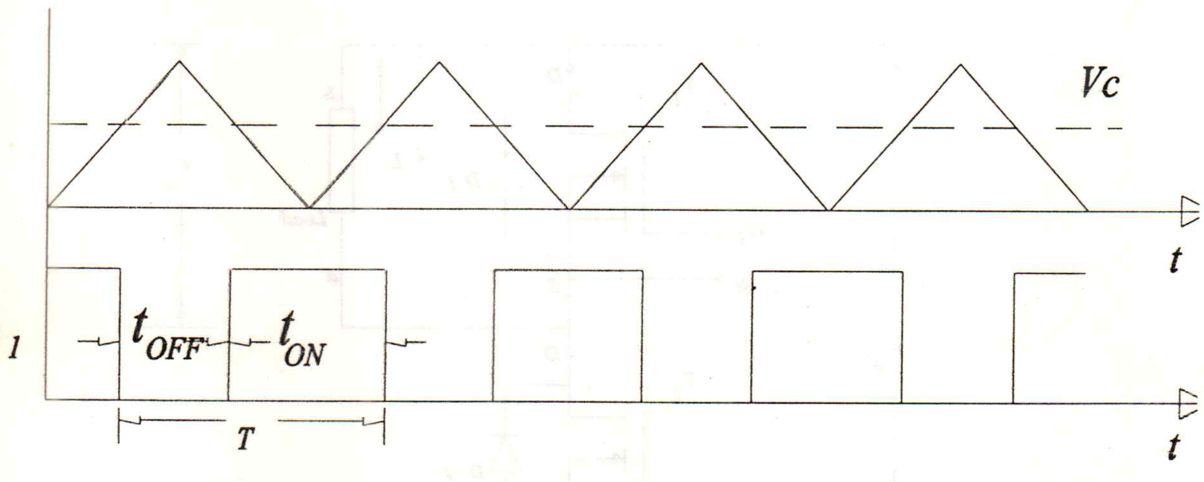


Fig. 4.7. PWM Signals with Triangular carrier for chopper circuit

4.6 MOSFET Chopper Circuit:

A two quadrant chopper circuit using power MOSFET is shown in Fig 4.8. As the power MOSFET has an integral anti parallel diode in its internal construction, external freewheeling diode is not necessary. The load terminal b is connected to the (-) ve terminal of the supply. When the MOSFET T1 is switched by applying the gating signal to its gate G1, the supply voltage is applied to the load with terminal 'a' at (+) ve.

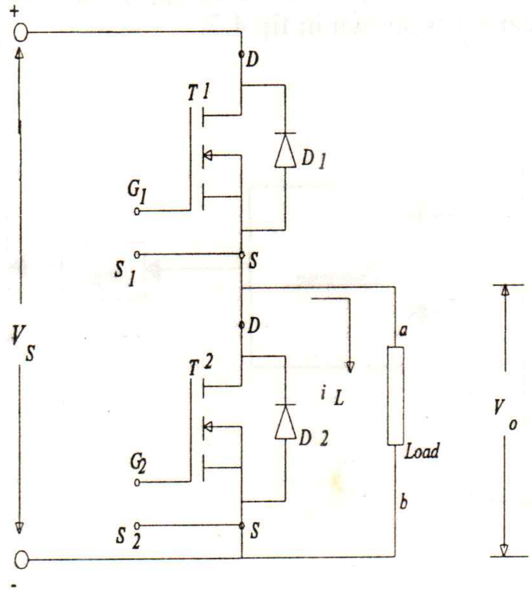


Fig.4.8 MOSFET Chopper circuit Operating in first Quadrant.

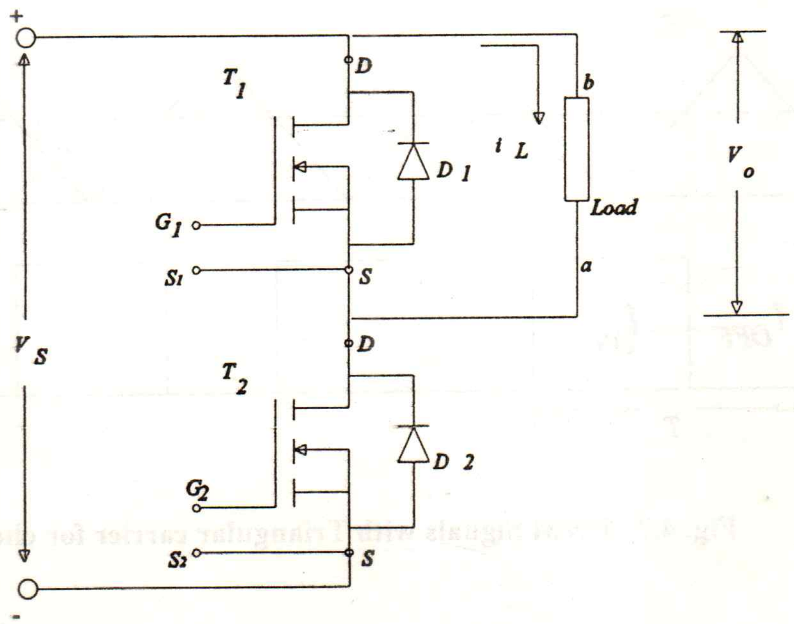


Fig.4.9 MOSFET Chopper circuit Operating in the Third Quadrant.

When T1 is switched OFF, T2 can be gated to conduct. But T2 cannot conduct as it does not form a closed circuit with supply and load. If the load is inductive then the freewheeling current will flow through the integral diode D2 of. MOSFET T2. The chopper is said to be operated in the first quadrant, as both the voltage and the current through the load are positive.

If the load terminal 'b' is connected to the (+) ve terminal of the supply as shown in fig.4.9 the chopper will operate in the third quadrant . In this only the MOSFET T2 can conduct current through the load from the supply. When T2 is switched ON by applying the gating signal to its gate G2, the load terminal 'b' becomes (+) Ve, and the terminal 'a' gets connected to the (-) Ve of the supply through the conducting MOSFET T2. When T2 is switched off the load current will freewheel through the diode D1. As the load voltage and current are negative in this case, the chopper is said to be operated in the third quadrant .

Eventhough complementary gating signals can be applied to the MOSFETs T1 and T2 only the appropriate device will only conduct depending on the connection of the load and the direction of the load current. When complementary gating signals are applied to the MOSFETs, the rising edges of the gating signals must be delayed to the extend of the turn-off time requirement of the MOSFETs, inorder avoid shoot through faults. The gating signals for T_1 and T_2 are obtained as shown in Fig.4.10.

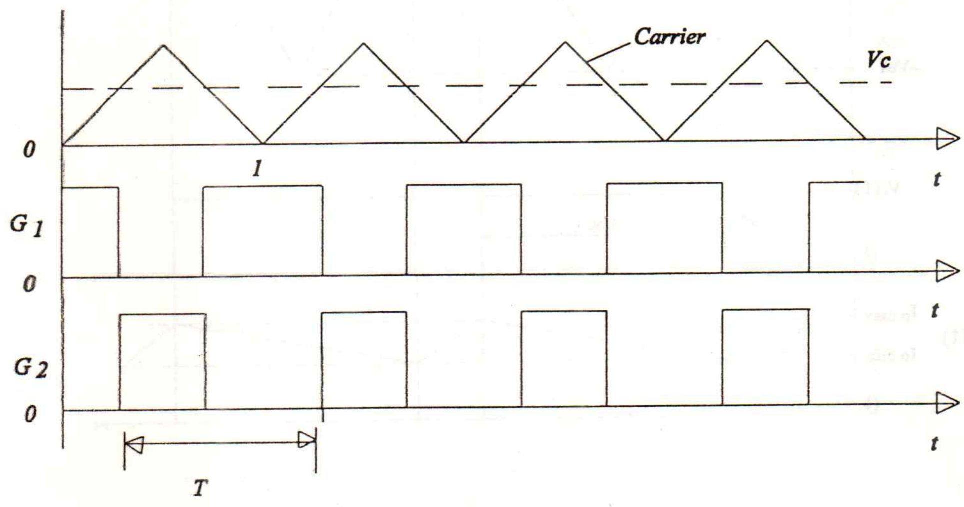


Fig.4.10 Gating Signals for T_1 and T_2.

4.7. Effect of Change of Carrier Frequency:

The gating signals are generated by comparing a carrier triangular waveform v_{tri} with the control voltage V_c. The carrier frequency is the variable one. With the constant control voltage V_c, carrier frequency can be varied from f_{min} to f_{max}. Turn on period as well as turn off period vary while the carrier frequency is varying. The current will be affected whenever the turn on and turnoff period changes. Based on the principle of current limit control, the current in the load is maintained between two limits. When the current exceeds upper limit, the chopper is switched off. During off period the load current free wheels and decreases exponentially it reaches the lower limit, the chopper is switched ON. Since the chopper operates between prescribed current limits, discontinuity cannot occur. The difference between I_{omax} and I_{omin} decides the switching frequency. The ripple in the load current can be reduced if the difference between the I_{omax} and I_{omin} limits is minimum. Therefore for the maximum value of carrier frequency ripple in the load current will be minimized.

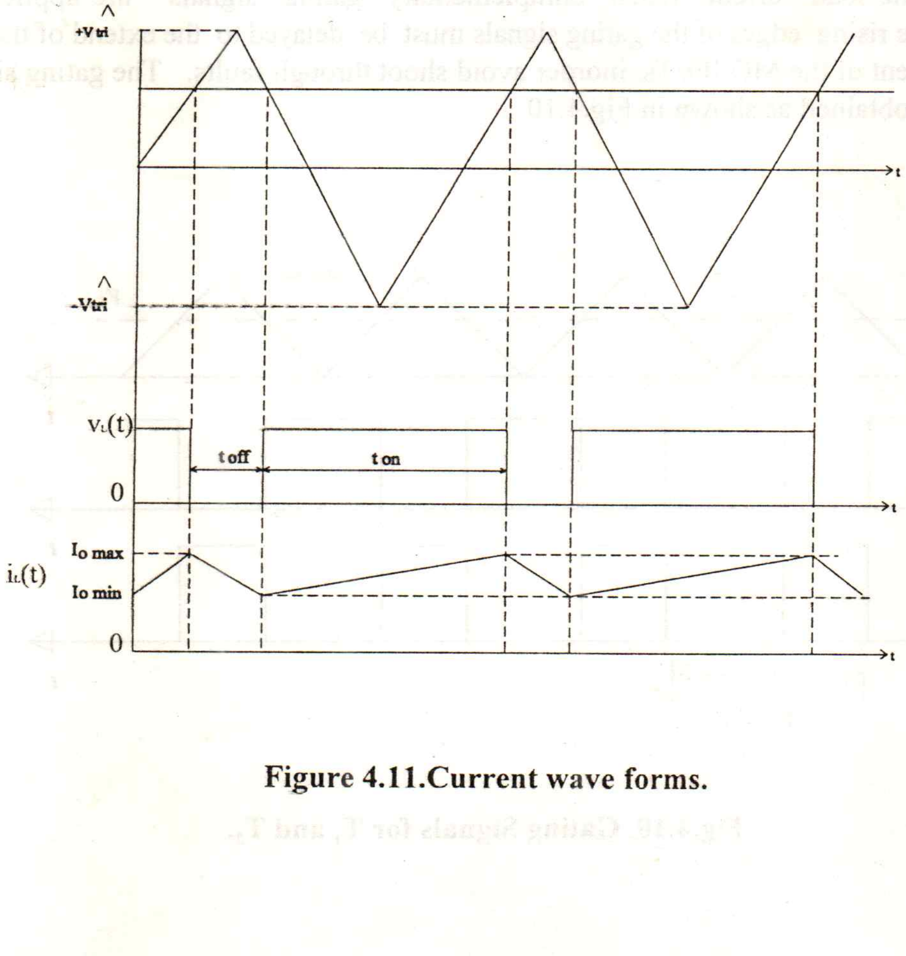


Figure 4.11.Current wave forms.

EXPERIMENT E-1: Study of Chopper Control Circuitry.

AIM:

To study the operation of the chopper control module

EQUIPMENTS REQUIRED:

1. IGBT/MOSFET Module [ITB-PEC16M2/M3]
2. Chopper Control Module [ITB-PEC16M5]
3. CRO
4. Rheostat

PROCEDURE:

1. Connect the power cable to the chopper control module.
2. Ensure that the ac main switch with indicator is in OFF position. Refer to the mimic diagram at the front panel and of Figure 2.4 in the manual.
3. Switch ON ac mains switch at the front panel.
4. Switch SW_1 to select minimum/maximum carrier frequency. Observe the triangular carrier waveform on a CRO at test point T1. Notedown minimum and maximum carrier frequency and its amplitude.
5. The carrier frequency determines the switching frequency of the chopper. Observe the PWM waveforms at test points T3 and T4. Vary the control voltage by means of pot P_2. Calculate the ON period and OFF period of the chopper.
6. For various modes of SW3, observe the gating signals at test points T_7, T_8, T_9 and T_{10} and tabulate them. Refer to Fig.2.5 for numbering the switches.
7. Switch ON SW2 the pulse release ON/OFF switch and check the gating signals at test points T_{11}, T_{12}, T_{13} and T_{14}.
8. Switch OFF SW2 and ac mains switch.

Table E.1: Gating signals for Different switch postions.

Switch Postions	Gating Signals to Devices

EXPERIMENT E-2: Single Quadrant Chopper.

AIM:

To study the operation of the single quadrant chopper with one switch.

EQUIPMENTS REQUIRED:

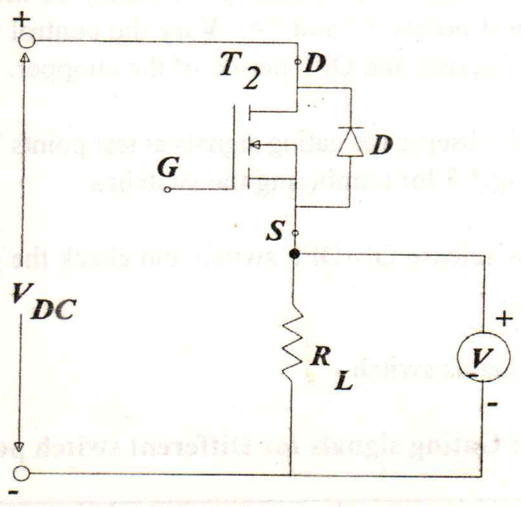
1. IGBT/MOSFET Module [ITB-PEC16M2/M3]
2. Chopper Control Module [ITB-PEC16M5]
3. CRO
4. Rheostat

PRECAUTION:

1. Ensure all switches are in the OFF position while doing connection.
2. Ensure pulse release ON/OFF switch is in OFF position, whenever power is switched ON to the chopper module.

PROCEDURE:

1. Using the chopper module connect the circuit as shown in Fig.E.2.1 use either the switch T_2 or T_4.



Fi.g.E.2.1 Single Quadrant Chopper.

2. Referring the mimic diagram shown in Fig.2. make the following connections, with power OFF to both modules.

   i. Connect V_{+1} to B_{21} using patch cords
   ii. Connect the load Rheostat between B_{23} and V_{-1}.
   iii. Connect a DC voltmeter (0-30)V across the load Rheostat. (B_{23} and V-2)
   iv. Connect the gating signal cable from the control module to the chopper module.

3. Connect the Power cable to chopper module and chopper control module. Connect the CRO to mains.

4. Switch on Power Supply to CRO. Switch on ac mains to control module and adjust the carrier frequency to about 2.2 Khz. Keep the mode switch SW_3 in the control module at position I, and the pulse release ON/OFF switch in OFF position.

5. Switch on power supply to the chopper module and switch ON SW1

6. Release the gating signal by switching on the switch SW_2 in the chopper control module.

7. Observe the load voltage waveform through the CRO. It will be as shown in fig.4.2.

8. Vary the duty cycle ratio by means of pot P2 and measure the output voltage Tabulate the reading as shown in tabular column 1. Measure the on period T_{ON} and the chopping period T using CRO. Calculate V_o using the formula V_o=D.V_{dc}

Table E.2.1 Single Quadrant Chopper

Sl.No.	V_o (V)	T_{ON}	$D = \frac{T_{ON}}{T}$	$V_o = V_{dc} \cdot D$

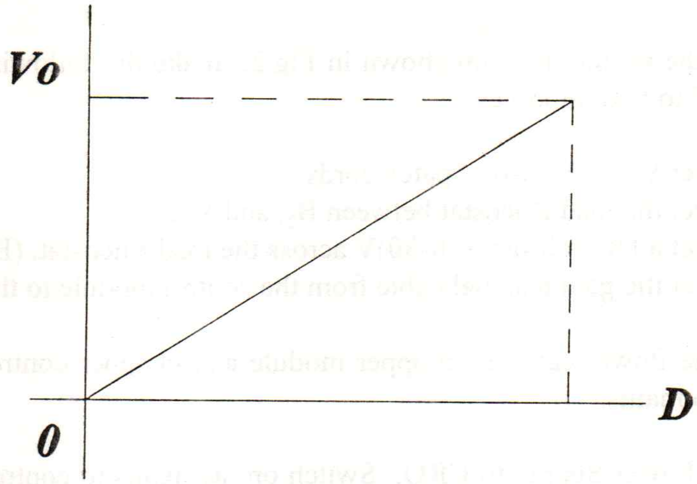


Fig.E.2.2 Duty Cycle Vs Voltage output.

9. Plot a graph between the output voltage V_o and the duty cycle ratio D. It will be as shown in Fig.E.2.2.

10. Keep the duty cycle ratio around 50% vary the chopper frequency from about 1 Khz to 2.2 Khz in steps. For each step note down the output dc voltage and meausre the freqeuncy and t_{ON} through theCRO. Tabulate the readings as shown in tabular column 2

Tabular Column E.2.2

Sl.No.	f_s KHz	V_o
1.	0.8	
2.	1.0	
3.	1.2	
4.	1.5	
5.	2.0	
6.	2.2	

11. Plot the Vo versus frequency characteristics. It will be as shown in Fig.E.2.3. In this the chopper is operated at variable switching frequency.

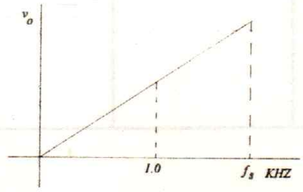


Fig.E.2.3 Outrput Voltage Versus Chopper frequency Characteristics.

EXPERIMENT E-3: Study of two Quadrant Chopper

INTRODUCTION:

The advantage of this circuit is that, voltage and current through the load can be made (+)ve or (-)ve. The circuit connection is shown in fig.E.4.1. If the load is connected across the device T2 (Fig.E.4.1) the load voltage and current are positive and the chopper will be operating in the first quadrant. If the load is connected across T_1, the load voltage and current will be negative and the chopper will be operating in the third quadrant. The two quadrants of operation of the circuit is shown in Fig.E.4.2.

AIM:

To study the operation of the two quadrant chopper with Resistive load.

EQUIPMENTS REQUIRED:

1. IGBT/MOSFET Module [ITB-PEC16M2/M3]
2. Chopper Control Module [ITB-PEC16M5]
3. CRO
4. Rheostat

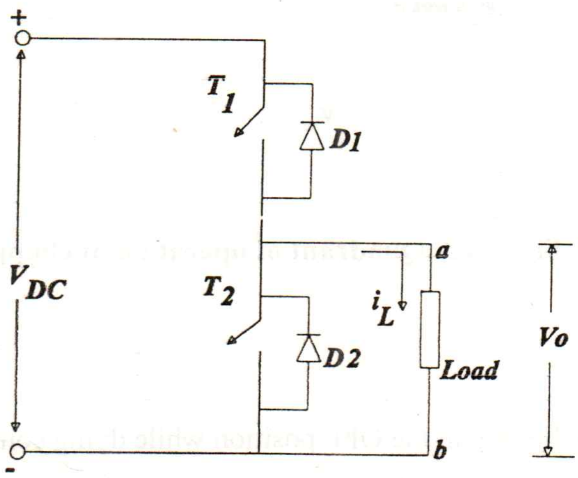


Fig.E.4.1 Two quadrant operation at First quadrant and Fourth Quadrant.

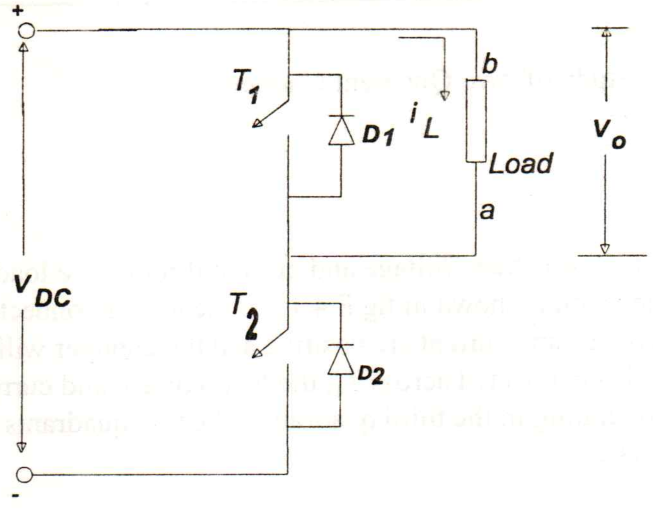


Fig.E.4.2 Chopper Circuit operating in the third quadrant and second quadrant.

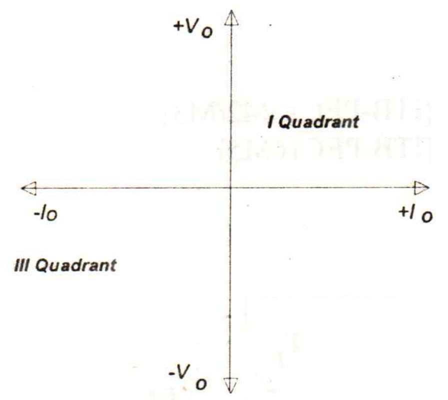


Fig.E.4.3 Quadrant of operation of chopper.

PRECAUTION:

1. Ensure all switches are in the OFF position while doing connection.
2. Ensure pulse release ON/OFF switch is in OFF position, whenever power is switched ON to the chopper module.

PROCEDURE:

1. Refer to the mimic diagram of the chopper module shown in Fig.2.1 (2.2) and make the following connections with power off to both modules.

   i. Connect B_{11} to V_{+1} using patch cords.
   ii. Connect B_{12} to B_{21} using patch cords.
   iii. Connect B_{23} to V_{-1} using patch cords.
   iv. Connect the load between B_{22} and V_{-2}.
   v. Connect a dc voltammeter (0-30) across the load with (+) termined at 'a' and (-) ve termined at 'b'.
   vi. Connect the gating signal cable from control module to chopper module.

2. Keep the duty cycle ratio at minimum and the pulse release switch SW2 at off position.

3. Switch on power supply to CRO and connect the CRO probe to measure the voltage across the load.

4. Switch on ac mains to both the modules switch on SW1 in chopper module so that DC power supply V_{dc} is established in the chopper circuit.

5. Keep the gating signal selection switch SW_3 at Position II. Release the gating signal by switching on SW_2. Vary the duty cycle ratio in steps and for each case measure the output voltage, the on period, T_{ON} and the chopping period T Tabulate the readings.

Table E.4.1: Two Quadrant Chopper

Sl.No.	V_o (V)	T_{ON}	$D = \frac{T_{ON}}{T}$	$V_o = V_{dc} \cdot D$

6. Switch off the DC power supply in chopper module and then block the gating signals by means of the switch SW_2 in chopper control module.

7. Now connect the load terminal 'b' to B_{11}.

8. Switch on dc supply in the chopper module. Adjust for minimum duty cycle ratio, by varying the control voltage pot and release the gating signal.

9. Observe the load voltage waveform, and measure the load voltage for various duty cycle ratio. The load voltage and current will be negative in this case.

EXPERIMENT E-4: Study of Chopper Circuit with R-L Load

INTRODUCTION:

The choppering frequency, of a chopper with, MOSFET/IGBT, can be relatively High (>2 Khz). With high switching frequency, the voltage and current can be smoothed, with smaller inductance. The current ripple will be very small. This can be understood by studying the operation of the chopper with inductive load. The chopper circuit is shown in Fig.4.1. The operation is explained in section 4.3.

AIM:

i. To study the operation of the chopper with inductive load operating with discontinuous current mode.

ii. To study the operation of the chopper with continuous current mode.

EQUIPMENTS REQUIRED:

i. IGBT/MOSFET Module [ITB-PEC16M2/M3]
ii Chopper Control Module [ITB-PEC16M5]
iii. CRO
iv. R-L load

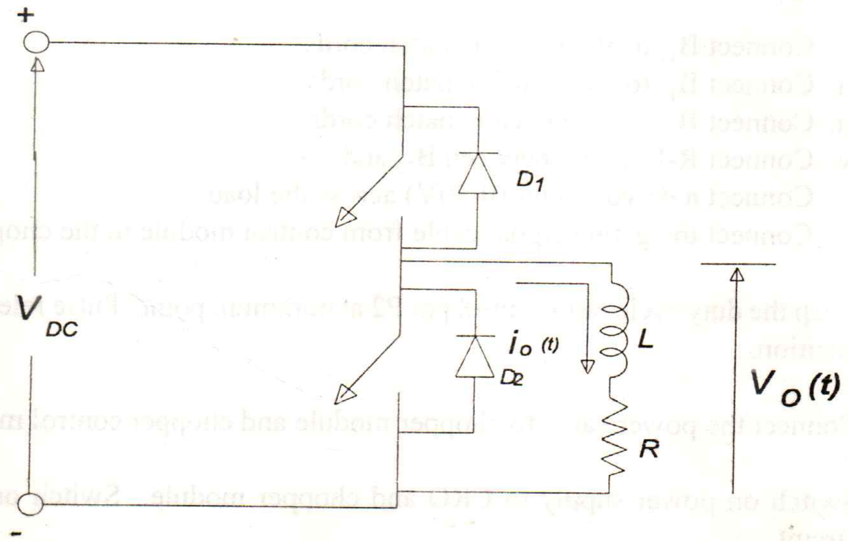


Fig.E.4.1 Chopper circuit with R-L Load.

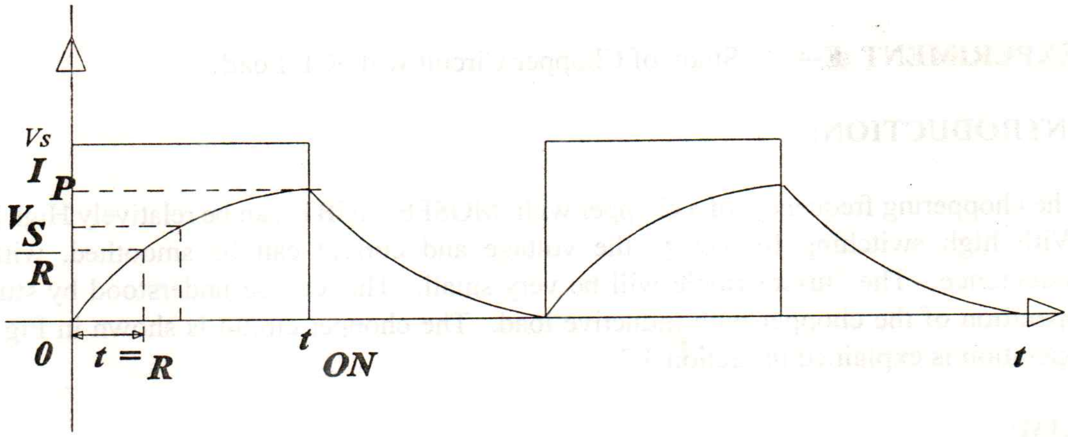


Fig.E.4.2 Voltage and current waveform.

PRECAUTION:

1. Ensure all switches are in the OFF position while doing connection.
2. Ensure pulse release ON/OFF switch is in OFF position, whenever power is switched ON to the chopper module.

PROCEDURE:

1. Referring to the mimic diagram of Fig.2.1 (or 2.2) make the following connections.

   i. Connect B_{11} to V_{+1} by using patch cords.
   ii. Connect B_{12} to B_{21} by using patch cords.
   iii. Connect B_{23} to V_{-1} by using patch cords.
   iv. Connect R-L Load between B_{22} and V-1.
   v. Connect a dc voltmeter (0-30V) across the load.
   vi Connect the gating signal cable from control module to the chopper module.

2. Keep the duty cycle ratio control pot P2 at minimum point. Pulse release switch SW2 in OFF position.
3. Connect the power cable to chopper module and chopper control module.
4. Switch on power supply to CRO and chopper module. Switch on dc supply to chopper circuit.
5. Switch on power supply to the chopper control module. Release the gating signal by switching on SW_4 in Chopper Control Module.

6. Observe the load voltage and load current waveforms through CRO and plot them, on a graph sheet to scale.

7. If necessary adjust the duty cycle ratio or the value of the inductance so that the current is discontinuous. The voltage and current waveforms will be as shown in Fig.E.4.2.

8. Measure t_{on}, the supply voltage level the peak current and the time taken t_τ for the current to reach 63% of final steady state value (V_s/R). The current during on period is governed by the equation

$$i(t) = \frac{V_s}{R}\left(1 - e^{-\frac{t}{\tau}}\right) \qquad (1)$$

where $\tau = L/R$- the time constant of the load circuit
V_s = dc voltage level
R= Load Resistance

The time-taken, for the current to reach 63% of final steady state value is equal to one time constant

$$t_\tau = \tau = \frac{L}{R} \qquad (2)$$

9. Switch off dc supply to the chopper circuit block the gating signals. Remove the load resistance from the circuit and measure its value using a multimeter. The load inductance is then calculated by

$$L = t_\tau \times R. \quad Henry \qquad (3)$$

10. Calculate the current i(t) at the end of on period $t = t_{on}$ using equation (1) and check whether it is equal to the measured value.

11. Repeat the experiment for various duty cycle ratio.

12. Study the current waveform for various carrier frequency. When carrier frequency is increased, the current ripples (Difference between I_2 & I_1) will be less. This is because the chopper on time and off time is less. The current will be smoother even for low value of load inductance.

Table E.4.1 Chopper with R-L Load Discontinuous Current

Sl.No.	D	Vs/R	i_p Measured	i_p Calculated

12. Repeat the experiment for continuous current mode. The voltage and current waveforms for continuous current will be as shown in Fig.E.4.3. Adjust the duty cycle ratio and Load inductance so that the current is continuous as shown in fig.E.4.3.

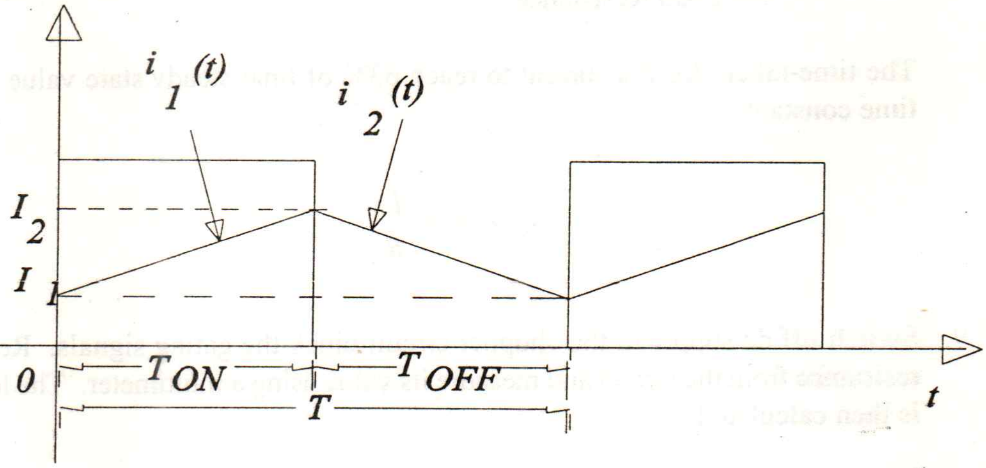


Fig.4.3. Load voltage and Current waveform under continuous current mode.

13. Write down the equations for the current $i_1(t)$ during on period $0 < t \leq t_{on}$, and $i_2(t)$ during off period $t_{ON} < t < T_o$.

14. Observe the load voltage and load current waveforms through CRO.

15. Plot the waveforms on a graph sheet to scale.

16. Measure the values of I_1 and I_2 under steady state condition through CRO. Measure the average dc voltage and current.

17. Measure the value of load resistance and inductance as before.

18. Calculate the values of I_1 and I_2 using equations (4.9) and (4.12) and check with the measured values.

19. Calculate the ripple in current as I_2-I_1 = ΔI_{max} . The average current Ia=≈(I_1+I_2)/2.

20. Compare the calculated values with the measured values of the ripple current and the average value of the load current.

Table E.4.2 R-L Load with continuous current

Sl.No.	D	Measured Values			Calculated Values		
		I_1	I_2	I_a	I_1	I_2	I_a