Zero-voltage and Zero-current Transition Converter

• Traditional converters operate with a sinusoidal current through the power switches, which results in high peak and rms currents for the power transistors and high voltage stresses on the rectifier diodes.

• When the line voltage or load current varies over a wide range, Quasi-Resonant Converters are modulated with a wide switching frequency range, making the circuit design difficult to optimize.

• As a compromise between the PWM and resonant techniques, various soft-switching PWM converter techniques proposed to aim at combining desirable features of both the conventional PWM and Quasi-Resonant techniques without a significant increase in the circulating energy.
Switching Transition

• To overcome the limitations of the quasi-resonant converters, zero-voltage transition (ZVT) or zero-current transition (ZCT) is the solution. Instead of using a series resonant network across the power switch, a shunt resonant network is used across the power switch.

• The features of the ZCT PWM and ZVT PWM soft-switching converters are summarized as follows:
  – Zero-current/voltage turn-off/on for the power switch
  – Low voltage/current stresses of the power switch and rectifier diode
  – Minimal circulating energy
  – Constant-frequency operation
  – Soft switching for a wide line and load range

• One disadvantage is that the auxiliary switch does not operate with soft switching; it is hard-switching, but the switching loss is much lower than that of a PWM converter.
ZVT & ZCT Switch

The ZVT and ZCT converters differ from the conventional PWM converters by the introduction of a resonant branch.

Figure 6.48(a) shows the ZVT-PWM switching cell

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**Fig 6.48** (a) ZVT PWM switching cell. (b) ZCT PWM switching cell.
The Boost ZVT PWM Converter

- The boost ZVT PWM, shown in Fig. 6.49, by placing the ZVT PWM switching cell shown in Fig. 6.48(a) into the conventional boost converter.

Fig 6.49 (a) Boost ZVT PWM. (b) Simplified equivalent circuit.
The switching cycle is divided into six modes

Figure 6.50 Equivalent circuits for the six modes of operation: (a) mode I, (b) mode II, (c) mode III, (d) mode IV, (e) mode V, and (f) mode VI.
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Steady State Analysis

Mode I \([t_0 \leq t < t_1]\)

- Mode I starts at \(t = t_0\) when the auxiliary switch \(S_1\) is turned \(ON\).

- Since the main switch, \(S\), and the auxiliary switch \(S_1\) were \(OFF\) prior to \(t = t_0\),

- The capacitor voltage \(V_c\), is equal to the output voltage \(V_o\) and also equal to the inductor voltage as given by,

\[
V_o = L \frac{di_l}{dt} = V_c
\]

The inductor current \(i_l\) is given by,

\[
i_l = \frac{V_o}{L} (t - t_0)
\]

The above equation assumes zero initial condition for \(i_l\).
Steady State Analysis (cont’d)

As long as the inductor current is less than $I_{in}$, the diode will stay conducting and the capacitor voltage remains at $V_o$. At time $t_1$, the inductor current becomes equal to $I_{in}$, $D$ stops conducting, and the circuit enters Mode II. From the above equation, we have,

$$I_{in} = \frac{V_o}{L}(t - t_0)$$

The time interval is given by

$$(t_1 - t_0) = \frac{L I_{in}}{V_o}$$

This is the inductor current charging state.

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

Mode II starts at $t_1$ when $D$ is OFF, resulting in a resonant stage between $L$ and $C$. During the time between $t_1$ and $t_2$, the main switch, remains OFF, and $S_1$ is still ON, but both diodes are OFF. The initial capacitor voltage is still $V_o$, but the initial $I_{in}$ has changed to $I_{in}$. The first order differential equations that represent this mode are given by,

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

$$v_c(t) = L \frac{di_L}{dt}$$
Steady State Analysis (cont’d)

Equation (6.109) is obtained from the above two equations.

\[
\frac{d^2 i_L}{dt^2} - \frac{1}{LC} i_L = \frac{1}{LC} I_{in}
\]

The solution for \( i_L \) and \( v_c \) is given by,

\[
i_L = \frac{V_o}{Z} \sin \omega_o (t - t_1) + I_{in}
\]

\[
v_c = V_o (2 - \cos \omega_o (t - t_1))
\]

The time interval between \( t_1 \) and \( t_2 \) is given by

\[
(t_2 - t_1) = \frac{1}{\omega_o} \cos^{-1}(2)
\]

The diode voltage starts to charge up due to the decreasing capacitor voltage.

\[
v_d = V_o - v_c
\]

Substituting for \( v_c \), the diode voltage becomes,

\[
v_d(t) = -V_o + V_o \cos \omega_o (t - t_1)
\]
Steady State Analysis (cont’d)

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

Mode III starts when the capacitor discharge to zero. In this mode the main switch, \( S \) remains \( OFF \), the auxiliary switch, \( S_1 \) is still \( ON \), and both diodes are \( OFF \). The switch anti-parallel diode \( () \) start conducting in this mode.

\[
v_c(t) = 0
\]

Mode IV \( [t_3 \leq t < t_4] \):

Mode IV starts at \( t = t_3 \), when the main switch, \( S \) is turned \( ON \) and the auxiliary switch, \( S_1 \) is turned \( OFF \). At \( t_3 \), the initial capacitor voltage is zero, and the inductor starts linearly discharging from \( i_L(t_2) \) to zero during \( t_3 \) to \( t_4 \). The diode \( D_1 \) remain \( OFF \) since its voltage is negative, but \( D_1 \) turns \( ON \) at \( t = t_3 \) to carry the inductor current.

The input voltage is equal to the inductor voltage, and the output voltage is equal to the negative of inductor voltage \( v_L \)

\[
v_L = L \frac{di_L}{dt} = -V_o
\]

The inductor current for \( t > t_2 \), is given by,

\[
i_L(t) = -\frac{V_o}{L}(t - t_2) + i_L(t_2)
\]
Steady State Analysis (cont’d)

Mode V \([t_4 \leq t < t_5]\):

In this mode, at \(t = t_4\) both switches are \(OFF\), and also both diodes are \(OFF\). The inductor current is zero, and the input current is only going through the capacitor,

\[
I_{in} = C \frac{dv_c}{dt}
\]

The capacitor voltage can be expressed as,

\[
v_c(t) = \frac{1}{C} I_{in} (t - t_4)
\]

The capacitor is charging up from zero and will reach the output voltage at \(t = t_5\)

The time interval is,

\[
(t_5 - t_4) = \frac{V_o C}{I_{in}}
\]

then it enters mode VI at this point.

Mode VI \([t_5 \leq t < t_6]\)

When the capacitor reaches the output voltage, \(D\) starts conducting, but in this mode, both switches are still \(OFF\). The diode current will equal the input current immediately. At \(t = t_5\), the capacitor voltage is equal to the output voltage until the auxiliary switch is turned \(ON\) again, then the cycle will repeat from mode I. The waveforms for the six modes of operation are shown in Fig.6.51.
Steady State Waveforms

Fig 6.51 Steady-state waveforms for the ZVT boost converter of Fig 6.49(b).