The ZCS Boost Converter

The boost-quasi-resonant converter with an M-type switch as shown in Fig. 6.13(a), with its equivalent circuit shown in Fig. 6.13(b).

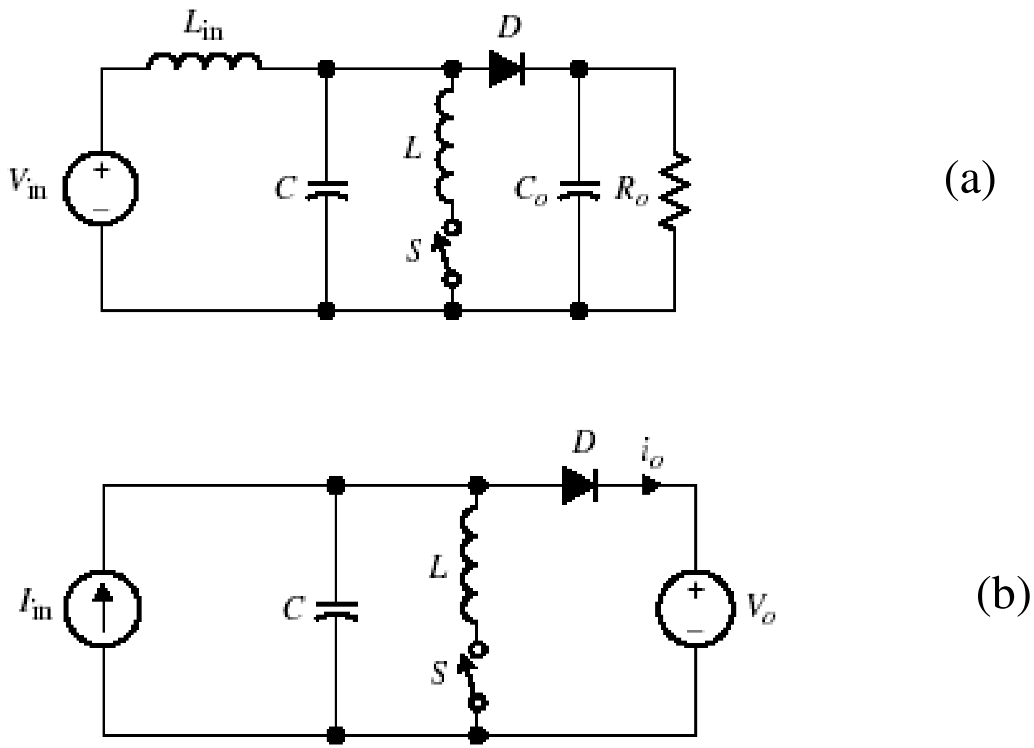

Fig 6.13 (a) ZCS boost converter with M-type switch. (b) Simplified equivalent circuit.

ZCS Boost: Equivalent Circuit Modes

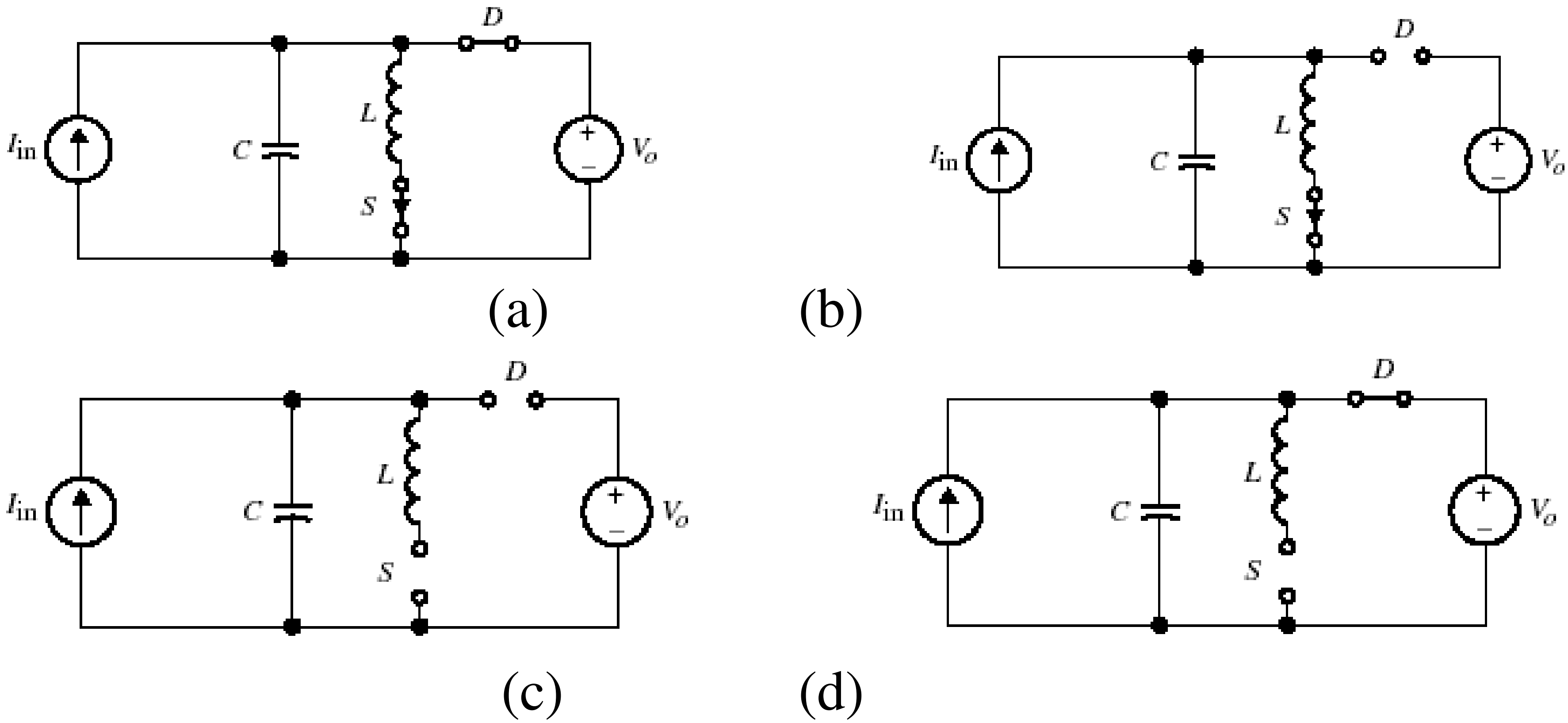

Fig 6.14 (a) Equivalent circuit for mode I. (b) Equivalent circuit for mode II. (c) Equivalent circuit for mode III. (d) Equivalent circuit for mode IV.

ZCS Boost Converter: Steady-State Analysis

Mode I [$0 \le t < t_1$]:

Assume switch and the diode are both *ON*

The output voltage is given by

$$V_o = L\frac{di_L}{dt}$$

The initial inductor current and capacitor voltage,

$$i_l(0) = 0 \qquad v_c(0) = V_o$$

Integrating Eq. (6.34), the inductor current becomes,

$$i_L(t) = \frac{V_o}{L}t + i_L(0) = \frac{V_o}{L}t$$

When the resonant inductor current reaches the input current, I_{in} , the diode turns *OFF*,

$$\frac{V_o}{L}t_1 = I_{in}$$

with t_1 given by,

$$t_1 = \frac{I_{in}L}{V_o}$$

At $t = t_1$, the diode turns *OFF* since $i_L = I_{in}$, and the converter enters Mode II.

Steady-State Analysis (cont'd)

Mode II [$t_1 \leq t < t_2$]:

The switch remains closed, but the diode is *OFF* at Mode II as shown in Fig. 6.14(b). This is a resonant mode during which the capacitor voltage starts decreasing resonantly from its initial value of Vo. When $i_L=I_{in}$, the capacitor reaches its negative peak. At t = t_2. i_L equals zero, and the switch turns *OFF*, hence, switching at zero-current.

The initial conditions,

$$v_c(t_1) = V_o \qquad i_L(t_1) = I_o$$

From Fig. 6.14(b), the first derivatives for i_L and v_c are,

$$L\frac{di_L}{dt} = v_c$$

$$C\frac{dv_c}{dt} = I_{in} - i_L$$

Using the same solution technique used in the buck converter to solve the above differential equations, the expression for i_L(t)

$$i_L(t) = I_{in} + \frac{V_o}{Z_o}\sin\omega_o(t - t_1) \qquad (6.37)$$

$$v_c(t) = V_o\cos\omega_o(t - t_1) \qquad (6.38)$$

where $\omega_o = \frac{1}{\sqrt{LC}}$

At , $t = t_2$ $i_L(t_2) = 0$ and the time interval can be obtained from evaluating Eq. (6.37) at $t = t_2$ to yield,

$$(t_2 - t_1) = \frac{1}{\omega_o}\sin^{-1}(-\frac{I_{in}Z_o}{V_o}) \qquad = \frac{1}{\omega_o}[\pi + \sin^{-1}(\frac{I_{in}Z_o}{V_o})] \qquad (6.39)$$

Steady-State Analysis (cont'd)

Mode III [$t_2 \le t < t_3$]:

Mode III starts at t, and the switch and the diode are both open as shown in Fig. 6.14(c). Since v_c is constant, the capacitor starts charging up by the input current source. The capacitor voltage,

$$v_c = \frac{1}{C}\int_{t_2}^{t} I_{in} dt$$

$$= \frac{I_{in}}{C}(t - t_2) + v_c(t_2) \qquad (6.40)$$

The diode begins conducting at $t = t_3$ when the capacitor voltage is equal to the output voltage, i.e. $v_c(t_3)=V_o$.

$$V_o = \frac{I_{in}}{C}(t_3 - t_2) + v_c(t_2)$$

Time interval in this period

$$t_3 - t_2 = \frac{I_{in}}{C}[V_o - v_c(t_2)] \qquad (6.41)$$

Mode IV [$t_3 \le t < t_4$]:

At t_3, the capacitor voltage is clamped to the output voltage, and the diode starts conducting again. The cycle of the mode will repeat again at the time of T_s when S is turned *ON* again

ZCS Boost-Typical Steady-State Waveforms

Typical steady state waveforms are shown in Fig. 6.15.

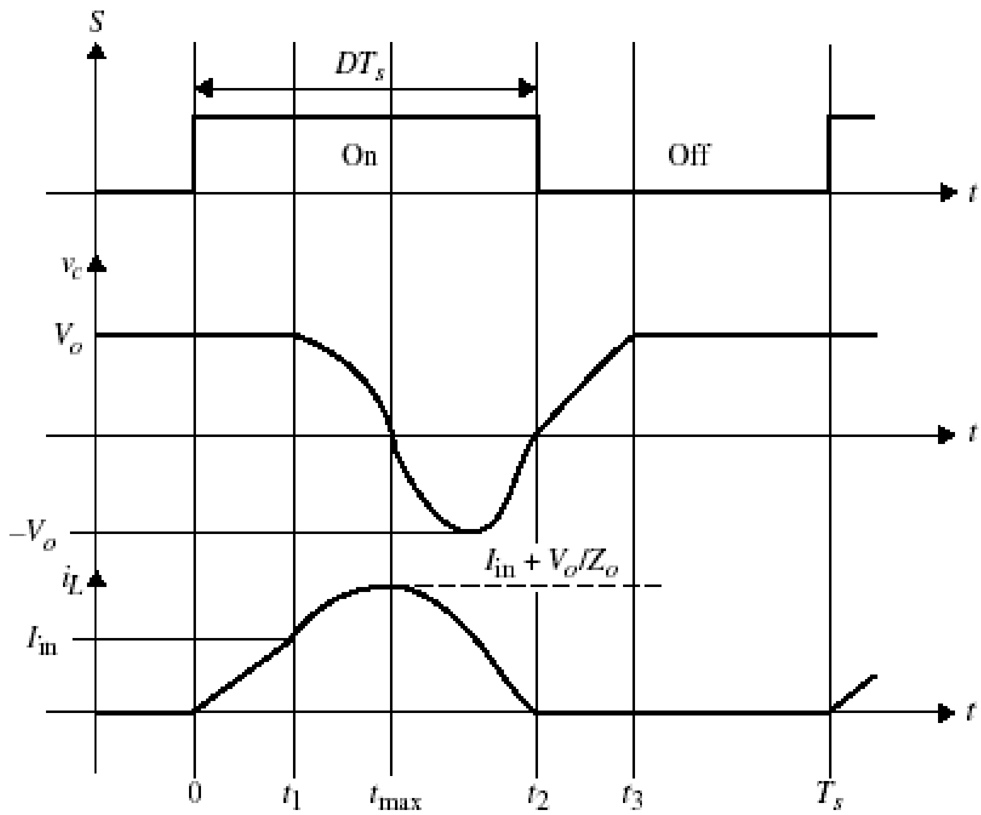

Fig 6.15 Steady-state waveforms of the boost converter with M-type switch.

ZCS Boost Converter

Voltage Gain

Conservation of energy per switching cycle to express the voltage gain, $M = V_o / V_{in}$

The input energy is,

$$E_{in} = V_{in} I_{in} T_s \tag{6.42}$$

The output energy,

$$E_o = \int_0^{T_s} i_o V_o dt \tag{6.43}$$

The output current equals $i_o = I_{in} - i_L$ and $i_o = I_{in}$ for intervals $0 \le t \le t_1$ and $t_3 \le t < T_s$,,

$$E_o = \int_0^{t_1} (I_{in} - i_L) V_o dt + \int_{t_3}^{T_s} I_{in} V_o dt \tag{6.44}$$

The input current is obtained from the conservation of output power as:

$$I_{in} = \frac{V_o^2}{V_{in} R}$$

ZCS Boost-Voltage Gain

Substituting for the input current and by evaluating Eq. (6.44), the output energy becomes

$$E_o = V_o \int_0^{t_1} (I_{in} - \frac{V_o}{L} t) dt + I_{in} V_o (T_s - t_3)$$
$$= V_o (I_{in} t_1 - \frac{1}{2} \frac{V_o}{L} t_1^2) + I_{in} V_o (T_s - t_3) \quad (6.45)$$

with $t_1 = \frac{I_{in} L}{V_o}$ and $(T_s - t_3) = T_s - [t_1 + (t_2 - t_1) + (t_3 - t_2)]$, and use the equations for $(t_3 - t_2)$ and $(t_2 - t_1)$ from Eqs. (6.39) and (6.41), Eq. (6.45) becomes,

$$E_o = -\frac{1}{2} I_{in}^2 L + V_o I_{in} [T_s - \frac{\alpha}{\omega_o} - \frac{C}{I_{in}} V_o (1 - \cos\alpha)] \quad (6.46)$$

The voltage gain expression is given by,

$$\frac{M-1}{M} = \frac{f_{ns}}{2\pi} \left[\frac{M}{2Q} + \alpha + \frac{Q}{M} (1 - \cos\alpha) \right] \quad (6.47)$$

where, α, M, I_o and f_{ns} are given as before.

ZCS Boost-Control Characteristic Curve

Fig 6.16 shows the characteristic curve for M vs. f_{ns} as a function of the normalized load.

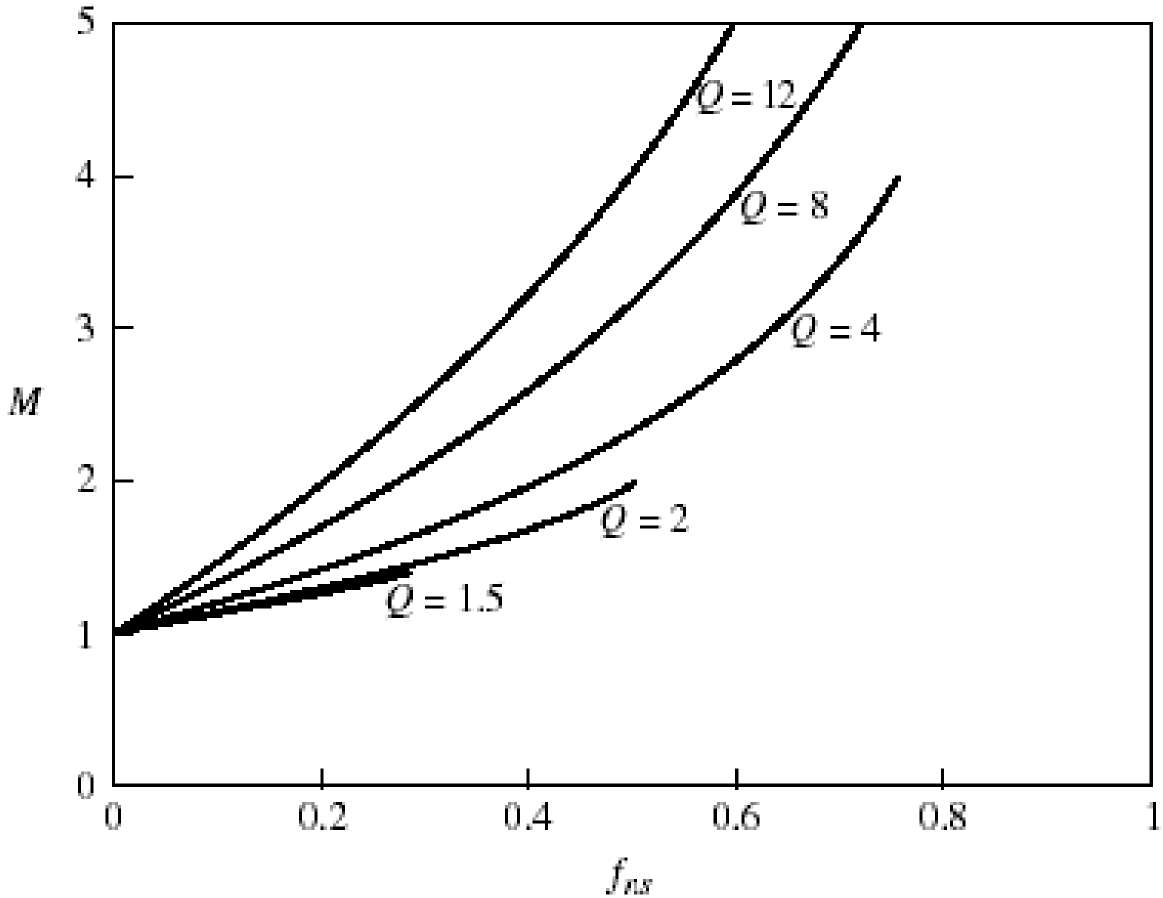

Fig 6.16 Characteristic curve for ***M*** vs. f_{ns} for the boost ZCS converter.

ZCS Boost Converter

Example 6.2

Design a boost ZCS converter for the following parameters: V_{in} = 20V, V_o = 40V. P_o =20W, f_s = 250kHz.

Solution:

The voltage gain is $M = \frac{V_o}{V_{in}} = \frac{40}{20} = 2$ Let us select $f_{ns} = 0.38$. From the characteristic curve of Fig. 6.16, Q can be approximated to 6.0

The characteristic impedance is given by,

$$Z_o = \frac{R_o}{Q} = \frac{80\,\Omega}{6} = 13.33\,\Omega \qquad (6.48)$$

Resonant frequency is,

$$f_o = \frac{f_s}{f_{ns}}$$

$$f_o = \frac{250\,kHz}{0.38} = 657.89\,kHz \qquad (6.49)$$

Solve Eqs. (6.48) and (6.49) for L and C

$$L = \frac{Z_o}{2\pi f_o} = \frac{13.33\Omega}{2\pi \times 657.89 \times 10^3} = 3.22 \times 10^{-6}\,H$$

$$C = \frac{1}{Z_o \omega_o} = \frac{1}{(13.33)(2\pi \times 657.89 \times 10^3)} = 18.14\,nF$$

ZCS Boost Converter

Example 6.3

Design a boost converter with ZCS, with the following design parameters: V_{in}=25V, P_0=30W at I_0=0.5A, and f_s=100kHz. Assume the output voltage ripple ΔV_0 is 0.2 %

***Solution*:**

The load resistance, $R = \frac{P_0}{I_0^2} = \frac{30}{(0.5)^2} = 120\Omega$

$$M = \frac{V_0}{V_s} = \frac{60}{25} = 2.4,$$

From the characteristic curve of Fig. 6.15, approximate Q to 6 when we assume f_n = 0.58.

$$f_o = \frac{100}{0.58} = 172.4kHz.$$

From Q and R_o, the characteristic impedance is obtained from,

$$Q = \frac{R_0}{Z_0} = \frac{120}{Z_0} = 6, \text{ and } Z_0 = 20 \qquad \sqrt{\frac{L}{C}} = 20$$

$$\omega_o = 2\pi\left(172\times10^3\right) = 1080.7\times10^3\, rad/\sec$$

$$\sqrt{\frac{1}{L\ \ C}} = 1080.7\times10^3$$

Solving for C and L

$$C = 46.27\eta F$$

$$L = 18.51\mu H$$

Example 6.3 (cont'd)

The time intervals are given by

$$t_1 = \frac{L_r I_i}{V_0} = \frac{18.51\times10^{-3}\times1.2}{60} = 0.370\mu s$$

$$t_2 - t_1 = \frac{1}{\omega_o}\sin^{-1}\left[\frac{-Z_0 I_i}{V_0}\right]$$

$$= \frac{1}{1080.7\times10^3}\sin^{-1}\left[-\frac{20\times1.2}{60}\right] = 3.29\mu s$$

$$t_3 - t_2 = \frac{1}{\omega_n}\frac{V_0}{Z_0 I_i}(1-\cos\alpha)$$

$$= \frac{1}{1080.7\times10^3}\frac{60}{20\times1.2}(1-\cos 3.553)$$

$$= 0.193\mu s$$

$$t_4 - t_3 = T - t_1 - (t_{12}) - (t_{23})$$

$$= 10 - 0.370 - 3.29 - 0.193 = 6.147\mu s$$

Other ZCS Boost Converter

Figure 6.17(a) shows the quasi-resonant boost converter by using the L-type resonant switch, and the simplified circuit and its steady state waveforms are shown in Fig.6. 17(b) and (c), respectively.

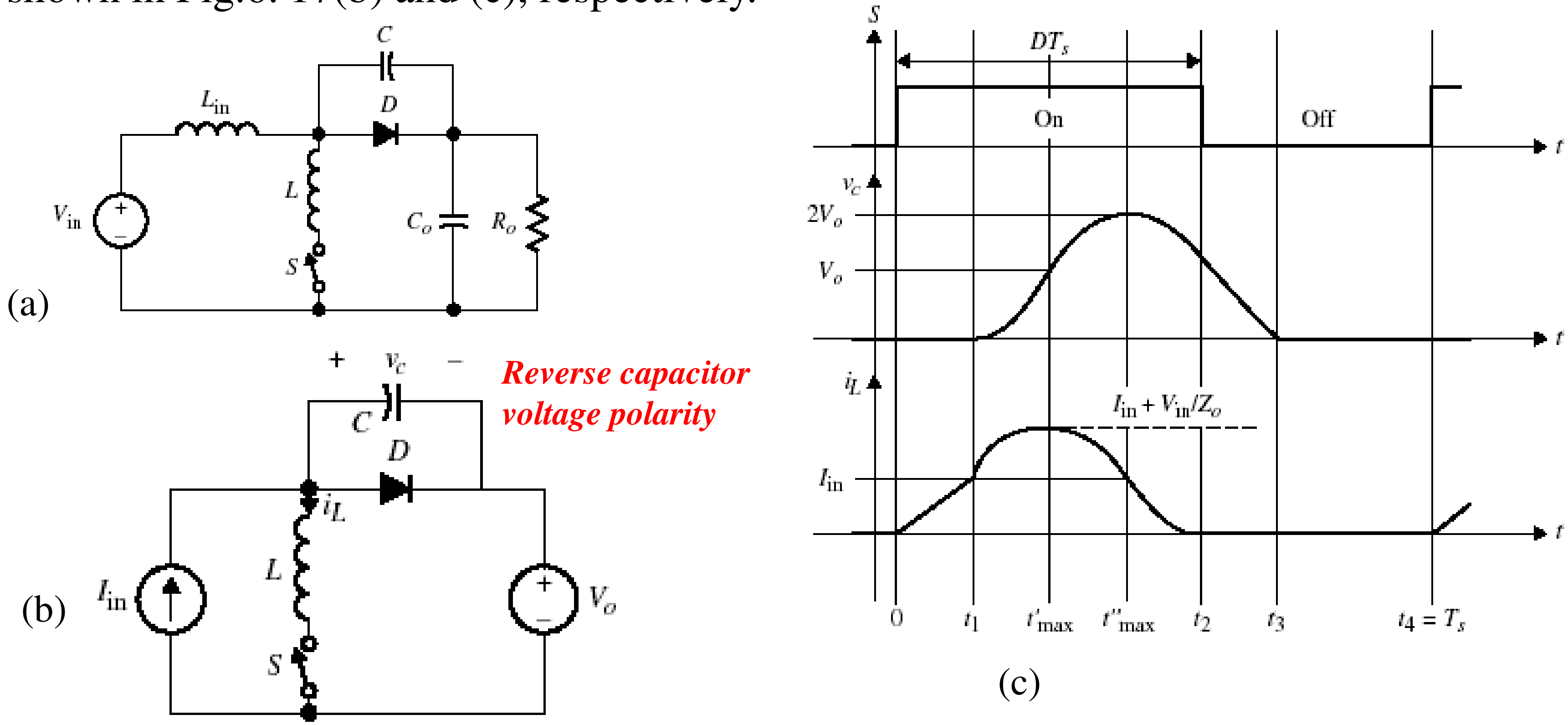

Fig 6.17 (a) ZCS boost converter with L-type switch. (b) Simplified equivalent circuit. (c) Steady-state waveforms.