Power Electronics

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KHANNA PUBLISHERS

Part2

7

Choppers

IN THIS CHAPTER

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Many industrial applications require power from dc voltage sources. Several of these applications, however, perform better in case these are fed from variable dc voltage sources. Examples of such dc systems are subway cars, trolley buses, battery-operated vehicles, battery-charging etc.

From ac supply systems, variable dc output voltage can be obtained through the use of phase-controlled converters (discussed in Chapter 6) or motor-generator sets. The conversion of fixed dc voltage to an adjustable dc output voltage, through the use of semiconductor devices, can be carried out by the use of two types of dc to dc converters given below [5].

AC Link Chopper. In the ac link chopper, dc is first converted to ac by an inverter (dc to ac converter). AC is then stepped-up or stepped-down by a transformer which is then converted back to dc by a diode rectifier, Fig. 7.1 (*a*). As the conversion is in two stages, dc to ac and then ac to dc, ac link chopper is costly, bulky and less efficient.

DC Chopper. A chopper is a static circuit that converts fixed dc input voltage to a variable dc output voltage directly, Fig. 7.1 (*b*). A chopper may be thought of as dc equivalent of an ac transformer since they behave in an identical manner. As choppers involve one stage conversion, these are more efficient.

Choppers are now being used all over the world for rapid transit systems. These are also used in trolley cars, marine hoists, forklift trucks and mine haulers. The future electric automobiles are likely to use choppers for their speed control and braking. Chopper systems offer smooth control, high efficiency, fast response and regeneration.

The power semiconductor devices used for a chopper circuit can be force-commutated thyristor, power BJT, power MOSFET, GTO or IGBT. These devices, in general, can be represented by a switch SW with an arrow as shown in Fig. 7.1 (*c*). When the switch is off, no

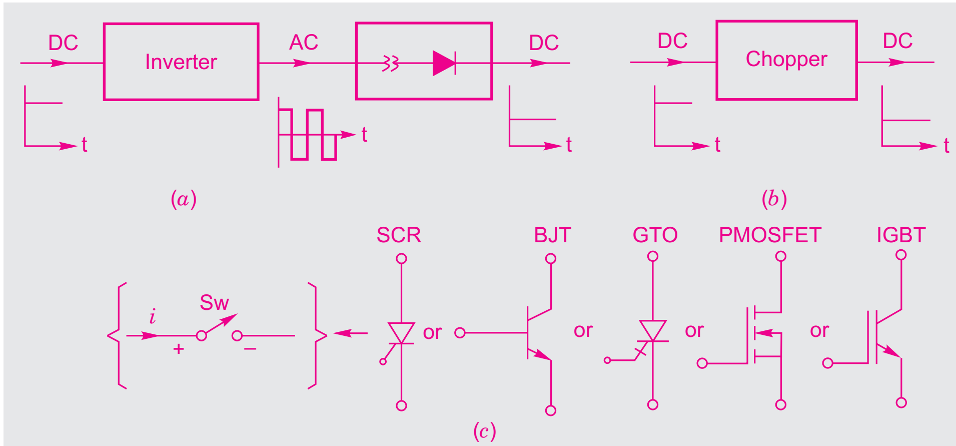

Fig. 7.1. (*a*) AC link chopper and (*b*) dc chopper (or chopper) (*c*) Representation of a power semiconductor device.

current can flow. When the switch is on, current flows in the direction of arrow only. The power semiconductor devices have on-state voltage drops of 0.5 V to 2.5 V across them. For the sake of simplicity, this voltage drop across these devices is neglected.

As stated above, a chopper is dc equivalent to an ac transformer having continuously variable turns ratio. Like a transformer, a chopper can be used to step down or step up the fixed dc input voltage. As step-down dc choppers are more common, the term dc chopper, or chopper, in this book would mean a step-down dc chopper unless stated otherwise.

The object of this chapter is to discuss the basic principles of chopper operation and the more common types of chopper configurations using ideal switches.

7.1 PRINCIPLE OF CHOPPER OPERATION

A chopper is a high speed on/off semiconductor switch. It connects source to load and disconnects the load from source at a fast speed. In this manner, a chopped load voltage as shown in Fig. 7.2 (*b*) is obtained from a constant dc supply of magnitude V_s. In Fig. 7.2 (*a*), chopper is represented by a switch *SW* inside a dotted rectangle, which may be turned-on or turned-off as desired. For the sake of highlighting the principle of chopper operation, the circuitry used for controlling the on, off periods of this switch is not shown. During the period T_{on}, chopper is on and load voltage is equal to source voltage V_s. During the interval T_{off}, chopper is off, load current flows through the freewheeling diode *FD*. As a result, load terminals are short circuited by *FD* and load voltage is therefore zero during T_{off}. In this manner, a chopped dc voltage is produced at the load terminals. The load current as shown in Fig. 7.2 (*b*) is continuous. During T_{on}, load current rises whereas during T_{off}, load current decays. From Fig. 7.2 (*b*), average load voltage V_0 is given by

$$V_0 = \frac{T_{on}}{T_{on} + T_{off}} V_s = \frac{T_{on}}{T} V = \alpha V_s \qquad \text{...(7.1)}$$

where T_{on} = on-time ; T_{off} = off-time

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

$\alpha = \dfrac{T_{on}}{T}$ = duty cycle

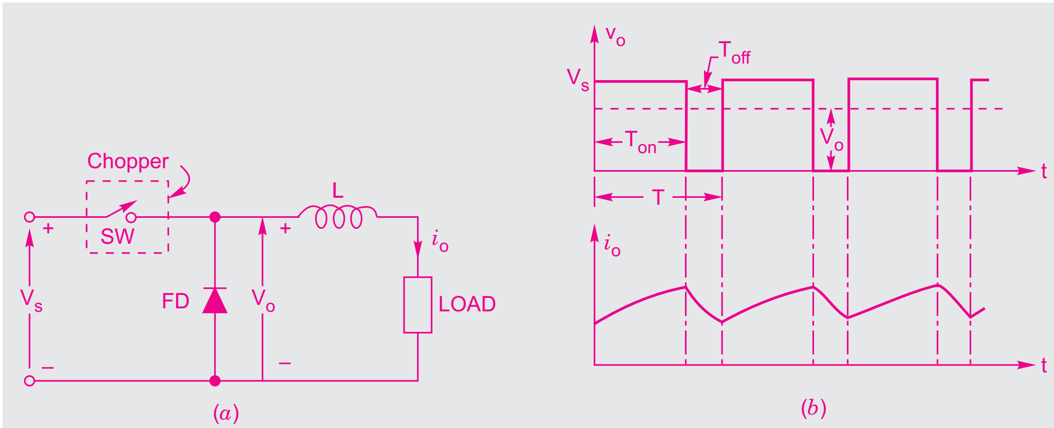

Fig. 7.2. (*a*) Elementry chopper circuit and (*b*) output voltage and current waveforms.

Thus load voltage can be controlled by varying duty cycle α. Eq. (7.1) shows that load voltage is independent of load current. Eq. (7.1) can also be written as

$$V_0 = f \cdot T_{on} \cdot V_s \quad \text{...(7.2)}$$

where $f = \dfrac{1}{T}$ = chopping frequency.

7.2 CONTROL STRATEGIES

It is seen from Eq. (7.1) that average value of output voltage V_0 can be controlled through α by opening and closing the semiconductor switch periodically. The various control strategies for varying duty cycle α are as follows :

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

These are now described one after the other.

7.2.1. Time Ratio Control (TRC)

As the name suggests, in this control scheme, time ratio T_{on}/T (as duty ratio or duty cycle) is varied. This is realized in two different strategies called *constant frequency system* and *variable frequency system* as detailed below :

1. Constant Frequency System

In this scheme, the on-time T_{on} is varied but chopping frequency f (or chopping period T) is kept constant. Variation of T_{on} means adjustment of pulse width, as such this scheme is also called *pulse-width-modulation scheme.*

Fig. 7.3 illustrates the principle of pulse-width modulation. Here chopping period T is constant. In Fig. 7.3 (*a*), $T_{on} = \frac{1}{4}T$ so that $\alpha = 0.25$ or $\alpha = 25\%$. In Fig. 7.3 (*b*), $T_{on} = \frac{3}{4}T$ so that $\alpha = 0.75$ or 75%. Ideally α can be varied from zero to unity. Therefore output voltage V_0 can be varied between zero and source voltage V_s.

2. Variable Frequency System

In this scheme, the chopping frequency f (or chopping period T) is varied and either (*i*) on-time T_{on} is kept constant or (*ii*) off-time T_{off} is kept constant. This method of controlling α is also called frequency-modulation scheme.

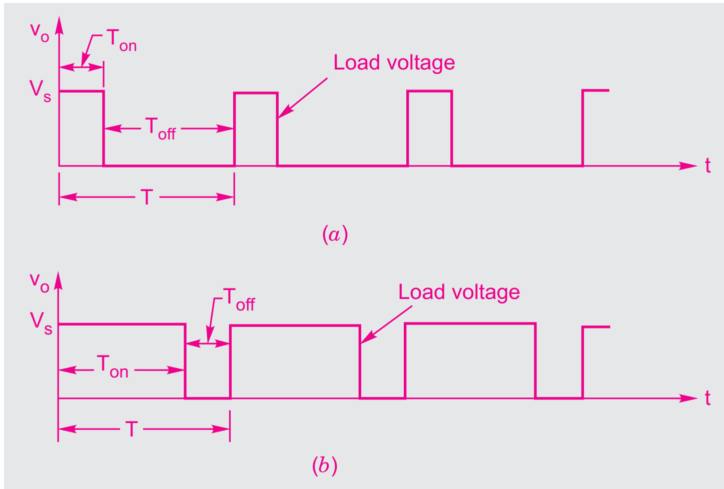

Fig. 7.3. Principle of pulse-width modulation (constant T).

Fig. 7.4 illustrates the principle of frequency modulation. In Fig. 7.4 (a), T_{on} is kept constant but T is varied. In the upper diagram of Fig. 7.4 (a), $T_{on} = \frac{1}{4}\,T$ so that $\alpha = 0.25$. In the

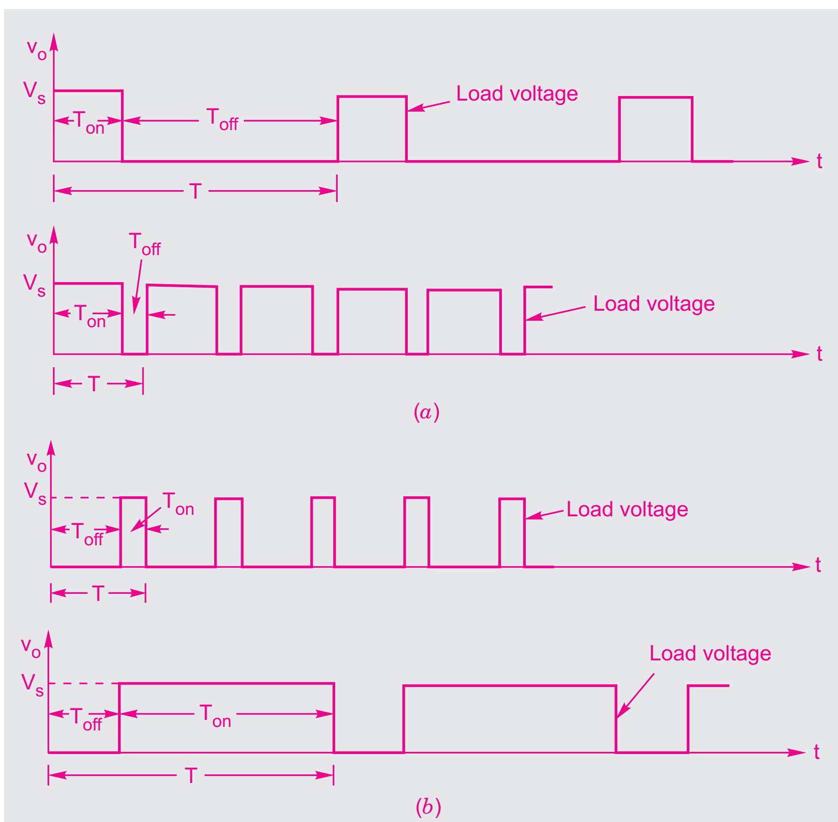

Fig. 7.4. Principle of frequency modulation. (a) on-time T_{on} constant and (b) off-time T_{off} constant.

lower diagram of Fig. 7.4 (*a*), $T_{on} = \frac{3}{4} T$ so that $\alpha = 0.75$. In Fig. 7.4 (*b*), T_{off} is kept constant and T is varied. In the upper diagram of this figure, $T_{on} = \frac{1}{4} T$ so that $\alpha = 0.25$ and in the lower diagram $T_{on} = \frac{3}{4} T$ so that $\alpha = 0.75$.

Frequency modulation scheme has some disadvantages as compared to pulse-width modulation scheme. These are as under :

(*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 α, frequency variation would be wide. As such, there is a possibility of interference with signalling and telephone lines in frequency modulation scheme.

(*iii*) The large off-time in frequency modulation scheme may make the load current discontinuous which is undesirable.

It is seen from above that constant frequency (PWM) scheme is better than variable frequency scheme. PWM technique has, however, a limitation. In this technique, T_{on} cannot be reduced to near zero for most of the commutation circuits used in choppers. As such, low range of α control is not possible in PWM. This can, however, be achieved by increasing the chopping period (or decreasing the chopping frequency) of the chopper.

7.2.2. Current-limit Control

In this control strategy, the on and off of chopper circuit is guided by the previous set value of load current. These two set values are maximum load current $I_{o.mx}$ and minimum load current $I_{o.mn}$

When load current reaches the upper limit $I_{o.mx}$, chopper is switched off. Now load current freewheels and begins to decay exponentially. When it falls to lower limit $I_{o.mn}$, chopper is switched on and load current begins to rise as shown in Fig. 7.5. Profile of load current shows that it fluctuates between $I_{o.mx}$ and $I_{o.mn}$, and therefore cannot be discontinuous.

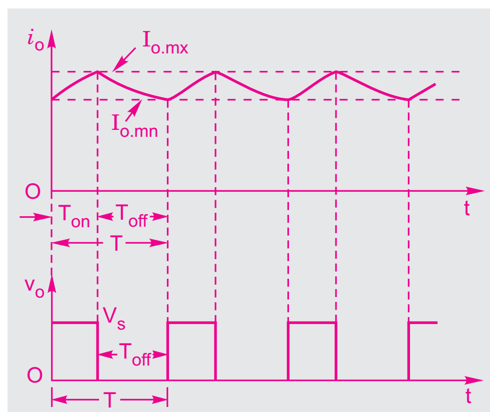

Fig. 7.5. Current-limit control for chopper.

Switching frequency of chopper can be controlled by setting $I_{o.mx}$ and $I_{o.mn}$. Ripple current ($= I_{o.mx} - I_{o.mn}$) can be lowered and this in turn necessitates higher switching frequency and therefore more switching losses.

Current-limit control involves feedback loop, the trigger circuitry for the chopper is therefore more complex. PWM technique is, therefore, more commonly used control strategy for the power control in chopper circuits.

7.3 STEP-UP CHOPPERS

For the chopper configuration of Fig. 7.2 (*a*), average output voltage V_0 is less than the input voltage V_s, *i.e.* $V_0 < V_s$; this configuration is therefore called step-down chopper. Average output voltage V_0 greater than input voltage V_s can, however, be obtained by a chopper called *step-up chopper*. Fig. 7.6 (*a*) illustrates an elementary form of a step-up chopper. In this article, working principle of a step-up chopper is presented.

In this chopper, a large inductor L in series with source voltage V_s is essential as shown in Fig. 7.6 (*a*). When the chopper CH is on, the closed current path is as shown in Fig. 7.6 (*b*) and inductor stores energy during T_{on} period. When the chopper CH is off, as the inductor current cannot die down instantaneously, this current is forced to flow through the diode and load for a time T_{off}, Fig. 7.6 (*c*). As the current tends to decrease, polarity of the emf induced in L is reversed as shown in Fig. 7.6 (*c*). As a result, voltage across the load, given by $V_0 = V_s + L\ (di/dt)$, exceeds the source voltage V_s. In this manner, the circuit of Fig. 7.6 (*a*) acts as a step-up chopper and the energy stored in L is released to the load.

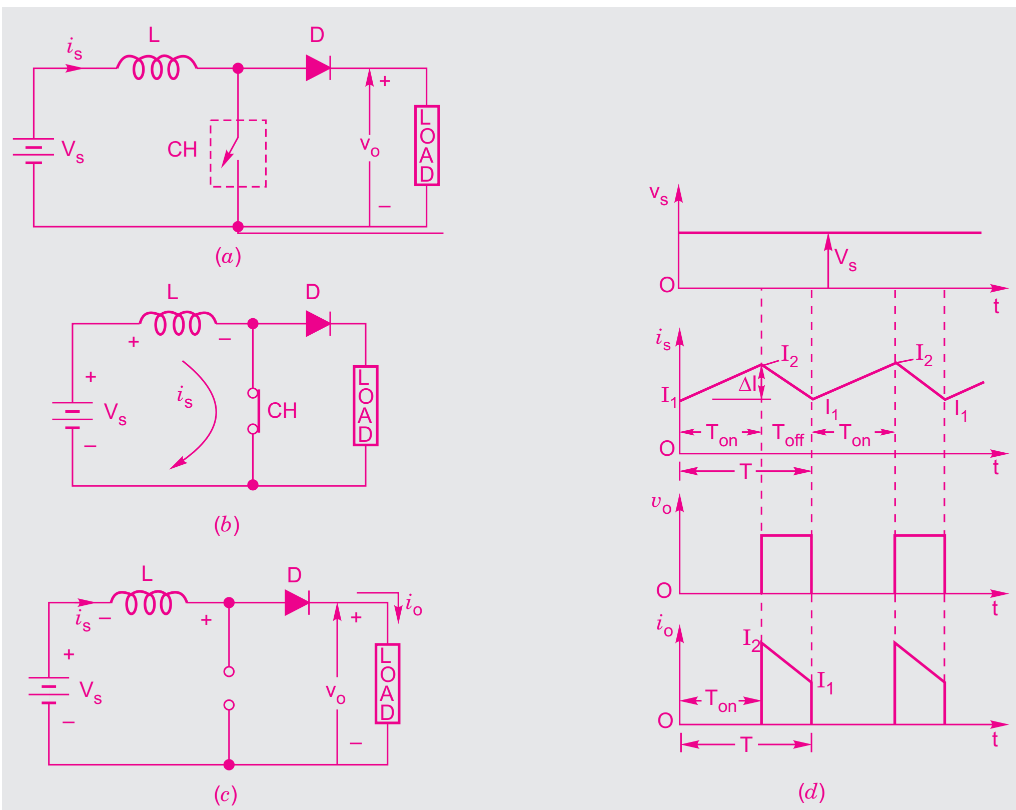

Fig. 7.6 (*a*) Step-up chopper (*b*) *L* stores energy (*c*) *L* . *di/dt* is added to V_s (*d*) voltage and current waveforms.

When CH is on, current through the inductance L would increase from I_1 to I_2 as shown in Fig. 7.6 (*d*). When CH is off, current would fall from I_2 to I_1. With CH on, source voltage is applied to L *i.e.* $v_L = V_s$. When CH is off, KVL for Fig. 7.6 (*c*) gives $v_L - V_0 + V_s = 0$, or $v_L = V_0 - V_s$. Here v_L = voltage across L. Variation of source voltage v_s, source current i_s, load voltage v_o and load current i_o is sketched in Fig. 7.6 (*d*). Assuming linear variation of output current, the energy input to inductor from the source, during the period T_{on}, is

$$W_{in} = \text{(voltage across } L\text{) (average current through } L\text{) } T_{on}$$

$$= V_s \cdot \left(\frac{I_1 + I_2}{2}\right) T_{on} \qquad ...(7.3a)$$

During the time T_{off}, when chopper is off, the energy released by inductor to the load is

$$W_{off} = \text{(voltage across } L\text{) (average current through } L\text{) } T_{off}$$

$$= (V_0 - V_s) \left(\frac{I_1 + I_2}{2}\right) \cdot T_{off} \qquad ...(7.3b)$$

Considering the system to be lossless, these two energies given by Eqs. (7.3*a*) and (7.3*b*) will be equal.

$$\therefore \quad V_s \left(\frac{I_1 + I_2}{2}\right) T_{on} = (V_0 - V_s) \left(\frac{I_1 + I_2}{2}\right) \cdot T_{off}$$

$$V_s \cdot T_{on} = V_0 T_{off} - V_s \cdot T_{off}$$

$$V_0 T_{off} = V_s (T_{on} + T_{off}) = V_s \cdot T$$

or

$$V_0 = V_s \frac{T}{T_{off}} = V_s \frac{T}{T - T_{on}} = V_s \frac{1}{1 - \alpha} \qquad ...(7.4)$$

It is seen from Eqn. (7.4) that average voltage across the load can be stepped up by varying the duty cycle. If chopper of Fig. 7.6 (*a*) is always off, $\alpha = 0$ and $V_0 = V_s$. If this chopper is always on, $\alpha = 1$ and $V_0 = \infty$ (infinity) as shown in Fig. 7.7 (*a*). In practice, chopper is turned on and off so that α is variable and the required step-up average output voltage, more than source voltage, is obtained.

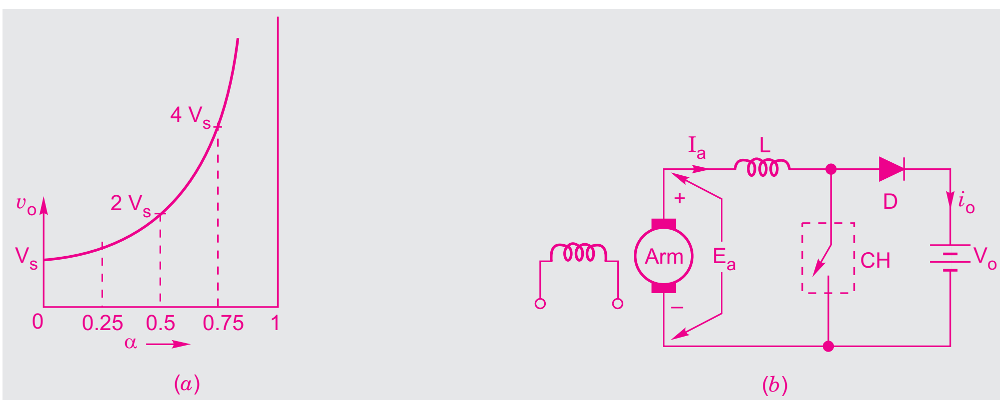

Fig. 7.7. (*a*) Variation of load voltage v_o with duty cycle (*b*) regenerative braking of dc motor.

The principle of step-up chopper can be employed for the regenerative braking of dc motors. This is illustrated in Fig. 7.7 (*b*) where motor armature voltage E_a represents V_s of Fig. 7.6 (*a*). Voltage V_o is the dc source voltage. When CH is on, L stores energy. When CH is off, L releases energy. In case $E_a/(1 - \alpha)$ exceeds V_o, dc machine begins to work as a dc generator and armature current I_a flows opposite to motoring mode. Power now flows from dc machine to source V_o causing regenerative braking of dc motor. Motor armature voltage E_a is directly proportional to field flux and motor speed. Therefore, even at decreasing motor speeds, regenerative braking can be made to take place provided duty cycle and field flux are so adjusted that $E_a/(1 - \alpha)$ is more than the fixed source voltage V_o.

Example 7.1. *For the basic dc to dc converter of Fig. 7.2 (a), express the following variables as functions of* V_s, *R and duty cycle* α *in case load is resistive :*

(*a*) *Average output voltage and current*

(*b*) *Output current at the instant of commutation*

(*c*) *Average and rms freewheeling diode currents*

(*d*) *Rms value of the output voltage*

(*e*) *Rms and average thyristor currents*

(*f*) *Effective input resistance of the chopper.*

Solution. The load voltage variation is shown in Fig. 7.2 (*b*). For a resistive load, output or load current waveform is similar to load voltage waveform.

(*a*) Average output voltage, $$V_0 = \frac{T_{on}}{T} V_s = \alpha V_s$$

Average output current, $$I_0 = \frac{V_0}{R} = \frac{T_{on}}{T} \cdot \frac{V_s}{R} = \alpha \frac{V_s}{R}$$

(*b*) The output current is commutated by the thyristor at the instant $t = T_{on}$. Therefore, output current at the instant of commutation is V_s/R.

(*c*) For a resistive load, freewheeling diode FD does not come into play. Therefore, average and rms values of freewheeling diode currents are zero.

(*d*) Rms value of output voltage $$= \left[\frac{T_{on}}{T} \cdot V_s^2\right]^{1/2} = \sqrt{\alpha} \cdot V_s$$

(*e*) Average thyristor current $$= \frac{T_{on}}{T} \cdot \frac{V_s}{R} = \alpha \frac{V_s}{R}$$

Rms thyristor current $$= \left[\frac{T_{on}}{T} \cdot \left(\frac{V_s}{R}\right)^2\right]^{1/2} = \sqrt{\alpha} \cdot \frac{V_s}{R}$$

(*f*) Average source current = average thyristor current = $\alpha \cdot \dfrac{V_s}{R}$

Effective input resistance of the chopper

$$= \frac{\text{dc source voltage}}{\text{average source current}} = \frac{V_s \cdot R}{\alpha \cdot V_s} = \frac{R}{\alpha}.$$

Example 7.2. *For type-A chopper of Fig. 7.2 (a), dc source voltage = 230 V, load resistance = 10 Ω. Take a voltage drop of 2 V across chopper when it is on. For a duty cycle of 0.4, calculate :*

(*a*) *average and rms values of output voltage and*

(*b*) *chopper efficiency.*

Solution. (*a*) When chopper is on, output voltage is (V_s – 2) volts and during the time chopper is off, output voltage is zero.

∴ Average output voltage $$= \frac{(V_s - 2)T_{on}}{T} = \alpha(V_s - 2)$$
$$= 0.4\,(230 - 2) = 91.2 \text{ V}$$

Rms value of output voltage,

$$V_{or} = \left[(V_s - 2)^2 \cdot \frac{T_{on}}{T} \right]^{1/2} = \sqrt{\alpha}\,(V_s - 2)$$

$$= \sqrt{0.4}\ (230 - 2) = 144.2 \text{ V}$$

(*b*) Power output or power delivered to load,

$$P_0 = \frac{V_{or}^2}{R} = \frac{(144.2)^2}{10} = 2079.364 \text{ W}$$

Power input to chopper, $P_i = V_s \cdot I_0 = 230 \times \frac{91.2}{10} = 2097.6$ W

Chopper efficiency $= \frac{P_0}{P_i} = \frac{2079.364}{2097.6} \times 100 = 99.13\%.$

Example 7.3. *A step-up chopper has input voltage of 220 V and output voltage of 660 V. If the conducting time of thyristor-chopper is 100 μs, compute the pulse width of output voltage.*

In case output-voltage pulse width is halved for constant frequency operation, find the average value of new output voltage.

Solution. From Eq. (7.4), $660 = 220 \dfrac{1}{1 - \alpha}$

or

$$\alpha = \frac{2}{3} = \frac{T_{on}}{T}$$

It is seen from Fig. 7.6 (*d*) that conducting time of chopper is $T_{on} = \frac{2}{3} T = 100$ μs. This gives chopping period $T = 100 \times \frac{3}{2} = 150$ μs

∴ Pulse width of output voltage $= T_{off} = T - T_{on} = 150 - 100 = 50$ μs

When pulse width of output voltage is halved, $T_{off} = \frac{50}{2} = 25$ μs

For constant frequency operation, $T = 150$ μs, $T_{on} = 150 - 25 = 125$ μs

∴ $$\alpha = \frac{T_{on}}{T} = \frac{125}{150} = \frac{5}{6}$$

∴ Average value of new output voltage, $V_o = 220 \dfrac{1}{1 - \frac{5}{6}} = 1320$ V.

Example 7.4. *A type-A chopper has input dc voltage of 200 V and a load of R = 10 Ω in series with L = 80 mH. If load current varies linearly between 12 A and 16 A, find the time ratio T_{on}/T_{off} for this chopper.*

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