DC – DC CONVERTER
(DC - CHOPPER

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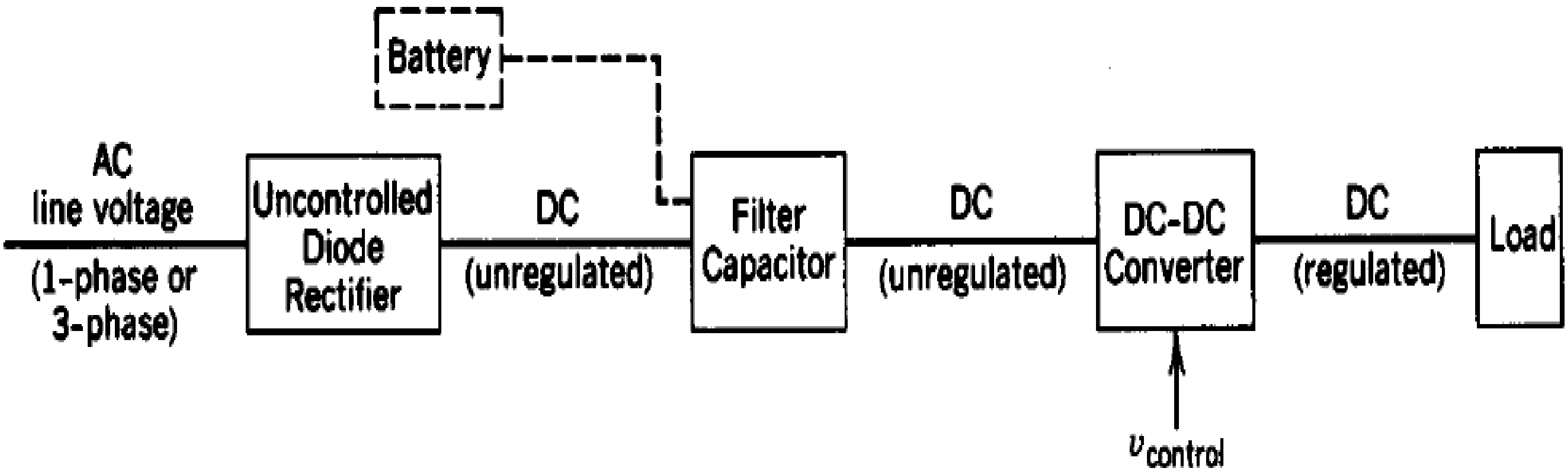
BLOCK DIAGRAM OF DC-DC CONVERTERS



A chopper is a static device which is used to obtain a variable dc voltage from a constant dc voltage source. A chopper is also known as dc-to-dc converter. The thyristor converter offers greater efficiency, faster response, lower maintenance, smaller size and smooth control. Choppers are widely used in trolley cars, battery operated vehicles, traction motor control, control of large number of dc motors, etc….. They are also used in regenerative braking of dc motors to return energy back to supply and also as dc voltage regulators.

Choppers are of two types:

- Step-down choppers
- Step-up choppers

In step-down choppers, the output voltage will be less than the input voltage whereas in step-up choppers output voltage will be more than the input voltage.

PRINCIPLE OF STEP-DOWN CHOPPER

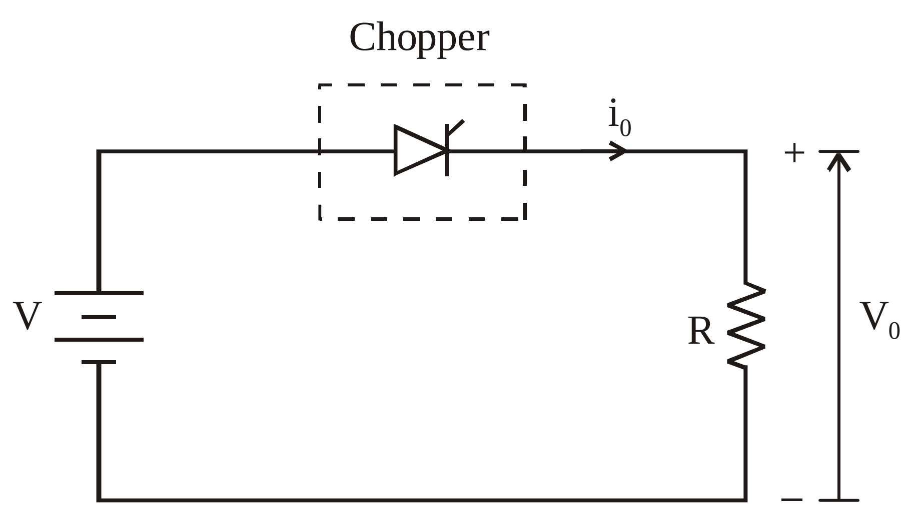


Fig. 2.1: Step-down Chopper with Resistive Load

Figure 2.1 shows 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 and when thyristor is OFF, the voltage across the load will be zero. The output voltage and current waveforms are as shown in figure 2.2.

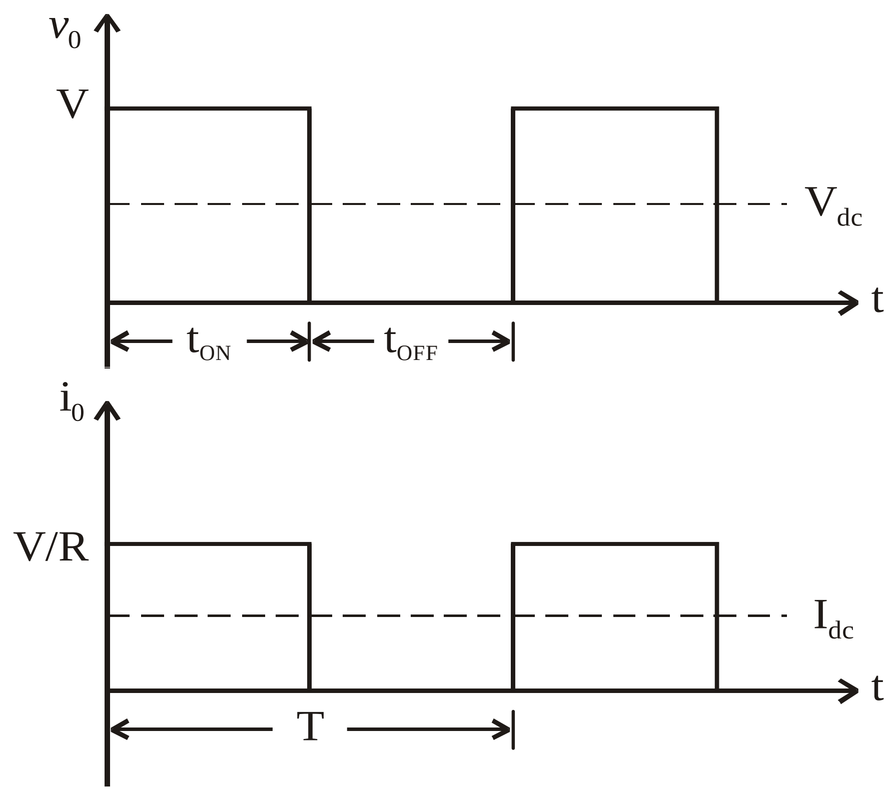


Fig. 2.2: Step-down choppers — output voltage and current waveforms

V_{dc} = average value of output or load voltage

I_{dc} = average value of output or load current

t_{ON} = time interval for which SCR conducts

t_{OFF} = time interval for which SCR is OFF.

$T = t_{ON} + t_{OFF}$ = period of switching or chopping period

$f = \frac{1}{T} =$ frequency of chopper switching or chopping frequency.

Average output voltage

$$V_{dc} = V\left(\frac{t_{ON}}{t_{ON} + t_{OFF}}\right) \qquad ...(2.1)$$

$$V_{dc} = V\left(\frac{t_{ON}}{T}\right) = V.d \qquad ...(2.2)$$

but $\left(\frac{t_{ON}}{t}\right) = d =$ duty cycle ...(2.3)

Average output current,

$$I_{dc} = \frac{V_{dc}}{R} \qquad ...(2.4)$$

$$I_{dc} = \frac{V}{R}\left(\frac{t_{ON}}{T}\right) = \frac{V}{R}d \qquad ...(2.5)$$

RMS value of output voltage

$$V_O = \sqrt{\frac{1}{T}\int_0^{t_{ON}} v_o^2 dt}$$

But during t_{ON}, $v_o = V$

Therefore RMS output voltage

$$V_O = \sqrt{\frac{1}{T}\int_0^{t_{ON}} V^2 dt}$$

$$V_O = \sqrt{\frac{V^2}{T}t_{ON}} = \sqrt{\frac{t_{ON}}{T}}.V \qquad ...(2.6)$$

$$V_O = \sqrt{d}.V \qquad ...(2.7)$$

Output power $$P_O = V_O I_O$$

But $$I_O = \frac{V_O}{R}$$

Therefore output power $$P_O = \frac{V_O^2}{R}$$

$$P_O = \frac{dV^2}{R} \qquad ...(2.8)$$

Effective input resistance of chopper

$$R_i = \frac{V}{I_{dc}} \qquad ...(2.9)$$

$$R_i = \frac{R}{d} \qquad ...(2.10)$$

The output voltage can be varied by varying the duty cycle.

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

In pulse width modulation the pulse width (t_{ON}) of the output waveform is varied keeping chopping frequency 'f' and hence chopping period 'T' constant. Therefore output voltage is varied by varying the ON time, t_{ON}. Figure 2.3 shows the output voltage waveforms for different ON times.

VARIABLE FREQUENCY CONTROL

In this method of control, chopping frequency f is varied keeping either t_{ON} or t_{OFF} constant. This method is also known as frequency modulation.

Figure 2.4 shows the output voltage waveforms for a constant t_{ON} and variable chopping period T.

In frequency modulation 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 t_{OFF} load current may become discontinuous.

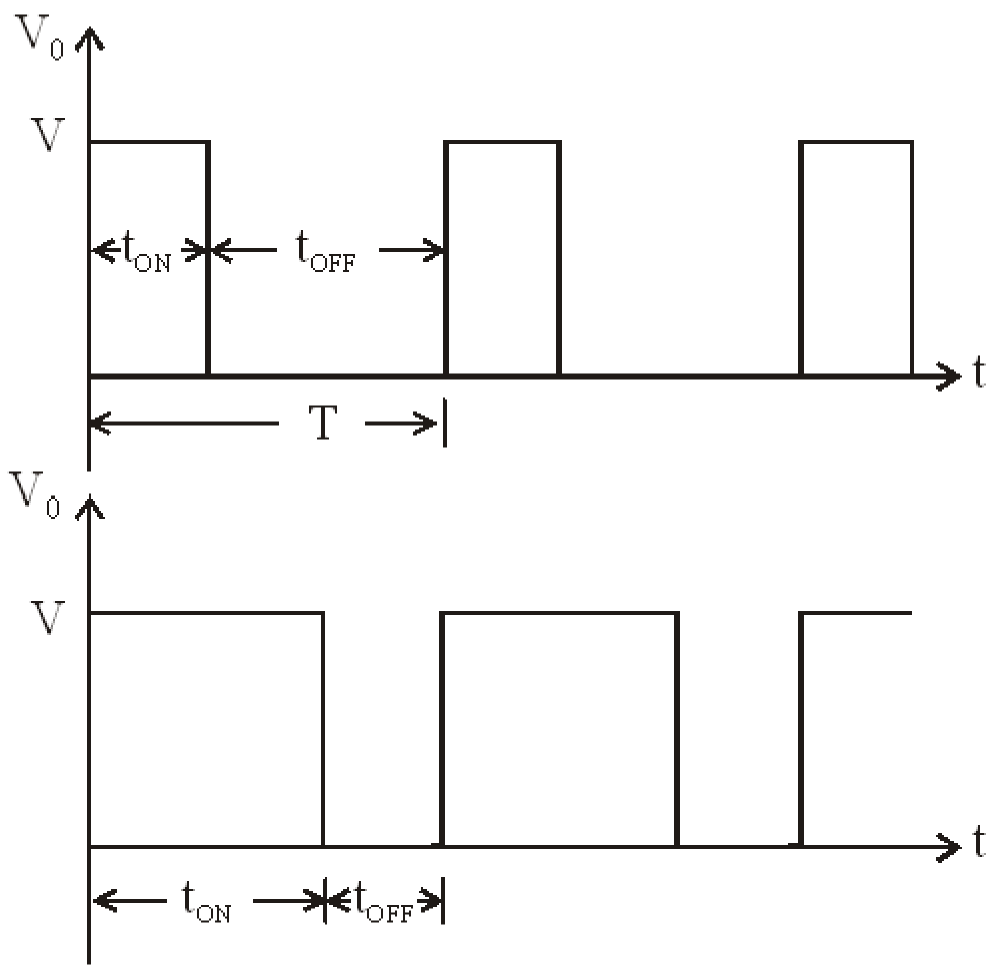


Fig. 2.3: Pulse Width Modulation Control

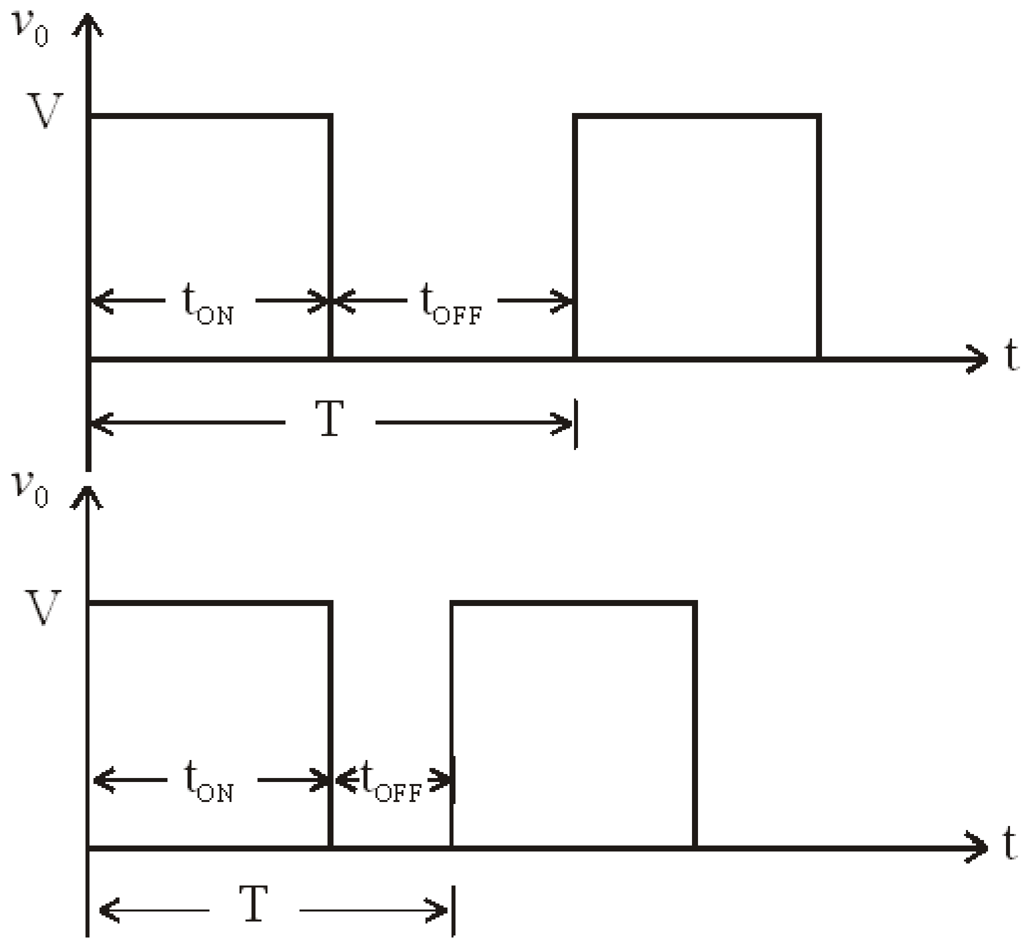


Fig. 2.4: Output Voltage Waveforms for Time Ratio Control

STEP-DOWN CHOPPER WITH R-L LOAD

Figure 2.5 shows a step-down chopper with R-L load and free wheeling diode. When chopper is ON, the supply is connected across the load. Current flows from the supply to the load. When chopper is OFF, the load current i_0 continues to flow in the same direction through the free-wheeling diode due to the energy stored in the inductor L. Thc load currcnt can bc continuous or discontinuous dcpcnding on thc valucs of L and duty cycle, d. For a continuous current operation the load current is assumed to vary between two limits I_{min} and I_{max}.

Figure 2.6 shows the output current and output voltage waveforms for a continuous current and discontinuous current operation.

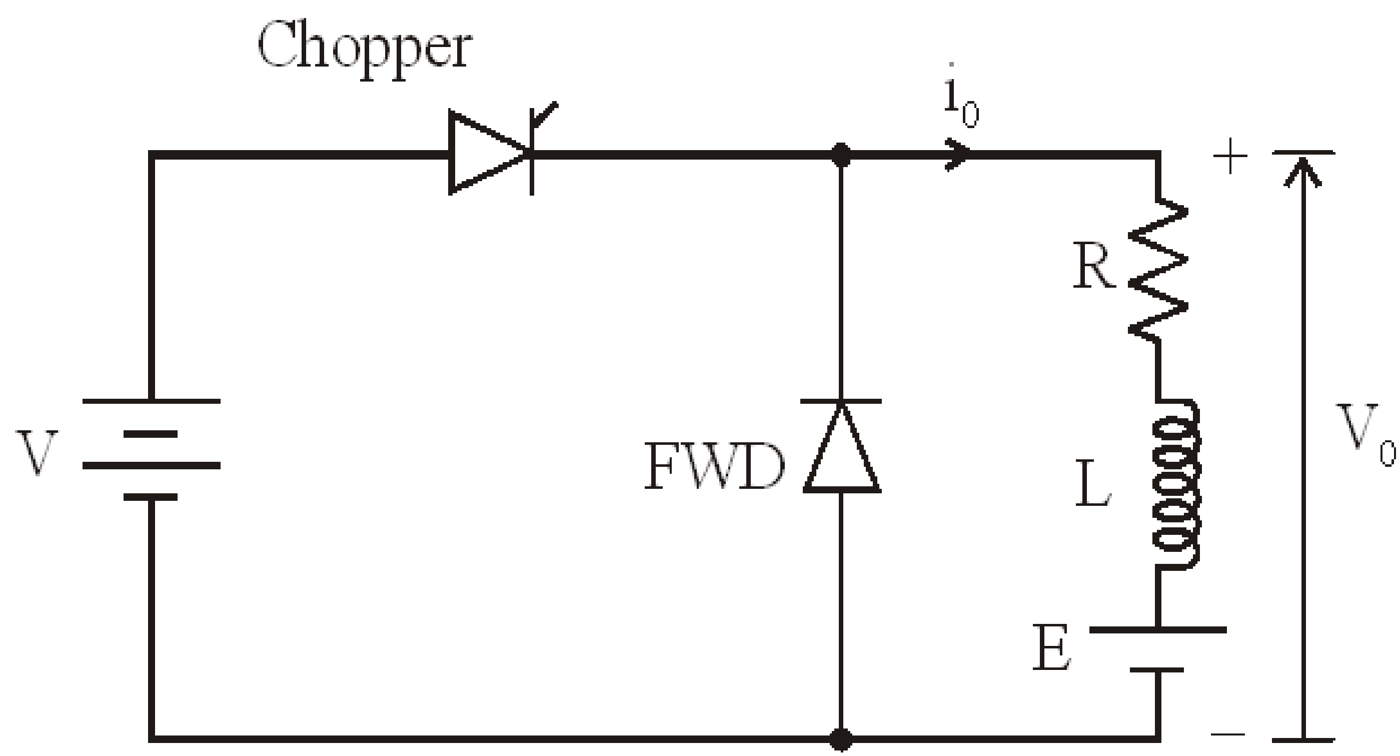


Fig. 2.5: Step Down Chopper with R-L Load

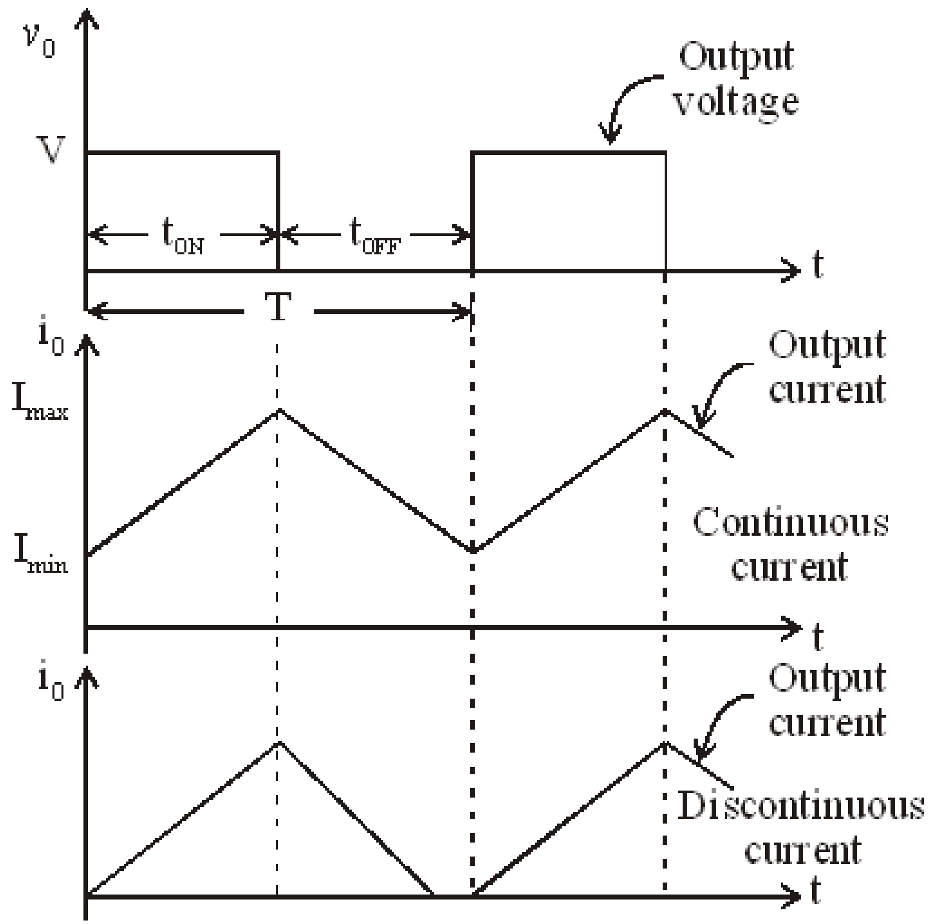


Fig. 2.6: Output Voltage and Load Current Waveforms (Continuous Current)

When the current exceeds I_{max} the chopper is turned-off and it is turned-on when current reduces to I_{min}.

EXPRESSIONS FOR LOAD CURRENT i_0 FOR CONTINUOUS CURRENT OPERATION WHEN CHOPPER IS ON $(0 \le t \le t_{ON})$

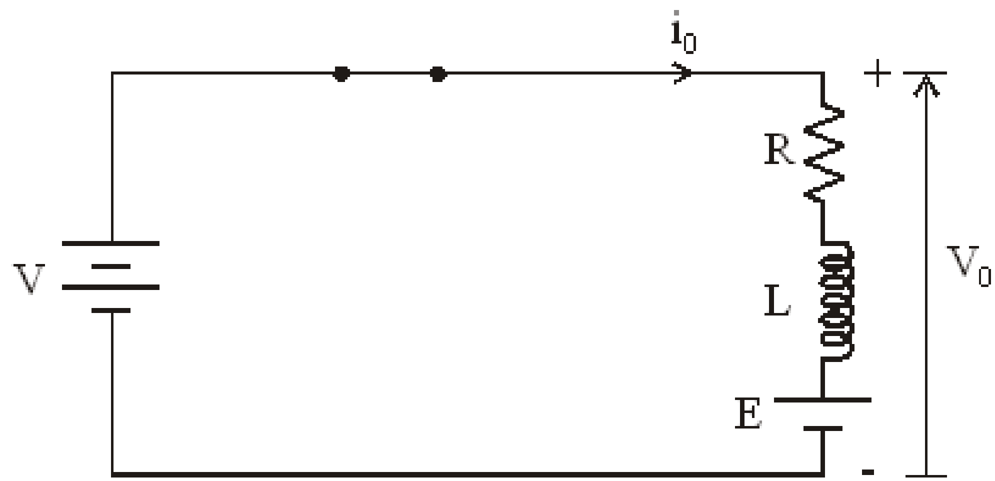


Fig. 2.5 (a)

Voltage equation for the circuit shown in figure 2.5(a) is

$$V = i_0 R + L\frac{di_0}{dt} + E \qquad \ldots(2.11)$$

Taking Laplace Transform

$$\frac{V}{S} = RI_0(S) + L\left[S.I_0(S) - i_0(0^-)\right] + \frac{E}{S} \qquad \ldots(2.12)$$

At $t=0$, initial current $i_O\left(0^-\right)=I_{\min}$

$$I_O(S)=\frac{V-E}{LS\left(S+\frac{R}{L}\right)}+\frac{I_{\min}}{S+\frac{R}{L}} \qquad \ldots(2.13)$$

Taking Inverse Laplace Transform

$$i_O(t)=\frac{V-E}{R}\left[1-e^{-\left(\frac{R}{L}\right)t}\right]+I_{\min}e^{-\left(\frac{R}{L}\right)t} \qquad \ldots(2.14)$$

This expression is valid for $0 \le t \le t_{ON}$. i.e., during the period chopper is ON.

At the instant the chopper is turned off, load current is

$$i_O\left(t_{ON}\right)=I_{\max}$$

When Chopper is OFF $\left(0 \le t \le t_{OFF}\right)$

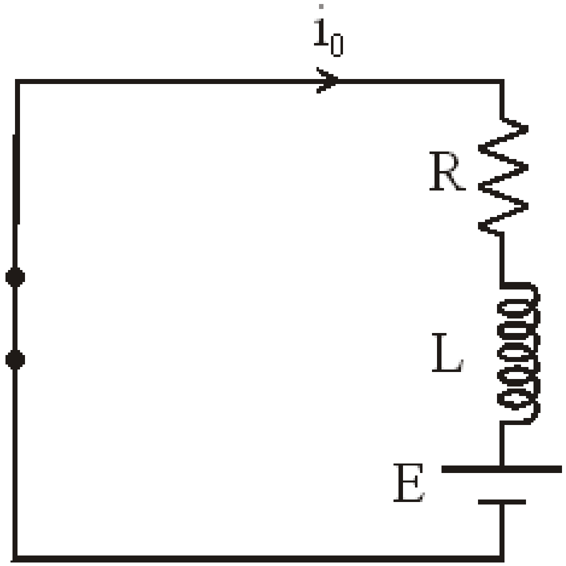


Fig. 2.5 (b)

Voltage equation for the circuit shown in figure 2.5(b) is

$$0 = Ri_O + L\frac{di_O}{dt} + E \qquad \ldots(2.15)$$

Taking Laplace transform

$$0 = RI_O(S) + L\left[SI_O(S) - i_O(0^-)\right] + \frac{E}{S}$$

Redefining time origin we have at $t = 0$, initial current $i_O(0^-) = I_{\max}$

Therefore $$I_O(S) = \frac{I_{\max}}{S + \frac{R}{L}} - \frac{E}{LS\left(S + \frac{R}{L}\right)}$$

Taking Inverse Laplace Transform

$$i_O(t) = I_{\max} e^{-\frac{R}{L}t} - \frac{E}{R}\left[1 - e^{-\frac{R}{L}t}\right] \qquad \ldots(2.16)$$

The expression is valid for $0 \le t \le t_{OFF}$, i.e., during the period chopper is OFF. At the instant the chopper is turned ON or at the end of the off period, the load current is

$$i_O(t_{OFF}) = I_{\min}$$

TO FIND $I_{\max}$ AND $I_{\min}$

From equation (2.14),

At $\quad t = t_{ON} = dT, \;\; i_O(t) = I_{\max}$

Therefore
$$I_{\max} = \frac{V - E}{R}\left[1 - e^{-\frac{dRT}{L}}\right] + I_{\min} e^{-\frac{dRT}{L}} \qquad \ldots(2.17)$$

From equation (2.16),

At $\quad t = t_{OFF} = T - t_{ON}, \;\; i_O(t) = I_{\min}$

$t = t_{OFF} = (1 - d)T$

Therefore
$$I_{\min} = I_{\max} e^{-\frac{(1-d)RT}{L}} - \frac{E}{R}\left[1 - e^{-\frac{(1-d)RT}{L}}\right] \qquad \ldots(2.18)$$

Substituting for $I_{\min}$ in equation (2.17) we get,

$$I_{\max} = \frac{V}{R}\left[\frac{1 - e^{-\frac{dRT}{L}}}{1 - e^{-\frac{RT}{L}}}\right] - \frac{E}{R} \qquad \ldots(2.19)$$

Substituting for I_{max} in equation (2.18) we get,

$$I_{min} = \frac{V}{R}\left[\frac{e^{\frac{dRT}{L}} - 1}{e^{\frac{RT}{L}} - 1}\right] - \frac{E}{R} \qquad \ldots(2.20)$$

$(I_{max} - I_{min})$ is known as the steady state ripple.

Therefore peak-to-peak ripple current

$$\Delta I = I_{max} - I_{min}$$

Average output voltage

$$V_{dc} = d.V \qquad \ldots(2.21)$$

Average output current

$$I_{dc\,(approx)} = \frac{I_{max} + I_{min}}{2} \qquad \ldots(2.22)$$

Assuming load current varies linearly from $I_{\min}$ to $I_{\max}$ instantaneous load current is given by

$$i_O = I_{\min} + \frac{(\Delta I).t}{dT} \; for \;\; 0 \le t \le t_{ON}(dT)$$

$$i_O = I_{\min} + \left(\frac{I_{\max} - I_{\min}}{dT} \right) t \qquad \ldots(2.23)$$

RMS value of load current

$$I_{O(RMS)} = \sqrt{\frac{1}{dT} \int_0^{dT} i_0^2 dt}$$

$$I_{O(RMS)} = \sqrt{\frac{1}{dT} \int_0^{dT} \left[I_{\min} + \frac{(I_{\max} - I_{\min})t}{dT} \right]^2 dt}$$

$$I_{O(RMS)} = \sqrt{\frac{1}{dT} \int_0^{dT} \left[I_{\min}^2 + \left(\frac{I_{\max} - I_{\min}}{dT} \right)^2 t^2 + \frac{2I_{\min}(I_{\max} - I_{\min})t}{dT} \right] dt}$$

RMS value of output current

$$I_{O(RMS)} = \left[I_{\min}^2 + \frac{(I_{\max} - I_{\min})^2}{3} + I_{\min}(I_{\max} - I_{\min}) \right]^{\frac{1}{2}} \qquad \ldots(2.24)$$

RMS chopper current

$$I_{CH} = \sqrt{\frac{1}{T}\int_0^{dT} i_0^2 dt}$$

$$I_{CH} = \sqrt{\frac{1}{T}\int_0^{dT} \left[I_{\min} + \left(\frac{I_{\max} - I_{\min}}{dT} \right) t \right]^2 dt}$$

$$I_{CH} = \sqrt{d} \left[I_{\min}^2 + \frac{(I_{\max} - I_{\min})^2}{3} + I_{\min}(I_{\max} - I_{\min}) \right]^{\frac{1}{2}}$$

$$I_{CH} = \sqrt{d}\, I_{O(RMS)} \qquad \ldots(2.25)$$

Effective input resistance is

$$R_i = \frac{V}{I_S}$$

Where I_S = Average source current

$$I_S = dI_{dc}$$

Therefore $$R_i = \frac{V}{dI_{dc}} \qquad ...(2.26)$$

PRINCIPLE OF STEP-UP CHOPPER

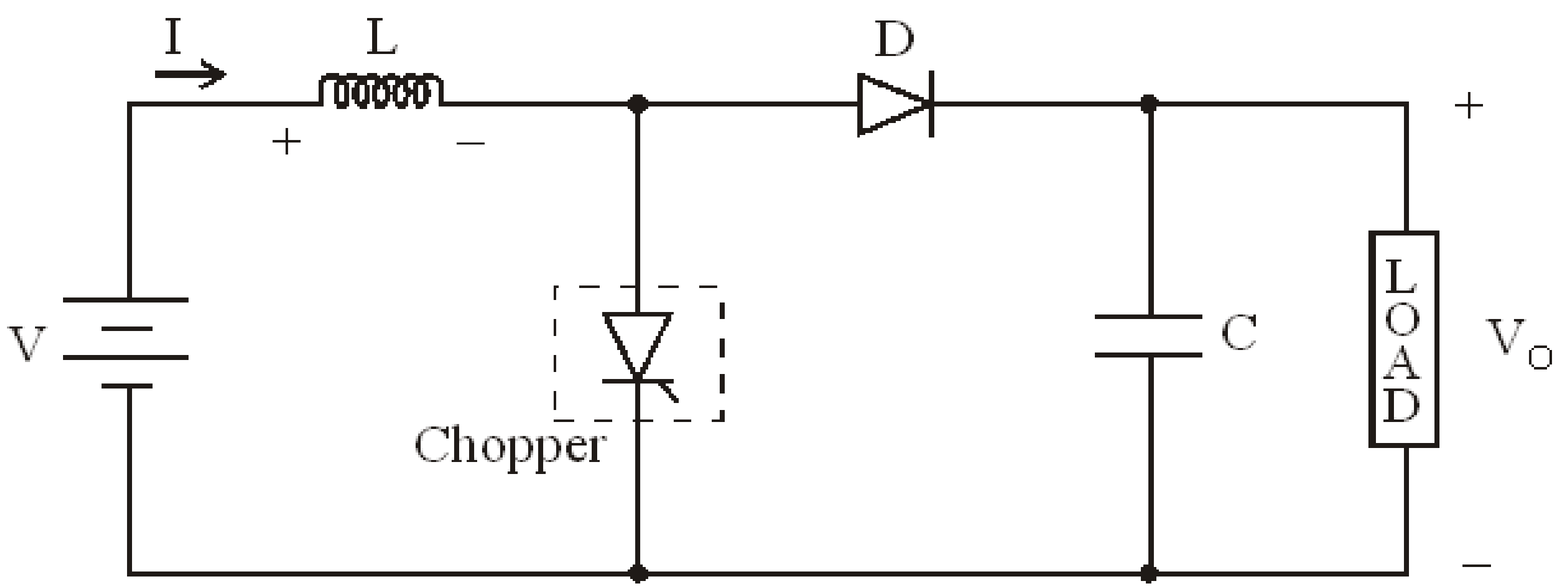


Fig. 2.13: Step-up Chopper

Figure 2.13 shows a step-up chopper to obtain a load voltage V_O 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, t_{ON}. When the chopper is off, the inductor current I is forced to flow through the diode D and load for a period, t_{OFF}. The current tends to decrease resulting in reversing the polarity of induced EMF in L. Therefore voltage across load is given by

$$V_O = V + L\frac{dI}{dt} \quad i.e., \quad V_O > V \qquad \ldots(2.27)$$

EXPRESSION FOR OUTPUT VOLTAGE

Assume the average inductor current to be I during ON and OFF time of Chopper

When Chopper is ON

Voltage across inductor $L = V$

Therefore energy stored in inductor = $V.I.t_{ON}$ ...(2.28),

where $t_{ON} = ON$ period of chopper.

When Chopper is OFF (energy is supplied by inductor to load)

Voltage across $L = V_O - V$

Energy supplied by inductor $L = (V_O - V) It_{OFF}$, where $t_{OFF} = OFF$ period of Chopper.

Neglecting losses, energy stored in inductor L = energy supplied by inductor L

Therefore $VIt_{ON} = (V_O - V) It_{OFF}$

$$V_O = \frac{V\left[t_{ON} + t_{OFF}\right]}{t_{OFF}}$$

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

Where T = Chopping period or period of switching.

$$T = t_{ON} + t_{OFF}$$

$$V_O = V\left(\frac{1}{1 - \frac{t_{ON}}{T}}\right)$$

Therefore $$V_O = V\left(\frac{1}{1-d}\right) \qquad ...(2.29)$$

Where $d = \frac{t_{ON}}{T} =$ duty cyle

For variation of duty cycle 'd' in the range of $0 < d < 1$ the output voltage V_0 will vary in the range $V < V_0 < \infty$.

CLASSIFICATION OF CHOPPERS

Choppers are classified as follows

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

CLASS A CHOPPER

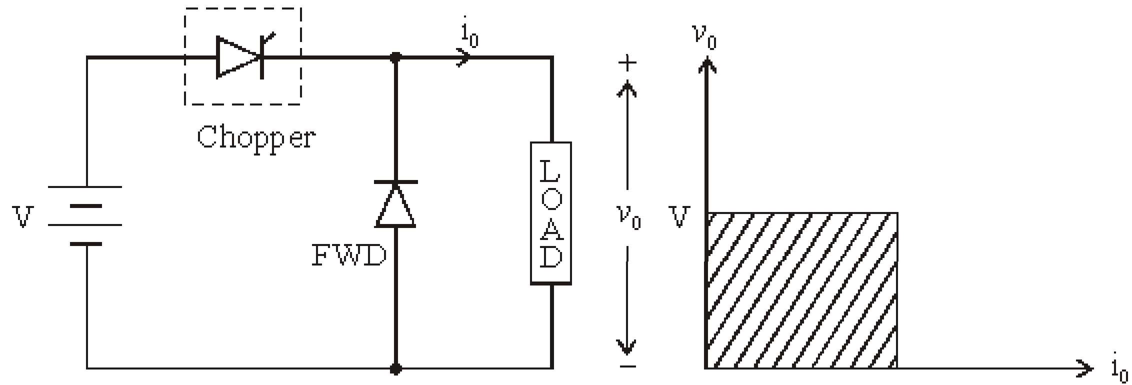


Fig. 2.14: Class A Chopper and $v_0 - i_0$ Characteristic

Figure 2.14 shows a *Class A Chopper* circuit with inductive load and free-wheeling diode. When chopper is *ON*, supply voltage *V* is connected across the load i.e., $v_0 = V$ and current i_0 flows as shown in figure. When chopper is OFF, $v_0 = 0$ and the load current i_0 continues to flow in the same direction through the free wheeling diode. Therefore the average values of output voltage and current i.e., v_0 and i_0 are always positive. Hence, *Class A Chopper* is a first quadrant chopper (or single quadrant chopper). Figure 2.15 shows output voltage and current waveforms for a continuous load current.

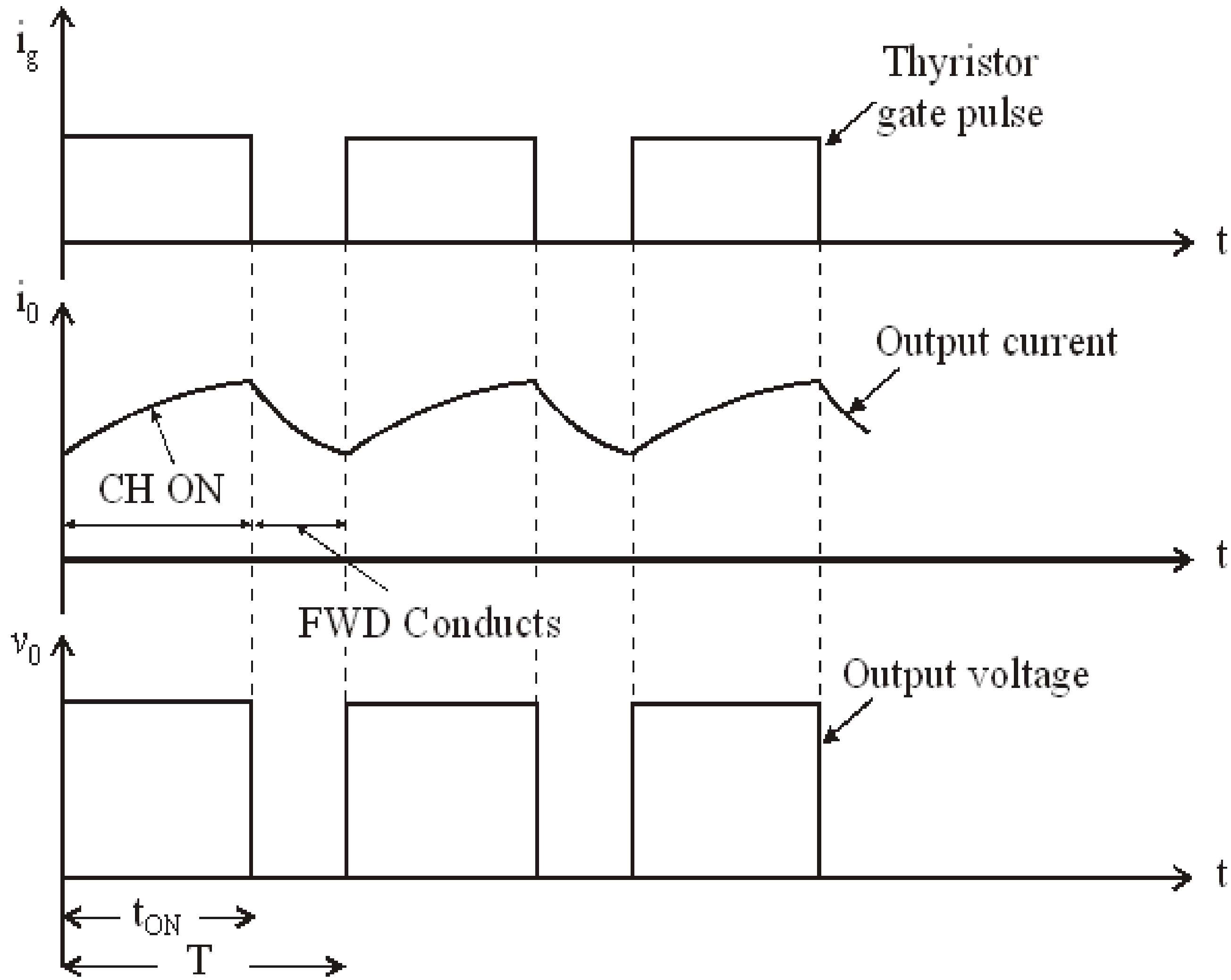


Fig. 2.15: First quadrant Chopper - Output Voltage and Current Waveforms

Class A Chopper is a step-down chopper in which power always flows from 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.*

CLASS B CHOPPER

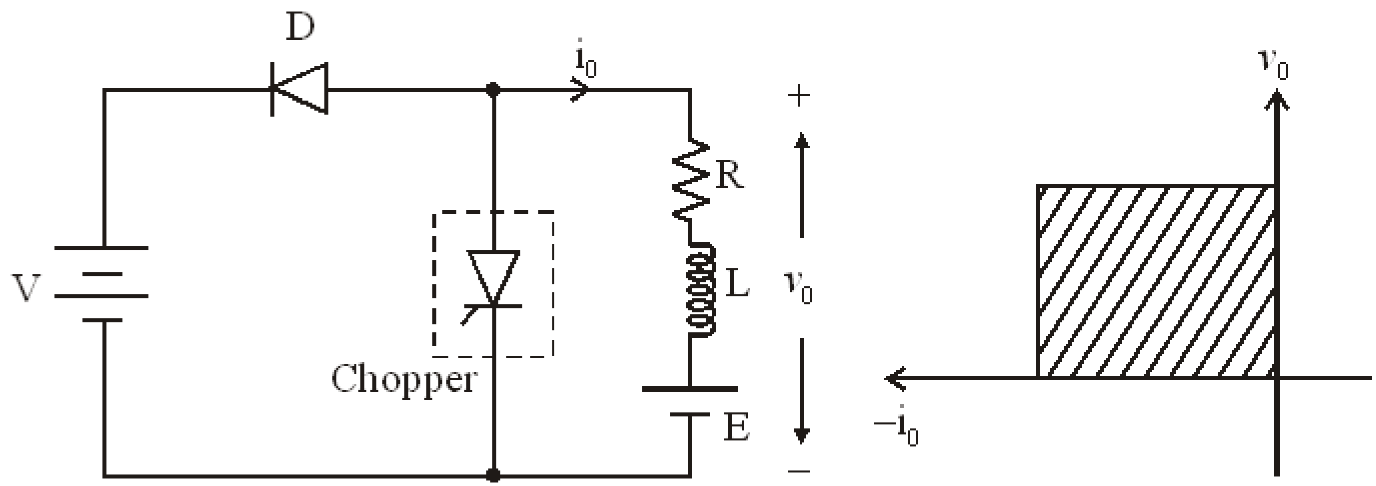
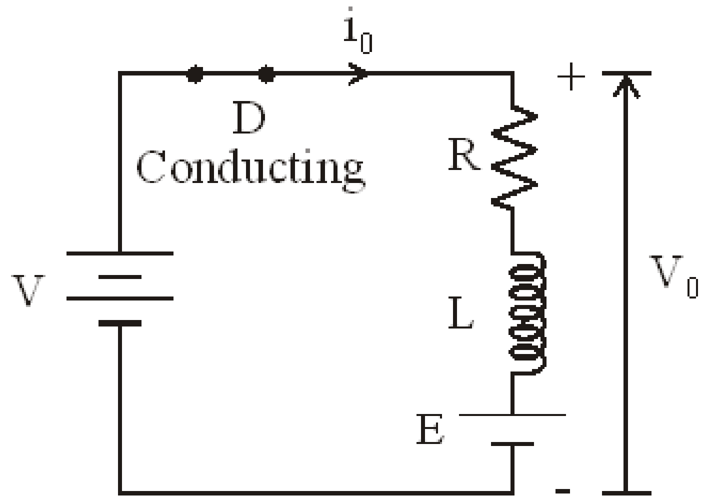


Fig. 2.16: Class B Chopper

Fig. 2.16 shows a *Class B Chopper* circuit. When chopper is ON, $v_0 = 0$ and E drives a current i_0 through L and R in a direction opposite to that shown in figure 2.16. During the ON period of the chopper, the inductance L stores energy. When Chopper is OFF, diode D conducts, $v_0 = V$ and part of the energy stored in inductor L is returned to the supply. Also the current i_0 continues to flow from the load to source. Hence the average output voltage is positive and 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. Figure 2.17 shows the output voltage and current waveforms of a *Class B Chopper*.

The output current equations can be obtained as follows. During the interval diode 'D' conducts (chopper is off) voltage equation is given by



$$V = \frac{Ldi_O}{dt} + Ri_O + E$$

For the initial condition i.e., $i_O(t) = I_{\min}$ at $t = 0$.

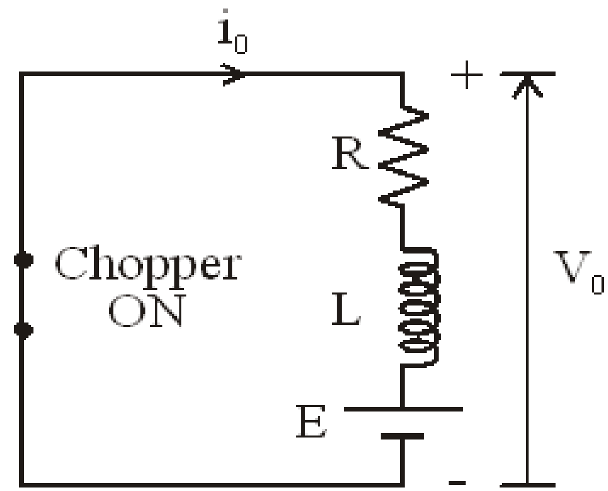
The solution of the above equation is obtained along similar lines as in step-down chopper with R-L load

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

At $t = t_{OFF} \qquad i_{(O)}(t) = I_{\max}$

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

During the interval chopper is ON voltage equation is given by



$$0 = \frac{L di_O}{dt} + R i_O + E$$

Redefining the time origin, at $t = 0 \quad i_O(t) = I_{max}$.

The solution for the stated initial condition is

$$i_O(t) = I_{max} e^{-\frac{R}{L}t} - \frac{E}{R}\left(1 - e^{-\frac{R}{L}t}\right) \qquad 0 < t < t_{ON}$$

At $t = t_{ON} \qquad i_O(t) = I_{min}$

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

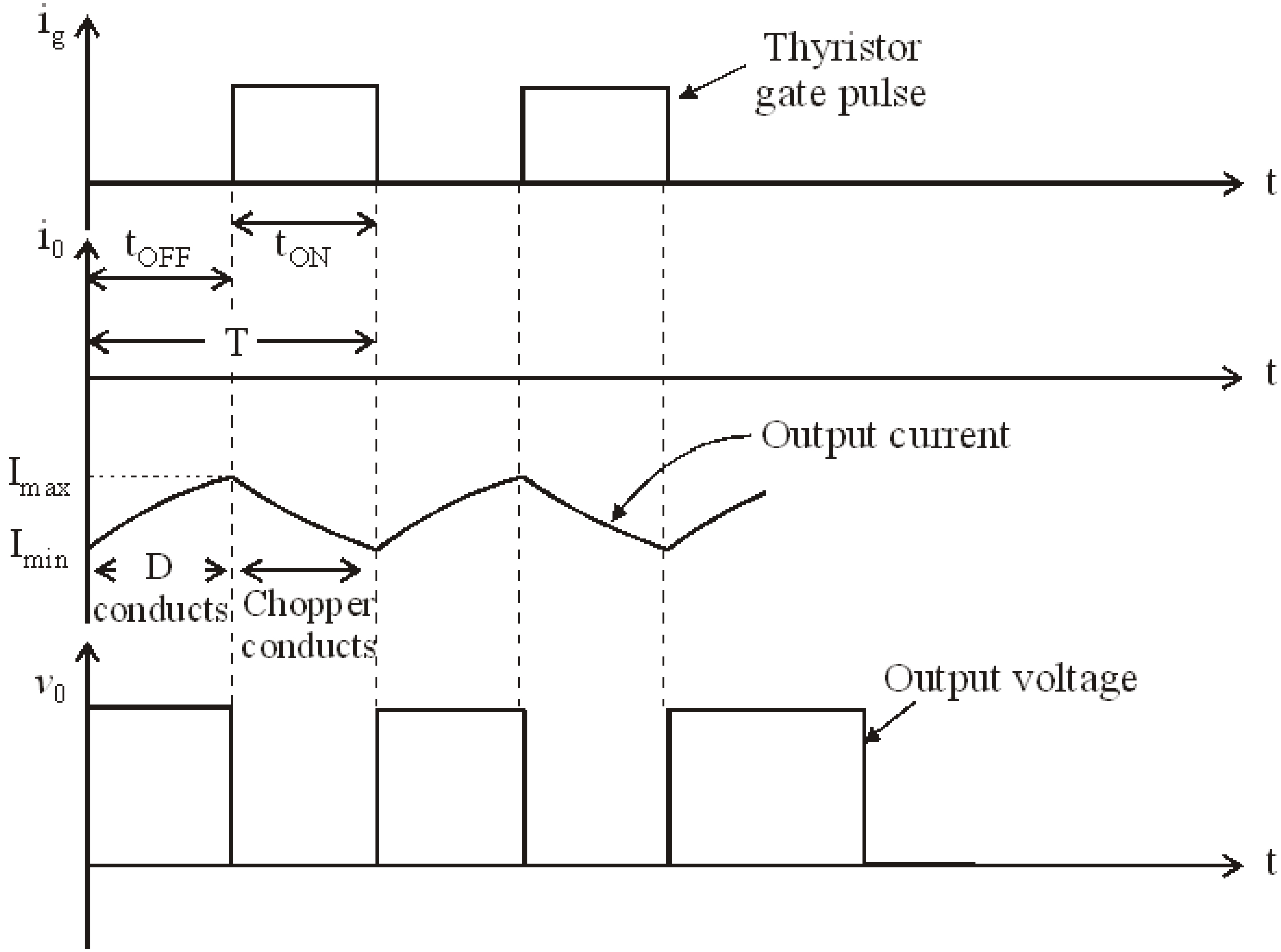


Fig. 2.17: Class B Chopper - Output Voltage and Current Waveforms

CLASS C CHOPPER

Class C Chopper is a combination of *Class A* and *Class B Choppers*. Figure 2.18 shows a *Class C* two quadrant Chopper circuit. For first quadrant operation, CH_1 is ON or D_2 conducts and for second quadrant operation, CH_2 is ON or D_1 conducts. When CH_1 is ON, the load current i_0 is positive. i.e., i_0 flows in the direction as shown in figure 2.18.

The output voltage is equal to $V\left(v_0 = V\right)$ and the load receives power from the source.

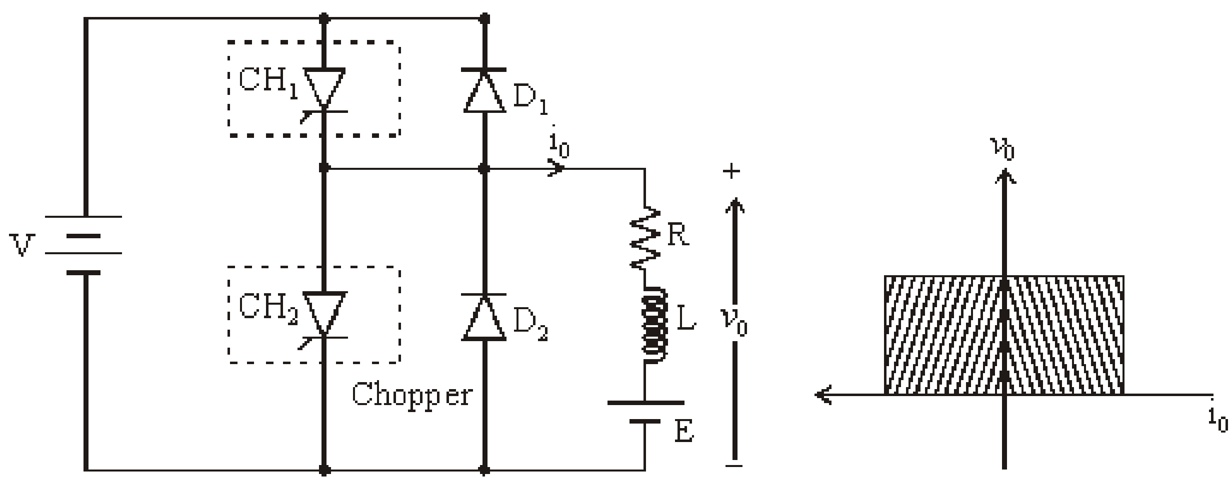


Fig. 2.18: Class C Chopper

When CH_1 is turned OFF, energy stored in inductance L forces current to flow through the diode D_2 and the output voltage $v_0 = 0$, but i_0 continues to flow in positive direction. When CH_2 is triggered, the voltage E forces i_0 to flow in opposite direction through L and CH_2. The output voltage $v_0 = 0$. On turning OFF CH_2, the energy stored in the inductance drives current through diode D_1 and the supply; output voltage $v_0 = V$ the input current becomes negative and power flows from load to source.

Thus the average output voltage v_0 is positive but the average output current i_0 can take both positive and negative values. Choppers CH_1 and CH_2 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. Figure 2.19 shows the output voltage and current waveforms.

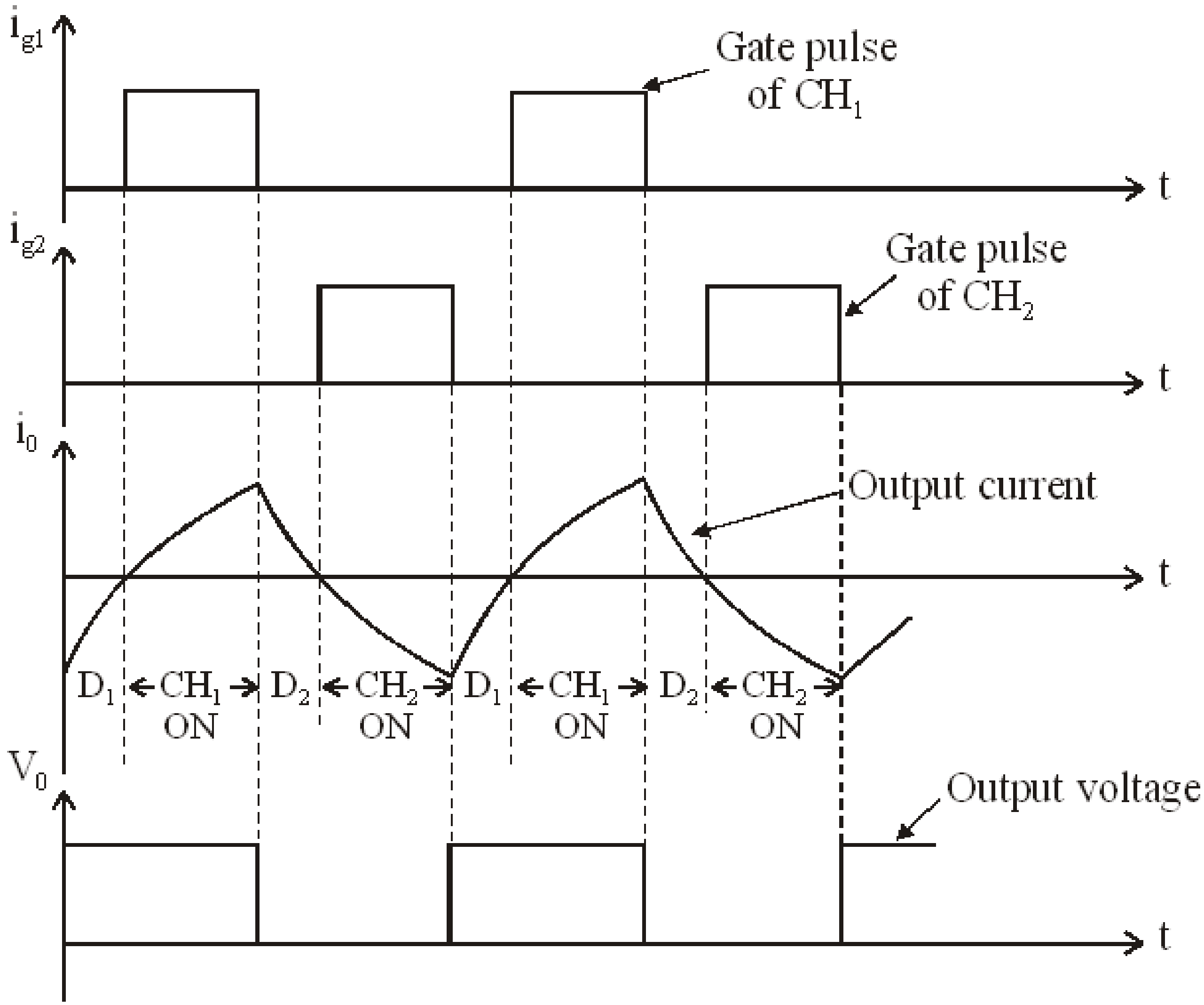


Fig. 2.19: Class C Chopper - Output Voltage and Current Waveforms

CLASS D CHOPPER

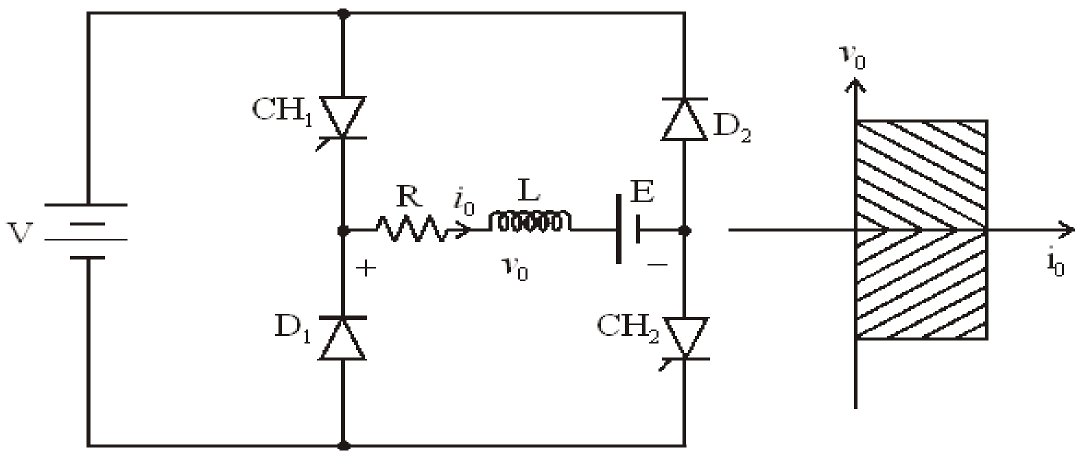


Fig. 2.20: Class D Chopper

Figure 2.20 shows a class D two quadrant chopper circuit. When both CH_1 and CH_2 are triggered simultaneously, the output voltage $v_O = V$ and output current i_O flows through the load in the direction shown in figure 2.20. When CH_1 and CH_2 are turned OFF, the load current i_O continues to flow in the same direction through load, D_1 and D_2, due to the energy stored in the inductor L, but output voltage $v_O = -V$. The average load voltage v_O is positive if chopper ON-time (t_{ON}) is more than their OFF-time (t_{OFF}) and average output voltage becomes negative if $t_{ON} < t_{OFF}$. Hence the direction of load current is always positive but load voltage can be positive or negative. Waveforms are shown in figures 2.21 and 2.22.

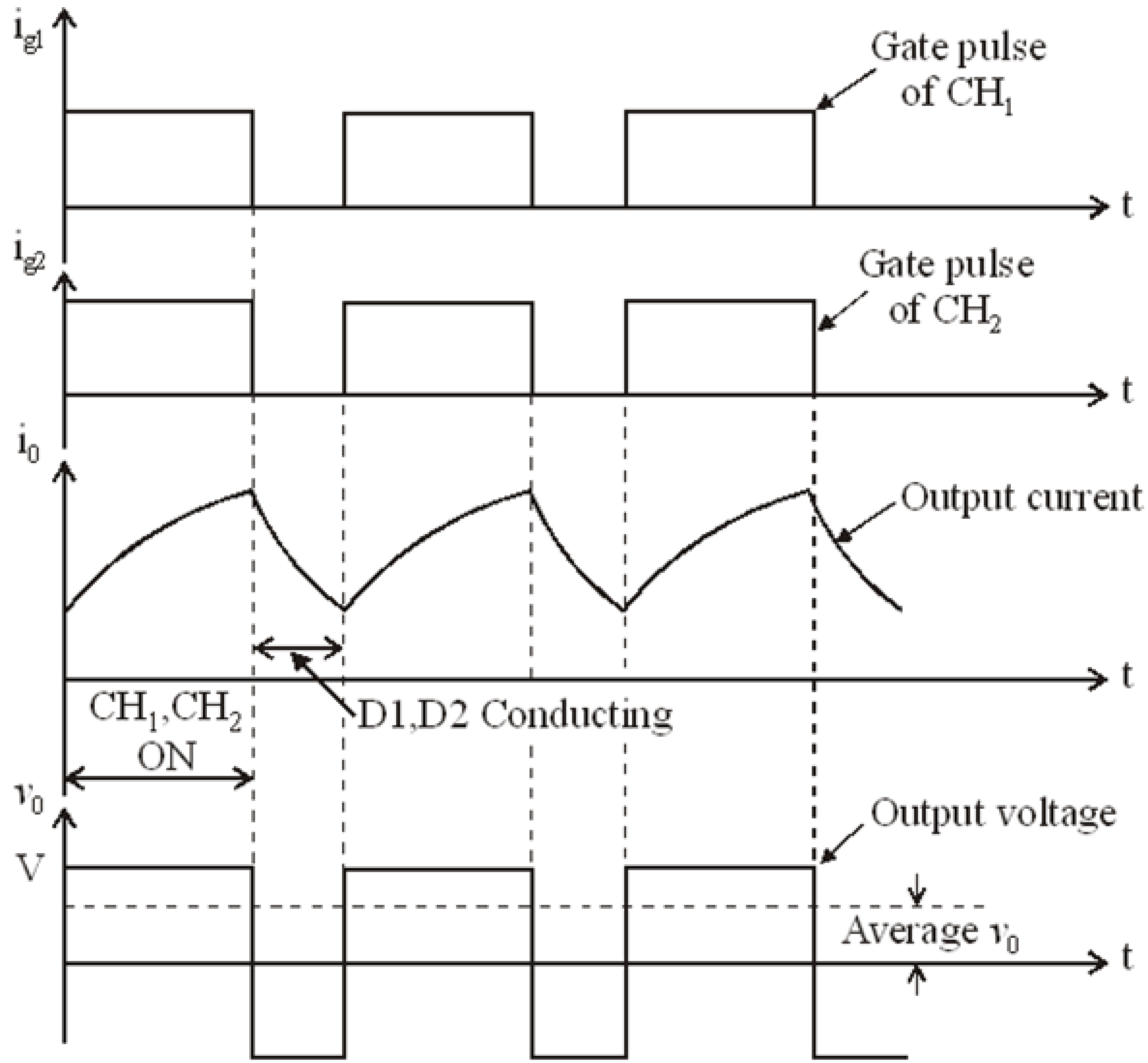


Fig. 2.21: Output Voltage and Current Waveforms for $t_{ON} > t_{OFF}$

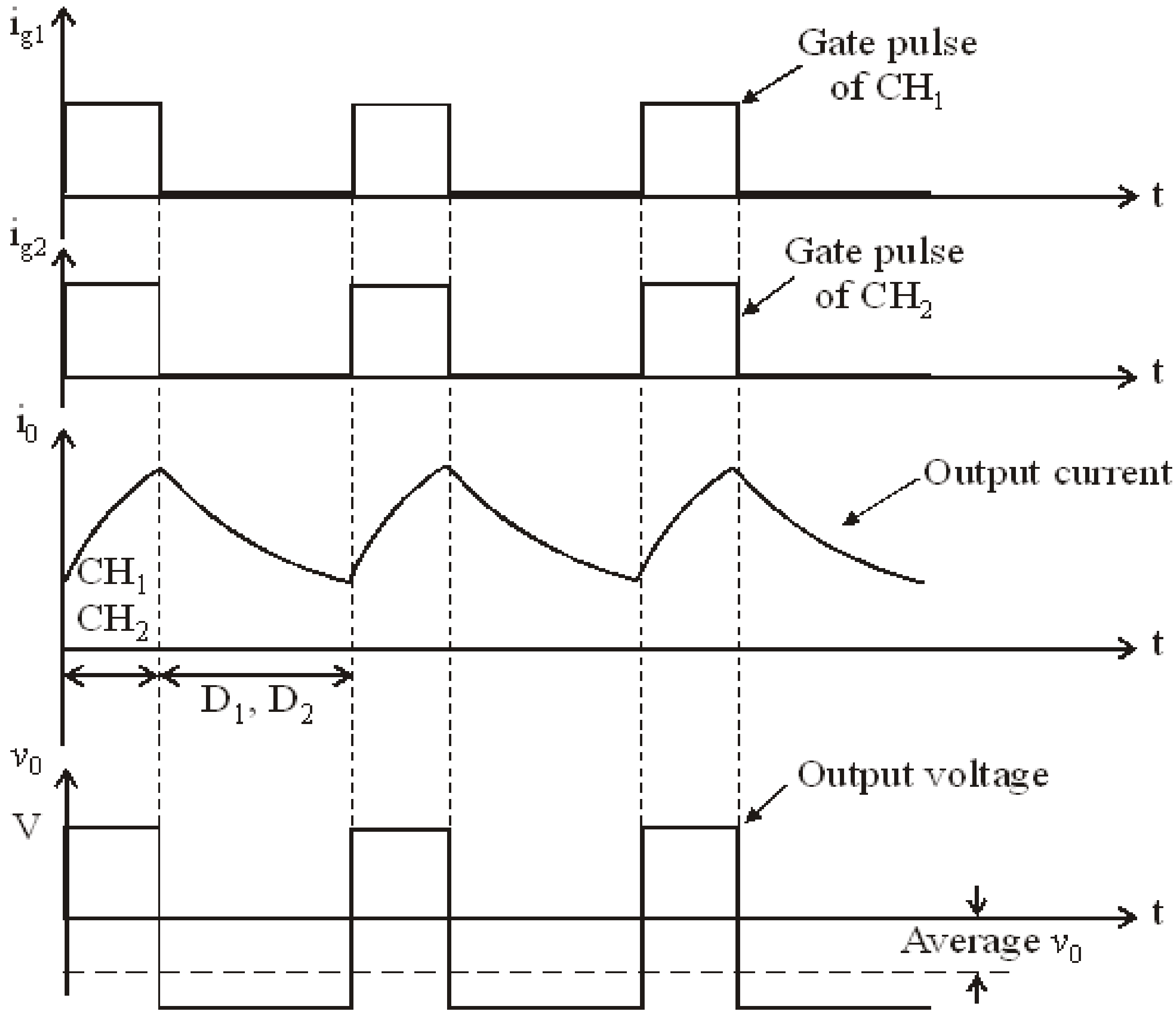


Fig. 2.22: Output Voltage and Current Waveforms for $t_{ON} < t_{OFF}$

CLASS E CHOPPER

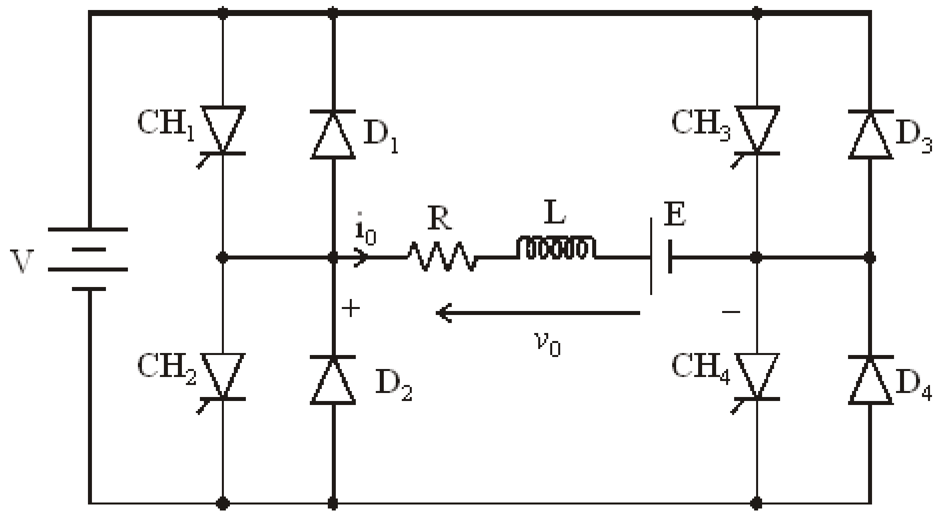


Fig. 2.23: Class E Chopper

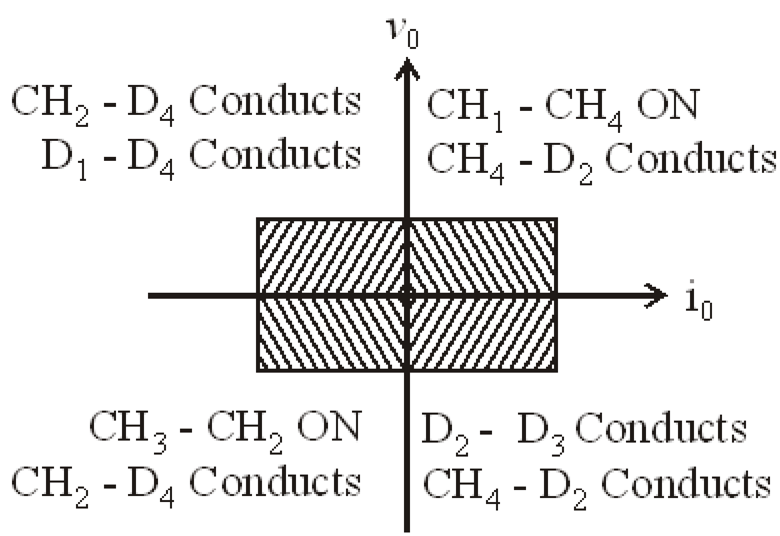


Fig. 2.23(a): Four Quadrant Operation

Figure 2.23 shows a class E 4 quadrant chopper circuit. When CH_1 and CH_4 are triggered, output current i_0 flows in positive direction as shown in figure 2.23 through CH_1 and CH_4, with output voltage $v_0 = V$. This gives the first quadrant operation. When both CH_1 and CH_4 are OFF, the energy stored in the inductor L drives i_0 through D_3 and D_2 in the same direction, but output voltage $v_0 = -V$. Therefore the chopper operates in the fourth quadrant. For fourth quadrant operation the direction of battery must be reversed. When CH_2 and CH_3 are triggered, the load current i_0 flows in opposite direction and output voltage $v_0 = -V$.

Since both i_0 and v_0 are negative, the chopper operates in third quadrant. When both CH_2 and CH_3 are OFF, the load current i_0 continues to flow in the same direction through D_1 and D_4 and the output voltage $v_0 = V$. Therefore the chopper operates in second quadrant as v_0 is positive but i_0 is negative. Figure 2.23(a) shows the devices which are operative in different quadrants.

Exercise

A Chopper circuit is operating on TRC at a frequency of 2 kHz on a 460 V supply. If the load voltage is 350 volts, calculate the conduction period of the thyristor in each cycle.

Solution

V = 460 V, V_{dc} = 350 V, f = 2 kHz

Chopping period $$T = \frac{1}{f}$$

$$T = \frac{1}{2\times10^{-3}} = 0.5\ m\sec$$

Output voltage $$V_{dc} = \left(\frac{t_{ON}}{T}\right)V$$

Conduction period of thyristor

$$t_{ON} = \frac{T\times V_{dc}}{V}$$

$$t_{ON} = \frac{0.5\times10^{-3}\times350}{460}$$

$$t_{ON} = 0.38\ \text{msec}$$