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).

![Diagram of ZVS Boost Converter](image)

**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 \( I_{in} \).

\[
I_{in} = i_L = i_c = C \frac{dv_c}{dt}
\]  \( (6.76) \)

With the initial capacitor voltage equals zero

\[
v_c(t) = \frac{I_{in}}{C} t
\]  \( (6.77) \)

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

\[
t_1 = \frac{CV_o}{I_{in}}
\]  \( (6.78) \)

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

\[
v_c(t) = V_o + I_{in} Z_o \sin \omega_o (t - t_1)
\]

(6.79)

Inductor current,

\[
i_L(t) = I_{in} \cos \omega_o (t - t_1)
\]

(6.80) \textbf{Book Correction}

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,

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

(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,

\[
v_c(t_2) = 0 \quad \text{(6.82a)}
\]

\[
i_L(t_2) = I_{in} \cos \omega_n(t_2 - t_1) \quad \text{Book Correction} \quad \text{(6.82b)}
\]

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

\[
L \frac{di_L}{dt} = V_o \quad \text{(6.83)}
\]

The inductor current becomes,

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

- 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)

\[
(t_3 - t_2) = \frac{L}{V_o} [I_{in} - i_L(t_2)] \quad \text{(6.85)}
\]
Steady-State Analysis (cont’d)

Substituting the initial condition into the equation,

\[(t_3 - t_2) = \frac{L}{V_o} I_{in} \left[ 1 - \cos \alpha (t_2 - t_1) \right] \quad \text{Book Correction} \]  \hspace{1cm} (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 \( t = T_s \).

![Steady-state waveforms for ZVS boost converter.](image)

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

- The voltage gain in terms of the normalized parameter:

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

(6.87)

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

![Control characteristic curve of \( M \) vs. \( f_{ns} \) for ZVT boost converter.](image)

**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, $f_s = \frac{1}{T_s} = \frac{1}{4\mu s} = 250kHz$ and, $f_o = \frac{f_s}{0.4} = \frac{250}{0.4} kHz = 625kHz$ the resonant frequency is obtained from,

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

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,

$$C = \frac{1}{(2\pi)(625)(10^3)(240.65)} = 1.06nF$$

$$L = 1.06 \times 10^{-9} \times (240.65)^2 = 61.3\mu F$$
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,

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

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

The critical inductor value is given by,

$$L_{crit} = \frac{R_o}{2 f_s} (1 - D)^2 D$$

$$= \frac{48.13}{2 \times 250 \times 10^3} (1 - 0.4)^2 (0.4)$$

$$= 13.9 \mu H$$

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),

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

(6.88)

*Book Correction*

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.](image)

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