1. Boost Converter (Step-Up Converter)

A converter can be used to step up a dc voltage and an arrangement for step-up operation is shown in Figure.1(a). When switch SW is closed for time t1, the inductor current rises and energy is stored in the inductor L. If the switch is opened for time t2, the energy stored in the inductor is transferred to load through diode D1 and the inductor current falls. Assuming a continuous current flow, the waveform for the inductor current is shown in Figure.1(b).

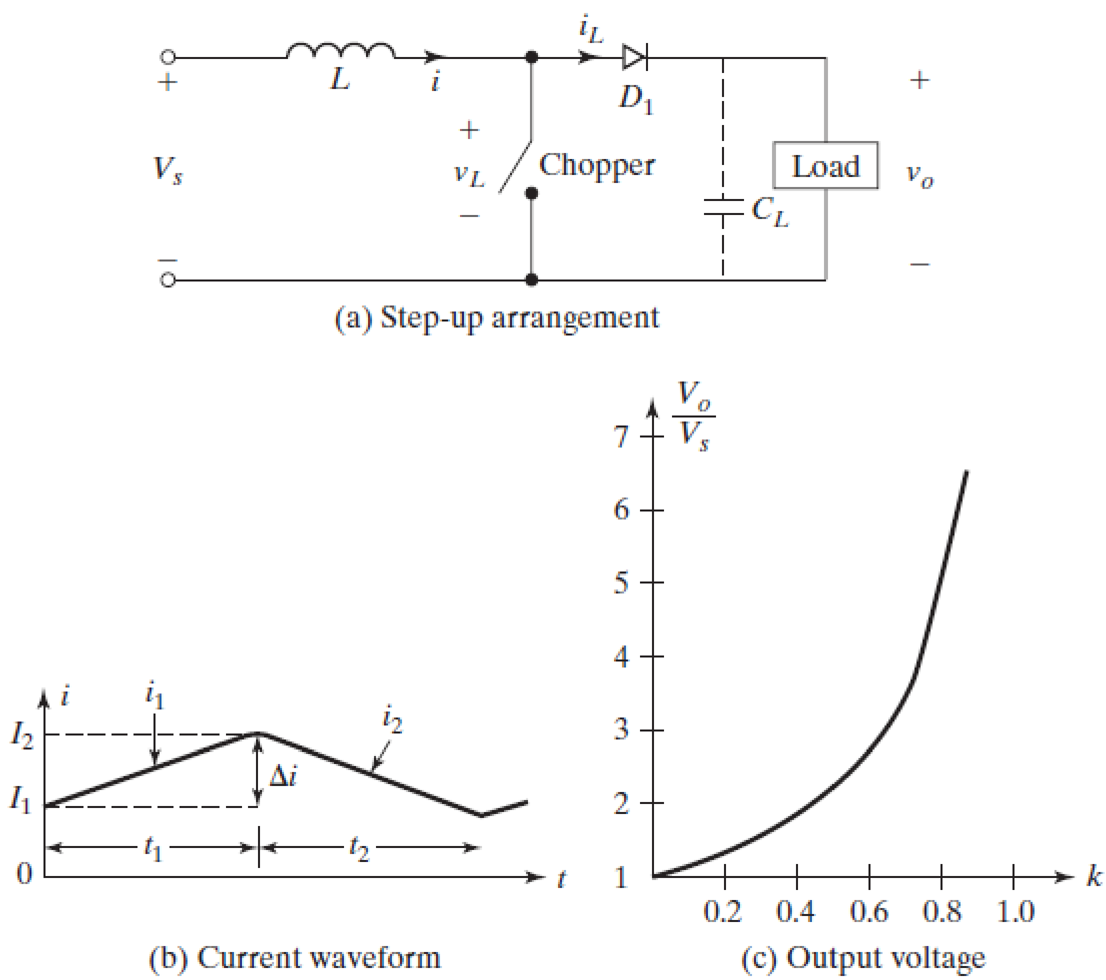

Figure.1: Arrangement for Step Up Operation

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When the converter is turned on, the voltage across the inductor is

$$v_L = L\frac{di}{dt}$$

and this gives the peak-to-peak ripple current in the inductor as

$$\Delta I = \frac{V_s}{L}t_1$$

The average output voltage is

$$v_o = V_s + L\frac{\Delta I}{t_2} = V_s\left(1 + \frac{t_1}{t_2}\right) = V_s\frac{1}{1-k}$$

If a large capacitor C_L is connected across the load as shown by dashed lines in Figure.1 a, the output voltage is continuous and v_o becomes the average value V_a. We can notice from Equation above that the voltage across the load can be stepped up by varying the duty cycle k and the minimum output voltage is Vs when k = 0. However, the converter cannot be switched on continuously such that k = 1. For values of k tending to unity, the output voltage becomes very large and is very sensitive to changes in k, as shown in Figure.1(c).

This principle can be applied to transfer energy from one voltage source to another as shown in Figure.2(a). The equivalent circuits for the modes of operation are shown in Figure.2(b). and the current waveforms in Figure 5.8c. The inductor current for mode 1 is given by

$$V_s = L\frac{di_1}{dt}$$

and is expressed as

$$i_1(t) = \frac{V_s}{L}t + I_1$$

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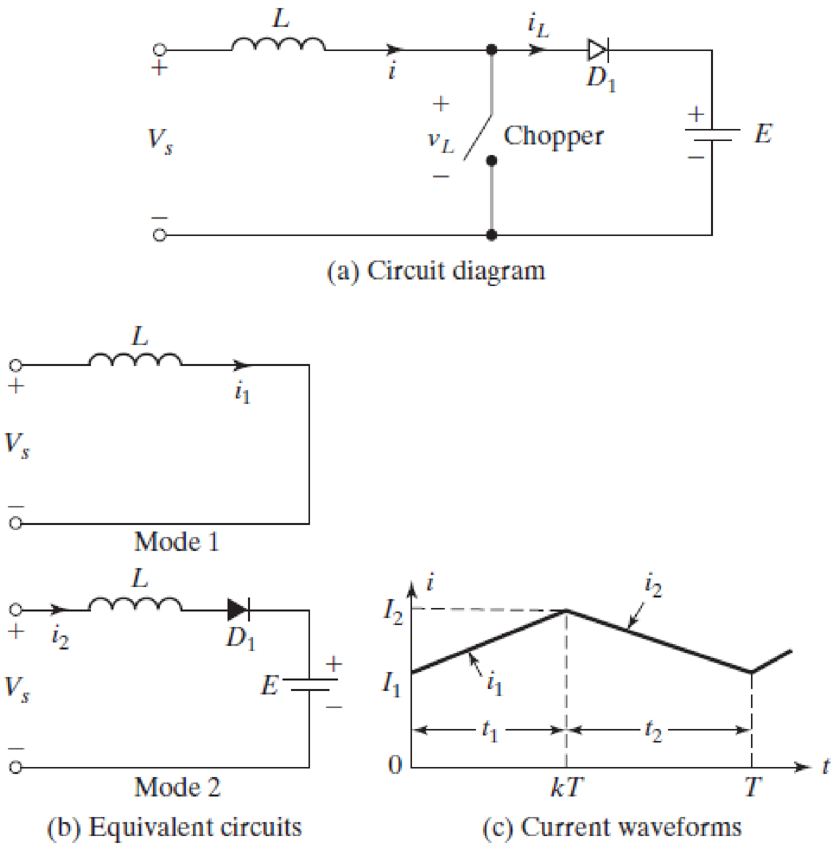

Figure.2: Arrangement for transfer of energy.

where I_1 is the initial current for mode 1. During mode 1, the current must rise and the necessary condition,

$$\frac{di_1}{dt} > 0 \quad \text{or} \quad V_s > 0$$

The current for mode 2 is given by

$$V_s = L\frac{di_2}{dt} + E$$

and is solved as

$$i_2(t) = \frac{V_s - E}{L}t + I_2$$

where I_2 is the initial current for mode 2.

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For a stable system, the current must fall and the condition is

$$\frac{di_2}{dt} < 0 \quad \text{or} \quad V_s < E$$

2. Step-Up Converter With a Resistive Load

A step-up converter with a resistive load is shown in Figure .3(a). When switch S1 is closed, the current rises through L and the switch. The equivalent circuit during mode 1 is shown in Figure.3(b) and the current is described by

$$V_s = L\frac{d}{dt}i_1$$

which for an initial current of I_1 gives

$$i_1(t) = \frac{V_s}{L}t + I_1$$

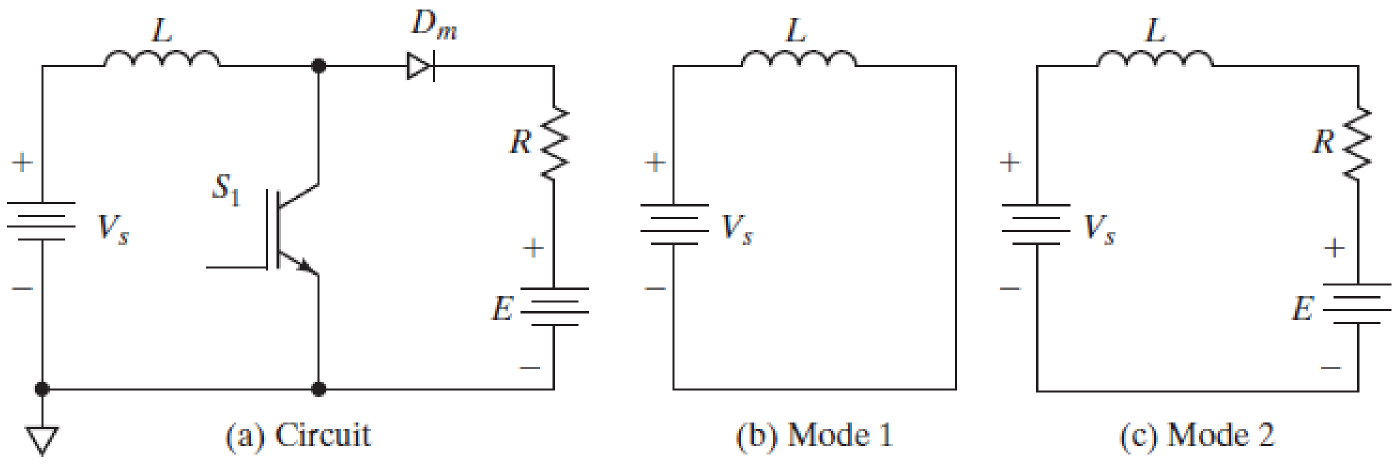

Figure.3: Step-up converter with a resistive load.

which is valid for $0 \le t \le kT$. At the end of mode 1 at t = kT,

$$I_2 = i_1(t = kT) = \frac{V_s}{L}kT + I_1$$

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When switch S1 is opened, the inductor current flows through the RL load. The equivalent circuit is shown in Figure.3(c) and the current during mode 2 is described by

where z = TR/L.

$$I_1 = \frac{V_s kz}{R}\frac{e^{-(1-k)z}}{1 - e^{-(1-k)z}} + \frac{V_s - E}{R}$$

$$I_2 = \frac{V_s kz}{R}\frac{1}{1 - e^{-(1-k)z}} + \frac{V_s - E}{R}$$

The ripple current is given by

$$\Delta I = I_2 - I_1 = \frac{V_s}{R}kT$$

Example.1: Finding the Currents of a Step-up Dc Converter

The step-up converter in Figure 5.9a has $V_s = 10\,\text{V}$, $f = 1\,\text{kHz}$, $R = 5\,\Omega$, $L = 6.5\,\text{mH}$, $E = 0\,\text{V}$, and $k = 0.5$. Find I_1, I_2 and ΔI. Use SPICE to find these values and plot the load, diode, and switch current.

Solution

Equations (5.43) and (5.44) give $I_1 = 3.64$ A (3.36 A from SPICE) and $I_2 = 4.4$ A (4.15 A from SPICE). The plots of the load current $I(L)$, the diode current $I(D_m)$, and the switch current $IC(Q_1)$ are shown in Figure 5.10.

3. Boost Regulators

In a boost regulator the output voltage is greater than the input voltage—hence the name “boost.” A boost regulator using a power MOSFET is shown in Figure. 4(a). Transistor M_1 acts as a controlled switch and diode D_m is an uncontrolled switch.

The circuit Figure.4 (a) is often represented by two switches as shown in Figure .4(b). The circuit operation can be divided into two modes. Mode 1 begins when transistor. M_1 is switched on at t = 0. The input current, which rises, flows through inductor L and transistor Q1. Mode 2 begins when transistor M1 is switched off at $t = t_1$. The current that was flowing through the transistor would now flow through L, C, load, and diode D_m.

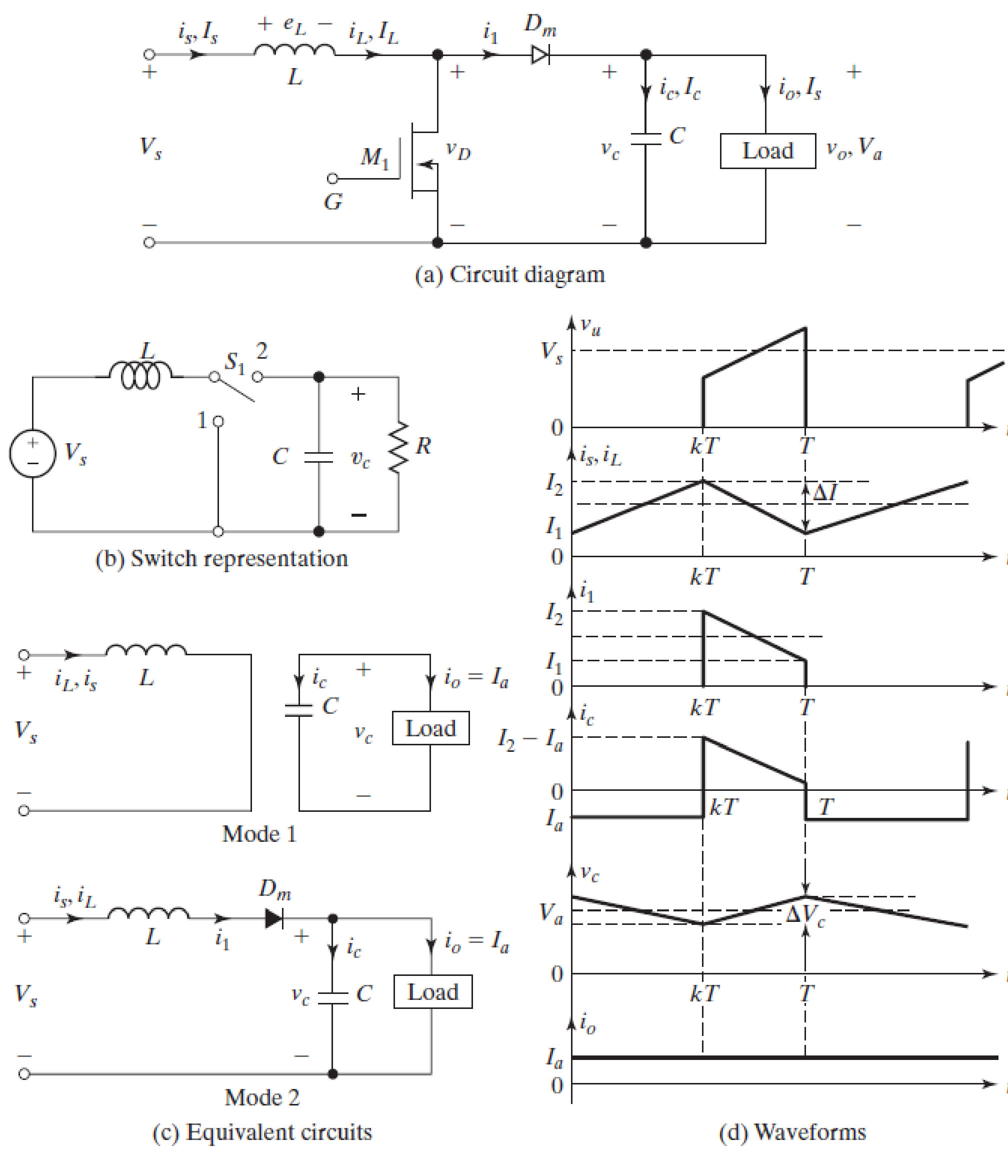

Figure.4: Boost regulator with continuous i_L.

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The inductor current falls until transistor M_1 is turned on again in the next cycle. The energy stored in inductor L is transferred to the load. The equivalent circuits for the modes of operation are shown in Figure.4 (c). The waveforms for voltages and currents are shown in Figure .4 (d) for continuous load current, assuming that the current rises or falls linearly. Assuming that the inductor current rises linearly from I_1 to I_2 in time t_1,

$$t_1 = \frac{\Delta I L}{V_s}$$

and the inductor current falls linearly from I_2 to I_1 in time t_2,

$$t_2 = \frac{\Delta I L}{V_a - V_s}$$

where $\Delta I = I_2 - I_1$

$$\Delta I = \frac{V_s t_1}{L} = \frac{(V_a - V_s) t_2}{L}$$

Substituting $t_1 = kT$ and $t_2 = (1 - k)T$ yields the average output voltage,

$$V_a = V_s \frac{T}{t_2} = \frac{V_s}{1 - k}$$

The average input current is

$$I_s = \frac{I_a}{1 - k}$$

Peak-to-peak inductor ripple current

$$\Delta I = \frac{V_s (V_a - V_s)}{f L V_a} \quad \Rightarrow \quad \Delta I = \frac{V_s k}{f L}$$

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Peak-to-peak capacitor ripple voltage

$$\Delta V_c = \frac{I_a(V_a - V_s)}{V_a f C} \quad \Rightarrow \quad \Delta V_c = \frac{I_a k}{fC}$$

Condition for continuous inductor current and capacitor voltage. If IL is the Average inductor current, at the critical condition for continuous conduction the inductor ripple current $\Delta I = 2I_L$.

which gives the critical value of the inductor L_c as

$$L_c = L = \frac{k(1-k)R}{2f}$$

The critical value of the capacitor C_c as

$$C_c = C = \frac{k}{2fR}$$

Example.2: Finding the Currents and Voltage in the Boost Regulator

A boost regulator in Figure 5.18a has an input voltage of $V_s = 5$ V. The average output voltage $V_a = 15$ V and the average load current $I_a = 0.5$ A. The switching frequency is 25 kHz. If L = 150 μH and C = 220 μF, determine (a) the duty cycle k, (b) the ripple current of inductor ΔI, (c) the peak current of inductor I2, (d) the ripple voltage of filter capacitor V_c, and (e) the critical values of L and C.

Solution:

$V_s = 5\,\text{V}$, $V_a = 15\,\text{V}$, $f = 25\,\text{kHz}$, $L = 150\,\mu\text{H}$, and $C = 220\,\mu\text{F}$.

a. From Eq. (5.70), $15 = 5/(1-k)$ or $k = 2/3 = 0.6667 = 66.67\%$.

b. From Eq. (5.75),

$$\Delta I = \frac{5 \times (15-5)}{25{,}000 \times 150 \times 10^{-6} \times 15} = 0.89\,\text{A}$$

c. From Eq. (5.73), $I_s = 0.5/(1 - 0.667) = 1.5\,\text{A}$ and peak inductor current,

$$I_2 = I_s + \frac{\Delta I}{2} = 1.5 + \frac{0.89}{2} = 1.945\,\text{A}$$

d. From Eq. (5.79),

$$\Delta V_c = \frac{0.5 \times 0.6667}{25{,}000 \times 220 \times 10^{-6}} = 60.61\,\text{mV}$$

e. $R = \frac{V_a}{I_a} = \frac{15}{0.5} = 30\,\Omega$

From Eq. (5.80), we get $L_c = \frac{(1-k)kR}{2f} = \frac{(1 - 0.6667) \times 0.6667 \times 30}{2 \times 25 \times 10^3} = 133\,\mu\text{H}$

From Eq. (5.81), we get $C_c = \frac{k}{2fR} = \frac{0.6667}{2 \times 25 \times 10^3 \times 30} = 0.44\,\mu\text{F}$