Pick up graded HW10. Turn in HW11

Final exam handed out in class on Friday, May 4. Due by 2pm on Wednesday May 9

For off-campus students, the final exam will be available on D2L. Off-campus students can start working on the final any time on or after Friday May 4. The exam is due in 5 days after the start, but no later than 5pm MT on Wednesday May 16. No work will be accepted after this time.

A sample final exam, with solutions has been posted on D2L in the “Content” section
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
\[ C_{\text{leg}1} + C_{\text{leg}2} = C_{\text{leg}3} + C_{\text{leg}4} \]

Detailed waveforms, including resonant transitions

\[ Q_1, Q_2 \text{ leg resonant frequency:} \]
\[ f_0 = \frac{1}{2\pi \sqrt{L_C (C_{\text{leg}1} + C_{\text{leg}2})}} \]

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

\[ Q_3, Q_4 \text{ leg resonant frequency:} \]
\[ f_0 = \frac{1}{2\pi \sqrt{L_C (C_{\text{leg}3} + C_{\text{leg}4})}} \]

\[ R_0 = \sqrt{\frac{L_C}{C_{\text{leg}3} + C_{\text{leg}4}}} \]
State-plane trajectory
Averaging

\[ \langle v_o \rangle = V = \frac{2}{T_s} \int_{0}^{\frac{T_s}{2}} v_o \, dt \]

Note: \( v_o = 0 \) whenever \( D_5 \) and \( D_6 \) both conduct.

\[ \langle v_o \rangle = V \quad \text{by volt. sec balance on } L_F \]

\[ \langle v_o \rangle = \frac{2}{T_s} \cdot \left[ nV_3 t_4 + \frac{1}{2} nV_3 t_5 \right] \]
Phase shift control

\[ \Phi T_s / 2 = t_1 + t_2 + t_3 + t_4 \]

So, \[ t_4 = \frac{\Phi T_s}{2} - t_1 - t_2 - t_3 \]

Hence,

\[ \langle v_o \rangle = \frac{2}{T_s} nV_g \left[ \frac{\Phi T_s}{2} - t_1 - t_2 - t_3 + \frac{1}{2} t_5 \right] \]

\[ M = \frac{V}{nV_g} = \frac{\langle v_o \rangle}{nV_g} = \Phi - \frac{2}{T_s} \left[ t_1 + t_2 + t_3 - \frac{1}{2} t_5 \right] \]

With \[ t_1 = \frac{1}{\omega_o} \tan^{-1} \left( \frac{1}{\sqrt{3} I} \right) \]

\[ t_2 + t_3 = \left( \frac{V_o}{I} + i_c \right) \frac{L_c}{V_g} \]

\[ t_5 = \frac{V_o}{nI} \left( C_{1eg3} + C_{1eg4} \right) \]
Phase shift control: result

Substitute and normalize to obtain

\[ M = \phi + \frac{F}{2\pi} \left[ \frac{1}{J} - 2 \tan^{-1} \left( \frac{1}{\sqrt{J^2 - 1}} \right) - 2J + 2\sqrt{J^2 - 1} \right] = \frac{V}{nV_g} \]

which is of the form

\[ M = \phi + F P_{2\nu T}(J) < \phi \]

with

\[ F = \frac{f_s}{f_0} \quad \text{and} \quad P_{2\nu T}(J) = \frac{1}{2\pi} \left[ \frac{1}{J} - 2 \tan^{-1} \left( \frac{1}{\sqrt{J^2 - 1}} \right) - 2(J + \sqrt{J^2 - 1}) \right] < 0 \]
Effect of ZVT: reduction of effective duty cycle

\[ ZVT: \quad M = \frac{V}{\sqrt{2} V_o} = \phi + F P_{2VT}(\gamma), \quad F = \frac{f_s}{f_0}, \quad P_{2VT}(\gamma) = \frac{1}{2\pi} \left[ \frac{1}{\gamma} - 2 \tan^{-1} \frac{1}{\sqrt{\gamma^2 - 1}} - 2(\gamma + \sqrt{\gamma^2 - 1}) \right] \]
Issues with this converter

It’s a good converter for many applications requiring isolation. But…

1. Secondary-side diodes operate with zero-current switching. They require snubbing or other protection to avoid failure associated with avalanche breakdown.

2. The resonant transitions reduce the effective duty cycle and conversion ratio. To compensate, the transformer turns ratio must be increased, leading to increased reflected load current in the primary-side elements.

3. During the intervals when both output diodes conduct, inductor $L_c$ stores energy (needed for ZVS to initiate the next $\phi T_s/2$ interval) and its current circulates around the primary-side elements—causing conduction loss.

$\phi = 1$ is the best choice.
Diode switching analysis
Intervals 1-3 (or 7-9): D5/D6 commutation
D6 turn OFF

for ZVS relatively large, \( \Rightarrow \) leakage of the transformer.

\[ i_c(t) \]
\[ L_c \]
\[ 1:n \]
\[ D_5 \]
\[ D_6 \]
\[ v_o \]

\[ -nI \]
\[ 2nV_g \]
\[ nV_g \]

excess energy in \( L_c \)

resonance between \( L_c \) and \( C_{D6} \)

peak inverse voltage of \( 4nV_g \)

failure

rev. recovery
Approaches to snub the diode ringing
Approaches to snub the diode ringing
(a) conventional diode snubber
Approaches to snub the diode ringing
(b) conventional passive voltage-clamp snubber
Approaches to snub the diode ringing
(c) simplify to one passive voltage-clamp snubber
Approaches to snub the diode ringing
(d) improvement of efficiency in voltage-clamp snubber
Approaches to snub the diode ringing
(e) active clamp lossless snubber
Approaches to snub the diode ringing
(f) primary-side lossless voltage clamp
Design Example
Sample final exam Problem 2 with solution (posted on D2L)

- $C_{leg} = 400 \text{ pF}$
- $250 \text{ V} < V_{g} < 350 \text{ V}$
- $V = 42 \text{ V}$
- Obtain ZVS for $300 \text{ W} < P_{load} < 1 \text{ kW}$
- $f_s = 400 \text{ kHz}$

Design the converter, i.e., specify $n$, $L_c$, find minimum and maximum of the control input $\phi$. Minimize the worse-case value of the transformer primary RMS current.