Chapter 8

Choppers

LEARNING OBJECTIVES:

- To describe the need and function of a chopper.
- To consider the operation of a d.c. chopper.
- To explain the different chopper control techniques.
- To examine the operation of step-up and step-down choppers.
- To classify the d.c. choppers in terms of their operating envelopes.
- To consider the operation of buck, boost, buck-boost and cuk-switching regulators.
- To explain the working principle and circuit analysis of Type A chopper.
- To explain the working principles of Type B, Type C, Type D and Type E chopper circuits.
- To consider the operation of various chopper commutation circuits.
- To examine the operation of Jones and Morgan chopper circuits.
- To explain the working principles of an a.c. chopper and a multiphase chopper.
- To consider the operation of buck, boost, buck-boost and cuk-switching regulators.

8.1 INTRODUCTION

To produce quality goods in any industry, the processes necessarily require the use of variable speed drives. Variable speed d.c. and a.c. drives are being increasingly used in all industries. These drives and processes take power from d.c. voltage sources. In many cases, conversion of the d.c. source voltage to different levels is required. For example, subway cars, trolley buses, or battery operated vehicles require power from a fixed voltage d.c. source. However, their speed control requires conversion of fixed voltage d.c. source to a variable-voltage d.c. source for the armature of the d.c. motor.

Generally, following techniques are available for obtaining the variable d.c. voltage from a fixed d.c. voltage:

(1) **Line Commutated Converters** (Conversion of AC supply to variable DC supply using controlled rectifiers; covered in Chapter 6).

(2) AC Link Chopper (inverter-rectifier) In this method the d.c. is first converted to a.c, by an inverter (d.c. to a.c. converter). The obtained a.c. is then stepped up or down by a transformer and then rectified back to d.c. by a rectifier. As the conversion is in two stages, d.c. to a.c. and a.c. to d.c., this technique is therefore, costly, bulky and less efficient. However, the transformer provides isolation between load and source. Figure 8.1 illustrates the conversion processes.

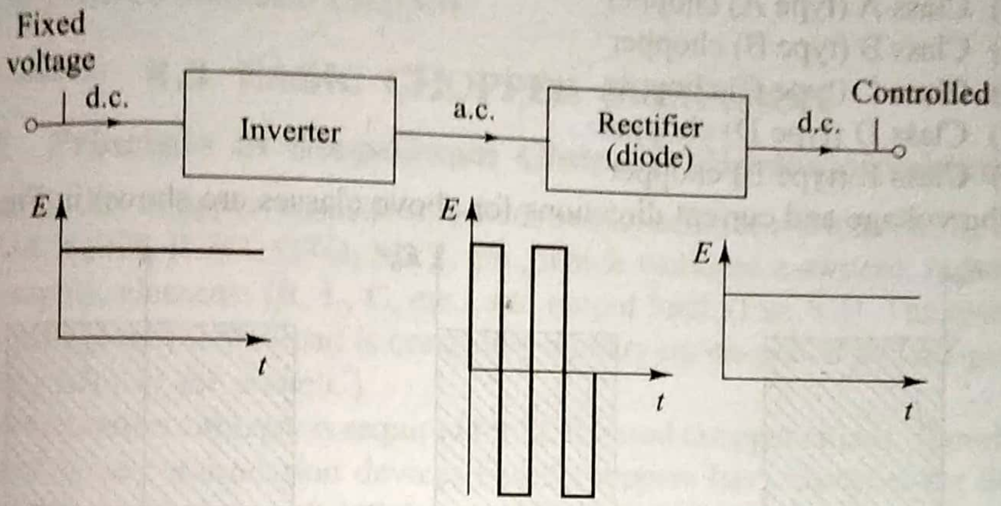


Fig. 8.1 *a.c.-link-chopper*

(3) DC Chopper (d.c. to d.c. power converters) A d.c. chopper is a static device (switch) used to obtain variable d.c. voltage from a source of constant d.c. voltage, Fig. 8.2. Therefore, chopper may be thought of as d.c. equivalent of an a.c. transformer since they behave in an identical manner. Besides, the saving in power, the d.c. chopper offers greater efficiency, faster response, lower maintenance, small size, smooth control, and, for many applications, lower cost, than motor-generator sets or gas tubes approaches.

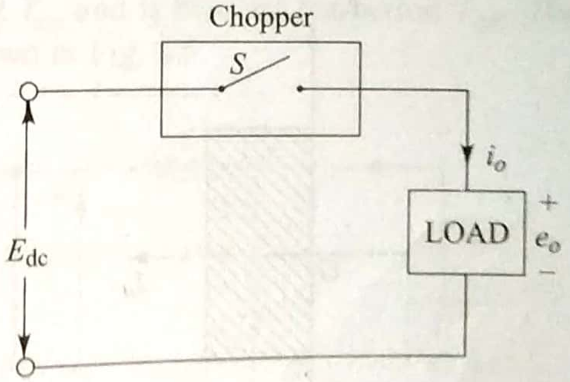


Fig. 8.2 *Basic chopper configuration*

Solid-state choppers due to various advantages are widely used in trolley cars, battery-operated vehicles, traction-motor control, control of a large number of d.c. motors from a common d.c. bus with a considerable improvement of power factor, control of induction motors, marine hoists, forklift trucks and mine haulers. The objective of this chapter is to discuss the basic principles of chopper operation and more common types of chopper configuration circuits.

8.2 BASIC CHOPPER CLASSIFICATION

DC choppers can be classified as:

(A) *According to the Input/Output Voltage Levels*

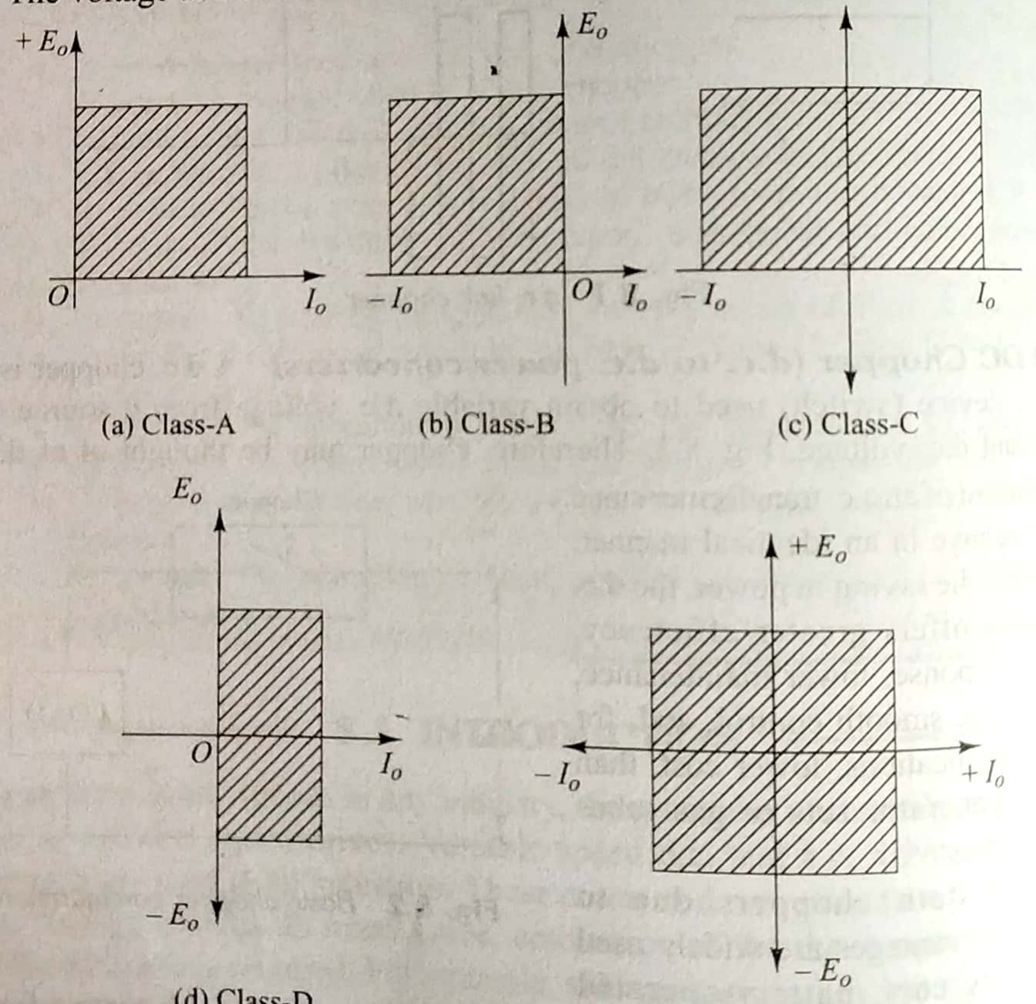
(i) *Step-down chopper:* The output voltage is less than the input voltage.

(ii) *Step-up chopper:* The output voltage is greater than the input voltage.

(B) According to the Directions of Output Voltage and Current

(i) Class A (type A) chopper
(ii) Class B (type B) chopper
(iii) Class C (type C) chopper
(iv) Class D (type D) chopper
(v) Class E (type E) chopper

The voltage and current directions for above classes are shown in Fig. 8.3.



(a) Class-A (b) Class-B (c) Class-C (d) Class-D (e) Class-E

Fig. 8.3 *Chopper configurations*

(C) According to Circuit Operation

(i) *First-quadrant chopper:* The output voltage and both must be positive. (Type A).

(ii) *Two-quadrant chopper:* The output voltage is positive and current can be positive or negative (class-C) or the output current is positive and the voltage can be positive or negative (class-D).

(iii) *Four-quadrant chopper:* The output voltage and current both can be positive or negative (class-E).

(D) According to Commutation Method

(i) Voltage-commutated choppers
(ii) Current-commutated choppers
(iii) Load-commutated choppers
(iv) Impulse-commutated choppers

8.3 BASIC CHOPPER OPERATION

8.3.1 Principle of Step-Down Chopper (Buck-Converter)

In general, d.c. chopper consists of power semiconductor devices (SCR, BJT, power MOSFET, IGBT, GTO, MCT, etc., which works as a switch), input d.c. power supply, elements (R, L, C, etc.) and output load. (Fig. 8.4). The average output voltage across the load is controlled by varying on-period and off-period (or duty cycle) of the switch.

A commutation circuitry is required for SCR based chopper circuit. Therefore, in general, gate-commutation devices based choppers have replaced the SCR-based choppers. However, for high voltage and high-current applications, SCR based choppers are used. The variations in on- and off periods of the switch provides an output voltage with an adjustable average value. The power-diode (D_P) operates in freewheeling mode to provide a path to load-current when switch (S) is OFF. The smoothing inductor filters out the ripples in the load current. Switch S is kept conducting for period T_{on} and is blocked for period T_{off}. The chopped load voltage waveform is shown in Fig. 8.5.

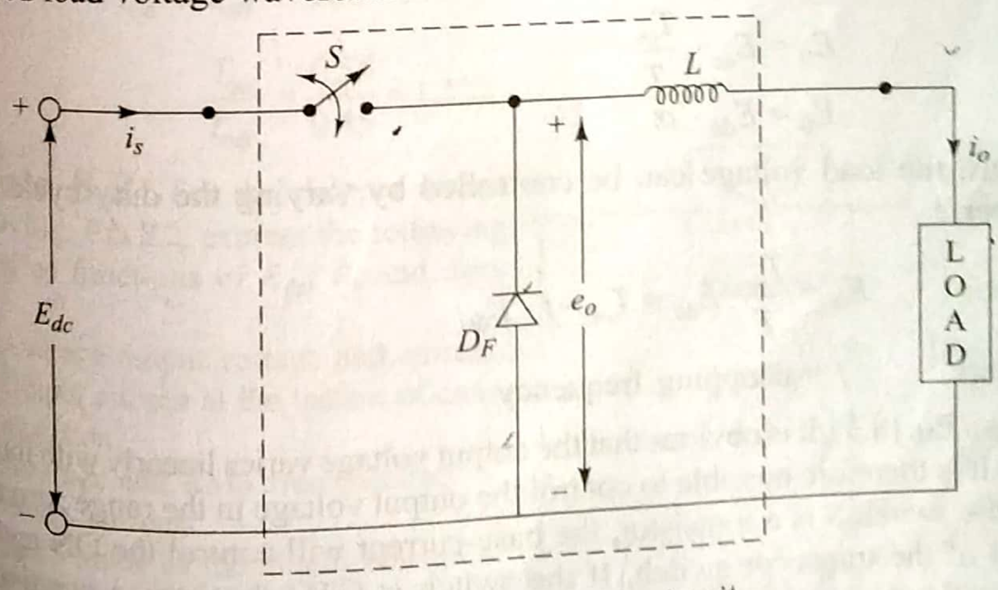


Fig. 8.4 *Basic chopper circuit*

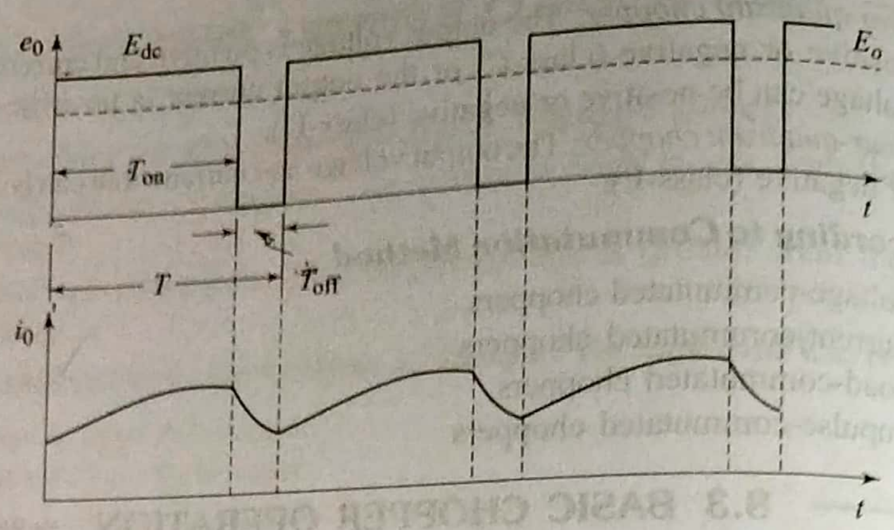


Fig. 8.5 *Output voltage and current waveforms*

During the period T_{on}, when the chopper is on, the supply terminals are connected to the load, terminals. During the interval T_{off}, when the chopper is off, load current flows through the freewheeling diode D_F. As a result, load terminals are short circuited by D_F and load voltage is therefore, zero during T_{off}. In this manner, a chopped d.c. voltage is produced at the load terminals.

From Fig. 8.5, the average load-voltage E_0 is given by

$$E_0 = E_{dc} \frac{T_{on}}{T_{on+off}} \tag{8.1}$$

where T_{on} = on-time of the chopper, T_{off} = off-time of the chopper

$T = T_{on} + T_{off}$ = chopping period

If $\alpha = \frac{T_{on}}{T}$ be the duty cycle, then above equation becomes,

$$E_0 = E_{dc} \cdot \frac{T_{on}}{T} \tag{8.2}$$

$$E_0 = E_{dc} \cdot \alpha \tag{8.3}$$

Thus, the load voltage can be controlled by varying the duty cycle of the chopper.

Also, $$E_0 = \frac{T_{on}}{T} E_{dc} = T_{on} \cdot f \cdot E_{dc} \tag{8.4}$$

where f = chopping frequency

From Eq. (8.3), it is obvious that the output voltage varies linearly with the duty-cycle. It is therefore possible to control the output voltage in the range zero to E_{dc}.

If the switch S is a transistor, the base-current will control the ON and OFF period of the transistor switch. If the switch is GTO thyristor, a positive gate pulse will turn-it ON and a negative gate pulse will turn it OFF. If the switch is an SCR, a commutation circuit is required to turn it OFF.

The average value of the load current is given by

$$I_0 = \frac{E_o}{R} = \frac{\alpha \cdot E_{dc}}{R} \tag{8.5}$$

The effective (RMS) value of the output voltage is given by

$$E_{o\,(RMS)} = \sqrt{\frac{E_{dc}^{\,2} \cdot T_{on}}{T}} = E_{dc} \cdot \sqrt{\frac{T_{on}}{T}}$$

$$= E_{dc}\sqrt{\alpha} \tag{8.6}$$

Solved Examples

Example 8.1 A d.c. chopper circuit connected to a 100 V d.c. source supplies an inductive load having 40 mH in series with a resistance of 5 Ω. A freewheeling diode is placed across the load. The load current varies between the limits of 10 A and 12 A. Determine the time ratio of the chopper.

Solution: The average value of the load current $= \dfrac{I_1 + I_2}{2} = \dfrac{10 + 12}{2} = 11$ A.

The maximum value of the load current $= \dfrac{100}{5} = 20$ A

Now, the average value of the voltage, $E_{0av} = 100 \times \dfrac{11}{20} = 55$ V

Also, $\quad E_{dc} \cdot \dfrac{T_{on}}{T_{on} + T_{off}} = E_{0av}$ or $\dfrac{T_{on}}{T_{on} + T_{off}} = \dfrac{E_{0av}}{E_{dc}}$

$$\frac{T_{on}}{T_{on} + T_{off}} = \frac{55}{100} = 0.55 \quad \therefore T_{on} = 0.55\,(T_{on} + T_{off})$$

$$\therefore \quad \frac{T_{on}}{T_{off}} = \frac{0.55}{0.45} = 1.222.$$

Example 8.2 For the chopper circuit shown in Fig. Ex. 8.2, express the following variables as functions of E_{dc}, R, and duty cycle α.

(i) Average output voltage and current.
(ii) Output current at the instant of commutation.
(iii) Average and RMS freewheeling diode currents.
(iv) RMS value of the output voltage.
(v) RMS and average load currents.

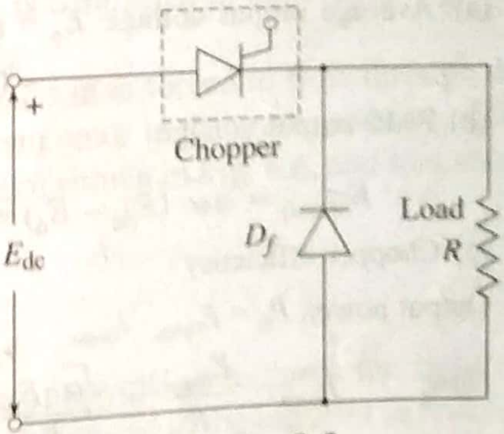


Fig. Ex. 8.2

Solution: With resistive load, load current waveforms are similar to load voltage waveforms.

∴ (i) Average output voltage $E_0 = E_{dc}\dfrac{T_{on}}{T} = E_{dc}\cdot\alpha.$

Average output current, $I_{0av} = \dfrac{E_0}{R} = \dfrac{E_{dc}}{R}\alpha.$

(ii) Output current at the instant of commutation $= \dfrac{E_{dc}}{R}.$

(iii) Freewheeling diode does not come into picture for a resistive load. Hence, average and RMS values of freewheeling diode currents are zero.

(iv) RMS value of output voltage

$$= \left[\frac{T_{on}}{T}E_{dc}^2\right]^{1/2} = \sqrt{\alpha}\cdot E_{dc}$$

(v) Now, average thyristor current

$$= \frac{E_{dc}}{R}\cdot\frac{T_{on}}{T} = \alpha\frac{E_{dc}}{R}$$

$$\text{RMS thyristor current} = \left(\alpha\cdot\left(\frac{E_{dc}}{R}\right)^2\right)^{1/2} = \sqrt{\alpha}\cdot\frac{E_{dc}}{R}$$

Example 8.3 A step-down dc chopper has a resistive load of R = 15 ohm and input voltage E_{dc} = 200 V. When the chopper remains ON, its voltage drop is 2.5 V. The chopper frequency is 1 kHz. If the duty cycle is 50%, determine:

(a) Average output voltage
(b) RMS output voltage
(c) Chopper efficiency
(d) Effective input resistance of chopper

Solution:

Given: Input voltage E_{dc} = 200 V, duty cycle α = 0.5

$R = 15\ \Omega$, F = 1 kHz, Chopper drop E_d = 2.5 V

(a) Average output voltage $E_0 = \alpha\cdot(E_{dc} - E_d)$

$= 0.5\ (200 - 2.5) = 98.75$ V

(b) RMS output voltage

$$E_{0(rms)} = \sqrt{\alpha}\ (E_{dc} - E_d) = \sqrt{0.5}\ (200 - 2.5) = 139.653 \text{ V}$$

(c) Chopper efficiency

Output power, $P_0 = E_{0rms}\cdot I_{0rms}$

Now, $I_{0rms} = \dfrac{E_{0rms}}{R} = \dfrac{\sqrt{\alpha}\cdot E_{dc}}{R}$

∴ $P_0 = \sqrt{\alpha}\cdot E_{dc}\cdot\dfrac{\sqrt{\alpha}\cdot E_{dc}}{R} = \dfrac{\alpha E_{dc}^2}{R}$

If E_d is the chopper drop, then

$$P_0 = \frac{\alpha (E_{dc} - E_d)^2}{R} = \frac{0.5\,(200 - 2.5)^2}{15} = 1300.21\ \omega$$

Now, the input power to the chopper is given by

$$P_i = \frac{1}{T}\int_0^T E_{dc}\ i_s\ dt = \frac{1}{T}\int_0^{T_{on}} E_{dc}\frac{(E_{dc} - E_d)}{R}\ dt = \frac{1}{T}\int_0^{\alpha\cdot T} \frac{E_{dc}\ (E_{dc} - E_d)}{R}\ dt$$

$$= \frac{E_{dc}\ (E_{dc} - E_d)}{T.R.}(t)_o^{\alpha_T} = \frac{\alpha\, E_{dc}\ (E_{dc} - E_d)}{R.} = \frac{0.5\,(200)\,(200 - 2.5)}{15} = 1316.67\ \text{W}$$

$\therefore$ Chopper efficiency, $\eta = \frac{P_o}{P_i} = \frac{1300.21}{1316.67} = 0.9874 = 98.74\%$

8.3.2 Principle of Step-up Choppers

The chopper configuration of Fig. 8.4 is capable of giving a maximum voltage that is slightly smaller than the input d.c. voltage (i.e. $E_0 < E_{dc}$). Therefore, the chopper configuration of Fig. 8.4 is called as step-down choppers. However, the chopper can also be used to produce higher voltages at the load than the input voltage (i.e., $E_0 \geq E_{dc}$). This is called as step-up chopper and is illustrated in Fig. 8.6.

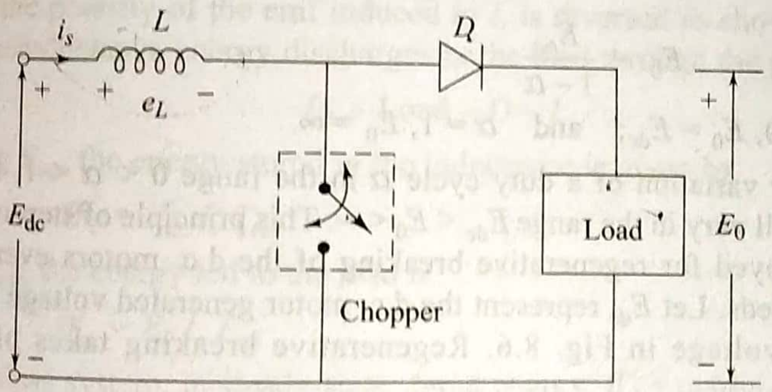


Fig. 8.6 *Step-up chopper or boost choppers*

When the chopper is ON, the inductor L is connected to the supply E_{dc}, and inductor stores energy during on-period, T_{on}.

When the chopper is OFF, the inductor current is forced to flow through the diode and load for a period T_{off}. As the current tends to decrease, polarity of the emf induced in inductor L is reversed to that of shown in Fig. 8.6, and as a result voltage across the load E_0 becomes

$$E_0 = E_{dc} + L\frac{di_s}{dt}$$

that is, the inductor voltage adds to the source voltage to force the inductor current into the load. In this manner, the energy stored in the inductor is released to the load. Here, higher value of inductance L is preferred for getting lesser ripple in the output.

During the time T_{on}, when the chopper is ON, the energy input to the inductor from the source is given by

$$W_i = E_{dc} I_s T_{on} \tag{8.7}$$

Equation 8.7 is based on the assumption that the source current is free from ripples.

Now, during the time T_{off}, when chopper is OFF, energy released by the inductor to the load is given by

$$W_0 = (E_0 - E_{dc}) I_s T_{off}. \tag{8.8}$$

Considering the system to be lossless, and, in the steady-state, these two energies will be equal.

$$\therefore \quad E_{dc} \cdot I_s T_{on} = (E_0 - E_{dc}) I_s T_{off}$$

$$\text{or} \quad E_0 = E_{dc} \frac{T_{on} + T_{off}}{T_{off}} \tag{8.9}$$

$$\text{or} \quad E_0 = E_{dc} \frac{T}{T - T_{on}} \tag{8.10}$$

$$\text{or} \quad E_0 = E_{dc} \frac{1}{T/T - T_{on}/T}, \text{ But, } \frac{T_{on}}{T} = \alpha$$

$$\therefore \quad E_0 = \frac{E_{dc}}{1-\alpha} \tag{8.11}$$

For $\alpha = 0, E_0 = E_{dc}$; and $\alpha = 1, E_0 = \infty$.

Hence, for variation of a duty cycle α in the range $0 < \alpha < 1$, the output voltage E_0 will vary in the range $E_{dc} < E_0 < \infty$. This principle of step-up chopper can be employed for regenerative breaking of the d.c. motors even at lower operating speeds. Let E_{dc} represent the d.c. motor generated voltage and E_0 the d.c. source voltage in Fig. 8.6. Regenerative breaking takes place when $\left(E_{dc} + L\frac{di_s}{dt}\right)$ exceeds E_0. Even at decreasing motor speeds, duty cycle α can be so adjusted that $\left(E_{dc} + L\frac{di_s}{dt}\right)$ is more than the fixed supply voltage E_0.

SOLVED EXAMPLE

Example 8.4 A step-up chopper is used to deliver load voltage of 500 V from a 220V d.c. source. If the blocking period of the thyristor is 80 μs, compute the required pulse width.

Solution: From Eq. (8.10) we have, $E_0 = E_{dc} \dfrac{T_{on} + T_{off}}{T_{off}}$

$$\therefore \quad 500 = 220 \frac{T_{on} + 80 \times 10^{-6}}{80 \times 10^{-6}}, \quad \therefore T_{on} = 101.6 \times 10^{-6} = 101.6 \ \mu s.$$

8.3.3 Principle of Step-Up/Down Choppers

A chopper can also be used both in step-up and step-down modes by continuously varying its duty cycle. The principle of operation is illustrated in Fig. 8.7. As shown, the output, voltage polarity is opposite to that of input voltage E_{dc}.

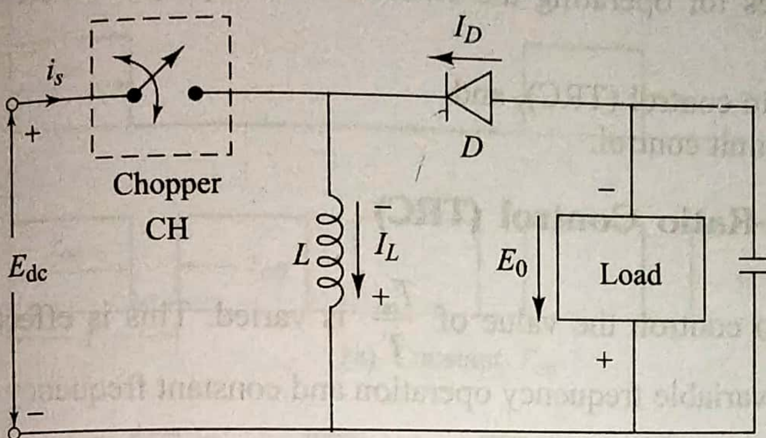


Fig. 8.7 *Step-up/down chopper*

When the chopper is ON, the supply current flows through the path E_{dc+} - $CH - L - E_{dc-}$. Hence, inductor L stores the energy during the T_{on} period. When the chopper CH is OFF, the inductor current tends to decrease and as a result, the polarity of the emf induced in L is reversed as shown in Fig. 8.7. Thus, the inductance energy discharges in the load through the path,

$$L_+ - \text{Load} - D - L_-.$$

During T_{on}, the energy stored in the inductance is given by,

$$W_i = E_{dc} I_s T_{on} \tag{8.12}$$

During T_{off}, the energy fed to the load is

$$W_o = E_0 I_s T_{off} \tag{8.13}$$

For a lossless system, in steady-state: Input energy, W_i = output energy, W_o

$$\therefore \; E_{dc} \cdot I_s \cdot I_{on} = E_0 I_s T_{off}, \text{ or } E_0 = E_{dc} \cdot \frac{T_{on}}{T_{off}} \tag{8.14}$$

or

$$E_0 = E_{dc} \cdot \frac{T_{on}}{T - T_{on}} = E_{dc} \cdot \frac{1}{T/T_{on} - T_{on}/T_{on}}$$

Substituting $\frac{T_{on}}{T} = \alpha$, we get, $E_0 = E_{dc} \cdot \frac{1}{1/\alpha - 1}$

or

$$E_0 = E_{dc} \frac{\alpha}{1-\alpha} \tag{8.15}$$

For $0 < \alpha < 0.5$, the step-down chopper operation is achieved and for $0.5 < \alpha < 1$, step-up chopper operation is obtained.

8.4 CONTROL STRATEGIES

It is seen from Eq. (8.3), that, average value of output voltage, E_0 can be controlled by periodic opening and closing of the switches. The two types of control strategies for operating the switches are employed in d.c. choppers. They are:

(1) Time-ratio control (TRC), and
(2) Current limit control.

8.4.1 Time-Ratio Control (TRC)

In the time-ratio control, the value of $\frac{T_{on}}{T}$ is varied. This is effected in two ways. They are variable frequency operation and constant frequency operation.

1. *Constant Frequency System* In this type of control strategy, the on-time T_{on}, is varied but the chopping frequency f ($f = 1/T$, and hence the chopping period T) is kept constant. This control strategy is also called as the *pulse-width modulation control*.

Figure 8.8 illustrates the principle of pulse-width modulation. As shown, chopping period T is constant. In Fig. 8.8(a), $T_{on} = \frac{1}{4}T$, so that duty cycle $\alpha = 25\%$. In Fig. 8.8 (b), $T_{on} = \frac{3}{4}T$, so that duty cycle $\alpha = 75\%$. Hence, the output voltage E_0 can be varied by varying the on-time T_{on}.

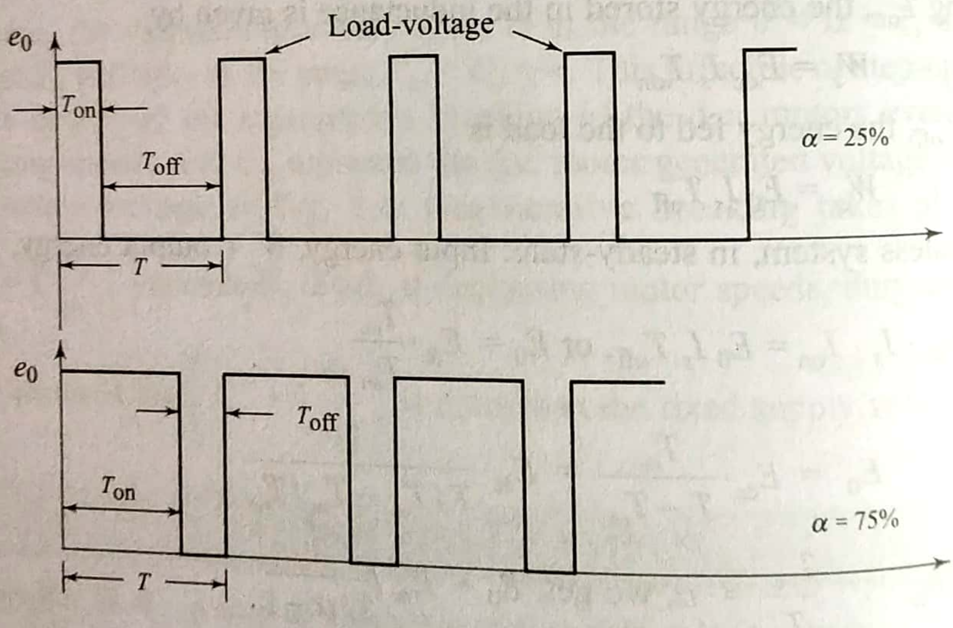


Fig. 8.8 *Pulse-width modulation control (constant frequency f)*

2. *Variable Frequency System* In this type of control strategy, the chopping frequency f is varied and either–

(a) ON-time, T_{on}, is kept constant or (b) OFF-time, T_{off}, is kept constant. This type of control strategy is also called as *frequency modulation control*.

Figure 8.9 illustrates the principle of frequency modulation. As shown in Fig. 8.9(a), chopping period T is varied but on-time T_{on} is kept constant. The output voltage waveforms are shown for two different duty cycles. In Fig. 8.9(b), chopping period T is varied but T_{off} is kept constant.

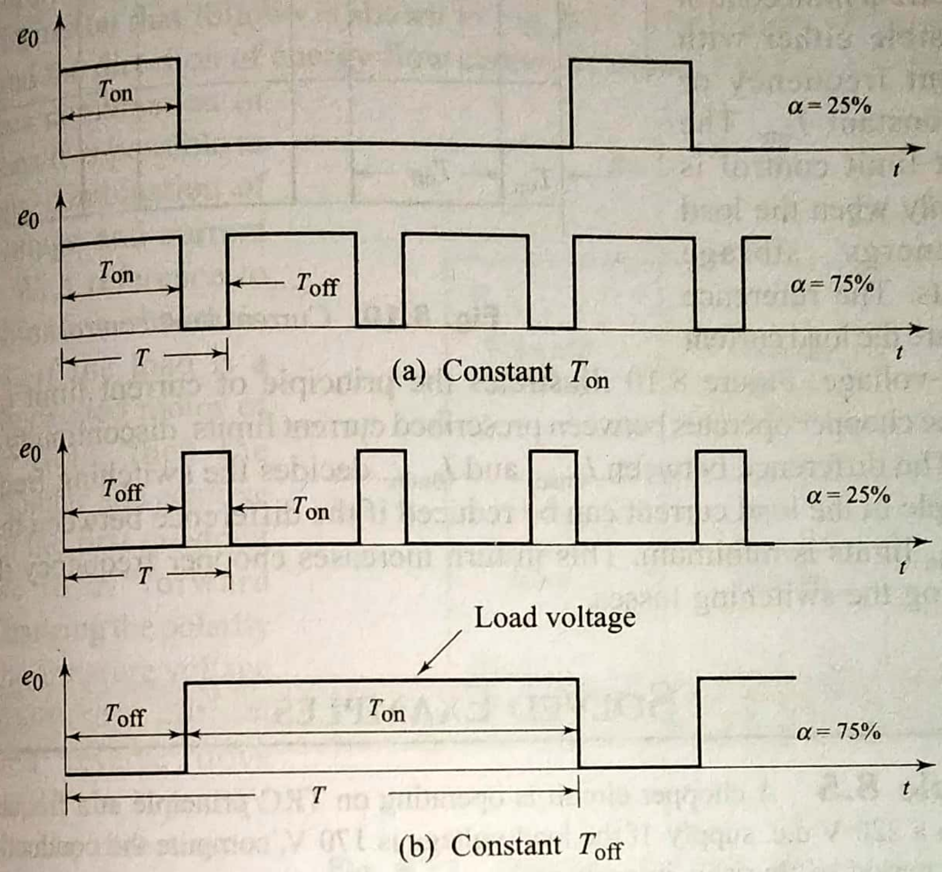


Fig. 8.9 *Output voltage waveforms for variable frequency system*

Frequency modulation control strategy has the following major disadvantages compared to pulse-width modulation control.

(i) The chopping frequency has to be varied over a wide range for the control of output voltage in frequency modulation. Filter design for such wide frequency variation is, therefore, quite difficult.

(ii) For the control of duty cycle, frequency variation would be wide. As such, there is a possibility of interference with signalling and telephone lines in frequency modulation technique.

(iii) The large OFF-time in frequency modulation technique may make the load current discontinuous, which is undesirable.

Thus, the constant frequency system (PWM) is the preferred scheme for chopper drives.

8.4.2 Current Limit Control

In current limit control strategy, the chopper is switched ON and OFF so that 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 freewheels and decreases exponential. When it reaches the lower limit, the chopper is switched ON. Current limit control is possible either with constant frequency or with constant T_{on}. The current limit control is used only when the load has energy storage elements. The reference values are the load current or load-voltage. Figure 8.10 illustrates the principle of current limit control. Since the chopper operates between prescribed current limits, discontinuity cannot occur. The difference between I_{0max} and I_{0min}, decides the switching frequency. The ripple in the load current can be reduced if the difference between the I_{0max} and I_{0min} limits is minimum. This in turn increases chopper frequency thereby increasing the switching losses.

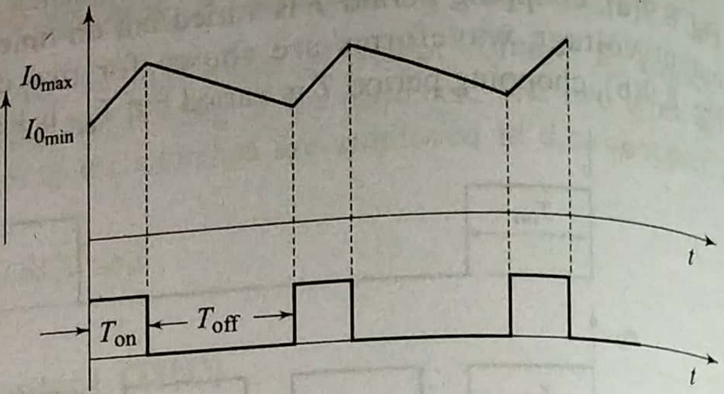


Fig. 8.10 *Current limit control*

SOLVED EXAMPLES

Example 8.5 A chopper circuit is operating on TRC principle at a frequency of 2 kHz on a 220 V d.c. supply. If the load voltage is 170 V, compute the conduction and blocking period of thyristor in each cycle.

Solution: From Eq. (8.2), $E_0 = E_{dc} \cdot T_{on} \cdot f$

Given : $f = 2$ kHz, $E_{dc} = 220$ V, $E_o = 170$.

Conduction period, $T_{on} = \dfrac{E_0}{E_{dc} \cdot f} = \dfrac{170}{220 \times 2 \times 10^3} = T_{on} = 0.386$ ms.

But, chopping period, $T = \dfrac{1}{f} = \dfrac{1}{2 \times 10^3} = 0.5$ ms

$\therefore$ Blocking period of SCR, $T_{off} = T - T_{on} = 0.5 - 0.386 = 0.114$ m sec.

Example 8.6 In a 110 V dc chopper drive using the CLC scheme, the maximum possible value of the accelerating current is 300 A, the lower-limit of the current pulsation is 140 A. The ON- and OFF periods are 15 ms and 12 ms, respectively. Calculate the limit of current pulsation, chopping frequency, duty cycle and the output voltage.

Solution: Given: $T_{on} = 15$ ms, $T_{off} = 12$ ms, $I_{0max} = 300\ A$, $I_{0min} = 140\ A$

Now, maximum limit of current pulsation = 300 – 140 = 160 A.

Chopping frequency $= \dfrac{1}{T} = \dfrac{1}{15+12} = 37$ Hz & ratio, $\alpha = \dfrac{T_{on}}{T} = \dfrac{15}{27} = 0.56$

Output voltage, $E_0 = \alpha E_{dc} = 0.56 \times 110 = 61.60$ V

8.5 CHOPPER CONFIGURATION

Choppers may be classified according to the number of quadrants of the $E_0 - I_0$ diagram in which they are capable of operating. A classification that is convenient for the discussion that follows is shown in Fig. 8.11. The polarity of the output voltage and the direction of energy flow cannot be changed in Figs 8.4 and 8.6. By various combination of connections it is possible to realize any combination of output voltage and current polarity. With reference to the combination shown in Fig. 8.11, if the load is a separately excited motor of constant field, then the positive voltage and positive current in the first quadrant give rise to a "forward drive." Changing the polarity of both the armature voltage and the armature current results in a "reverse" drive (quadrant III). In II and IV quadrants, the direction of energy flow is reversed and the motor operates as a *generator braking* rather than driving.

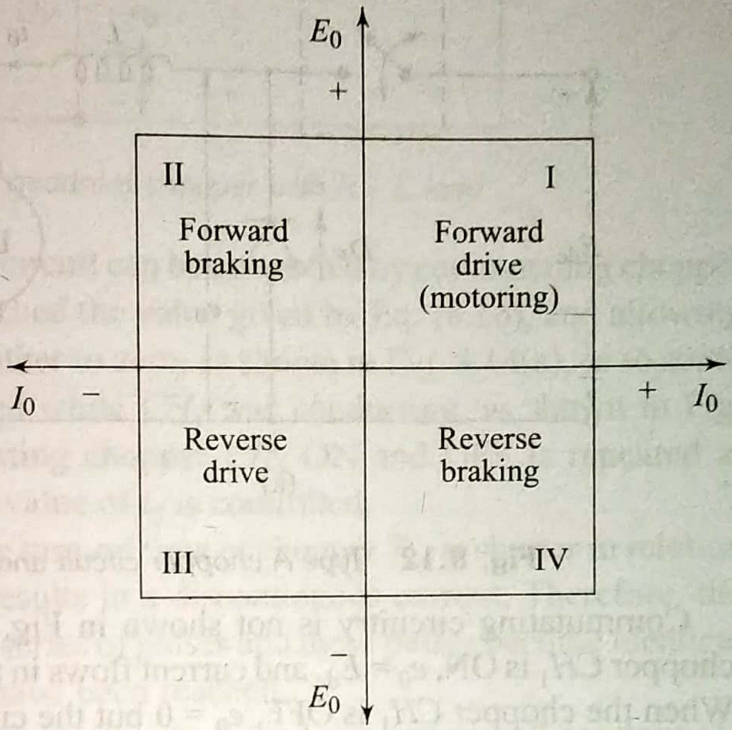


Fig. 8.11 *Polarities of output voltage and current*

In regenerative breaking, most of the breaking energy is returned to the supply. The condition for regeneration is that the rotational emf must be more than the applied voltage so that the current is reversed and the mode of operation changes from motoring to generating. It was observed that about 35% of the energy put into an automotive vehicle during typical urban traction is theoretically recoverable by regenerative breaking. However, the exact value of the recoverable energy is a function of the type of driving, the efficiency of the drive train, gear ratios in the drive/train etc. Therefore, the choppers which gives this regenerative breaking facility are widely used compared to systems without regenerative breaking.

D.C. chopper circuits are combined in accordance with the quadrants, in which a d.c. motor assumed as a load is required to operate. In the first and third quadrants, for instance, a resistance may also serve as a load, but a generating mode can be maintained over any significant span of time only, if the load is capable of delivering sustained power. This section describes the classification of various chopper configurations.

8.5.1 First Quadrant or Class A Chopper [Step-down Chopper with R-L Load]

Figure 8.12 illustrates the basic power circuit of first quadrant chopper. The term 'first quadrant' signifies that circuit parameters E_0 and I_0 occur only in the first quadrant of $E_0 - I_0$ diagram.

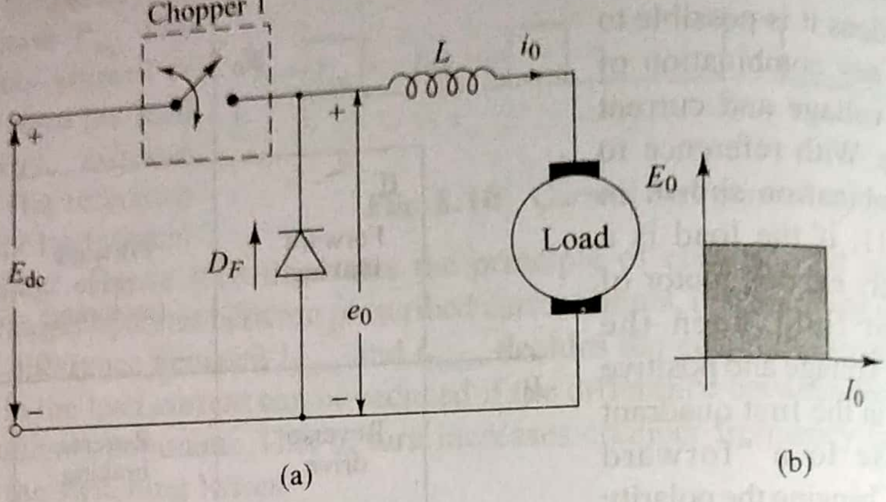


Fig. 8.12 *Type A chopper circuit and $E_0 - I_0$ characteristic*

Commutating circuitry is not shown in Fig. 8.12 for simplicity. When the chopper CH_1 is ON, $e_0 = E_{dc}$ and current flows in the direction shown in Fig. 8.12. When the chopper CH_1 is OFF, $e_0 = 0$ but the current i_0 flows in the load in the same direction through freewheeling diode D_f. Therefore, both average load voltage E_0 and current I_0 are positive and thus power flows from source to load. This operation is shown by the hatched area in Fig. 8.12(b). Therefore, this configuration is used for motoring operation of d.c. motor load. Class A chopper circuit is also called as step-down chopper as average output voltage E_0 is always less than the d.c. input voltage E_{dc}. Due to the motoring operation, this chopper is also called as motoring chopper.

1. *Steady-state Time-domain Analysis* Class A chopper circuit of Fig. 8.12 can also be drawn in terms of three separate circuit elements, as shown in Fig. 8.13. Here, load is R–L E_b type load. E_b is the load voltage which may be a d.c. motor or a battery.

The operation of this system may be understood from the consideration of the waveforms of the circuit variables shown in Fig. 8.14. This Fig. 8.14 shows the two modes of circuit operation.

(i) When chopper CH_1 is ON, the supply voltage E_{dc} appears at the terminals of the armature circuit and, the current i_0 would increase until it reached the steady-state value expressed by

$$i_0 = \frac{E_{dc} - E_b}{R} \tag{8.16}$$

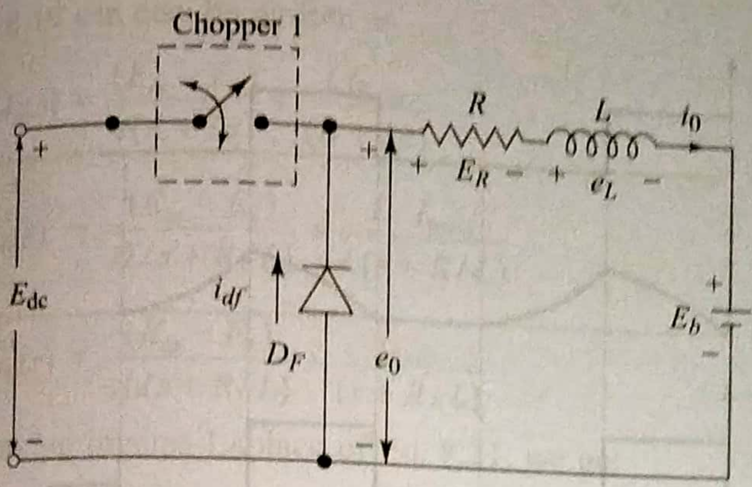


Fig. 8.13 *First quadrant chopper with R – L load*

The average current I_0 in the circuit can be controlled by commutating chopper CH_1 before the current has reached the value given by Eq. (8.16), and allowing it to decay through diode DF either to zero, as shown in Fig. 8.14(a), or to some lower value than it had attained while CH_1 was conducting, as shown in Fig. 8.14(b). If this process of turning chopper CH_1 ON and OFF is repeated at regular intervals, then average value of i_0 is controlled.

As shown in Fig. 8.14(a), the turn-on time of chopper T_{on} is shorter in relation to chopping period T, which results in a discontinuous current. Therefore, the current waveform consists of a series of pulses and these pulses become identical when steady-state conditions have been reached.

If turn-on time T_{on} is longer in relation to T, the load current will not decay to zero during the interval $T_{on} < t < T$, but will merely decrease until CH_1 is again turned-on. Therefore, in the steady state, the current will flow continuously as shown in Fig. 8.14(b).

***Mode 1:* $0 \leq t \leq T_{on}$** When the chopper is ON, current flows through the path $E_{dc+} - R - L - E_b - E_{dc-}$. For this mode of operation, the differential equation governing its performance is given by

$$E_{dc} = R \cdot i_0 + L\frac{di_0}{dt} + E_b, \text{ for } 0 \leq t \leq T_{on} \tag{8.17}$$

***Mode 2:* $T_{on} \leq t \leq T$** When chopper is OFF, the load current continuously flowing through the freewheeling diode D_f. For this mode of operation, the differential equation governing its performance is given by

$$0 = R \cdot i_0 + L\frac{di_0}{dt} + E_b, \text{ for } T_{on} \leq t \leq T \tag{8.18}$$

From Fig. 8.14(b), it is observed that the initial value of current for Eq. (8.17) is I_{0min} and I_{0max} for Eq. (8.18).