Zero-voltage transition converters: the phase-shifted full bridge converter

Buck-derived full-bridge converter
Zero-voltage switching of each half-bridge section
Each half-bridge produces a square wave voltage. Phase-shifted control of converter output

A popular converter for server front-end power systems
Efficiencies of 90% to 95% regularly attained
Controller chips available
usually assume

\[ C_{leg1} + C_{leg2} = C_{legs} + C_{legs} \]

Detailed waveforms, including resonant transitions

\[ Q_1, Q_2 \text{ legs resonant frequency:} \]

\[ f_0 = \frac{1}{2\pi \sqrt{L_C(C_{leg1} + C_{leg2})}} \]

\[ R_0 = \sqrt{\frac{L_C}{C_{leg1} + C_{leg2}}} \]

\[ Q_3, Q_4 \text{ legs resonant frequency:} \]

\[ f_0 = \frac{1}{2\pi \sqrt{L_C(C_{legs} + C_{legs})}} \]

\[ R_0 = \sqrt{\frac{L_C}{C_{legs} + C_{legs}}} \]

Subintervals:

<table>
<thead>
<tr>
<th>Subinterval</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>0</th>
</tr>
</thead>
</table>
| Conducting devices: | \( Q_2 \) | \( D_4 \) | \( D_4 \) | \( Q_1 \) | \( Q_1 \) | \( Q_1 \) | \( X \) | \( D_4 \) | \( Q_1 \) | \( X \) | \( D_4 \) | \( \{ Q_2 \} \) | \( \{ P-A \} \)
| \( D_5 \) | \( D_5 \) | \( D_5 \) | \( X \) | \( X \) | \( D_5 \) | \( D_5 \) | \( D_5 \) | \( D_5 \) | \( X \) | \( X \) | \( D_6 \) | \( \{ D_5 \} \) | \( \{ \text{Secondary diodes} \} \)
Intervals 1-3: D5/D6 commutation

\[ i_s(t) \]

\[ v_d(t) \]

\[ v_c(t) \]

\[ n_l/(C_{eq3}+C) \]

\[ Q_2 \text{ turns off.} \]

\[ D_5, D_6 \text{ can not be off at the same time} \]

\[ i_c - n_i_5 + n_i_6 = 0 \]

\[ i_5 = \frac{1}{2} \left( \frac{i_c}{n} + I \right) \]

\[ i_6 = \frac{1}{2} \left( -\frac{i_c}{n} + I \right) \]

\[ i_c = n (i_5 - i_6) \]

\[ \text{short: } i_6 = I , i_5 = 0 \]

\[ \text{end: } i_6 = 0 , i_5 = I \]

\[ i_c = -nI \]

\[ i_c = +nI \]
Interval 1

Begins when $Q_2$ turns off

$D_4$, $D_5$, $D_6$ conduct

Note that when $D_5$ and $D_6$ both conduct,
then the transformer secondary is short-circuited.

$i_c < 0$. Initial $v_2 = 0$, $i_c = -nI < 0$!

$$v_2 = C_{\text{on}1} + C_{\text{on}2}$$

center at 0, 0
initial pt. $m_2 = 0$

$k = -1$

Subinterval: 0 1 2

Conducting devices:

$Q_2$ $D_1$

$D_4$ $D_5$

$D_3$ $D_6$ $D_7$ $D_8$

4
Normalized state plane

- Light load ZVS
  - Worst case: $I = I_{\text{min}}$
- $(C_{\text{eq1}} + C_{\text{eq2}})_{\text{min}} = \text{device caps.}$
  - $(R_{\text{on}} \cdot C_{\text{ds}})$
- Pick $L_c$ large enough to enable ZVS

Normalized state plane:

Define $V_{\text{base}} = V_g$

$$F_{\text{base}} = \frac{V_g}{R_0}, \quad R_0 = \sqrt{\frac{L_c}{C_{\text{eq1}} + C_{\text{eq2}}}}$$

$$\omega_0 = \frac{1}{\sqrt{L_c \left( C_{\text{eq1}} + C_{\text{eq2}} \right)}}$$

$$j_c = \frac{j_c}{F_{\text{base}}}, \quad J = \frac{nI}{F_{\text{base}}}, \quad m_2 = \frac{v_2}{V_{\text{base}}}$$

Initial $j_c = -J, \quad m_2 = 0$

ZVS condition:

$$J \geq 1$$
$$\frac{nI}{V_g/R_0} \geq 1$$
$$nI \geq V_g/R_0$$
$$nI \geq V_g \sqrt{\frac{C_{\text{eq1}} + C_{\text{eq2}}}{L_c}}$$

$r_i = J$
Solution of state plane

Interval ends when $v_2 = v_g$, forward-biasing $D_1$. At end of interval, $m_2 = 1$ and $j_0 = -j_{c1}$.

Solution of state plane geometry:

$$j_{c1} = \sqrt{r_1^2 - 1} = \sqrt{J^2 - 1}$$

and

$$\alpha = \omega_0 t_1 = \tan^{-1} \left( \frac{1}{j_{c1}} \right) = \tan^{-1} \left( \frac{1}{\sqrt{J^2 - 1}} \right)$$

where interval 1 length $= t_1$.

For zero-voltage switching, we require $J \geq 1$.

If $J < 1$, then $v_2$ never reaches $v_g$, and switching loss occurs when $Q_1$ turns on.
**Subintervals 2 and 3**

Initial \( i_c = -i_{c1} \)

Let \( t_3 + t_2 = \text{length of intervals } 2 \) and 3

Interval end when \( i_c = uI + i_{c1} \); \( D_6 \) then becomes reverse-biased

So \( \frac{V_g}{L_c} (t_2 + t_3) = uI + i_{c1} \)

\[ t_3 + t_2 = \left( uI + i_{c1} \right) \frac{L_c}{V_g} \]
Subinterval 4

Power delivery from $V_g$ to $V$

Circuit is

$Q_1$

$V_g$

$nI$

$i_c = nI$ constant

$V_o = nV_g$

$V_c$

$Q_4: V_c = 0$

Power is transferred through switches and transformer to output.

Interval ends when controller turns off $Q_4$.

$L_F >> n^2L_c$

$nV_g$

$L_c \cdot n^2 + L_F$

$V_o = nV_g$

$C_F$

$t$

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Conducting devices:
Subinterval 5

$v_4$ charges from 0 to $v_g$, with slope $\frac{nI}{C_{leg3} + C_{leg4}}$

Length of interval is $t_S = \frac{V_g}{nI} \left( C_{leg3} + C_{leg4} \right)$

During this interval, voltage across $L_c$ is $L_c \frac{d(nI)}{dt} \times 0$ and $V_o = n(v_g - v_4)$

ZVS: output current charges $C_{leg}$ without requiring $J > 1$
Subinterval 6

- Current $i_c$ circulates around primary-side elements, causing conduction loss.
- This current arises from stored energy in $L_c$.
- The current is needed to induce ZVS during next subinterval.
- To maximize efficiency, minimize the length of this subinterval by choosing the turns ratio $n$ such that $M = V/nV_g$ is only slightly less than 1.
Subintervals 7 to 11 and 0 are symmetrical to subintervals 1 to 6
Complete state plane trajectory: