1. Buck Converter (Step-Down Converter With RL Load)

A converter with an *RL* load is shown in Figure.1. The operation of the converter can be divided into two modes. During mode 1, the converter is switched on and the current flows from the supply to the load. During mode 2, the converter is switched off and the load current continues to flow through freewheeling diode *Dm*.

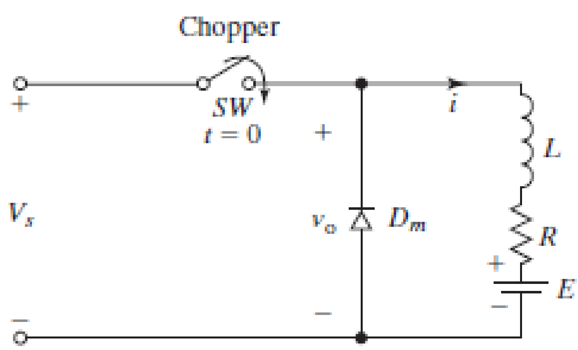

Figure.1: Dc Converter with RL Load

The equivalent circuits for these modes are shown in Figure 2. The load current and output voltage waveforms, load current and output voltage waveforms are shown in Figure.2. with the assumption that the load current rises linearly. However, the current flowing through an RL load rises or falls exponentially with a time constant. The load time constant $\tau = L/R$ is generally much higher than the switching period T. Thus, the linear approximation is valid for many circuit conditions and simplified expressions can be derived within reasonable accuracies.

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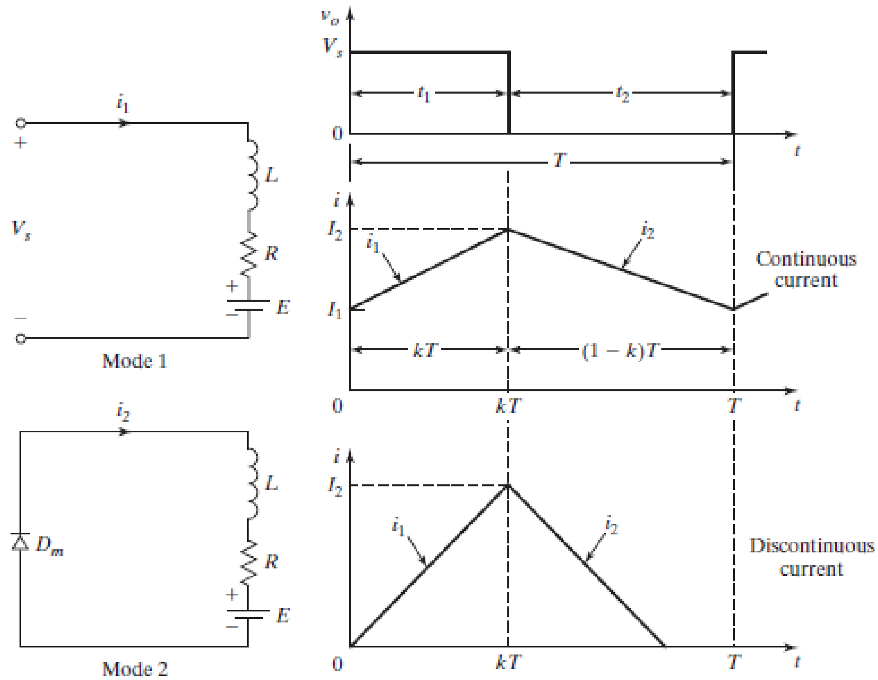


(a) Equivalent circuits (b) Waveforms

The load current for mode 1 can be found from

$$V_s = Ri_1 + L\frac{di_1}{dt} + E$$

This mode is valid $0 \leq t \leq t_1\ (= kT)$; and at the end of this mode, the load current becomes

$$i_1(t = t_1 = kT) = I_2 \tag{5.20}$$

The load current for mode 2 can be found from

$$0 = Ri_2 + L\frac{di_2}{dt} + E$$

With initial current $i_2(t = 0) = I_2$ and redefining the time origin (i.e., $t = 0$) at the beginning of mode 2, we have

This mode is valid for $0 \leq t \leq t_2\,[=(1 - k)T]$. At the end of this mode, the load current becomes

$$i_2(t = t_2) = I_3 \tag{5.22}$$

At the end of mode 2, the converter is turned on again in the next cycle after time, $T = 1/f = t_1 + t_2$.

Under steady-state conditions, $I_1 = I_3$. The peak-to-peak load ripple current can be determined from Eqs. (5.19) to (5.22). From Eqs. (5.19) and (5.20), I_2 is given by

$$I_2 = I_1 e^{-kTR/L} + \frac{V_s - E}{R}\left(1 - e^{-kTR/L}\right) \quad (5.23)$$

From Eqs. (5.21) and (5.22), I_3 is given by

$$I_3 = I_1 = I_2 e^{-(1-k)TR/L} - \frac{E}{R}\left(1 - e^{-(1-k)TR/L}\right) \quad (5.24)$$

Solving for I_1 and I_2 we get

$$I_1 = \frac{V_S}{R}\left(\frac{e^{kz} - 1}{e^{z} - 1}\right) - \frac{E}{R} \quad (5.25)$$

where $z = \frac{TR}{L}$ is the ratio of the chopping or switching period to the load time constant.

$$I_2 = \frac{V_s}{R}\left(\frac{e^{-kz} - 1}{e^{-z} - 1}\right) - \frac{E}{R} \quad (5.26)$$

The peak-to-peak ripple current is

$$\Delta I = I_2 - I_1$$

the maximum ripple current can be approximated to

$$\Delta I_{\max} = \frac{V_s}{4fL}$$

Example.1: Finding the Currents of a Dc Converter with an RL Load

A converter is feeding an RL load as shown in Figure 5.4 with $V_s = 220$ V, $R = 5\,\Omega$, $L = 7.5$ mH, $f = 1$ kHz, $k = 0.5$, and $E = 0$ V. Calculate (a) the minimum instantaneous load current I_1, (b) the peak instantaneous load current I_2, (c) the maximum peak-to-peak load ripple current, (d) the average value of load current I_a, (e) the rms load current I_o, (f) the effective input resistance R_i seen by the source, (g) the rms chopper current I_R, and (h) the critical value of the load inductance for continuous load current. Use PSpice to plot the load current, the supply current, and the freewheeling diode current.

Solution

$V_s = 220$ V, $R = 5\ \Omega$, $L = 7.5$ mH, $E = 0$ V, $k = 0.5$, and $f = 1000$ Hz. From Eq. (5.23), $I_2 = 0.7165 I_1 + 12.473$ and from Eq. (5.24), $I_1 = 0.7165 I_2 + 0$.

a. Solving these two equations yields $I_1 = 18.37$ A.

b. $I_2 = 25.63$ A.

c. $\Delta I = I_2 - I_1 = 25.63 - 18.37 = 7.26$ A. From Eq. (5.29), $\Delta I_{\max} = 7.26$ A and Eq. (5.30) gives the approximate value, $\Delta I_{\max} = 7.33$ A.

d. The average load current is, approximately,

$$I_a = \frac{I_2 + I_1}{2} = \frac{25.63 + 18.37}{2} = 22\ \text{A}$$

e. Assuming that the load current rises linearly from I_1 to I_2, the instantaneous load current can be expressed as

$$i_1 = I_1 + \frac{\Delta I t}{kT} \qquad \text{for } 0 < t < kT$$

The rms value of load current can be found from

$$I_o = \left(\frac{1}{kT}\int_0^{kT} i_1^2\, dt\right)^{1/2} = \left[I_1^2 + \frac{(I_2 - I_1)^2}{3} + I_1(I_2 - I_1)\right]^{1/2} \tag{5.32}$$

$$= 22.1\ \text{A}$$

f. The average source current

$$I_s = kI_a = 0.5 \times 22 = 11\ \text{A}$$

and the effective input resistance $R_i = V_s/I_s = 220/11 = 20\ \Omega$.

g. The rms converter current can be found from

$$I_R = \left(\frac{1}{T}\int_0^{kT} i_1^2\, dt\right)^{1/2} = \sqrt{k}\left[I_1^2 + \frac{(I_2 - I_1)^2}{3} + I_1(I_2 - I_1)\right]^{1/2} \tag{5.33}$$

$$= \sqrt{k} I_o = \sqrt{0.5} \times 22.1 = 15.63\ \text{A}$$

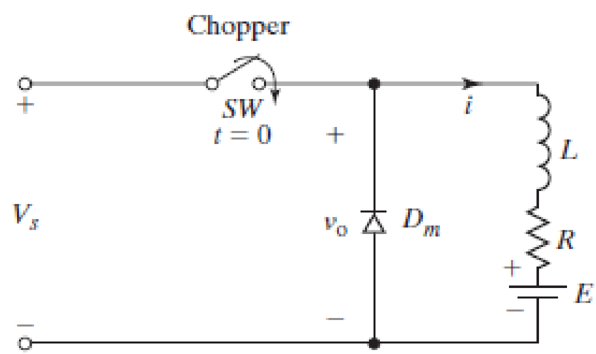
h. We can rewrite Eq. (5.31) as

$$V_S\left(\frac{e^{kz} - 1}{e^z - 1}\right) = E$$

which, after iteration, gives, $z = TR/L = 52.5$ and $L = 1\ \text{ms} \times 5/52.5 = 0.096$ mH. The SPICE simulation results [32] are shown in Figure 5.6, which shows the load current $I(R)$, the supply current $-I(V_s)$, and the diode current $I(D_m)$. We get $I_1 = 17.96$ A and $I_2 = 25.46$ A.

Example.1: Finding the Load Inductance to Limit the Load Ripple Current

The converter in Figure has a load resistance R = 0.25 _, input voltage Vs = 550 V, and battery voltage E = 0 V. The average load current Ia = 200 A and chopping frequency f = 250 Hz. Use the average output voltage to calculate the load inductance L, which would limit the maximum load ripple current to 10% of Ia.



Solution

$V_s = 550$ V, $R = 0.25\ \Omega$, $E = 0$ V, $f = 250$ Hz, $T = 1/f = 0.004$ s, and $\Delta i = 200 \times 0.1 = 20$ A. The average output voltage $V_a = kV_s = RI_a$. The voltage across the inductor is given by

$$L\frac{di}{dt} = V_s - RI_a = V_s - kV_s = V_s(1 - k)$$

If the load current is assumed to rise linearly, $dt = t_1 = kT$ and $di = \Delta i$:

$$\Delta i = \frac{V_s(1 - k)}{L}kT$$

For the worst-case ripple conditions,

$$\frac{d(\Delta i)}{dk} = 0$$

This gives $k = 0.5$ and

$$\Delta i L = 20 \times L = 550(1 - 0.5) \times 0.5 \times 0.004$$

and the required value of inductance is $L = 27.5$ mH.

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