Classification of Resonant-Switch Converters

ZVS-QR

Converter examples

High-frequency view of the switch network

Buck

Boost

Buck-Boost

Cuk
20.3.1 The zero-voltage-switching quasi-resonant switch cell (ZVS-QR)

When the previously-described operations are followed, then the converter reduces to

A full-wave version based on the PWM buck converter:

ZVS-QR

Switch conversion ratio

- $\mu = 1 - FP\left(\frac{1}{f_s}\right)$, half-wave
- $\mu = 1 - FP\left(\frac{1}{f_s}\right)$, full-wave

ZVS boundary

- $J_s \geq 1$

Peak transistor voltage

$V_{peak} = (1 + J_s) V_i$

A problem with the quasi-resonant ZVS switch cell: peak transistor voltage becomes very large when zero voltage switching is required for a large range of load currents.
ZVS-QR State Plane Trajectory

The average output voltage:

\[
\langle m_o \rangle = 1 - \langle m_c \rangle
\]

\[
\langle v_o \rangle = \mu v_T \quad \text{with} \quad \mu = 1 - F \left( \frac{S_T}{T} \right)
\]

\[
P = \frac{1}{2W} \left[ \frac{1}{2} \frac{1}{T} + \pi + \sin^{-1} \frac{1}{2} + S_T + \sqrt{S_T^2 - 1} \right]
\]

Type b: \( P(S_T) = \mu \langle \frac{v_o}{v_T} \rangle \)

- Transformer.
- \( \mu \) controlled by \( F, S_T \).
- Also depends on \( v_T \) and \( I_T \).
Results:

Quasi-resonant switches

<table>
<thead>
<tr>
<th>Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>type a</strong></td>
<td>( \frac{2}{3} &lt; \beta &lt; 1 )</td>
</tr>
<tr>
<td><strong>type b</strong></td>
<td>( \frac{4}{3} &lt; \beta &lt; 1 )</td>
</tr>
</tbody>
</table>

Output characteristics: Full-wave ZVS buck

\[ V = \left(1 - \frac{R}{R_o}\right) V_i \quad \text{with} \quad I \geq \frac{V_i}{R_o} \]

With relative load \( R = V/R_o \geq V_i/R_o \)

\[ R \leq \left(1 - \frac{2}{3}\right) R_o \]
20.3.2 The ZVS multiresonant switch

When the previously-described operations are followed, then the converter reduces to

A half-wave version based on the PWM buck converter:

![ZVS-MR Operating Modes](image)

ZVS QSW Converters: Already Studied

Original one-switch version

Add synchronous rectifier

Lecture 21
20.2.3 Quasi-square-wave resonant switches

When the previously-described operations are followed, then the converter reduces to

![Diagram of ZCS and ZVS switches]

A quasi-square-wave ZCS buck with input filter

- The basic ZCS QSW switch cell is restricted to $0 \leq \mu \leq 0.5$
- Peak transistor current is equal to peak transistor current of PWM cell
- Peak transistor voltage is increased
- Zero-current switching in all semiconductor devices
Ac modeling of quasi-resonant converters

Use averaged switch modeling technique: apply averaged PWM model, with \( d \) replaced by \( \mu \).

Buck example with full-wave ZCS quasi-resonant cell:

Full-wave ZCS quasi-resonant switch cell

\[ \begin{align*}
L_1 & \quad i_1(t) \\
\text{Gate} & \quad \text{driver} \\
Q_1 & \quad v_1(t) \\
\text{Frequency} & \quad \text{modulator}
\end{align*} \]

\[ \begin{align*}
L_2 & \quad i_2(t) \\
D_1 & \quad v_2(t) \\
D_2 & \quad C \\
R & \quad v(t)
\end{align*} \]

Ac modeling of QR converters

Quasi-resonant converters inherit properties of PWM parents, with switch conversion ratio \( \mu \) playing the role of the PWM switch duty cycle \( d \).

AC modeling approach:

- Start from \( \mu(v, i, f_s) \) found for the resonant switch
- Perturb and linearize

\[ \hat{\mu} = \frac{\partial \mu}{\partial v} \hat{v} + \frac{\partial \mu}{\partial i} \hat{i} + \frac{\partial \mu}{\partial f_s} \hat{f}_s \]

- Replace \( d \) with \( \hat{\mu} \) in the small-signal AC dynamic model of the PWM parent converter

\[ \hat{d} \rightarrow \hat{\mu} \]
Example 1: Half-wave ZCS quasi-resonant buck

Buck Converter Small Signal Model

Averaged SSM model by:
- waveform averaging
- state space averaging

Switch averaging
ZVS-QR buck AC model

Example 2: Half-wave ZCS-QR buck
Perturb and Linearize

Perturbation and linearization of $\mu(v_1, i_2, f)$:

$\mu(t) = K_v v_1(t) + K_i i_2(t) + K_f f(t)$

with

$K_v = -\frac{\partial \mu}{\partial j_i} \frac{R_0 i_2}{V_i^2}$

$K_i = -\frac{\partial \mu}{\partial j_v} \frac{R_0}{V_i}$

$K_f = \frac{\mu_0}{F_s}$

$V_i = \frac{\partial \mu}{\partial v_i} \bigg|_{NOM} = \frac{\partial \mu}{\partial i_2} \frac{\partial i_2}{\partial v_i} = \frac{\partial \mu}{\partial v_i} \left( -\frac{R_0}{V_i^2} \right)$

AC SSM of half-wave ZCS-QR buck

Diagram of the AC SSM of half-wave ZCS-QR buck converter.
### Summary of results

<table>
<thead>
<tr>
<th>Switch</th>
<th>μ₀</th>
<th>( \mu_{\text{loop}} )</th>
<th>( k_i )</th>
<th>( k_e )</th>
<th>( k_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWM</td>
<td>D</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2CS HW</td>
<td>( \frac{E_{\text{F}}}{2} \sqrt{\sin^2(2\theta_f) + (1 + \sqrt{1 + \Delta})} )</td>
<td>( \frac{\partial u}{\partial t} )</td>
<td>( \frac{E_{\text{F}}}{2} \sqrt{\sin^2(2\theta_f) + (1 + \sqrt{1 + \Delta})} )</td>
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<td>2CS FW</td>
<td>( \frac{E_{\text{F}}}{2} \sqrt{2\sin^2(2\theta_f) + (1 + \sqrt{1 + \Delta})} )</td>
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