Using output-plane characteristic to design a parallel resonant converter with a transformer.

Keep same $V_{bore} = V_g$, $I_{bore} = V_g/R_o$

Given op. point $V$, $I$ at the output:

\[
\begin{align*}
M_{op} &= \frac{V_h}{V_g} \\
J_{op} &= \frac{nI}{V_g/R_o}
\end{align*}
\]

Use the same resonator, e.g. output plane char.

$n$ is an additional degree of freedom.
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\[ V = \text{const (given), regulated} \]

\[ V_{gmin} \leq V_g \leq V_{gmax}, \text{ input voltage} \quad \Rightarrow \quad M_{min} \leq M \leq M_{max} \]

\[ I_{min} \leq I \leq I_{max}, \quad P_{min} \leq P \leq P_{max}, \quad \text{output power} \]

\[ J = \frac{nI_{g}}{V_{g}/R_{o}} = \frac{nP}{V_{g} \cdot V} \cdot R_{o} = \frac{n}{\frac{V}{n} \cdot M} \cdot V \]

\[ J = \left( \frac{n^2 PR_{o}}{V^2} \right) \]
Design considerations

Output voltage $V$ is to be regulated over a range of operating points.

Typical specifications are of the form

\[ P_{\text{max}} \leq P \leq P_{\text{min}} \]
\[ V_{g_{\text{max}}} \leq V_g \leq V_{g_{\text{min}}} \]

$V$ is regulated

How specifications map into the converter output plane

\[ M = \frac{V}{nV_g} \]
\[ J = \frac{nR_0I}{V_g} \]

The turns ratio $n$ can be chosen to map the range of voltage operating points to any valid range of $M$:

\[ M_{\text{min}} = \frac{V}{nV_{g_{\text{max}}}} \]
\[ M_{\text{max}} = \frac{V}{nV_{g_{\text{min}}}} \]

Current and power are related to $J$:

\[ J = (M) \left( \frac{n^2 R_0 P}{V^2} \right) \]

Hence

\[ J_{\text{min}} = \frac{n P_{\text{min}} R_0}{V_{g_{\text{max}}} V} \]
\[ J_{\text{max}} = \frac{n P_{\text{max}} R_0}{V_{g_{\text{min}}} V} \]
Mapping the specifications into the output plane

\[ M_{\text{min}} = \frac{V}{n \, V_{g\text{max}}} \]

\[ M_{\text{max}} = \frac{V}{n \, V_{g\text{min}}} \]

\[ J_{\text{min}} = \frac{n \, P_{\text{min}} \, R_0}{V_{g\text{max}} \, V} \]

\[ J_{\text{max}} = \frac{n \, P_{\text{max}} \, R_0}{V_{g\text{min}} \, V} \]

\[ J = (M) \left( \frac{n^2 \, R_0 \, P}{V^2} \right) \]
Design example
Off-line dc-dc converter

Design a dc-dc converter using a parallel resonant converter, to meet the following specifications:

**input voltage:**
\[ V_g = 270\text{Vdc} \pm 20\% \]
so \[ V_{g_{\text{max}}} \geq V_g \geq V_{g_{\text{min}}} \]
with \[ V_{g_{\text{max}}} = 324\text{V} \]
\[ V_{g_{\text{min}}} = 216\text{V} \]

**output voltage:** regulated 5Vdc
so \[ V = 5\text{V} \]

**load current:**
max. load current \[ I_{\text{max}} = 40\text{A} \]
min. load current \[ I_{\text{min}} = 4\text{A} \]
so \[ I_{\text{max}} \geq I \geq I_{\text{min}} \]

**maximum switching frequency:** \[ f_{\text{s_{max}}} = 1\text{ MHz} \]

It is desired to operate MOSFET devices with zero-voltage switching.
Choice of range of operating points

Here, “converter design” involves selection of a valid range of $M$ and $J$, that is mapped into the range of converter specifications through selection of the turns ratio and characteristic impedance according to

$$n = \frac{V}{M_{\text{max}} V_{g\text{min}}}$$

$$R_0 = \frac{J_{\text{max}} V_{g\text{min}}}{n I_{\text{max}}} = J_{\text{max}} M_{\text{max}} \frac{V_{g\text{min}}^2}{V I_{\text{max}}}$$

The values of $L$ and $C$ are then chosen as follows:

$$L = \frac{R_0}{2\pi f_0}$$

$$C = \frac{1}{2\pi f_0 R_0}$$

$$f_0 = \frac{f_{\text{smax}}}{F_{\text{max}}}$$
One possible design

Corners of the operating region for the design $M_{\text{max}} = 1.2$, $J_{\text{max}} = 0.9$

<table>
<thead>
<tr>
<th>point</th>
<th>$V_g$</th>
<th>I</th>
<th>M</th>
<th>J</th>
<th>F</th>
<th>$f_s$, kHz</th>
<th>$I_{\text{Lpk}}$</th>
<th>$V_{\text{Cpk}}$</th>
<th>Status</th>
</tr>
</thead>
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<tr>
<td>A</td>
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<td>1.2</td>
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<td>1.06</td>
<td>746</td>
<td>2.02</td>
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<td>1.29</td>
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<tr>
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<td>0.60</td>
<td>1.26</td>
<td>884</td>
<td>2.49</td>
<td>426</td>
<td>ZVS</td>
</tr>
</tbody>
</table>

Operating region overlayed on the converter output characteristics

A possible design would be to pick $M$ and $J$ points in the converter output characteristics that result in ZVS operation.
PRC with capacitive output filter (no filter inductor)

- Description:
  - Circuit diagram with components labeled:
    - $Q_1, Q_2, Q_3, Q_4, D_1, D_2, D_3, D_4, D_5, D_6, D_7, D_8, L, C$
    - Input voltage $V_g$
    - Capacitive output filter $C_f$
    - Transformer $n = 1: n$
  - Notes:
    - Motivation: no LF, good for high-voltage output.
    - Potential problems:
      - Larger $C_f$
      - EMI ripple current through $C_f$

- Formulas:
  - 2 Diodes conduction: $V_C = \begin{cases} V \\ -V \end{cases}$
  - No diodes conduction:

- References:
State-Plane Trajectory (in one of possible modes)
Typical waveforms (in one of possible modes)