ZERO-Voltage Switching Topologies

Switch Implementation

Figure 6.23(a) shows a MOSFET switch implementation by including an internal body diode and parasitic capacitance.

We will assume $C_{gd}$ and $C_{gs}$ are too small to be included.

![MOSFET implementation diagram](image)

**Fig 6.23** (a) MOSFET implementation.
ZVS Resonant Switch Arrangements

- Figure 6.24(a) shows the two possible switch implementations using L- and M-type resonant switches.
- The half-wave L-type and M-type MOSFET implementations are shown in Fig 6.24(b), whereas Fig 6.24(c) shows the full-wave implementations for L- and M-type switches.

Fig 6.24 (a) Resonant switch arrangement types for ZVS operation. (b) Half-wave MOSFET implementation. (c) Full-wave MOSFET implementation.
Steady State Analyses of Quasi-Resonant Converters

The Buck Converter

Replacing the switch in Fig. 6.7(a) by the M-type switch of Fig. 6.24(a), we obtain a new ZVS buck converter as shown in Fig. 6.25(a). The simplified equivalent circuit is given in Fig. 6.25(b).

**Fig 6.25** (a) Quasi-resonant buck converter with M-type switch. (b) Simplified equivalent circuit.
Equivalent circuit modes under the steady state condition.

Under steady-state conditions, there are four modes of operation.

Fig 6.26 Equivalent circuits for (a) mode I, (b) mode II, (c) mode III \((t_2 \leq t < t_{2'})\), (d) mode III \((t_{2'} \leq t < t_3)\), and (e) mode IV.
Steady State Analysis

Mode I \([0 \leq t < t_1]\)

Assume initially the power switch is conducting, and the diode is OFF. Mode I starts at \(t=0\) when the switch is turned OFF.

The initial capacitor voltage, \(v_c\) is zero, and the inductor current is \(I_o\)

\[
\begin{align*}
    v_c(0) &= 0 \\
    i_L(0) &= I_o
\end{align*}
\]

Applying KCL to Fig. 6.26(a),

\[
C \frac{dv_c}{dt} = i_L
\]

since \(i_L = I_o\), the capacitor starts to charge,

\[
v_c(t) = \frac{1}{C} I_o t \quad (6.61)
\]

The voltage across the output diode,

\[
v_D = V_{in} - v_c
\]

As long as \(v_c < V_{in}\), the diode remains OFF.
Steady State Analysis (cont’d)

The capacitor voltage reaches the input voltage, $V_{in}$, at $t = t_1$, causing the diode to turn ON. Hence, at $t = t_1$, we have

$$v_c(t_1) = V_{in}$$

and $t_1$ can be expressed as

$$t_1 = \frac{CV_{in}}{I_o}$$

At $t = t_1$, the circuit enters Mode II.
Mode II \([t_1 \leq t < t_2]\):

Mode II starts at \(t_1\) with diode turns \(ON\), circuit enters the resonant stage. At \(t = t_2\), the capacitor voltage tends to go negative, hence, forcing the diode across \(S\) to turn \(ON\). The initial condition,

\[
\begin{align*}
    v_c(t_1) &= V_{in} \\
    i_L(t_1) &= I_o
\end{align*}
\]

The expressions of the current and the voltage

\[
\begin{align*}
    i_L(t) &= I_o \cos \omega_o(t - t_1) \\
    v_c(t) &= V_{in} + I_o Z_o \sin \omega_o(t - t_1)
\end{align*}
\]

The period between \(t_1\) and \(t_2\) is given by,

\[
\begin{align*}
    t_2 - t_1 &= \frac{1}{\omega_o} \sin^{-1}\left(\frac{-V_{in}}{I_o Z_o}\right) = \frac{\alpha}{\omega_o} \\
    \text{and the inductor current at } t = t_2 \text{ is,} \\
    i_L(t_2) &= I_o \cos \alpha \quad \alpha = \sin^{-1}\left(\frac{-V_{in}}{I_o Z_o}\right) = \omega_o (t_2 - t_1)
\end{align*}
\]
Steady State Analysis (cont’d)

Mode III \([t_2 \leq t < t_3]\):

At \(t_2\), the capacitor voltage becomes zero, and the inductor current starts to charge linearly, and it reaches the output current at \(t = t_3\). The body diode of the switch turns \textit{ON} at \(t = t_2\).

The initial value of the capacitor voltage in Mode III is zero

\[ v_c(t_2) = 0 \]

The inductor voltage,

\[ L \frac{di_L}{dt} = V_{in} \quad (6.67) \]

The inductor current can be expressed as,

\[ i_L(t) = \frac{V_{in}}{L} (t - t_2) + I_o \cos \alpha \quad (6.68) \]

At \(t = t_3\), the inductor current reaches the output current \(i_L(t_3) = I_o\), forcing the diode to turn \textit{OFF}.

Time interval from \(t_3 - t_2\) is

\[ t_3 - t_2 = \frac{I_o L}{V_{in}} (1 - \cos \alpha) \quad (6.69) \]
Steady State Analysis (cont’d)

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

In this mode, the inductor current is trapped and held constant at $i_L = I_o$, with $v_C = 0$, i.e.,

\[
i_L = I_o \\
v_C = 0
\]

Mode IV will continue as long as the switch remains on. By turning off the switch at $t = t_4 = T_s$, the switching cycle repeats. The dead time $t_4 - t_3$ is given by,

\[
t_4 - t_3 = T_s - \Delta t_1 - \Delta t_2 - \Delta t_3
\]

(6.70)
Figure 6.27 Steady-state waveforms for the ZVS buck converter.
ZVS Buck Converter - Voltage Gain

The input energy is given by,

\[ E_{in} = \int_{0}^{T_s} i_{in} V_{in} \, dt \]

\( i_{in} \) is the current which is equal to \( i_L(t) \). Hence, we have

\[ E_{in} = \int_{0}^{t_1} i_L(t) V_{in} \, dt + \int_{t_1}^{t_2} i_L(t) V_{in} \, dt + \int_{t_2}^{t_3} i_L(t) V_{in} \, dt + \int_{t_3}^{T_s} i_L(t) V_{in} \, dt \]  \hspace{1cm} (6.71)

The inductor current equals the output current in Mode I and IV, and for \( t_1 \leq t < t_2 \) and \( t_2 \leq t < t_3 \),

\[ E_{in} = V_{in} [I_o t_1 + I_o \sqrt{L/C} \sin \omega_o (t_2 - t_1) + \frac{V_{in}}{2L} (t_3 - t_2)^2 \]

\[ + I_o \cos \alpha (t_3 - t_2) + I_o (T_s - t_3)] \]  \hspace{1cm} (6.72)

Substituting for the time intervals \( t_1 \), \( (t_2-t_1) \), \( (t_3-t_2) \) and \( (T_s-t_3) \) using the normalized parameters \( M \), \( Q \), and \( \omega_o \)

\[ E_{in} = V_{in} I_o \left[ \frac{-Q}{M \omega_o} - \frac{ML}{2R} \right] + \frac{T_s}{\omega_o} - \frac{\alpha}{\omega_o} + \frac{ML}{R} \cos \alpha - \frac{ML}{2R} \cos^2 \alpha \]  \hspace{1cm} (6.73)
ZVS Buck Converter - Voltage Gain (cont’d)

The output energy is expressed by,

\[ E_o = \int_0^{T_s} I_o V_o dt = I_o V_o T_s \]

Equating the input and output energy

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

A plot of the control characteristic curve of \( M \) vs. \( f_{ns} \) is shown in Fig. 6.28.

**Fig 6.28** Control characteristic curve of \( M \) vs. \( f_{ns} \) for ZVS buck converter.