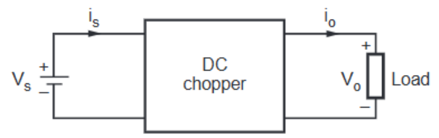
Module-5

DC-DC Converters: *Introduction, principle of step down a chopper with R and RL load; the principle of step up chopper with R load, Control strategies, performance parameters, DC-DC converter classification.*

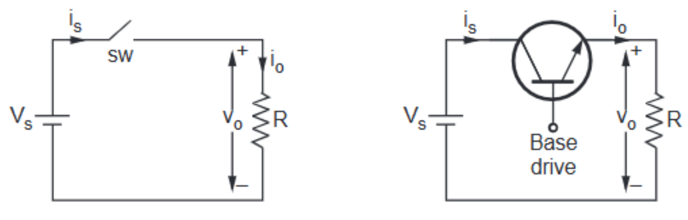
Introduction:

The DC choppers convert the input DC voltage into fixed or variable DC output. The chopper has fixed or variable DC input, Vs. And the output Vo is also fixed or variable. Hence DC chopper is also called as dc to dc converter. The output Vo can be greater or less than the input. Hence the choppers can be step-down or step-up type. Choppers are used in dc traction drives, trolley cars, marine lifts etc. The dc choppers use switching principle. Hence they have high efficiency. The dynamic response of choppers is fast due to switching nature of the devices.



Basic inputs/outputs of DC chopper

Principle of Step-down Operation:



(a) Basic step down chopper

(b) Step - down chopper with transistor as a switch

Fig.1

Fig. 1 shows the circuit diagram of the basic step-down chopper. The switch (sw) can be a power transistor, SCR, GTO, power MOSFET, IGBT or similar switching device. Normally the drop in the switch is very small and it is neglected. Fig. 2 shows the waveforms of the step-down chopper with resistive load.

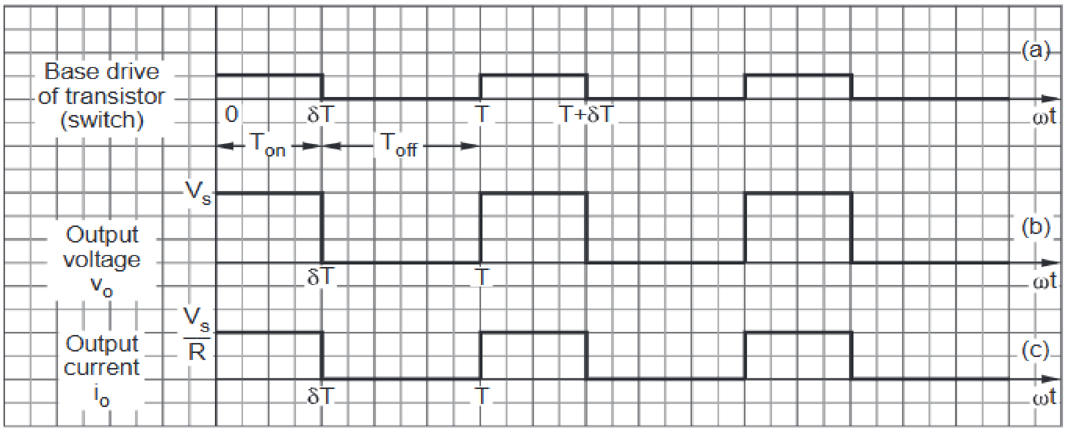


Fig. 2 Waveforms of the step-down chopper with resistive load

Chopper Control Techniques: The chopper can be operated as constant frequency or variable frequency. These are also called as Time Ratio Control (TRC) techniques.

1. Constant frequency operation: The chopper frequency is kept constant. Hence total period T remains constant. T_{on} and T_{off} both are varied to vary the duty cycle. The advantage is that the filter components are easy to design. operation. Shown in fig (a) & (b)

2. Variable frequency operation: The frequency of the chopper varies when duty cycle is to be varied. When Ton is varied Toff is kept constant and vice versa. The filter design is difficult for this type of chopper Ton is kept constant and Toff is varied. This also varies 'T'. Shown in fig (c) & (d)

3. Current limit control: In this type of control, the output current is sensed. When the current exceeds i_O(max), the chopper is turned off; when output current reduces below io(min), the chopper is turned on. Fig. (e) and (f) shows the waveforms for this operation.

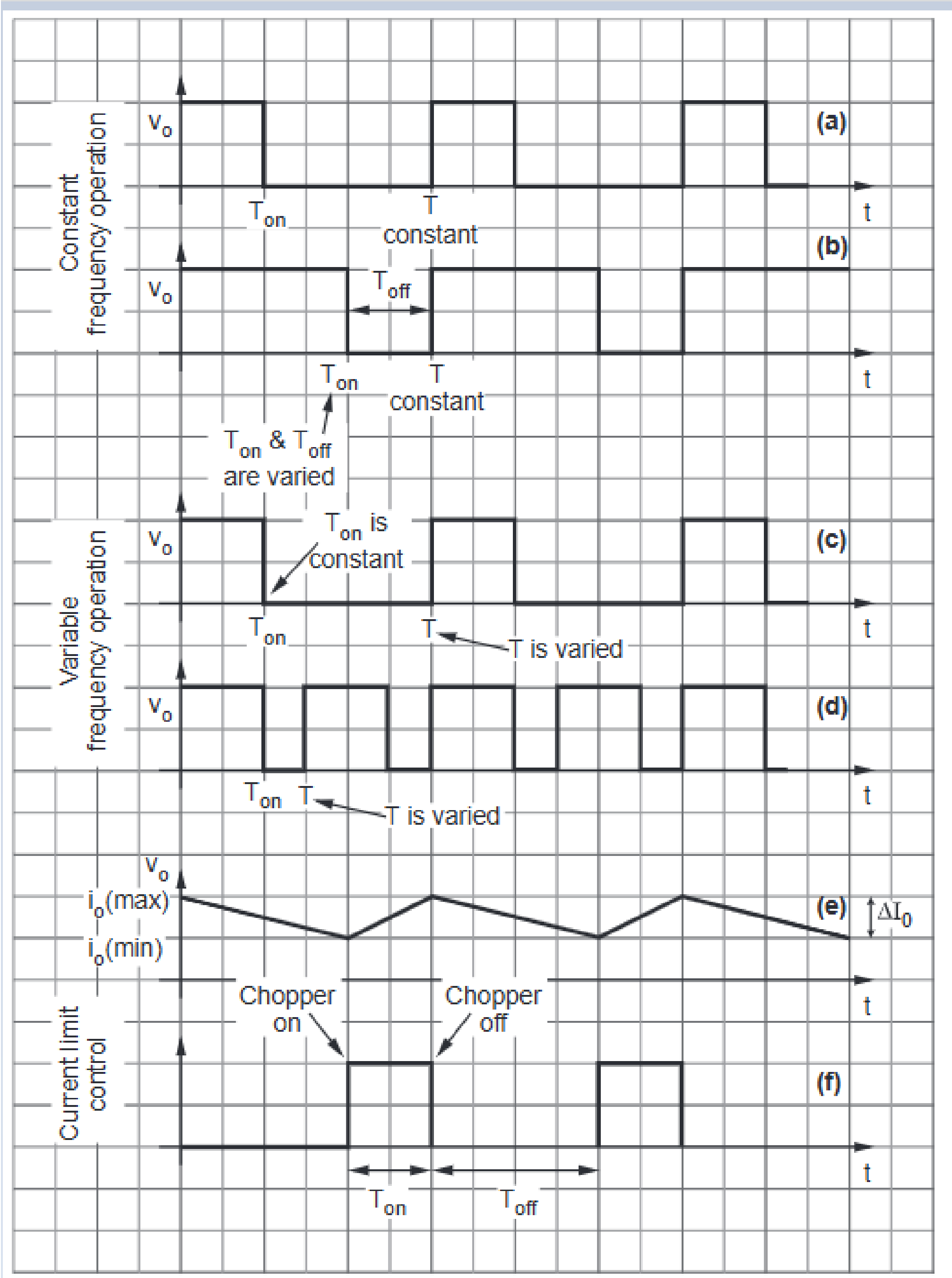


Fig. .3 Chopper control schemes

(i) To obtain $v_{o(av)}$:

The average value is given as,

$$V_{o(av)} = \frac{1}{T}\int_0^T v_o(t)\, dt$$

In the output voltage waveform of Fig. 6.2.2 observe that $v_o = V_s$ from 0 to δT, rest of the time v_o is zero. Hence above equation can be written as,

$$V_{o(av)} = \frac{1}{T}\int_0^{\delta T} V_s\, dt = \frac{V_s}{T}\int_0^{\delta T} dt = \frac{V_s}{T}\cdot \delta T$$

$$\therefore \quad V_{o(av)} = \delta\, V_s$$

Here $\delta = \frac{T_{on}}{T}$ is called the *duty cycle of the chopper. The value of duty cycle lies between* $0 \le \delta \le 1$.

(ii) To obtain $V_{o(r.m.s.)}$

The r.m.s. value of output is given as,

$$V_{o(r.m.s.)} = \left[\frac{1}{T}\int_0^T v_o^2(t)\, dt\right]^{\frac{1}{2}}$$

We know from Fig. 6.2.2 that $v_o = V_s$ from 0 to δT (i.e. when the transistor switch is on). Hence above equation becomes,

$$V_{o(r.m.s.)} = \left[\frac{1}{T}\int_0^{\delta T} V_s^2\, dt\right]^{\frac{1}{2}} = \left[\frac{V_s^2}{T}\int_0^{\delta T} dt\right]^{\frac{1}{2}} = \left[\frac{V_s^2}{T}\cdot \delta T\right]^{\frac{1}{2}}$$

$$\therefore \quad V_{o(r.m.s.)} = \sqrt{\delta}\, V_s$$

Output power

The load power can be calculated as,

$$P_o = \frac{1}{T}\int_0^{\delta T} \frac{v_o^2}{R}\, dt$$

$$= \frac{1}{T}\int_0^{\delta T} \frac{(V_s - V_{ch})^2}{R}$$

$$= \frac{1}{T}\cdot \frac{(V_s - V_{ch})^2}{R}\int_0^{\delta T} dt$$

$$= \frac{1}{T}\cdot \frac{(V_s - V_{ch})^2}{R}\cdot \delta T$$

$$= \frac{\delta (V_s - V_{ch})^2}{R}$$

If the chopper is lossless, then $V_{ch} = 0$ and output power will be,

$$P_o = \frac{\delta V_s^2}{R}$$

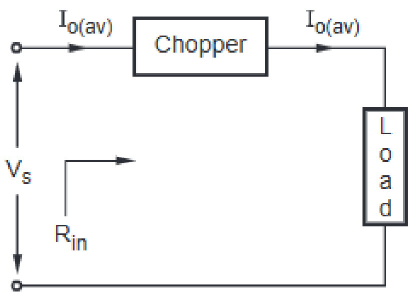


Fig Effective input resistance

(iii) Effective input resistance

Fig. shows that the average current flowing from the input is basically output average current, i.e. $I_{o(av)}$. The input voltage is supply voltage V_s. Hence effective input resistance will be,

$$R_{in} = \frac{V_s}{I_{o(av)}}$$

Putting for $I_{o(av)} = \frac{V_{o(av)}}{R}$ in above equation,

$$R_{in} = \frac{V_s}{\frac{V_{o(av)}}{R}} = R \cdot \frac{V_s}{V_{o(av)}}$$

Since $\delta = \frac{V_{o(av)}}{V_s}$, above equation becomes,

$$R_{in} = \frac{1}{\delta} R$$

Step-down Chopper with RL Load:

Choppers are used to drive the DC motors. These motors are considered as RL (inductive) load. Fig. shows the circuit diagram of step-down chopper having an inductive load.

Transistor is used as a switch. It can be MOSFET, GTO, IGBT or SCR also. Since the load is inductive, freewheeling diode D_{FW} is used in the circuit.

Normally the inductive loads are motors. Hence back emf 'E' is also shown in the circuit diagram as a part of load. Such loads are also called as 'RLE' load.

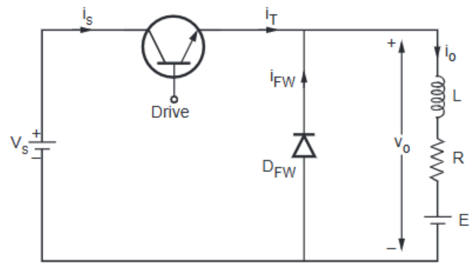
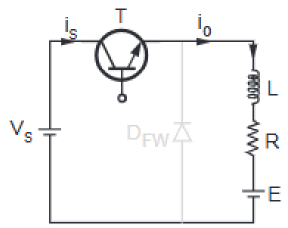
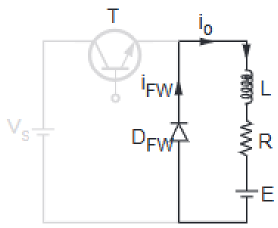


Fig. Step-down chopper with RL load



Equivalent circuit - I

Mode-1



Equivalent circuit - II

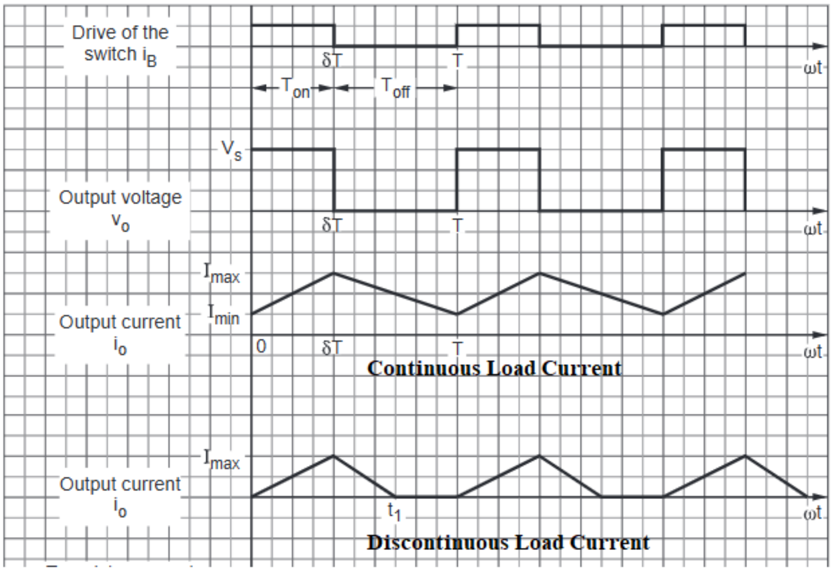
Mode-2

Continuous and Discontinuous current in DC chopper

Continuous Load Current: The output voltage is equal to supply voltage ($v_o = v_s$) when the switch is 'ON'. The output current is assumed continuous. At T, the output current reaches to maximum value I_{max}.

From δT to T the switch is 'OFF'. At δT, the output current is at I_{max}. When the switch is turned off, the load inductance tries to maintain the output current in the same direction. This current flows through the freewheeling diode D_{FW}. The freewheeling diode is forward biased due to load inductance voltage $L\frac{d_{i0}}{d_t}$. Output voltage is zero when freewheeling diode conducts.

Discontinuous Load Current: If the inductance of the load is small then load current may be discontinuous. The load current increases from zero when the switch is tuned 'on'. The current reaches to 'I_{max}' at δT. The switch is turned off at δ T. From δT to T, the switch is 'off'. The freewheeling diode conducts from δT to t_l. At t_1, the load current becomes zero. The load inductance supplies the energy from δT to t_l (i.e. freewheeling). The load current is zero from tl to T. Thus the load current is discontinuous.



Principle of Step-up Operation:

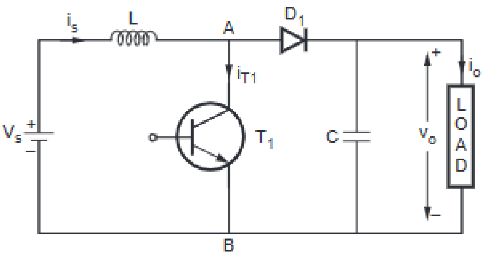
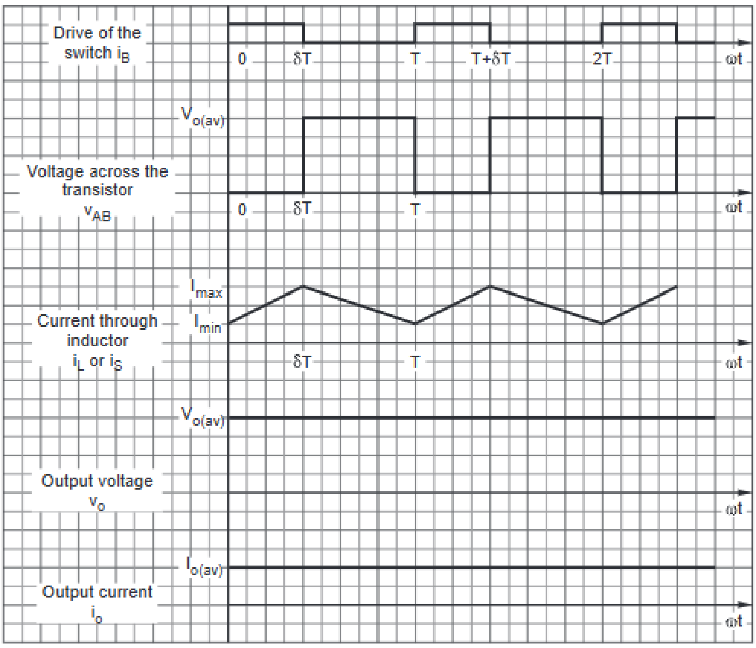
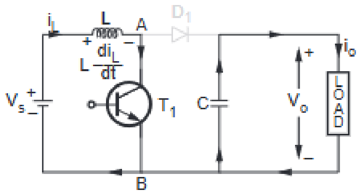


Fig. Step-up chopper having transistor as a switch

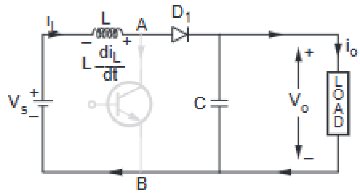


The average value of output voltage $V_{o(av)}$ is always less than or equal to supply voltage Vs in step-up chopper $V_{0(av)} \geq$Vs.

Fig. shows the circuit diagram of the step-up chopper. Observe that there is an inductance in series with the supply Vs. A switch (transistor GTO, MOSFET etc) is connected across inductance and supply. A filter capacitor C is used across the load to make Vo smooth. The diode D_1 the reverse flow of output current when switch is turned 'on'.



Equivalent Circuit - I



Equivalent Circuit - II

The drive of the switch is shown at the beginning. The transistor is turned on from 0 to δT. Hence current flows through the inductance from the supply. The inductance current rises and inductance stores the energy from the supply. The equivalent circuit- in the above Fig. shows this operation, Note that the drop in the inductance is $L\frac{di_L}{dt}$ with the polarity shown. The voltage v_{AB} = O. We have assumed that the output voltage and current are continuous and ripple-free, The capacitor maintains the voltage 'Vo' and supplies the current 'io' when transistor is 'on'. Hence the diode Dl is reverse biased and it not conduct.

At δT transistor (switch) is turned off, Hence the inductance generates a large voltage $L\frac{di_L}{dt}$ to maintain the current i_L in the same direction. Diode Dl is forward biased and it starts conducting. Thus output voltage will be

$$v_o = V_s + L\frac{di_L}{dt}$$

Thus the output voltage Of the chopper is greater than supply voltage Vs. This shows the step-up operation. The voltage induced in the inductance adds to the supply voltage and this total voltage appears as output voltage. The capacitor also charges to this boosted voltage. The inductance as well as supply provides the energy to the load from δT to T (i.e. when the switch is off). The current through the inductance decreases because its stored energy goes on reducing. At T, the transistor is again turned on and the cycle repeats.

Derive an expression for average output voltage Of the step-up chopper.

Let the average voltage across the inductance be V_L. The value of this voltage over one cycle (0 to T) will be,

$$V_L = \frac{1}{T}\int_0^T v_L(t)\,dt$$

The inductance voltage is $v_L(t) = L\frac{di_L}{dt}$. Hence above equation will be,

$$V_L = \frac{1}{T}\int_0^T L\frac{di_L(t)}{dt}\,dt$$

$$= \frac{L}{T}\int_0^T di_L(t) \qquad \text{... } \mathbf{(1)}$$

The above integration is with respect to inductance current $di_L(t)$, hence we should change the limits appropriately.

At $t=0$ (lower limit), $i_L(t) = I_{\min}$

and at $t=T$ (upper limit), $i_L(t) = I_{\min}$

Hence equation 6.4.1 will be,

$$V_l = \frac{L}{T}\int_{I_{min}}^{I_{min}} d\, i_L(t) = \frac{L}{T}\left[i_L(t)\right]_{I_{min}}^{I_{min}}$$

$$= \frac{L}{T}\left[I_{min} - I_{min}\right] = 0 \qquad \text{... (2)}$$

Thus the average voltage across the inductance is zero. The inductance stores the energy when the switch is 'ON' and supplies the energy to the load when the switch is 'OFF'.

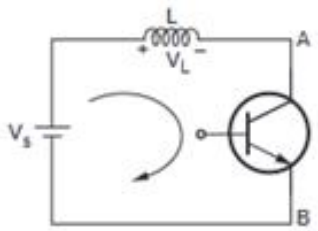


Fig. Loop formed by supply, inductance and switch in step-up chopper

Now let us consider the loop formed by supply voltage V_s, inductance and switch. This loop is shown in Fig. 6.4.3. The voltage across the switch is v_{AB}. The waveform of v_{AB} is shown in Fig. 6.4.2. The average value of v_{AB} can be obtained as follows :

$$V_{AB} = \frac{1}{T}\int_0^T v_{AB}(t)\, dt$$

In Fig. observe that $v_{AB} = V_{o(av)}$ from δT to T and rest of the period it is zero. Hence above equation becomes,

$$V_{AB} = \frac{1}{T}\int_{\delta T}^{T} V_{o(av)}\, dt = \frac{V_{o(av)}}{T}(T - \delta T)$$

$$= V_{o(av)}(1-\delta) \qquad \cdots (3)$$

By KVL to the loop shown in Fig.

$$V_s = V_L + V_{AB}$$

The above equation holds for steady state. Putting values from equation 2 and 3 in above equation,

$$V_s = 0 + V_{o(av)}(1-\delta)$$

$$\therefore \quad V_{o(av)} = \frac{V_s}{1-\delta} \qquad \cdots (4)$$

This equation gives the value of average output voltage. When $\delta = 0$, $V_{o(av)} = V_s$ and $V_{o(av)} \to \infty$ as δ approaches to unity. The value of duty cycle 'δ' lies between 0 and 1.

Performance Parameters:

The choppers are used for speed control of dc motors. The performance of choppers is affected by many parameters. These parameters are listed below.

1. **Duty cycle δ :** The duty cycle of the chopper controls its output voltage. The value of duty cycle lies between and 1. Normally the duty cycle of the chopper is varied smoothly in case of inductive loads.

2. Operating speeds Of switch (devices) : The operating speed Of the devices used in the chopper depends upon turn on and turn Off times. MOSFETs have very small turn-off and turn-on times. Hence MOSFETs operate at very high speeds (i.e. up to 1 MHz). SCRs have very small speeds since their turn-on and turn-off times are longer. The switching frequency of the chopper depends upon the speed of the device.
3. **Frequency of the chopper (f) :** The frequency of the chopper is $f = \frac{1}{T}$, where T is the period of output voltage waveform. As the switching frequency is increased, the ripple frequency of vo and io also increases. Hence the cost and size of filtering components L and C is reduced. The output current tends to become continuous at high switching frequencies. Due to high switching harmonics in the output are also reduced.

DC-DC Converter Classification:

The choppers are classified depending upon the directions of current and voltage flows. These choppers operate in different quadrants of v_o —i_o plane,

There are broadly following types of choppers :

1. Class A chopper
2. Class B chopper
3. Class C chopper
4. Class D chopper
5. Class E chopper

Class A Chopper:

The class A chopper operates in the first quadrant of v_o —i_o plane as shown in Fig. The output current and output voltage both are positive. These values never go negative. This type of chopper operates as the rectifier. The energy always flows from source to the load. Hence it is also called as forward motoring. The step-down chopper is basically class A chopper.

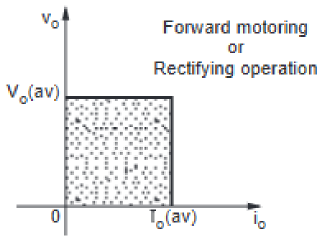


Fig. Class A chopper operates in the first quadrant

Class B Chopper:

The class B chopper operates in the second quadrant of the v_o —i_o plane as shown in Fig. The load voltage is positive and load current is negative. The load current flows out of the load. Since the current flows from load to the source, the energy is transferred from load to the source. This is also called as inverting operation. Such situation occurs during the braking of dc motor. The energy associated with back e.m.f. of the motor is fed back to the source. Hence current becomes negative, Since motor rotates in the same direction, it is called forward regenerative braking. 'Ihe word regeneration means energy is fed from load to the source during braking.

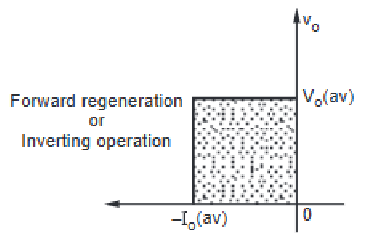


Fig. Class B chopper operates in the second quadrant

In the above circuit, the supply voltage is Vs. The Dl allows the current flow only from load to the source. Here motor load is assumed. L and R are the inductance and resistance of the motor. E_b is the back e.m.f. of the motor. Here note that E_b is responsible for negative current flow.

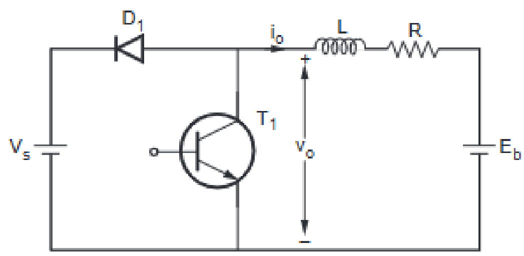
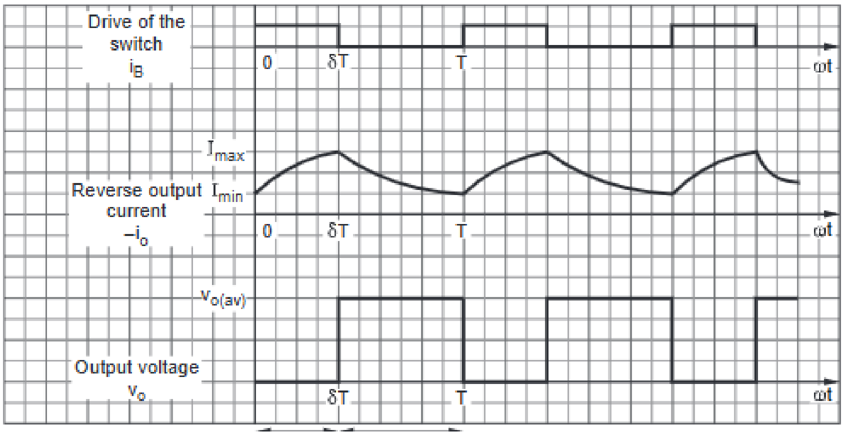


Fig. Circuit diagram of class B chopper

When the transistor (i.e. switch) is turned on, the negative current flows from E_b, R,L and T_1. This current keeps on increasing, The waveforms are shown in Fig. The switch is 'on' from 0 to δT. The current i_o flows through E_b, R,L and switch in negative direction. From equivalent circuit the current rises to and reaches to I_{max} at δt. The inductance stores energy during this period. The energy is supplied by back emf E_b. At δt, the switch is turned off. The diode D_1 is forward biased and the negative output current flows through supply V_S. The output voltage is equal to $V_{o(av)}$. The current is forced through supply voltage V_s. Thus supply voltage consumes power. This power is transferred from load inductance and E_b. At T, the switch is turned on again and the cycle repeats.



Class C Chopper:

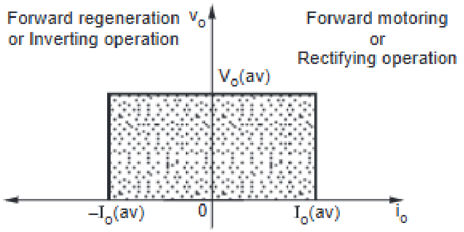


Fig. Class C chopper operates in two quadrants

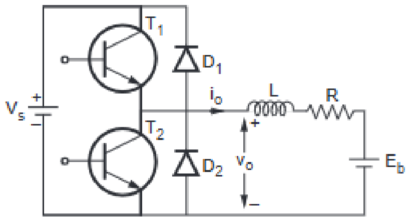


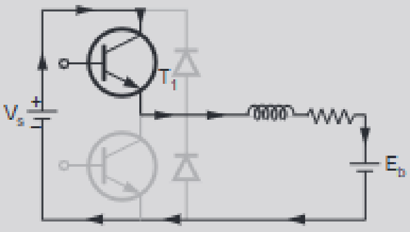
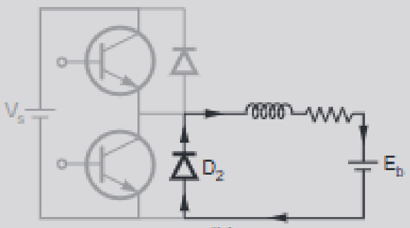
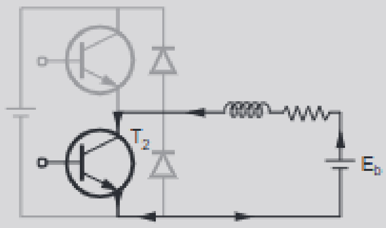
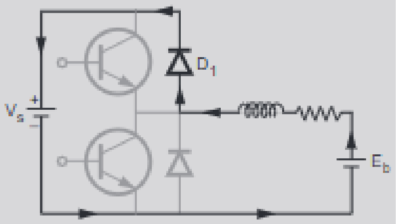
Fig. Class C chopper

The class C chopper operates in two quadrants. It is the combination of class A and B choppers. Fig.shows the quadrants of operation of this chopper. It operates as a rectifier as well as invertor. In the first quadrant forward motoring takes place and in the second quadrant forward regenerative braking takes place.

Fig, shows the circuit diagram of class C chopper having transistor switches. It is basically obtained by combining class A and B choppers. T_1 and D_2 conducts for the operation in the first quadrant (i.e. Class A). In the above circuit diagram, note that whenever T_1 or D_2 conduct, the output current and voltage will be always positive.

Whenever T2 or D1 conduct, the chopper operates in the second quadrant (i.e. Class B). It is inverting operation. In Fig output Current is negative whenever T_2 or D_1 conduct. The energy is fed back to the supply when D_1 conducts. Note that v_0 always remains positive.

Table shows the various equivalent circuits showing operation of this chopper.

Equivalent circuit	Quadrant	Description
 (a)	I Forward motoring or rectifying	T_1 conducts and energy flows from source to load. v_o and i_o are positive.
 (b)	I Forward motoring or rectifying	D_2 conducts i_o is positive and v_o is zero. Freewheeling takes place. Inductance supplies energy to the load.
 (c)	II Forward regenerative braking	T_2 conducts i_o is negative. E_b supplies energy to the Inductance v_o is zero.
 (d)	II Forward regenerative braking or inverting	D_1 conducts inductance supplies energy to the source v_o is positive and i_o is negative.

Class D Chopper:

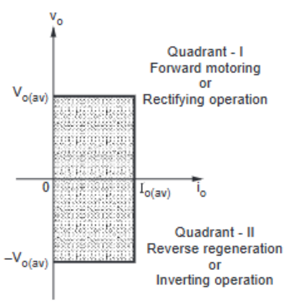


Fig. Class D chopper operates in I and IV quadrants

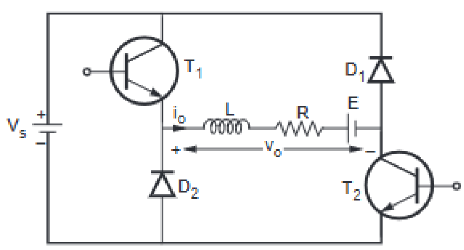


Fig. Class D chopper

The class D chopper also operates in two quadrants. The output current is always positive. The output voltage can be positive or negative. When v_o and i_o both are positive, the rectifying operation takes place. It is also called forward motoring. When the voltage is reversed, the inverting operation takes place. The energy is fed from load to the source. The IVth quadrant operation is also called reverse regeneration.

Fig. shows the circuit diagram Of class D chopper having transistor switches. When Tl and T 2 are conducting, output current and output voltage both are positive. Power is taken from the source and given to the load. This is operation in the first quadrant, i.e. rectifying, When Tl and T2 are switched off, the load inductance generates the large voltage to maintain the current in the same direction. The inductance voltage forward biases diodes Dl and D2, This situation is shown in below table The diodes conduct and supply energy from load to the source. The output voltage is negative. Hence chopper operates in IVth quadrant.

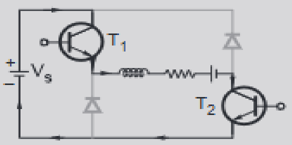
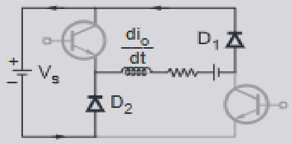
Equivalent circuit	Quadrant	Description
	I Rectifying or forward motoring	T_1, T_2 conduct power flows from source to the load
	IV Inverting or reverse regenerative braking	i_o is maintained in the same direction by inductance voltage $L\frac{di_o}{dt}$. Diodes D_1 and D_2 are forward biased and conduct.

Table Operation of class D chopper

Class E Chopper:

Class E is a four quadrant chopper. It operates in the four quadrants of $v_o - i_o$ in as shown in Fig. The output current as well as voltage both can take positive or negative values. The first quadrant is forward motoring. The output voltage and current both are positive. The IIIrd quadrant is reverse motoring. This means the motor rotates in the opposite direction compared to first quadrant, Since the power flows from source to the load in IIIrd quadrant, it is called rectifying operation. In II nd and IVth quadrant, the power flows from load to the source hence it is called an inverting operation.

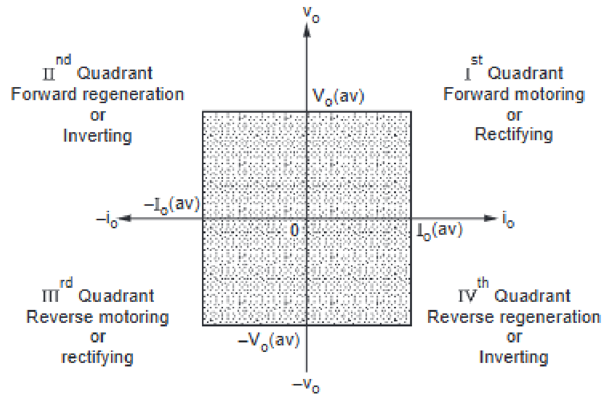


Fig. Four quadrant operation

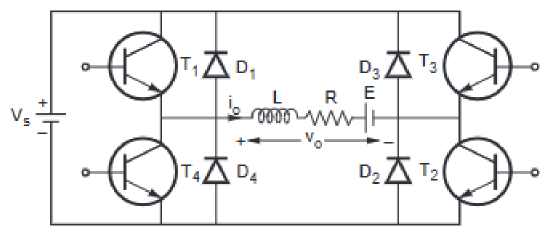
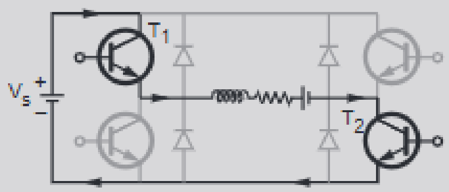
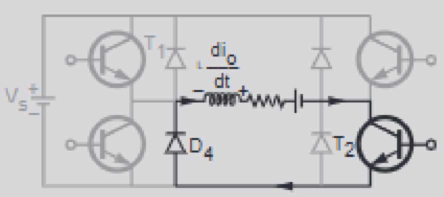
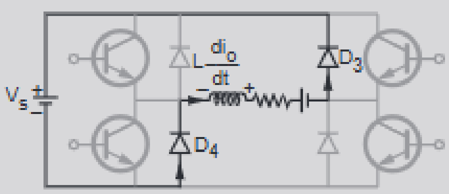
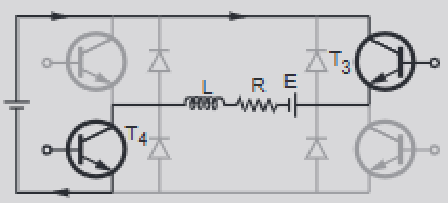
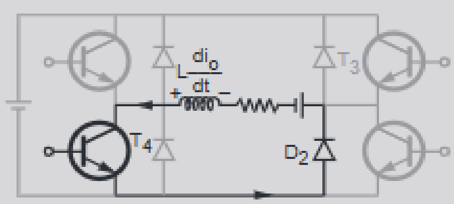
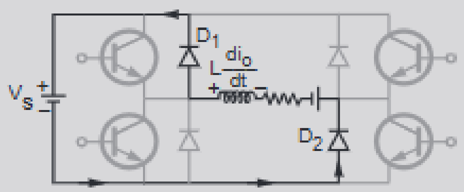


Fig. Circuit diagram of four quadrant chopper

Fib shows the circuit diagram of the four quadrant chopper having transistor switches. Whenever Tl and T2 conducts the chopper operates in the 1st quadrant. v_o and i_o both are positive. When T 3 and T4 conduct v_o and i_o both are negative. The chopper operates in the third quadrant. Table shows the operation of this chopper with equivalent circuits.

Equivalent circuit	Quadrant	Description
	I Forward motoring or rectifying	T_1 and T_2 conducts load consumes the power from the source
	I Forward motoring	T_1 turned off but T_2 conducts Hence current i_o flows through T_2 and D_4. Load inductor induces voltage as shown freewheeling action takes place.
	IV Inverting operation i_o positive v_o negative.	T_2 is turned off. Hence inductance forces current through D_3 and D_4. This current flows through supply. load energy is fed to the supply.
	III Rectifying operation motor rotates in opposite direction	To reverse the direction of rotation of the motor, T_3 and T_4 are turned on. v_o and i_o both are negative. E is shown negative since motor rotates in opposite direction.
	III Freewheeling operation motor rotates in the same direction.	T_3 is turned off, but T_4 remains on. To maintain the current in the same direction inductance generates voltage and i_o flows in same direction through D_2 and T_4. This is freewheeling action.
	II Inverting operation i_o negative v_o positive	T_4 is turned off. Hence inductance forces current through D_1 and D_2. This current flows through supply. Load energy is fed to the supply.

DC – AC Converter

DC-AC Converters: *Introduction, principle of operation single phase bridge inverters, performance parameters, three phase bridge inverters, voltage control of single phase inverters, Harmonic reductions, Current source inverters*

Introduction: Inverters are devices that convert DC to AC and are commonly powered by batteries or controlled rectifiers. They are used in applications like induction motor drives, UPS, standby power supplies, and induction heating. The output voltage waveform can be a square wave, quasi-square wave, or low-distorted sine wave. The voltage can be controlled via switches, with Pulse Width Modulation (PWM) being a common technique for controlling the output. These are known as PWM inverters. Non-sinusoidal output contains harmonics, which can be reduced with proper control schemes.

Inverters can be categorized into:

1. Voltage Source Inverters (VSI) or Voltage Fed Inverters (VFI) – where the input DC voltage remains constant.
2. Current Source Inverters (CSI) or Current Fed Inverters (CFI) – where the input current is constant.

Some inverters feature a controlled DC input voltage, known as Variable DC Link Inverters, which allows adjustment of the output. Inverters can produce either single-phase or three-phase output.

Single Phase Bridge Inverter:

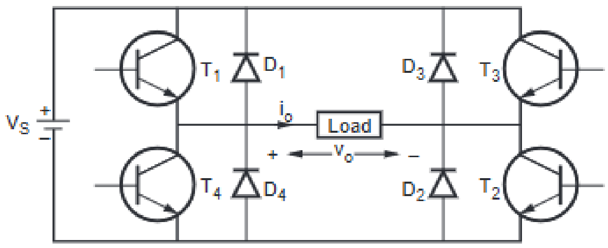
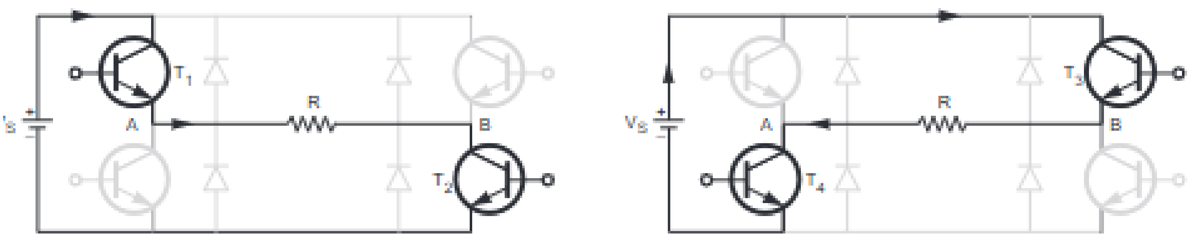


Fig. Single phase bridge inverter

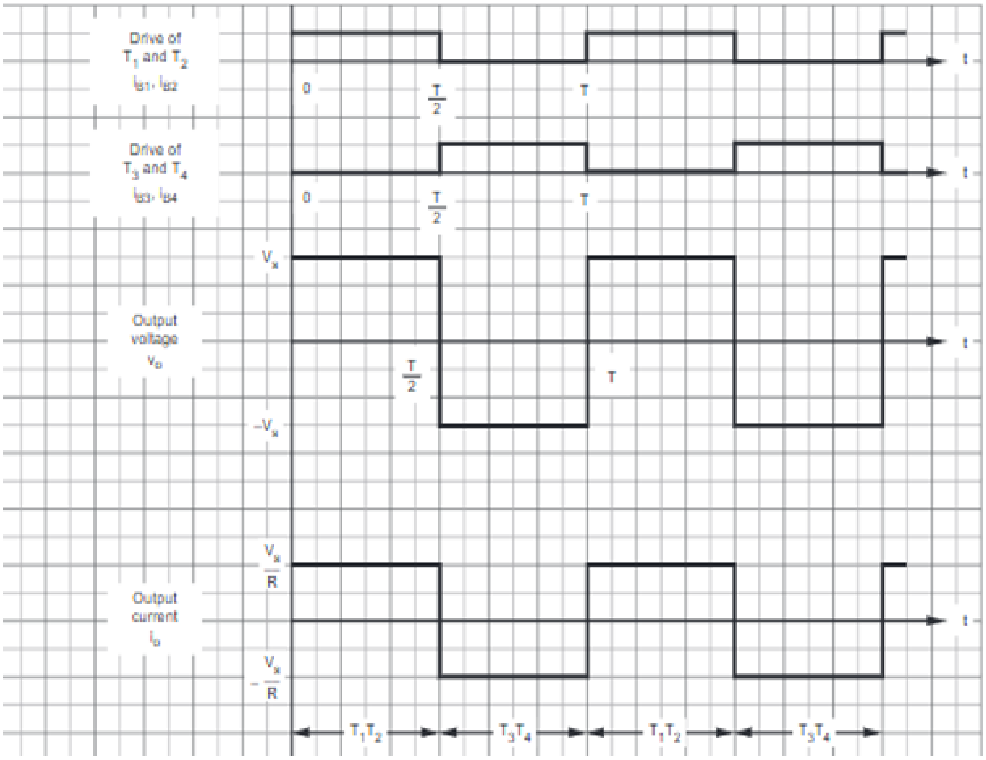
Fig. shows the circuit diagram of the full bridge inverter. Observe that there are four transistors and four diodes. The diodes are required for feedback when the load is inductive.



Equivalent Circuit - I

Equivalent Circuit - II

At $\frac{T}{2}$ transistors Tl and T2 are turned off, and Transistors T 3 and T' conduct from $\frac{T}{2}$ to T. Equivalent circuit-II shows the current path. Note that the output current is negative. The voltage is also negative, Thus in positive half cycle, Tl and T2 conduct. And in negative half cycle, T 3 and T4 conduct. The amplitude of the output voltage is ± Vs. The output is the square wave. The currents through transistors are also shown in the Fig.



Operation with Inductive load: Consider the operation of 1 bridge inverter with inductive (R-L) load. Fig. shows the circuit diagram of bridge inverter having RL load. The waveforms of this circuit are shown in Fig.

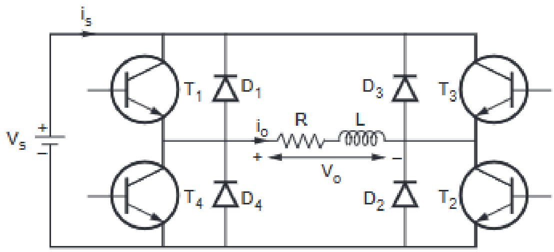


Fig. 1ϕ bridge inverter having inductive load

Mode - I (Tl , T2 conducts):

Tl and T2 are applied the drive at t —O. But they do not conduct till h. Diodes Dl and D2 conduct from 0 to t1

Hence Tl and T2 are reverse biased and they do not conduct. From tl to T/2

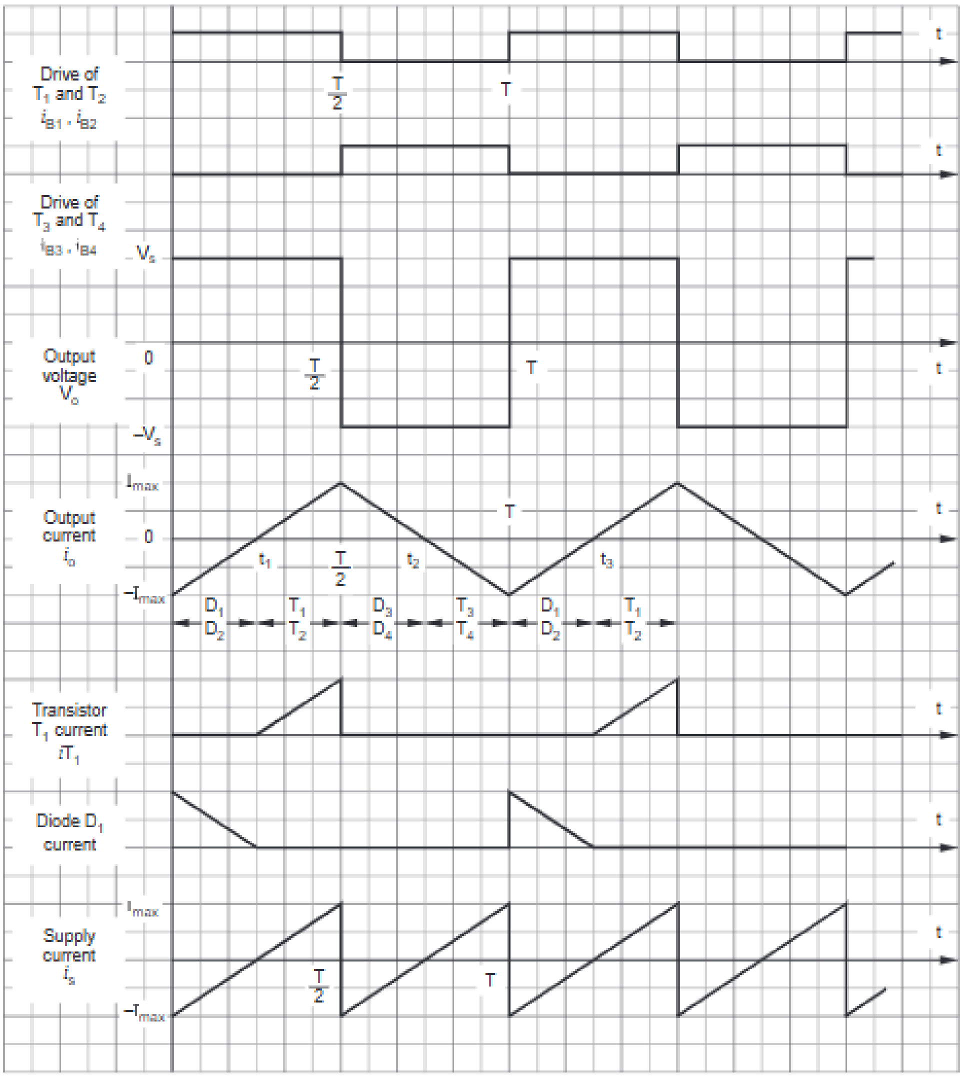


Fig. 7.4.4 Waveforms of bridge inverter for inductive load

Mode - I (T_1, T_2 conducts)

T_1 and T_2 are applied the drive at $t = 0$. But they does not conduct till t_1. Diodes D_1 and D_2 conduct from 0 to t_1.

Hence T_1 and T_2 are reverse biased and they do not conduct. From t_1 to $\frac{T}{2}$, T_1 and T_2 conduct. The equivalent circuit is shown in Fig. 7.4.5. The load current is positive and it increases from zero to $+ I_{max}$. The output voltage is also positive.

Refer Fig. 7.4.5 on next page.

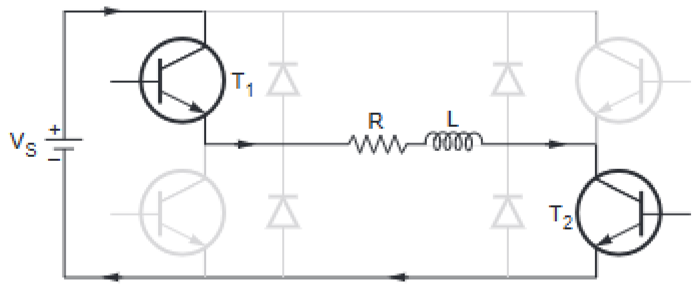


Fig. 7.4.5 T_1 **and** T_2 **conduct from** t_1 **to** $\frac{T}{2}$

Mode - II (D_3 and D_4 conducts)

At $\frac{T}{2}$, transistors T_1 and T_2 are turned off and T_3, T_4 are applied drives. The load inductance generates the large voltage $L\frac{di_o}{dt}$ with polarities shown in Fig. 7.4.6. The diodes D_3 and D_4 are forward biased due to inductance voltage. These diodes conduct and output current flows through DC supply. The energy stored in the load inductance is supplied to the DC supply. This operation is called *feedback operation*. Note that the supply current i_s is negative when diodes D_3, D_4 are conducting. Due to conduction of D_3 and D_4, transistors T_3 and T_4 are reverse biased. Hence they do not conduct, even though base drives are applied. At t_2, the load current becomes zero. Hence transistors T_3 and T_4 start conducting.

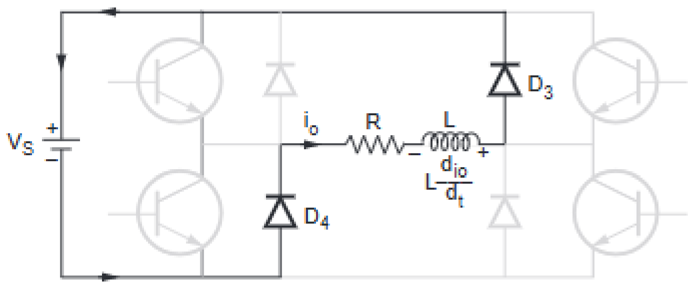


Fig. 7.4.6 D_3 **and** D_4 **conduct from** $\frac{T}{2}$ **to** t_2

Mode - III (T_3 and T_4 conduct)

At t_2 the transistors T_3 and T_4 start conducting. Fig. 7.4.7 shows the equivalent circuit for this operation. The output current is negative and increases towards $-I_{max}$. The supply current i_s is positive. The output voltage is negative during this period.

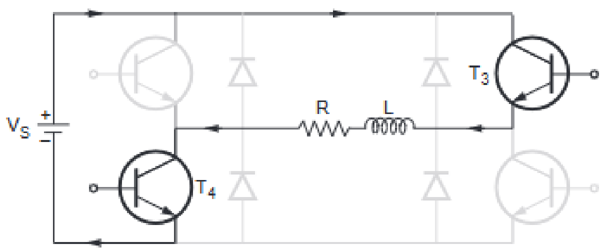


Fig. 7.4.7 T_3 **and** T_4 **conduct from** t_2 **to T**

Mode - IV (D_1 and D_2 conduct from T to t_3 i.e. from 0 to t_1)

At T, transistors T_3 and T_4 are turned off and T_1, T_2 are applied the drive. The output current is at $-I_{max}$. Hence load inductance generates the large voltage $L\frac{di_o}{dt}$ with polarities as shown in Fig. 7.4.8. Due to this voltage the diodes D_1 and D_2 are forward biased. Hence they start conducting. The output current flows through the DC supply and it goes on decreasing. The energy stored in the load inductance is supplied to the DC supply during this period. This is called feedback operation. Transistors T_1 and T_2 are reverse biased due to conduction of D_1 and D_2. Hence T_1 and T_2 do not conduct even if their base drive is applied. At t_3 (i.e. at t_1), the output current becomes zero. Hence T_1 and T_2 start conducting. The output current becomes positive. This is beginning of mode - I discussed earlier. Then the cycle repeats.

The load energy is fedback to DC supply whenever diodes conduct. The supply current is negative. And energy flows from supply to the load whenever transistors conduct. The supply current is positive when transistors conduct. The output voltage waveform is square wave having amplitudes of $\pm V_s$.

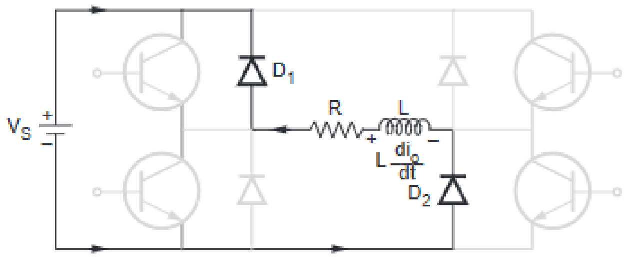


Fig. 7.4.8 D_1 and D_2 conduct from 0 to t_1 i.e. from T to t_3

7.4.3 Advantages and Disadvantages of Full Bridge Inverter

Advantages of full bridge inverter

i) Output voltage is equal to DC source voltage.

ii) Only one DC source is required.

Disadvantages of full bridge inverter

i) Four power devices are required.

ii) Device reverse voltage is equal to DC voltage.

Three Phase Inverters:

Single phase inverters are used for low power applications. For higher powers and 3ϕ induction motor drives, 3ϕ inverters are used. An inverter generates 3ϕ output R,Y and B. The load can be connected to the inverter in star or delta mode. Fig. 7.5.1 shows the circuit diagram of a 3ϕ inverter which uses BJTs.

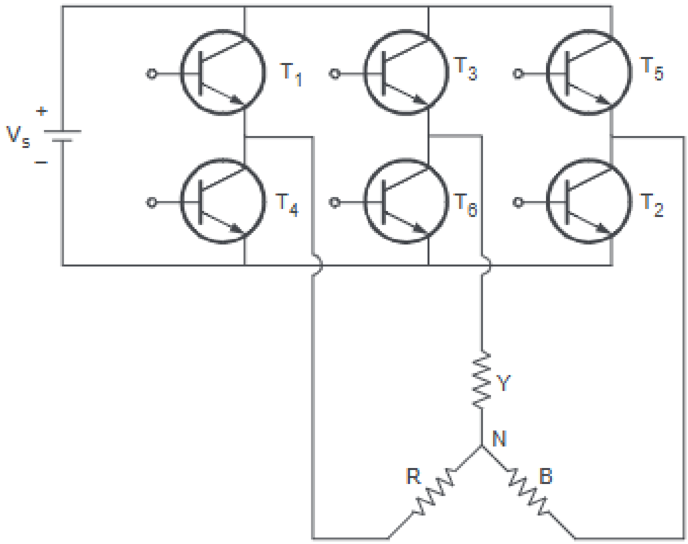


Fig. 7.5.1 Circuit diagram of 3ϕ bridge inverter with star load

As shown in above circuit, there are six BJTs, T_1, T_2, T_3, T_4, T_5 and T_6. Observe that the upper three BJTs are numbered as, T_1, T_3 and T_5. Similarly lower three BJTs are numbered as T_4, T_6 and T_2. Here T_1 and T_4 are connected to phase R. When T_1 conducts, R is connected to $+V_s$. When T_4 conducts, R is connected to $-V_s$. Similarly T_3 and T_6 are connected to y. And T_5 and T_2 are connected to B.

Depending upon the drives applied to BJTs, there are two types of 3ϕ inverters :

i) 180° conduction and

ii) 120° conduction

In 180°, each BJT conducts for 180°, and in 120°, each BJT conducts for 120°.

7.5.1 180° Conduction Type 3ϕ Inverter

The circuit diagram of Fig. 7.5.1 remains the same. The base drives of all the six BJTs are shown in Fig. 7.5.3. The base drive of T_1 is applied for 180° and it is off for remaining 180°. Base drive of T_2 is applied with 60° delay with respect to T_1. Similarly base drives of other transistors are also delayed by 60° with respect to previous one. One cycle of 360° is divided into six intervals of 60° each. These intervals are named as I, II III, IV, V and VI. In each interval three transistors conduct. For example in interval I, T_1, T_5 and T_6 are applied the base drive. Thus in interval I, T_1, T_5 and T_6 are conducting. Fig. 7.5.2 shows an equivalent circuit for this interval. Normally the drop in BJTs can be neglected.

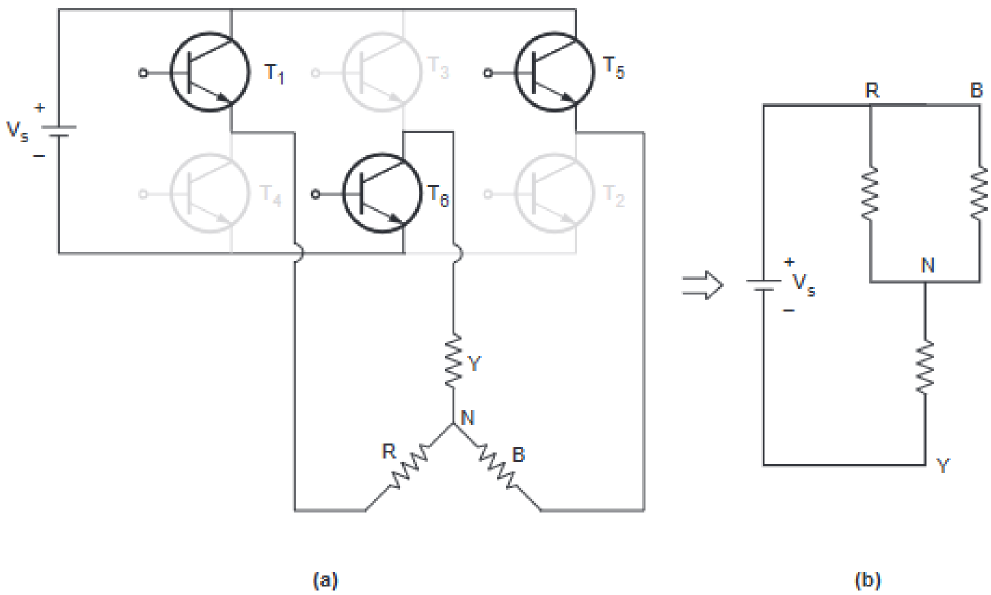


Fig. 7.5.2 Equivalent circuit for T_1, T_6, T_5 conduction

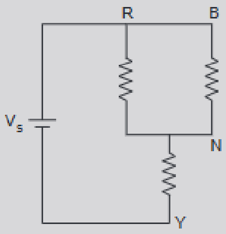
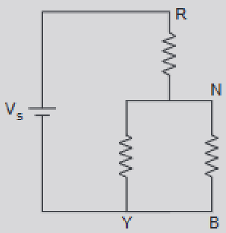
The simplified equivalent circuit is shown in Fig. 7.5.2 (b). Observe that 'R' is connected to $+V_s$ through T_1 and 'B' is connected to $+V_s$ through T_5. Similarly 'Y' is connected to $-V_s$ through T_6. Now the phase and line voltages can be easily evaluated i.e.,

$$V_{RY} = V_s$$

$$V_{RN} = V_{BN} = \frac{V_s}{3}$$

$$V_{YN} = -\frac{2V_s}{3}$$

Here it is assumed that all the phases of load have same resistance. This procedure is repeated for all the 6 intervals and shown in table 7.5.1.

Interval	Conducting transistors	Equivalent circuit	Line voltage V_{RY}	Phase voltage, V_{RN}
I	5 6 1		V_s	$\frac{V_s}{3}$
II	6 1 2		V_s	$\frac{2V_s}{3}$

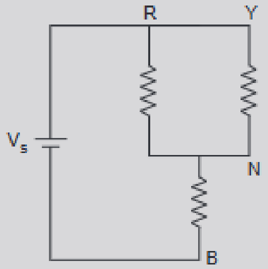
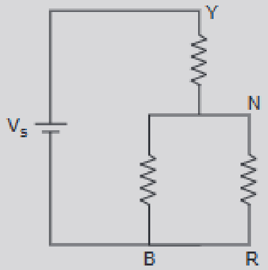
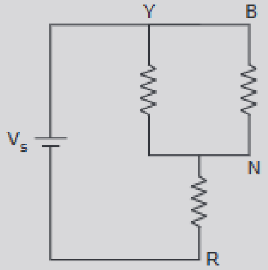
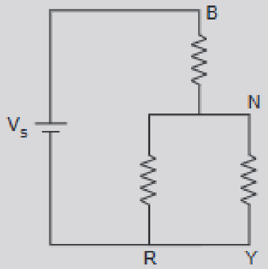
III	1 2 3		0	$\frac{V_s}{3}$
IV	2 3 4		$-V_s$	$-\frac{V_s}{3}$
V	3 4 5		$-V_s$	$-\frac{2V_s}{3}$
VI	4 5 6		0	$-\frac{V_s}{3}$

Table 7.5.1 Analysis of 3 ϕ inverter (180° conduction)

Based on analysis given in table 7.5.1, the waveforms are drawn in Fig. 7.5.3. Waveforms in Fig. 7.5.3 (a) are base drives of all the six BJTs. Observe that the successive base drives of delayed by 60°. Fig. 7.5.3 (b) shows the load voltage V_{RY}. It has maximum value of $\pm V_s$. It is quasi square wave. Voltages of other lines will be 60° delayed with respect to V_{RY}. All line voltages will have similar waveforms.

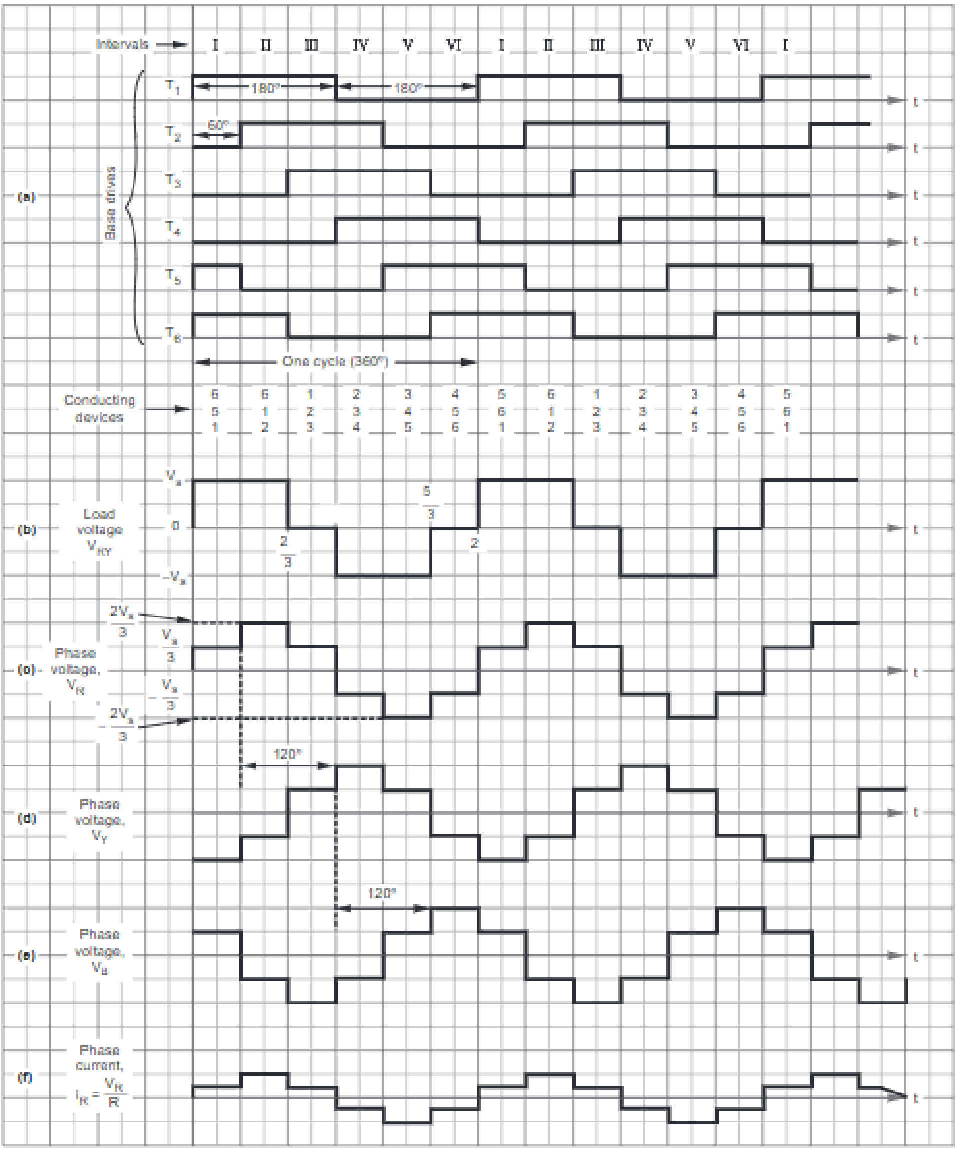


Fig. 7.5.3 Waveforms of 180° mode inverter

Fig. 7.5.3 (c) shows phase voltage V_{RN}. It is six step waveform. Its values are $\pm \frac{2V_s}{3}$. The phase voltage V_Y and V_B are also similar to V_R. They have 120° phase shift with respect to each other. For example V_Y is lagging by 120° with respect to V_R. Thus the three phase AC output is generated by the inverter. For resistive loads, the phase current will be similar to phase voltage. Fig. 7.5.3 (f) shows current waveform for 'R' phase.

7.5.1.1 Mathematical Analysis of Waveforms

The line voltage is quasi square wave. It's r.m.s. value can be obtained as,

$$V_{line(rms)} = \left[\frac{1}{2\pi}\int_0^{2\pi} V_{RY}^2 \, d\,\omega t\right]^{\frac{1}{2}}$$

From waveforms of Fig. 7.5.3 (b),

$$V_{line(rms)} = \left\{\frac{1}{2\pi}\left[\int_0^{\frac{2\pi}{3}} V_s^2 d\,\omega t + \int_{\pi}^{\frac{5\pi}{3}} V_s^2 d\,\omega t\right]\right\}^{\frac{1}{2}}$$

$$= \left\{\frac{1}{2\pi} V_s^2\left[\left(\frac{2\pi}{3} - 0\right) + \left(\frac{5\pi}{3} - \pi\right)\right]\right\}^{\frac{1}{2}}$$

$$\therefore \quad \boxed{V_{line(rms)} = V_s\sqrt{\frac{2}{3}}} \quad \ldots (7.5.1)$$

This equation is applicable to all the six line voltages. Now rms value of phase can be obtained by,

$$V_{ph(rms)} = \frac{V_{line(rms)}}{\sqrt{3}}$$

$$\therefore \quad \boxed{V_{ph(rms)} = \frac{\sqrt{2}}{3} V_s} \quad \ldots (7.5.2)$$

This equation is applicable to all the three phase voltages.

The line voltage V_{RY} is quasi square wave. It can be expressed by Fourier series. i.e,

$$v_{RY} = \sum_{n=1,3,5\ldots}^{\infty} \frac{4V_s}{n\pi}\cos\frac{n\pi}{6}\sin n\left(\omega t + \frac{\pi}{6}\right) \quad \ldots (7.5.3)$$

Similarly other line voltages can be expressed by Fourier series. Only they will be phase shifted. Above equation shows that line voltage contains only odd harmonics. The fundamental component of line voltage can be obtained by putting n = 1 in above equation i.e.,

$$v_1 = \frac{4V_s}{\pi}\cos\frac{\pi}{6}\sin\left(\omega t + \frac{\pi}{6}\right) \quad \ldots (7.5.4)$$

$$= \frac{4V_s}{\pi}\cdot\frac{\sqrt{3}}{2}\sin\left(\omega t + \frac{\pi}{6}\right)$$

$$= \frac{2\sqrt{3}V_s}{\pi}\sin\left(\omega t + \frac{\pi}{6}\right) \quad \ldots (7.5.5)$$

Thus fundamental component of line voltage is sine wave with phase shift of $\frac{\pi}{6}$. Its peak value is $\frac{2\sqrt{3}V_s}{\pi}$. Hence r.m.s. value of fundamental component is,

$$V_{1(rms)} = \frac{V_{1(peak)}}{\sqrt{2}}$$

$$= \frac{2\sqrt{3}V_s}{\pi}\cdot\frac{1}{\sqrt{2}}$$

$$\therefore \quad \boxed{V_{1(rms)} = 0.7797\ V_s} \quad \ldots (7.5.6)$$

2q

7.6 Voltage Control of Single Phase Inverters

June/July-11, Jan.-10, July/.Aug.-09

The output voltage of the inverter needs to be varied as per load requirement. Whenever the input DC varies, the output voltage can change. Hence these variations needs to be compensated. In case of motor drives the ratio of voltage to frequency $\left(\frac{V}{f}\right)$ is maintained constant. The output voltage and frequency of the inverter is adjusted to keep $\frac{v}{f}$ constant. Similarly, in UPS the output voltage of inverter is to be regulated. These all the reasons indicate that the output voltage of inverter is to be controlled. The pulse width modulation (PWM) techniques are mainly used for voltage control. These techniques are most efficient and they control the drives of the switching devices.

Following are the PWM techniques :

i) Single pulse width modulation

ii) Multiple pulse width modulation

iii) Sinusoidal pulse width modulation

iv) Modified sinusoidal pulse width modulation

v) Phase displacement control

Out of the above techniques, sinusoidal PWM techniques are most widely used. They control the output voltage as well as reduce the harmonics.

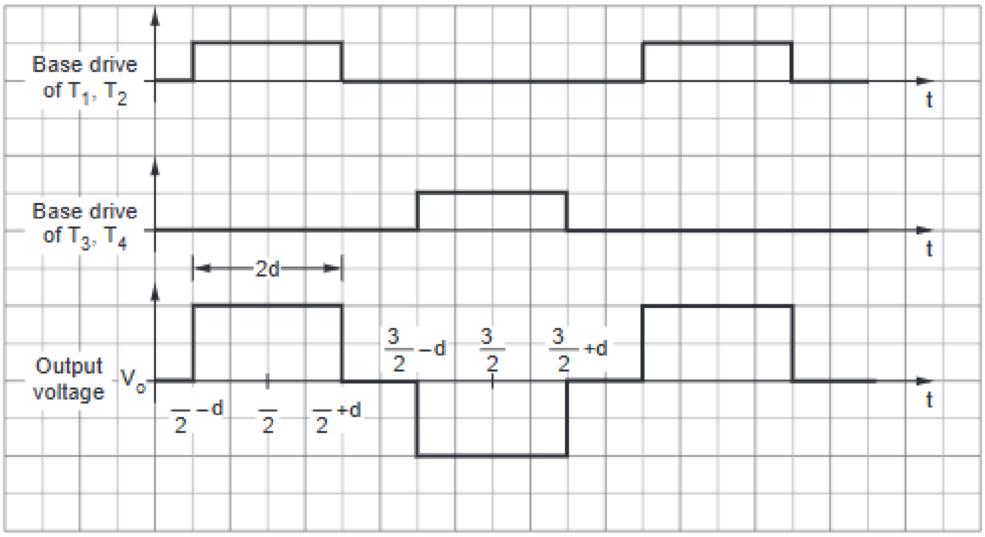
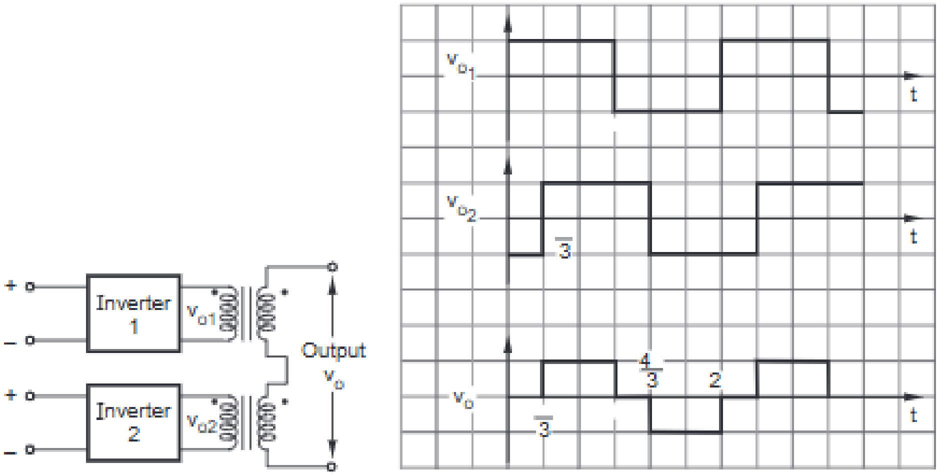


Fig. 7.6.1 Output voltage control using single pulse modulation

7.6.6 Harmonic Elimination by Transformer Connections

The method is similar to phase displacement control. The outputs of two inverter are connected in series as shown in Fig. 7.6.7 (a).



(a) Transformer connection (b) Waveforms

Fig. 7.6.7 Circuit and waveform of harmonics reduction by transformer connection

Mathematical Analysis

The output of inverter 1 is square wave and it contains only odd harmonics

i.e. $V_{o1} = A_1 \sin \omega t + A_3 \sin 3\omega t + A_5 \sin 5\omega t + ...$

The output of inverter 2 is delayed by $\frac{\pi}{3}$ with respect to inverter-1 hence it can be expressed as,

$$v_{o2} = A_1 \sin\left(\omega t - \frac{\pi}{3}\right) + A_3 \sin 3\left(\omega t - \frac{\pi}{3}\right) + A_5 \sin 5\left(\omega t - \frac{\pi}{3}\right) + ...$$

The output voltage becomes,

$$\begin{aligned} v_o &= v_{o1} + v_{o2} \\ &= A_1\left[\sin \omega t + \sin\left(\omega t - \frac{\pi}{3}\right)\right] + A_3\left[\sin 3\omega t + \sin 3\left(\omega t - \frac{\pi}{3}\right)\right] \\ &\quad + A_5\left[\sin 5\omega t + \sin 5\left(\omega t - \frac{\pi}{3}\right)\right] + ... \\ &= A_1\left[\sin \omega t + 0.5 \sin \omega t - \frac{\sqrt{3}}{2}\cos \omega t\right] + A_3[\sin 3\omega t - \sin 3\omega t] \\ &\quad + A_5\left[\sin 5\omega t + 0.5 \sin 5\omega t + \frac{\sqrt{3}}{2}\cos 5\omega t\right] + ... \\ &= A_1\left[1.5 \sin \omega t - \frac{\sqrt{3}}{2}\cos \omega t\right] + A_5\left[1.5 \sin 5\omega t + \frac{\sqrt{3}}{2}\cos 5\omega t\right] + ... \end{aligned}$$

Here let us use $A \cos(x) - B \sin(x) = R \cos(x + \theta)$ where $R = \sqrt{A^2 + B^2}$ and $\theta = \tan^{-1}\frac{B}{A}$, then above equation becomes,

$$v_o = \sqrt{3} A_1 \cos\left(\omega t + \frac{\pi}{3}\right) + \sqrt{3} A_5 \cos\left(\omega t - \frac{\pi}{3}\right) + ...$$

Here note that third harmonic and its multiples is totally absent. Thus the transformer connection and appropriate phase shift can eliminate the harmonics.

7.7 Current Source Inverters

In the previous sections, we studied voltage source inverters (VSI) or voltage fed inverters. The input voltage in these inverters remains constant and current depends on the load. There are another type of inverters in which input current remains constant. These inverters are called *current source inverters* (CSI) or current fed inverters. The output current also remains constant and the output voltage depends upon the load.

7.7.1 1ϕ Transistorised Current Source Inverter

Fig. 7.7.1 shows the circuit diagram of the 1ϕ transistorised CSI. There are four transistors and four diodes. The diodes are used to block the reverse voltages appearing across the transistors. Since the input current remains constant, it must flow continuously. Hence any two transistor must be always on. Fig. 7.7.2 shows the waveforms of this CSI. From 0 to t_1, transistors T_1 and T_4 are conducting. Hence no current flows through the load. The load current is zero. The supply current 'I' is by passed through T_1 and T_4. Note that this does not create any short circuit of the supply, since input current remains constant at 'I'.

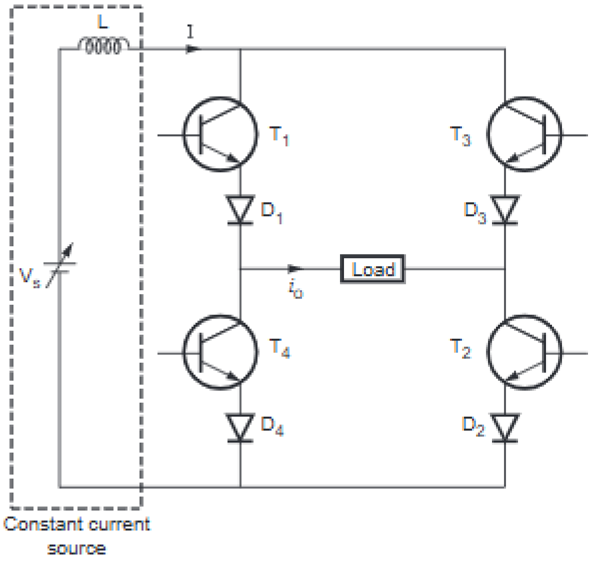


Fig. 7.7.1 Circuit diagram of transistorized CSI

From t_1 to t_2 transistors T_1 and T_2 conduct. Hence current flows through 'I'. As shown in Fig. 7.7.2, this current is positive of constant amplitude 'I'.

From t_2 to t_3, transistors T_2 and T_3 conduct. Hence supply current flows through $T_3 - D_3 - T_2 - D_2$. No current flows through the load. Hence output current is zero in this period.

From t_3 to t_4, transistors T_3 and T_4 conduct. Hence current flows through the load. It is negative current of constant amplitude. Thus the load current is alternating (AC). At t_4, transistor T_1 is turned on and T_3 is turned off. Hence supply current flows through T_1 and T_4 and the cycle repeats.

Here note that the supply current keeps on flowing continuously. The supply current is kept constant by connecting a large inductor 'L' in series with DC supply. The supply voltage V_s is adjusted to keep current constant.

Let the current flows for the duration of 'δ' in the load for half cycle. Then the load current can be expressed in fourier series as,

$$i_{on} = \sum_{n=1,3,5,\dots}^{\infty} \frac{4I}{n\pi} \sin\frac{n\delta}{2} \sin n\omega t \qquad \dots (7.7.1)$$

By selecting the proper width of the current pulse, some of the harmonics can be eliminated in the load current.

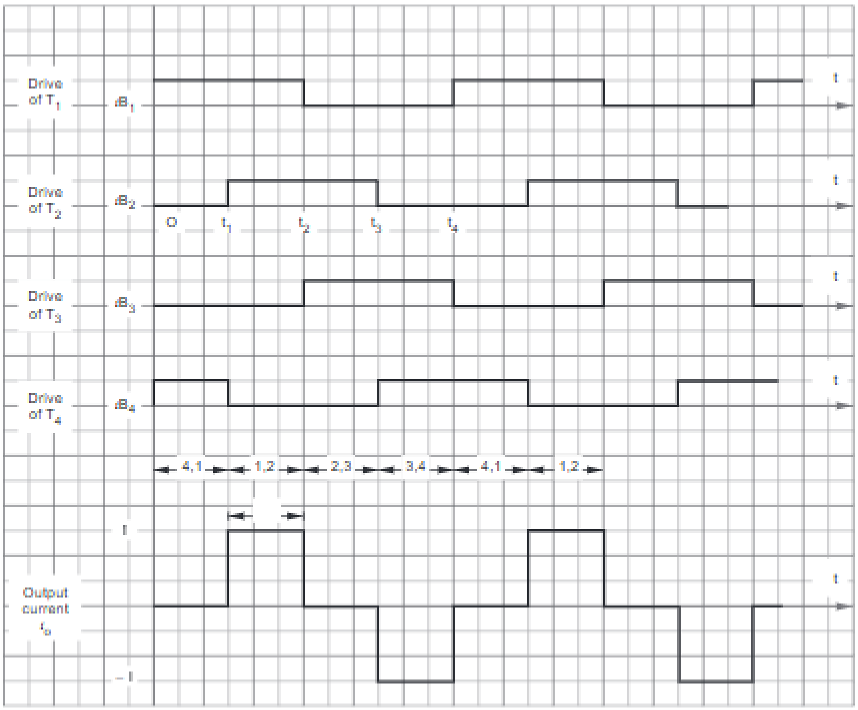


Fig. 7.7.2 Waveforms of transistorized CSI

Advantages of CSI

1. The input current is constant. Hence there is no possibility of short circuit.
2. CSI can handle reactive or regenerative loads without freewheeling diodes.
3. The maximum current of the power devices is limited (i.e. fixed).

Drawbacks of CSI

1. It needs large inductance to generate constant current source.
2. Since the current is limited, the dynamic response of CSI is slow.
3. Voltage spikes are generated when switching of devices take place. Filters are required to suppress these spikes.

7.7.2 Thyristorized Current Source Inverter (Capacitor Commutated Current Source Inverter)

Fig. 7.7.3 shows the circuit diagram of thyristorized current source inverter. The constant current source is formed by connecting the DC supply in series with the large

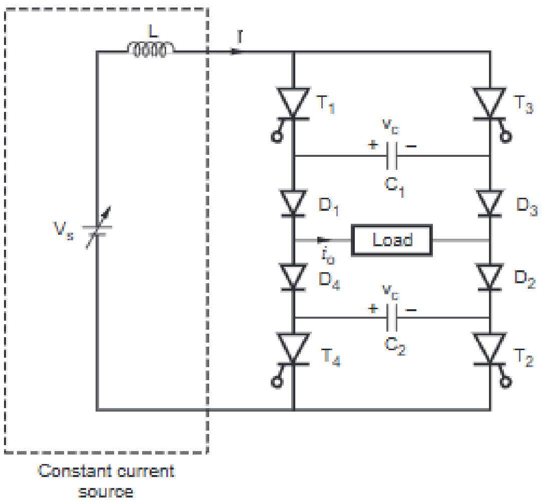


Fig. 7.7.3 Thyristorized current source inverter

inductor. In the positive half cycle current flows through $T_1 - D_1$ - load - $D_2 - T_2$. The capacitors are charged to the polarities as shown.

T_3 and T_4 are turned on to start negative half cycle of the load current. The voltage of C_1 is applied across T_1 in reverse direction. Similarly the voltage of C_2 is applied in reverse direction across T_2. Hence T_1 and T_2 turn off due to impulse commutation. The capacitors then charge to opposite polarities and the load current flows through $T_3 - D_3$ – load – $D_4 - T_4$. The thyristors T_1 and T_2 can then be turned on to initiate positive half cycle and turn off T_3 and T_4.

The advantage of this circuit is that it need only capacitor as the commutating component. Thus thyristor CSI are easy to implement. The commutation time depends upon load current and load voltage. The diodes isolate capacitors C_1 and C_2 from load voltage.

7.7.3 Comparison between VSI and CSI

Table 7.7.1 shows the comparison between Current Source Inverter (CSI) and Voltage Source Inverter (VSI).

Sr. No.	Voltage source inverter (VSI)	Current source inverter (CSI)
1	Input is constant voltage.	Input is constant current.
2	Short circuit can damage the circuit.	Short circuit cannot damage the circuit.
3	Peak current of power device depends on load.	Peak current of power device is limited.
4	Current waveform depends on load.	Voltage waveform depends on load.
5	Freewheeling diodes are required in case of inductive load.	Freewheeling diodes are not required.

Table 7.7.1 Comparison between VSI and CSI