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

\[
\hat{\mu} = \left. \frac{\partial \mu}{\partial v} \right|_{v=v} \hat{v} + \left. \frac{\partial \mu}{\partial i} \right|_{i=i} \hat{i} + \left. \frac{\partial \mu}{\partial f_s} \right|_{f_s=f_s} \hat{f}_s
\]

- Replace $d$ with $\mu$ in the small-signal AC dynamic model of the PWM parent converter (from ECEN5797 Intro to PE)
Example 1: Full-wave ZCS-QR Buck

\[ F = \frac{f_s}{f_0} \]

\[ \mu \approx F \]
Small-signal AC model of the PWM buck converter

Textbook, Fig.7.17(a)
Small-signal AC model of the full-wave ZCS-QR buck
Example 2: Half-wave ZCS-QR buck

Now, $\mu$ depends on $j_s$:

$$\mu(t) = \frac{f_s(t)}{f_0} \frac{P_1}{2} \left( j_s(t) \right)$$

$$j_s(t) = R_0 \frac{\langle i_{2r}(t) \rangle}{\langle v_{1r}(t) \rangle} T_s$$

$$R_0 = \frac{E_{ic}}{C_r}$$

Half-wave ZCS quasi-resonant switch cell

$$\hat{\mu} = \frac{\partial \mu}{\partial f_s} \hat{f_s} + \frac{\partial \mu}{\partial \hat{i}_2} \hat{i}_2 + \frac{\partial \mu}{\partial \hat{v}_1} \hat{v}_1$$

not good!
Perturb and linearize $\mu$:

$$\mu = \frac{F_0}{J_0} P_{v_2}(J_0) = \frac{F_0}{J_0} P_{v_2}(J_0)$$

$$J_0 = \frac{R_0 I_2}{V_1}, \quad F = \frac{F_0}{J_0}$$

Perturbation and linearization of $\mu(v_{1r}, i_{2r}, f_s)$:

$$\mu(t) = K_v \dot{v}_{1r}(t) + K_i \dot{i}_{2r}(t) + K_c \dot{f}_s(t)$$

with

$$K_v = -\frac{\partial \mu}{\partial j_s} \frac{R_0 I_2}{V_1^2}$$

$$K_i = \frac{\partial \mu}{\partial j_s} \frac{R_0}{V_1}$$

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

$f_s = \frac{1}{\alpha \sqrt{1 - J_s^2}}$

$J_s = R_0 \frac{I_2}{V_1}$

$\alpha$ of $f_s(t)$

$FS =$ steady-state SW frequency = DC of $f_s(t)$

$K_v = \frac{\partial \mu}{\partial v_1} = \frac{\partial \mu}{\partial j_s} \frac{\partial j_s}{\partial v_1} = \frac{\partial P_{v_2}(J_0)}{\partial j_s} \left[ - \frac{I_2}{V_1^2} \right]$
Small-signal AC model of the half-wave ZCS-QR buck
Predicted small-signal transfer functions
Half-wave ZCS buck

\[ G_{vg}(s) = G_{g0} \frac{1}{1 + \frac{1}{Q} \frac{s}{\omega_0} + \left( \frac{s}{\omega_0} \right)^2} \]

\[ G_{vc}(s) = G_{c0} \frac{1}{1 + \frac{1}{Q} \frac{s}{\omega_0} + \left( \frac{s}{\omega_0} \right)^2} \]

Full-wave: poles and zeroes are same as PWM

Half-wave: effective feedback reduces Q-factor and dc gains
A detailed solved example posted on the HW10 page

Fig. 1 Closed-loop quasi-resonant converter.
### Summary of the linearization/perturbation results

<table>
<thead>
<tr>
<th>Switch</th>
<th>( \mu_0 )</th>
<th>( \frac{\partial \mu}{\partial J_x} )</th>
<th>( K_i )</th>
<th>( K_v )</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>( K_d = 1 )</td>
</tr>
<tr>
<td>ZCS HW</td>
<td>( \frac{E}{2\pi} \left( \frac{J_T}{2} + 2\pi \sin^{-1}(\frac{1}{J_T}) \right) + \frac{1}{J_T} (1 + \sqrt{1 - J_T^2}) )</td>
<td>( \frac{\partial \mu}{\partial J_T} = \frac{E}{2\pi} \left( \frac{1}{2} (1 + \sqrt{1 - J_T^2}) \right) )</td>
<td>( - \frac{\partial \mu}{\partial J_T} = \frac{R_0}{V_T} )</td>
<td>( - \frac{\partial \mu}{\partial J_T} = \frac{R_0 I_T}{V_T^2} )</td>
<td>( K_f = \frac{\mu_0}{F_{x_0}} )</td>
</tr>
<tr>
<td>ZCS FW</td>
<td>( \frac{E}{2\pi} \left( \frac{J_T}{2} + 2\pi \sin^{-1}(\frac{1}{J_T}) \right) + \frac{1}{J_T} (1 - \sqrt{1 - J_T^2}) )</td>
<td>( \frac{\partial \mu}{\partial J_T} = \frac{E}{2\pi} \left( \frac{1}{2} (1 - \sqrt{1 - J_T^2}) \right) )</td>
<td>0</td>
<td>0</td>
<td>( K_f = \frac{\mu_0}{F_{x_0}} )</td>
</tr>
<tr>
<td>ZVS HW</td>
<td>( \frac{1}{2\pi} \frac{E}{J_T} \left( \frac{1}{2} + \pi + \sin^{-1}(\frac{1}{J_T}) \right) J_T (1 + \sqrt{1 - J_T^2}) )</td>
<td>( \frac{\partial \mu}{\partial J_T} = \frac{1}{2\pi} \frac{E}{J_T} \left( \frac{1}{2} (1 + \sqrt{1 - J_T^2}) \right) )</td>
<td>( - \frac{\partial \mu}{\partial J_T} = \frac{R_0}{V_T} )</td>
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<td>( \frac{1}{2\pi} \frac{E}{J_T} \left( \frac{1}{2} + 2\pi \sin^{-1}(\frac{1}{J_T}) \right) J_T (1 - \sqrt{1 - J_T^2}) )</td>
<td>( \frac{\partial \mu}{\partial J_T} = \frac{1}{2\pi} \frac{E}{J_T} \left( \frac{1}{2} (1 - \sqrt{1 - J_T^2}) \right) )</td>
<td>0</td>
<td>0</td>
<td>( K_f = \frac{\mu_0}{F_{x_0}} )</td>
</tr>
</tbody>
</table>
How about 2-switch ZVS-QSW?

\[ \mu \approx d - a \cdot j, \quad a = \text{constant} \]

\[ \hat{\mu} = \hat{d} - a \frac{\hat{v}}{\hat{i}} \quad \hat{v} \text{ couple at the DC op point.} \]

\[ j = \frac{i}{V} \cdot R_0 \quad R_0 = \sqrt{\frac{E_r}{\xi_r}} \]

\[ i = \text{average of } I \text{ current.} \]

\[ V = \text{average of } V \text{ voltage.} \]
Small-signal AC model of the two-transistor ZVS-QSW

\[ \hat{v} = \hat{v}_g \]

\[ i_1 \]

\[ 1 : \mu_0 \]

\[ \hat{\mu} V_g \]

\[ L \]

\[ C \]

\[ R \]

\[ + \]

\[ - \]

\[ \hat{i} \]

\[ K_v \]

\[ K_i \]

\[ \hat{\mu} \]

\[ \text{Buck example.} \]

\[ \hat{d} \] control input, as in PWM converter.
Constant-Frequency Soft-Switching Converters

- Introduction and a brief survey
- Active-clamp (auxiliary-switch) soft-switching converters,
  - Active-clamp forward converter
  - Textbook 20.4.2 and on-line notes
- The zero-voltage transition full-bridge converter
  - Textbook Section 20.4.1 and on-line notes
- “DC Transformer”
Soft-switching converters with constant switching frequency

- With two or more active switches, we can obtain zero-voltage switching in converters operating at constant switching frequency.

- The second switch may be one that is already in the PWM parent converter (synchronous rectifier, or part of a half or full bridge). In other cases, the second switch is an additional “auxiliary” switch.

Examples:

- Two-switch quasi-square wave (with synchronous rectifier)
- Two-switch multi-resonant (with synchronous rectifier)
- Active-clamp switch (forward, flyback, other converters)
- Phase-shifted bridge with zero voltage transitions

- These converters can exhibit stresses and characteristics that approach those of the parent hard-switched PWM converters, but with zero-voltage switching over a range of operating points.
Two-switch ZVS-QSW converters: already studied

- Q2 can be viewed as a synchronous rectifier
- Additional degree of control is possible: let Q2 conduct longer than D2 would otherwise conduct
- Constant switching frequency control is possible, with behavior similar to conventional PWM
- Can obtain $\mu < 0.5$
The multiresonant switch

Basic single-transistor version

2-switch (synchronous rectifier) version