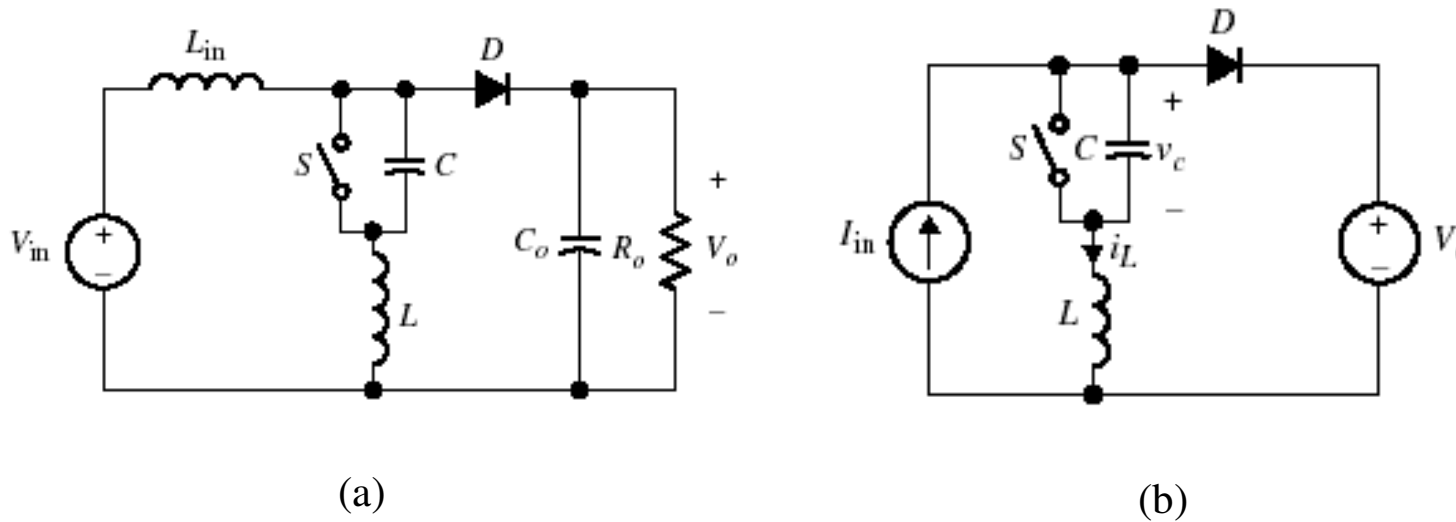


## ZVS Boost Converter

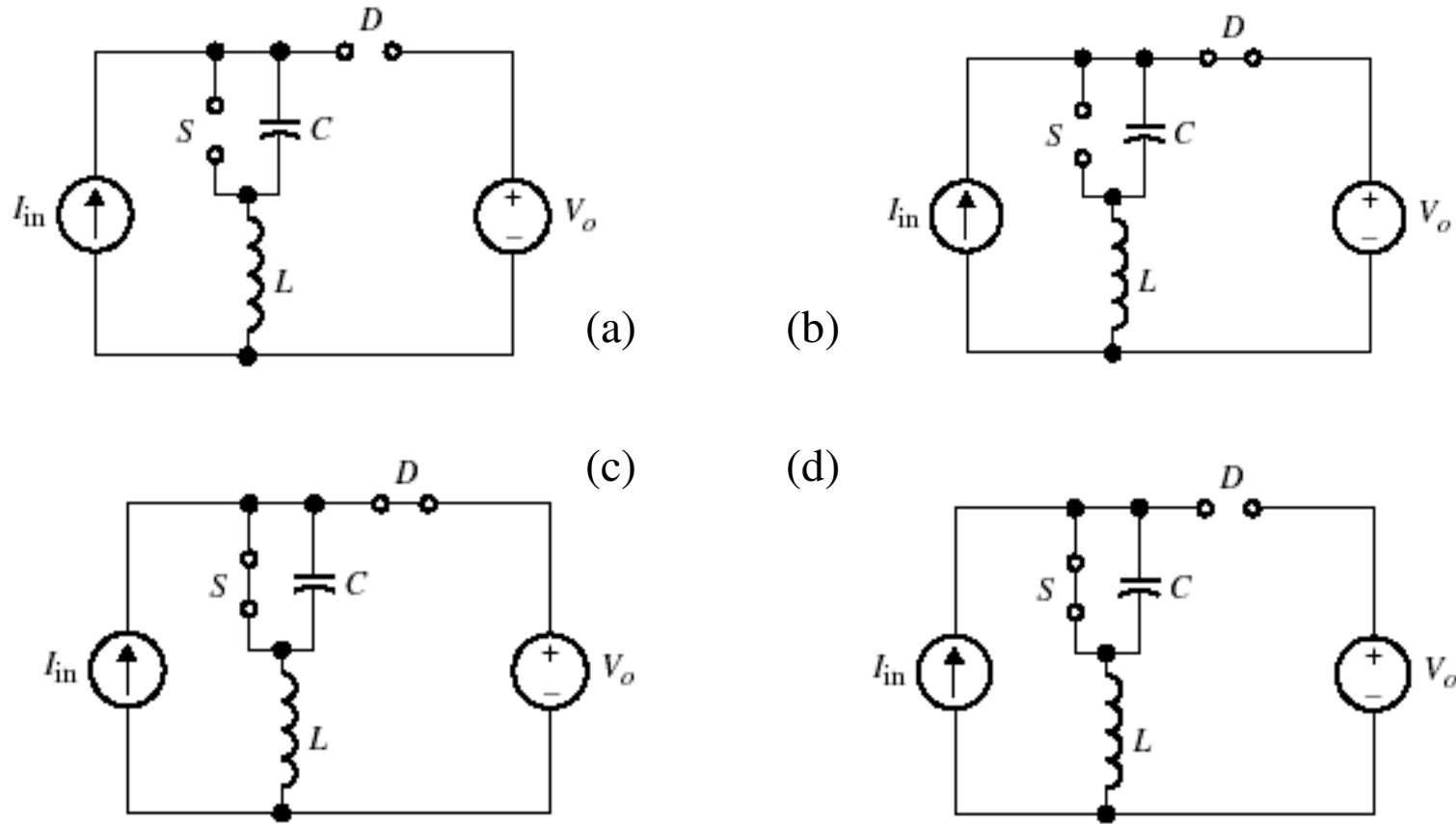
The quasi-resonant boost converter by using the M-type switch as shown in Fig. 6.29(a) with its simplified circuit shown in Fig. 6.29(b).



**Fig 6.29** (a) Quasi-resonant boost converter with M-type switch. (b) Equivalent circuit.

## ZVS Boost Converter – Equivalent Circuit Modes

The four circuit modes of operation are shown in Fig. 6.30.



**Fig 6.30** equivalent circuit nodes. (a) Mode I. (b) Mode II. (c) Mode III. (d) Mode IV.

## Steady-State Analysis

### Mode I [ $0 \leq t < t_1$ ]:

Assume for  $t < 0$ , the switch is closed while D is open. At  $t=0$ , the switch is turned *OFF*, allowing the capacitor to charge by the constant current  $I_{in}$ ,

$$I_{in} = i_L = i_C = C \frac{dv_c}{dt} \quad (6.76)$$

With the initial capacitor voltage equals zero

$$v_c(t) = \frac{I_{in}}{C} t \quad (6.77)$$

The capacitor voltage reaches the output voltage at  $t = t_1$   $v_c(t_1) = V_o$  ,

$$t_1 = \frac{CV_o}{I_{in}} \quad (6.78)$$

At  $t = t_1$   $v_c = V_o$  ,the diode starts conducting since , and the converter enters Mode II.

## Steady-State Analysis (cont'd)

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

At  $t = t_1$ , the resonant stage begins since D is *ON* and S is *OFF*,

The initial conditions are  $v_c(t_1) = V_o$  and  $i_L(t_1) = I_{in}$ .

The expression for  $v_c(t)$  is given by

$$v_c(t) = V_o + I_{in} Z_o \sin \omega_o (t - t_1) \quad (6.79)$$

Inductor current,

$$i_L(t) = I_{in} \cos \omega_o (t - t_1) \quad \text{Book Correction} \quad (6.80)$$

Evaluating Eq. (6.79) at  $t = t_2$  with  $v_c(t_2) = 0$ , the time interval between  $t_1$  to  $t_2$  can be found to be,

$$(t_2 - t_1) = \frac{1}{\omega_o} \sin^{-1} \left( \frac{-V_o}{I_{in} Z_o} \right) \quad (6.81)$$

## Steady-State Analysis (cont'd)

### Mode III [ $t_2 \leq t < t_3$ ]:

- Mode III starts at  $t_2$  when  $v_c$  reaches zero, and the switch diode (anti-parallel diode) turns ON, clamping the voltage across C to zero
- At  $t = t_2'$ , S turns ON at ZVS. The switch picks up the current, and the inductor current linearly increases to  $I_{in}$ .

The initial conditions at  $t = t_2$  are,

$$v_c(t_2) = 0 \quad (6.82a)$$

$$i_L(t_2) = I_{in} \cos \omega_o(t_2 - t_1) \quad \text{Book Correction} \quad (6.82b)$$

Because the capacitor voltage is zero, the inductor voltage is equal to the output voltage.

$$L \frac{di_L}{dt} = V_o \quad (6.83)$$

The inductor current becomes,

$$i_L(t) = \frac{V_o}{L}(t - t_2) + i_L(t_2) \quad (6.84)$$

- To achieve ZVS, the switch can be turned ON anytime after  $t_2$  and before  $t_2'$ .

At  $t = t_3$ ,  $i_L$  reaches  $I_{in}$  (**Book Correction**), resulting in the time interval given in Eq. (6.85)

$$(t_3 - t_2) = \frac{L}{V_o} [I_{in} - i_L(t_2)] \quad (6.85)$$

## Steady-State Analysis (cont'd)

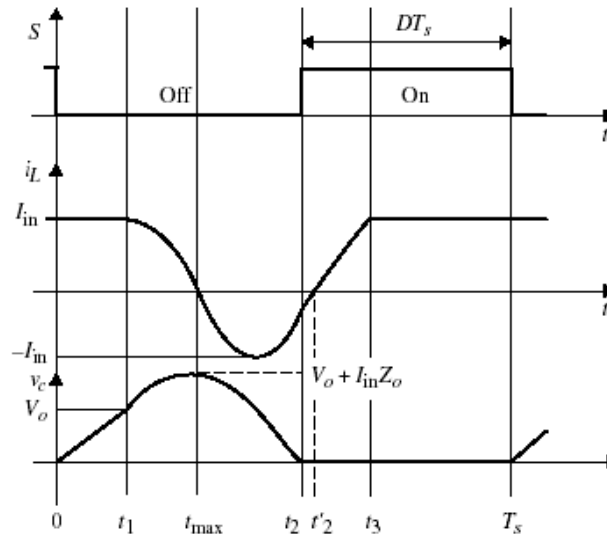
Substituting the initial condition into the equation,

$$(t_3 - t_2) = \frac{L}{V_o} I_{in} [1 - \cos \omega t_o (t_2 - t_1)] \quad \text{Book Correction} \quad (6.86)$$

At  $t = t_3$ , the output diode turns *OFF* and the entire  $I_{in}$  current flows in the transistor and the inductor.

### Mode IV [ $t_3 \leq t < t_4$ ]:

At time  $t_3$ , the inductor current reaches  $I_{in}$  (*Book Correction*), and the output diode turns *OFF*, but the switch remains closed. The cycle of the mode will repeat again at  $t = T_s$ .



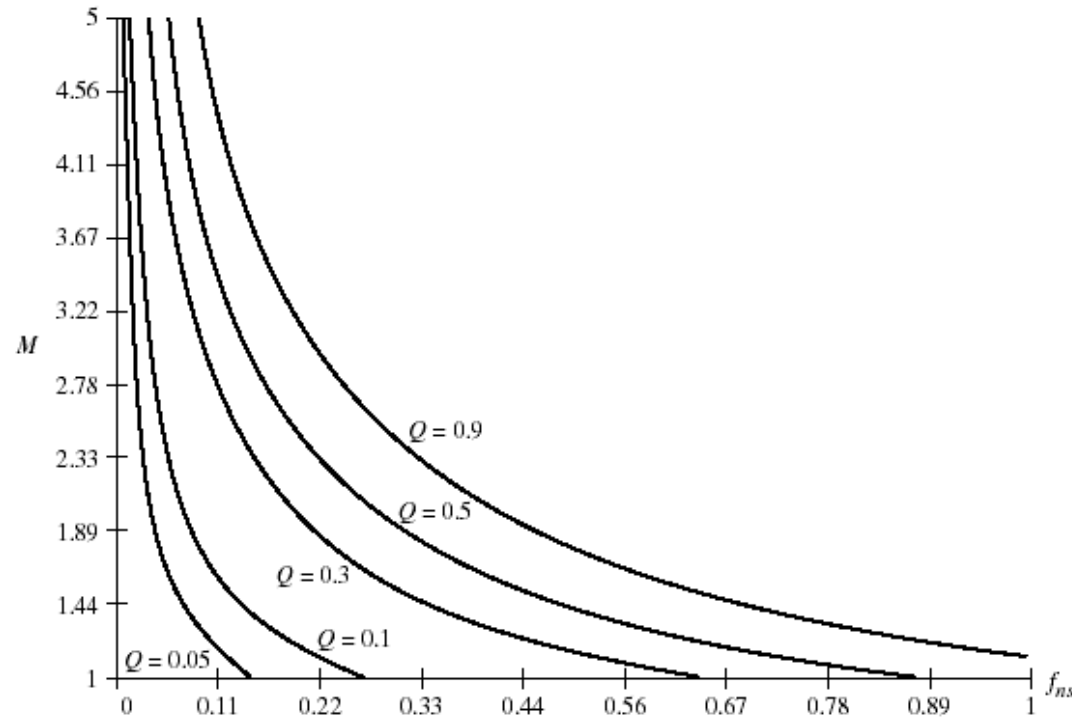
**Fig 6.31** Steady-state waveforms for ZVS boost converter.

## Voltage Gain:

- The voltage gain in terms of the normalized parameter:

$$\frac{1}{M} = \frac{f_{ns}}{2\pi} \left[ \frac{Q}{2M} + \alpha + \frac{M}{Q} (1 - \cos \alpha) \right] \quad (6.87)$$

- A plot of the control characteristic curve of  $M$  vs.  $f_{ns}$  is shown in Fig. 6.32.



**Fig 6.32** Control characteristic curve of  $M$  vs.  $f_{ns}$  for ZVT boost converter.

## ZVS Boost Converter

### Example 6.5

Design a ZVS-QRC boost converter for the following design parameters:  $V_{in}=30V$ ,  $P_0=30W$  at  $V_0=38V$ ,  $f_{ns}=0.4$ , and  $T_s=4 \mu s$ . Assume the output voltage ripple is limited to 2% at  $D = 0.4$ .

### Solution:

The voltage gain is  $M = \frac{V_o}{V_{in}} = 1.3$  and with  $f_{ns} = 0.4$ , we obtain  $Q = 0.2$ . Using the switching frequency,  $f_s = \frac{1}{T_s} = \frac{1}{4 \mu s} = 250 kHz$  and,  $f_o = \frac{f_s}{0.4} = \frac{250}{0.4} kHz = 625 kHz$  the resonant frequency is obtained from,

$$\omega_0 = \frac{1}{\sqrt{L C}} = (2\pi)(625) \times 10^3$$

The second equation in terms of L and C is obtained from,

$$Q = \frac{R_o}{Z_o} = \frac{R_o}{\sqrt{L/C}} = 0.2$$

The load resistance is,

$$R_o = \frac{38^2}{30} = 48.13 \Omega$$

Substituting in the above relation for Q, we obtain

$$\sqrt{\frac{L}{C}} = \frac{48.13}{0.2} = 240.65$$

Solving the above two equations for C and L, we obtain,

$$C = \frac{1}{(2\pi)(625)(10^3)(240.65)} = 1.06 nF \quad L = 1.06 \times 10^{-9} \times (240.65)^2 = 61.3 \mu F$$

To calculate  $L_o$  and  $C_o$ , using the voltage ripple to be 2%, we use the following relation,

$$\frac{D}{f_s R_o C_o} = 0.02$$

where,

$$D \approx \frac{f_n}{f_s} = 0.4$$

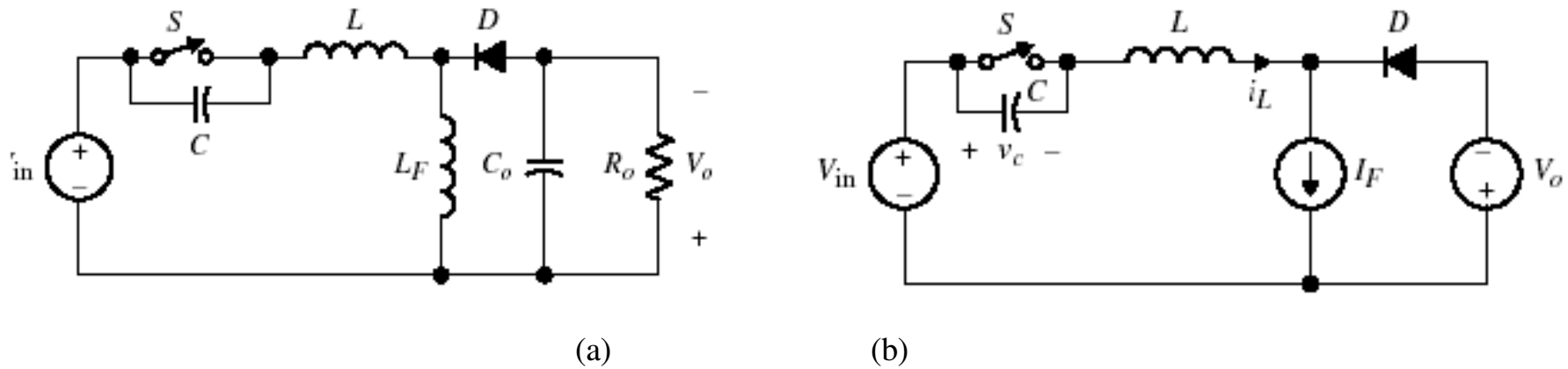
$$\begin{aligned} C_o &= \frac{0.4}{f_s R_o} \frac{100}{0.2} \\ &= \frac{40}{0.2 \times 250 \times 10^3 \times 48.13} = 16.6 \mu F \end{aligned}$$

The critical inductor value is given by,

$$\begin{aligned} L_{crit} &= \frac{R_o}{2f_s} (1-D)^2 D \\ &= \frac{48.13}{2 \times 250 \times 10^3} (1-0.4)^2 (0.4) \\ &= 13.9 \mu H \end{aligned}$$

To achieve a limited ripple current, it is recommended that  $L_o$  be set to be about a 100 times the critical inductor value. So we select  $L_o = 1.4$  mH.

# The Buck-Boost Converter



**Fig 6.34** (a) ZVS buck-boost converter with M-type switch. (b) Simplified equivalent circuit.

# Equivalent Modes

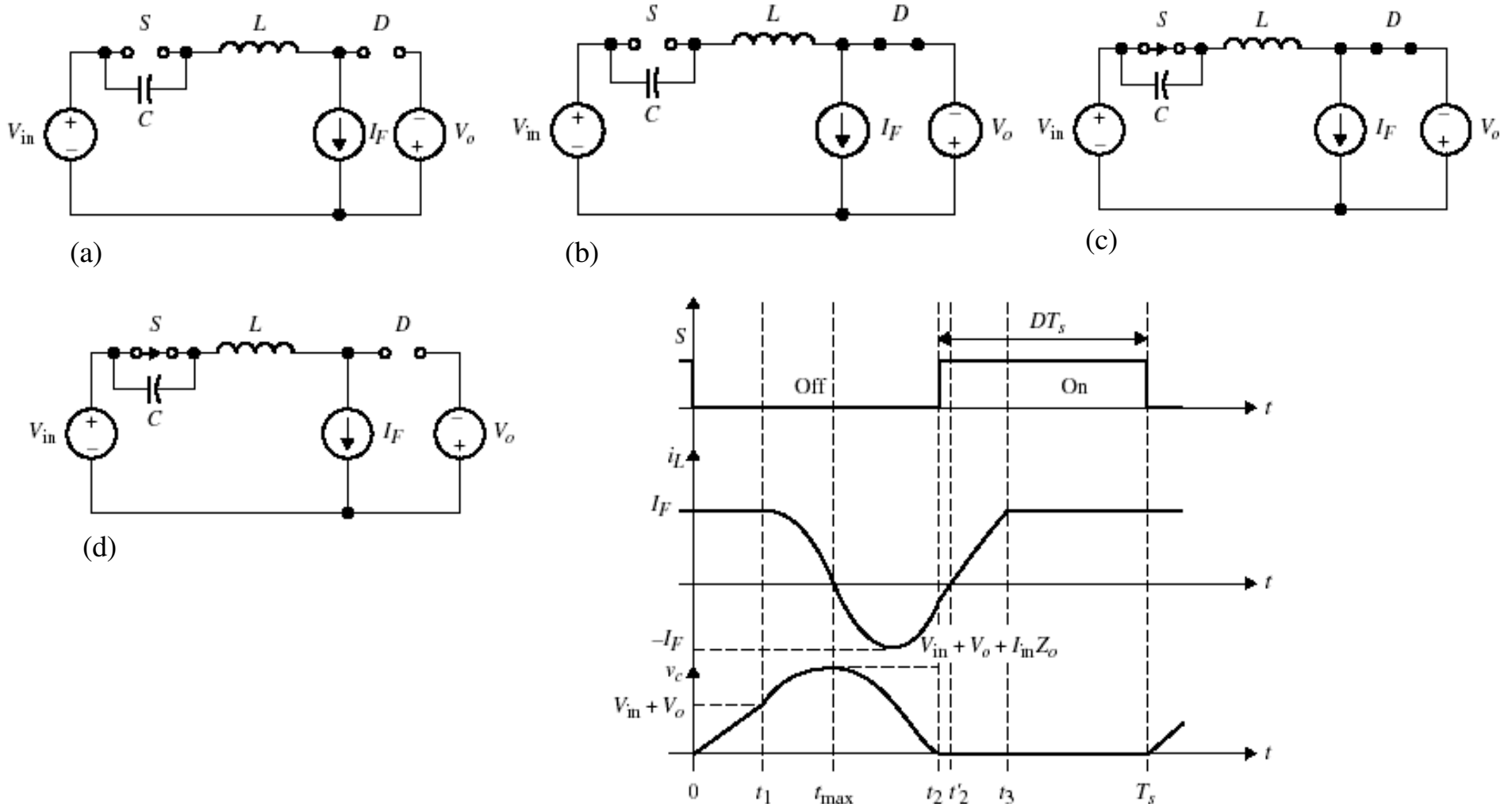


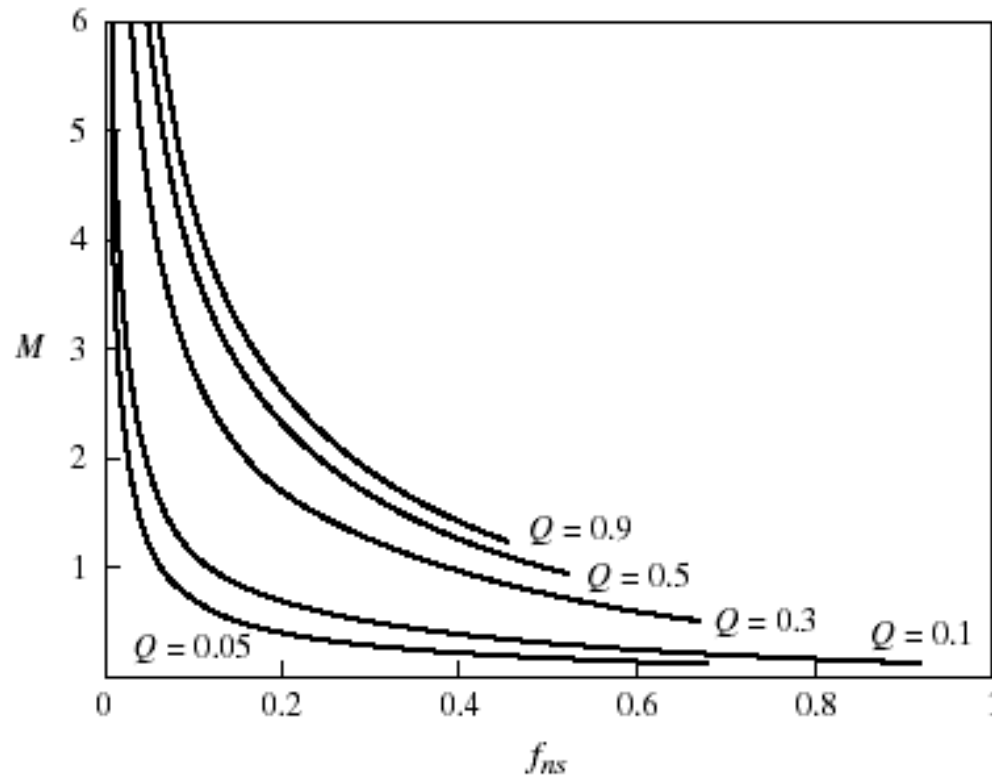
Fig 6.35 Equivalent circuits for (a) mode I, (b) mode II, (c) mode III, and (d) mode IV. (e) Steady-state waveforms for  $v_c$  and  $i_L$ .

## Voltage Gain

The voltage gain in terms of  $M$ ,  $Q$ , and  $f_{ns}$  is given in Eq. (6.88),

$$M = \frac{1}{\frac{f_{ns}}{2\pi} \left[ \frac{Q}{2M} + \alpha + \frac{M}{Q} (1 - \cos \alpha) \right]} - 1 \quad \text{Book Correction} \quad (6.88)$$

Figure 6.36 shows the control characteristic curve for  $M$  vs.  $f_{ns}$ .



**Fig 6.36** Control characteristic curve of  $M$  vs.  $f_{ns}$  for ZVS buck-boost converter.