DC-DC Converters (DC –Choppers)

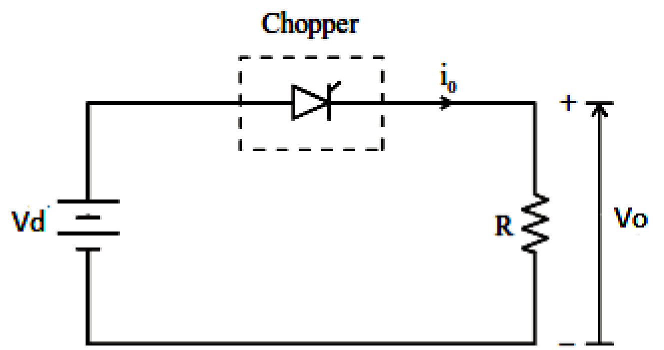
A dc-to-dc converter, also known as dc chopper, is a static device which is used to obtain a variable dc voltage from a constant dc voltage source. Choppers are widely used in trolley cars, battery operated vehicles, traction motor control, control of large number of dc motors, etc….. They are also used as dc voltage regulators.

Choppers are of two types: (1) Step-down choppers, and (2) 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

Figure 1 shows a step-down chopper with resistive load. The thyristorin 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 waveform is as shown in Fig. 2.

Fig.1 Chopper circuit.



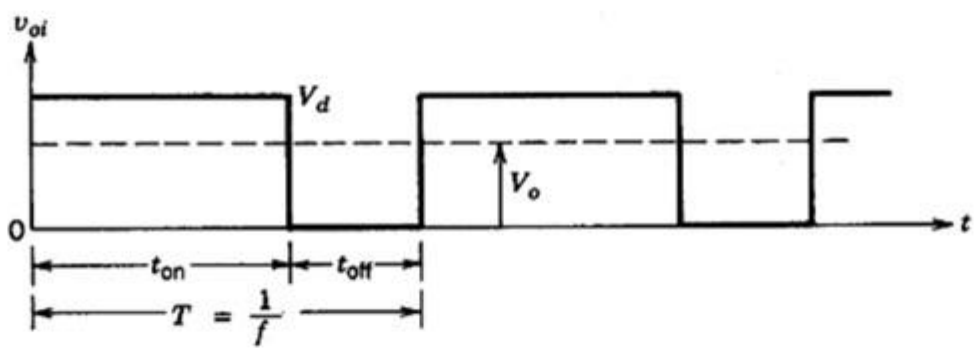


Fig.2 Chopper output voltage waveform, R- load.

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

- t_{ON} is varied keeping chopping frequency '*f*' & chopping period 'T' constant.
- Output voltage is varied by varying the ON time t_{ON}

ANALYSIS OF A STEP-DOWN CHOPPER WITH R-LOAD

Referring to Fig.2, the average output voltage v_o can be found as

Let T= control period = $t_{on} + t_{off}$

$$v_o = V_{av} = \frac{1}{T}\int_0^{t_{on}} V_d \quad dt$$

$$V_o = V_d \frac{ton}{T} = V_d(\gamma)$$

$$where\ ,\gamma = \frac{ton}{T} = Duty\ cycle$$

- Maximum value of γ =1 when t_{on} =T (t_{off}= 0)
- Minimum value of γ = 0 when t_{on} = 0 (t_{off} = 0)

The output voltage is stepped down by the factor γ ($0 \le V_o \le V_d$) .Therefore this form of chopper is a step down chopper.

The R.M.S. value of the output voltage $v_{o,rms} = \sqrt{\frac{1}{T}\int_0^{ton} v_0^{\ 2}\,dt} = \sqrt{\gamma}\ v_d$

The Output power = $\frac{v_{o,rms}^{\ \ 2}}{R} = \gamma\ \frac{v_d^{\ 2}}{R}$

Input current (Assume 100% efficiency) $I_a = \frac{P}{V} = \frac{\gamma v_d^2}{R} \frac{1}{v_d} = \frac{\gamma v_d}{R}$

f= chopping frequency = $\left(\frac{1}{chopping \quad period\,(T)}\right)$ = 1/ T

<u>The ripple factor</u>, *RF*

It is a measure of the ripple content.

$$RF = \sqrt{\left(\frac{Vo_{rms}}{Vo}\right)^2 - 1} = \sqrt{\left(\frac{\gamma V_d^{\,2}}{\gamma^2 V_d^2}\right) - 1} = \sqrt{\frac{1}{\gamma} - 1} = \sqrt{\frac{1-\gamma}{\gamma}}$$

Note1: In this type of chopper both the voltage and current are always positive, hence this chopper is called a single-quadrant Buck converter or class – A chopper.

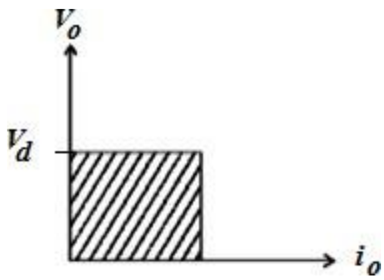


Fig.3 Single – quadrant operation

Note2: The chopper switch can also be implemented by using a power BJT, power MOSFET, GTO, and IGBT transistor. The practical devices have a finite voltage drop ranging from 0.5V to 2V, and for the sake of simplicity, the voltage drop of their power semi-conductor devices are neglected.

Example 1: A transistor dc chopper circuit (Buck converter) is supplied with power form an ideal battery of 100 V. The load voltage waveform consists of rectangular pulses of duration 1 ms in an overall cycle time of 2.5 ms. Calculate, for resistive load of 10 Ω.

(a) The duty cycle γ.

(b) The average value of the output voltage V_o.

(c) The rms value of the output voltage V_{orms}.

(d) The ripple factor RF.

(e) The output dc power.

Solution:

(a) ton = 1ms , T=2.5 ms

$$\gamma = \frac{t_{on}}{T} = \frac{1\ ms}{2.5\ ms} = 0.4$$

(b) $V_{av} = V_o = \gamma\ V_d = 0.4 \times 100 = 40$ V.

(c) $V_{orms} = \sqrt{\gamma}\, V_i = \sqrt{0.4} \times 100 = 63.2$ V.

(d) $RF = \sqrt{\frac{1-\gamma}{\gamma}} = \sqrt{\frac{1-0.4}{0.4}} = 1.225$

(e) $I_a = \frac{Vo}{R} = \frac{40}{10} = 4A$

$P_{av} = I_a\ V_o = 4 \times 40 = 160$ W

STEP-DOWN CHOPPER WITH R-L LOAD

Consider a class-A chopper circuit with R-L load as shown in Fig.4.This is a step down chopper with one quadrant operation.

If we use the simplified linear analysis by considering that T<< τ, where ($T = t_{on} + t_{off}$) . In this case the current is continuous as shown in Fig.5.

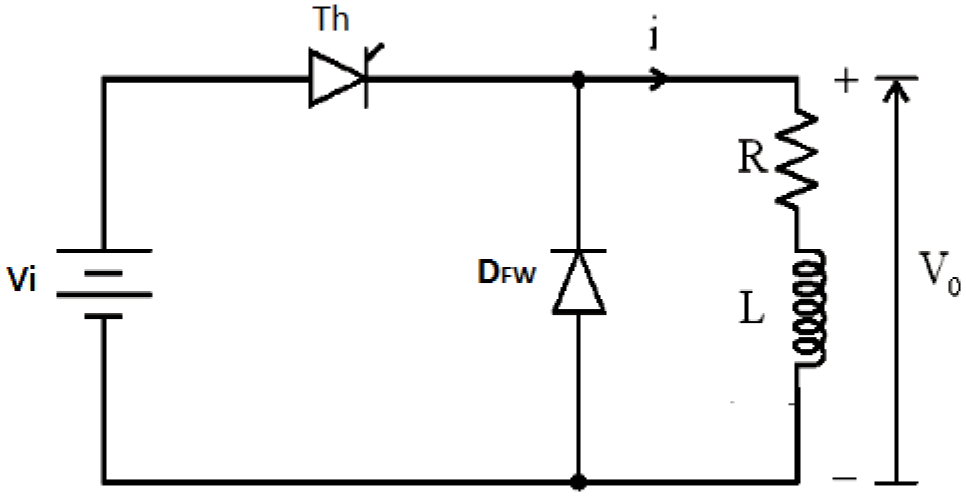


Fig.4

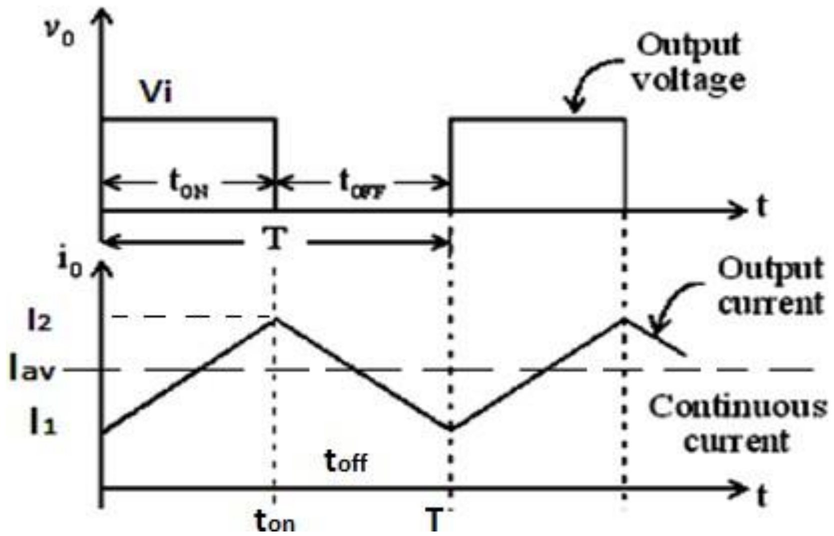


Fig.5

Referring to Fig.5:

- The current variation is almost linear and the current waveform becomes triangular.
- During the ON period , the equation govern the circuit is

$$V_d = R\mathrm{i} + L\frac{d\mathrm{i}}{dt}$$

Since $\frac{d\mathrm{i}}{dt}$ = constant, hence during ON period:

$$\frac{d\mathrm{i}}{dt} = \frac{I_2 - I_1}{t_{on}} = \frac{\Delta I}{t_{on}}$$

Where ΔI is the peak - to -peak of the load current .Thus the equation of the current is given by:

$$\mathrm{i}_1 = I_1 + \frac{\Delta \mathrm{I}}{\gamma T} t \qquad\qquad 0 \leq t \leq t_{on}$$

Where $\gamma = \frac{ton}{T}$

During the off period:

$$\frac{d\mathrm{i}}{dt} = \frac{I_1 - I_2}{t_{off}} = -\frac{\Delta}{t_{off}} = -\frac{\Delta \mathrm{I}}{T - t_{on}} = -\frac{\Delta \mathrm{I}}{T - \gamma T} = -\frac{\Delta \mathrm{I}}{(1-\gamma)T}$$

Hence, during the off the equation of the current is

$$\mathrm{i}_2 = I_2 - \frac{\Delta \mathrm{I}}{(1-\gamma)T}(t - t_{on}) \qquad\qquad t_{on} \leq t \leq T$$

The average value of the output current is

$$I_{av} = \frac{1}{T}\left[\frac{1}{2} t_{on}(I_2 - I_1) + \frac{1}{2} t_{off}(I_2 - I_1) + I_1 T\right]$$

$$I_{av} = \frac{1}{2}(I_2 + I_1)$$

Example 2; An 80 V battery supplies RL load through a DC chopper. The load has a freewheeling diode across it is composed of 0.4 H in series with 5Ω resistor. Load current, due to improper selection of frequency of chopping, varies widely between 9A and 10.2.

(a) Find the average load voltage, current and the duty cycle of the chopper.

(b) What is the operating frequency f ?

(c) Find the ripple current to maximum current ratio.

Solution:

(a) The average load voltage and current are:

$V_{av} = V_o = \gamma\, V_d$

$$I_{av} = \frac{1}{2}(I_2 + I_1) = \frac{9+10.2}{2} = 9.6A$$

$$I_{av} = \frac{V_{av}}{R} = \frac{\gamma V_d}{R} \qquad or \qquad \gamma = \frac{I_{av}\ R}{V_i} = \frac{9.6 \ x\ 5}{80} = 0.6$$

$V_{av} = 0.6 \text{ x } 80 = 48$ V.

(b) To find the operating (chopping) frequency:

During the ON period,

$$V_d = R\mathrm{i} + L\frac{d\mathrm{i}}{dt} \qquad \dots\dots\dots\dots\dots (1)$$

Assuming $\frac{d\mathrm{i}}{dt} \cong constant$

$$\frac{d\mathrm{i}}{dt} \cong \frac{\Delta}{t_{on}} = \frac{10.2-9}{\gamma T} = \frac{1.2}{\gamma T}$$

From eq.(1) $\qquad L\frac{d\mathrm{i}}{dt} \cong V_d - I_{av}\,R = 80 - 5x9.6 = 32V$

or $\qquad \frac{d\mathrm{i}}{dt} = \frac{32}{L} = \frac{32}{0.4} = 80\ A.s$

but $\frac{di}{dt} = \frac{1.2}{\gamma T} = 80 = \frac{1.2}{0.6\,T}$

$$\therefore \quad T = \frac{1.2}{0.6x80} = 25\,ms$$

Hence $\quad f = \frac{1}{T} = \frac{1}{25x10^{-3}} = 40\,Hz$

The maximum current I_m occurs at γ = 1,

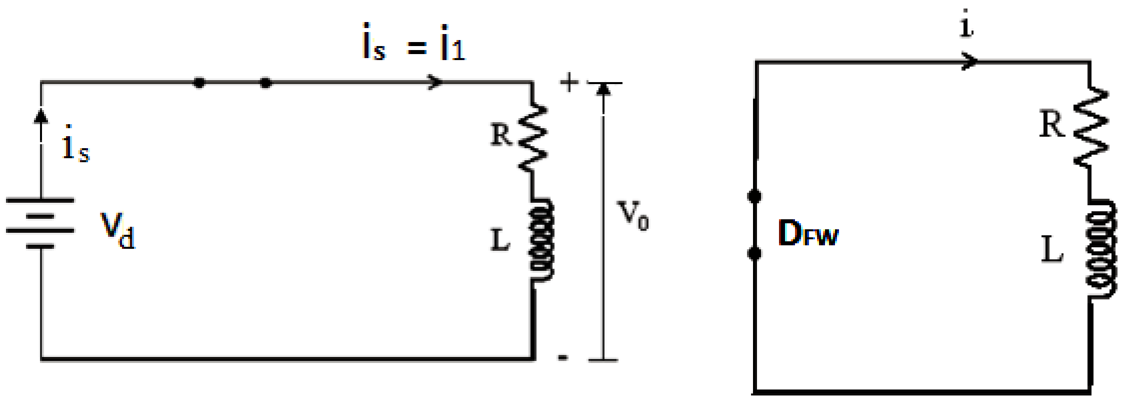
$$\therefore \; I_m = \frac{\gamma V d}{R} = \frac{1x80}{5} = 16A$$

Ripple current $I_r = \Delta I = 10.2 - 9 = 1.2$ A

$$\therefore \; \frac{I_r}{I_m} = \frac{1.2}{16} = 0.075 \quad or \;\; 7.5\%\,.$$

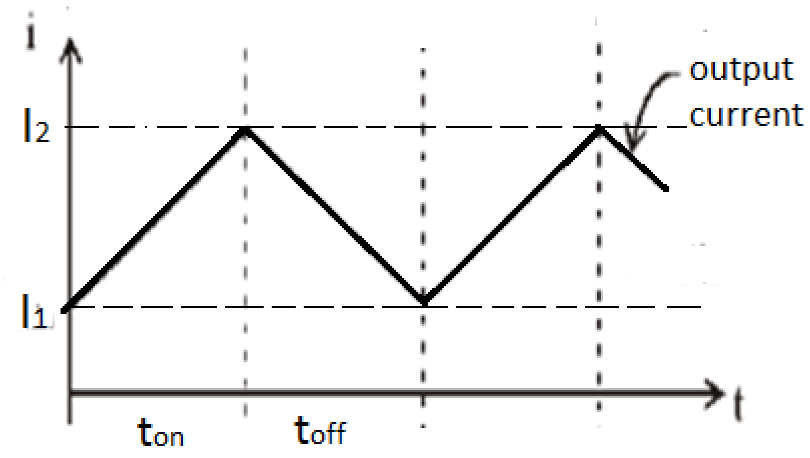
<u>Input Current I_s</u>

For the class-A chopper had shown in Fig.4, the On-state and OFF- state equivalent circuits are as depicted in Fig.6. When the thyristor is closed (during the ON period), the load current "i" rises from I_1 to I_2 and falls from I_2 to I_1 during the off period as shown in Fig.7(a).The input current i_s flows during the ON period only as shown in Fig .7(b).

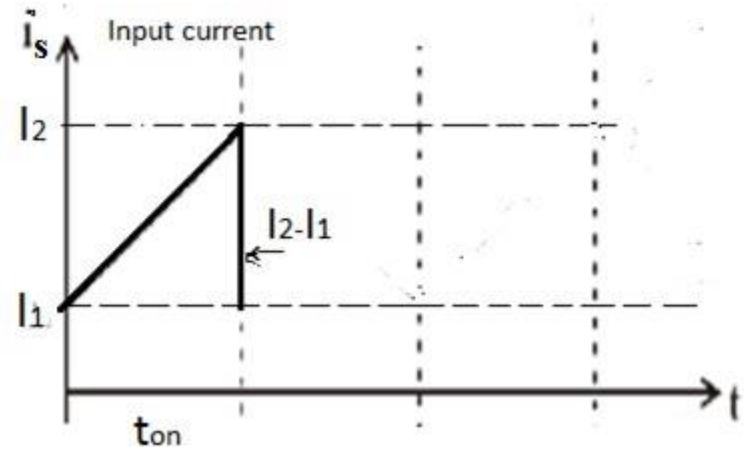


ON- State Equivalent CCT OFF – State Equivalent CCT

Fig.6



(a)



(b)

Fig.7

The equation of the input current is

$$i_s = i_1 = I_1 + \frac{\Delta I}{\gamma T} t \qquad 0 \le t \le t_{on}$$

$$i_s = 0 \qquad t_{on} \le t \le T$$

The average value of the current drawn from the supply is simply found by,

$$I_{s(av)} = \frac{1}{T}[\frac{1}{2} t_{on} (I_2 - I_1)] + \frac{t_{on} I_1}{T}$$

$$I_{s(av)} = \frac{1}{T}[\frac{1}{2} t_{on} (I_2 + I_1)] = \frac{t_{on}}{2T} (I_2 + I_1) = \gamma I_{av}$$

Minimum and Maximum Load Currents

The minimum current I_1 and maximum current I_2 can be found from the following two equations:

$$I_1 = I_{min} = \frac{V_o}{R} - \frac{t_{off}}{2L} V_o$$

$$I_2 = I_{max} = \frac{V_o}{R} + \frac{t_{off}}{2L} V_o$$

Where $\boldsymbol{V_o = V_{av}}$

Note: The proof of these two equations is not needed

Example 3: A DC Buck converter operates at frequency of 1 kHz from 100V DC source supplying a 10 Ω resistive load. The inductive component of the load is 50mH.For output average voltage of 50V volts, find:

(a) The duty cycle

(b) t_{on}

(c) The rms value of the output current

(d) The average value of the output current

(e) I_{max} and I_{min}

(f) The input power

(g) The peak-to-peak ripple current.

Solution:

(a) $V_{av} = V_o = \gamma\, V_d$

$$\gamma = \frac{V_{av}}{V_d} = \frac{50}{100} = 0.5$$

(b) T= 1/ f = 1 / 1000 = 1ms

$$\gamma = \frac{t_{on}}{T}$$

$t_{on} = \gamma\, T$ = 05 x1ms= 0.5 ms .

(c) $V_{orms} = \sqrt{\gamma}\, V_{\mathrm{i}} = \sqrt{0.5}\; x\, 100 = 70.07\, V$

(d) $I_{av} = \frac{V_{av}}{R} = \frac{50}{10} = 5\ A$

(e) $I_{max} = \frac{V_{av}}{R} + \frac{t_{\mathrm{off}}}{2L} V_{av} = \frac{50}{10} + \frac{(1-0.5)x10^{-3}}{2x50x10^{-3}} x50$

= 5 + 0.25 = 5,25 A

$I_{\min} = \frac{V_{av}}{R} - \frac{t_{\mathrm{off}}}{2L} V_{av} = \frac{50}{10} - \frac{(1-0.5)x10^{-3}}{2x50x10^{-3}} x50$

= 5 - 0.25 = 4.75 A

(f)

$$I_{s(av)} = \frac{\gamma}{2}\,(I_{\min} + I_{max}) = \gamma I_{av} = 0.5\ x5 = 2.5A$$

$$P_{\mathrm{in}} = I_{s(av)} V_d = 2.5\ x100 = 250\ \mathrm{W}$$

(g) $I_{\_} = \Delta I = I_{max} - I_{min} = 5.25 - 4.75 = 0.5A$