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
Phase-shifted control

Approximate waveforms and results

(as predicted by analysis of the parent hard-switched converter)

\[ d = \phi = \frac{(t_1 - t_0)}{\left(\frac{T_s}{2}\right)} \quad 0 - 100\% \]

\[ M(\phi) = \frac{V}{V_g} = n\phi \]

\[ v = \langle v_o \rangle = nV_g \phi \]
usually assume

\[ C_{\text{leg}1} + C_{\text{leg}2} = C_{\text{leg}3} + C_{\text{leg}4} \]

Detailed waveforms, including resonant transitions

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

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

\[ R_0 = \sqrt{\frac{L_C}{C_{\text{leg}1} + C_{\text{leg}2}}} \]

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

\[ f_0 = \frac{1}{2\pi \sqrt{L_C (C_{\text{leg}3} + C_{\text{leg}4})}} \]

\[ R_0 = \sqrt{\frac{L_C}{C_{\text{leg}3} + C_{\text{leg}4}}} \]
Result of analysis

Basic configuration: full bridge ZVT

\[ M = \frac{V}{nV_g} = \phi + FP_{ZVT}(J) \]

\[ F = \frac{f_s}{f_0} < 0 \]

\[ P_{ZVT}(J) = \frac{1}{2\pi} \left[ \frac{1}{J} - 2\tan^{-1}\left(\frac{1}{\sqrt{J^2 - 1}}\right) - 2\left(J + \sqrt{J^2 - 1}\right) \right] \]

- Phase shift \( \phi \) assumes the role of duty cycle \( d \) in converter equations
- Effective duty cycle is reduced by the resonant transition intervals
- Reduction in effective duty cycle can be expressed as a function of the form \( FP_{ZVT}(J) \), where \( P_{ZVT}(J) \) is a negative number similar in magnitude to 1. \( F \) is generally pretty small, so that the resonant transitions do not require a substantial fraction of the switching period
- Circuit looks symmetrical, but the control, and hence the operation, isn’t. One side of bridge loses ZVS before the other.
ZVT Analysis

Subinterval:

- 0: $Q_4$, $D_4$
- 1: $D_5$, $D_6$
- 2: $Q_1$, $Q_4$
- 3: $D_2$, $Q_1$
- 4: $Q_4$
- 5: $Q_3$, $Q_4$
- 6: $Q_1$, $Q_3$
- 7: $D_3$, $Q_4$
- 8: $Q_4$, $D_5$
- 9: $Q_3$, $Q_4$
- 10: $Q_3$, $Q_4$
- 11: $D_5$, $D_6$
- 12: $Q_4$, $D_4$

Conducting devices:

- $Q_4$, $D_4$
- $D_5$, $D_6$
- $Q_1$, $Q_4$
- $D_2$, $Q_1$
- $Q_4$
- $Q_3$, $Q_4$
- $Q_1$, $Q_3$
- $D_3$, $Q_4$
- $Q_4$, $D_5$
- $Q_3$, $Q_4$
- $D_5$, $D_6$
- $Q_4$, $D_4$

$nI/\left(C_{leg3}+C_{leg4}\right)$

$-nI/\left(C_{leg3}+C_{leg4}\right)$

$v_s = 0$

$v_s = V_g$

$v_s = -V_g$

$i_s(t)$

$t_0$, $V_g/L_c$

$t_1$, $-V_g/L_c$

$nI$
Intervals 1-3: D5/D6 commutation

Q₂ turns off.

D₅, D₆ can not be off at the same time.

ON at the same time is possible.

\[ i_c = n(t_s - t_c) \]

\[ i_s + i_6 = I \]

\[ i_c = n(t_s - t_c) \]

Subinterval:

0 1 2 3 4

Q₂ X D₁ D₂ Q₁

Conducting devices:

D₄ D₃ D₄ D₃ D₂ D₆

D₃ D₆ D₆ X D₆

\[ i_c = -nI \]

\[ i_c = 0, t_s = I \]

\[ i_c = +nI \]