Course Focuses

- Course focuses on design and modeling of “high frequency” power electronics
  - Course website: http://web.eecs.utk.edu/~dcostine/ECE581
  - Goal of course is understanding of motivations and issues with high frequency power electronics; analysis and design techniques; applications

Prerequisites:
- Undergraduate Circuits sequence, Microelectronics, ECE 481 – Power Electronics, or equivalent

Contact Info

Instructor: Daniel Costinett

- Office: MK504
- OH: T: 11-12, W: 9-10, By appointment
- E-mail: Daniel.Costinett@utk.edu
- Email questions will be answered within 24 hours (excluding weekends)
- Please use [ECE 581] in the subject line
Course Structure

- Course meets MWF 10:10-11:-0 am
- Plan to spend ~9 hours per week on course outside of lectures
- Grading:
  - Homework/Lab: 40%
    - One homework per week
    - Assignments due on Fridays unless otherwise noted on course website
    - One design competition outside of class time
  - Midterm: 25%
    - Tentatively scheduled for October 29th
  - Final: 35%

Assignments

- Assignments due at the start of lecture on the day indicated on the course schedule
- No late work will be accepted except in cases of documented medical emergences
- Collaboration is encouraged on all assignments except quizzes and exams; Turn in your own work
- All work to be turned in through canvas
Textbook and Materials

• The textbook
  will reference chapters 19-20 and reference materials from prior chapters. The textbook is available on-line from campus network. Purchase is not required for this course.

• MATLAB/Simulink, LTSpice will be used; All installed in the Tesla Lab

• Lecture slides and notes, additional course materials, homework, due dates , etc. posted on the course website

• Additional information on course website

Introduction

• Why high frequency?
  − Power Density
  − Control Bandwidth

• Techniques
  − Devices
  − Control
  − Topologies
  − Passives
Motivating Example

Baseline Design

- Use TI WebBench (webench.ti.com) to get a baseline design

<table>
<thead>
<tr>
<th>Param</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$V_g$</td>
<td>12 V</td>
</tr>
<tr>
<td>$V_{out}$</td>
<td>48 V</td>
</tr>
<tr>
<td>$R_{out}$</td>
<td>48 Ω</td>
</tr>
<tr>
<td>$\Delta V_{out}$</td>
<td>0.1 V</td>
</tr>
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</table>
LTSpice Simulation

<table>
<thead>
<tr>
<th>L</th>
<th>C_{out}</th>
<th>f_{s}</th>
<th>Diode</th>
<th>η (Sim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22,\mu H</td>
<td>22,\mu F</td>
<td>202,k</td>
<td>Si (FR)</td>
<td>93.9%</td>
</tr>
</tbody>
</table>

LTSpice Simulation
Switching Transition

Diode Reverse Recovery
Datasheet RR Characteristics

Charge Storage
IGBT Current Tailing

Example: buck converter with IGBT

Transistor turn-off transition

\[ P_{sw} = \frac{1}{f_s} \int_{t_{sw}}^{t_{off}} p_A(t) \, dt = (W_{on} + W_{off}) \, f_s \]

Schottky Diode

<table>
<thead>
<tr>
<th>L</th>
<th>C_{out}</th>
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<tr>
<td>22uH</td>
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</tr>
</tbody>
</table>
Simulation Waveforms

Switching Transition – FET turn ON
Switching Transition – FET turn OFF

MOSFET Switching Behaviors

5 Typ. output characteristics
$I_D=f(V_{DS}); T=25°C$
parameter: $V_{GS}$

6 Typ. drain-source on resistance
$R_{DSS}=f(I_D); T=25°C$
parameter: $V_{GS}$
MOSFET Stored Charge

Device Capacitances
Device Capacitances

DCM: Soft Switching

<table>
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<tr>
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<td>22uF</td>
<td>202k</td>
<td>Si Schottky</td>
<td>95.8%</td>
</tr>
<tr>
<td>4.6uH</td>
<td>22uF</td>
<td>202k</td>
<td>Si Schottky</td>
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</table>
MOSFET Turn-On

1 MHz Operation

Id(M2)+Id(M1)

I(D1)

V(sw)

V(g1)

V(sw,out)*I(D1)

V(sw)*Id(M2)+Id(M1)

V(out)*I(R1)

V(out)

V(sw)

-1.03 μJ

1.92 μs 1.96 μs 2.00 μs 2.04 μs

0.0 μs 0.3 μs 0.6 μs 0.9 μs 1.2 μs 1.5 μs 1.8 μs 2.1 μs 2.4 μs 2.7 μs 3.0 μs

-20 W

-10 W

0 W

10 W

20 W

100 W

200 W

300 W

400 W

500 W

-14 V

-7 V

0 V

7 V

14 V

21 V

28 V

35 V

42 V

49 V

56 V

63 V

-60 V

-30 V

0 V

30 V

60 V

90 V

120 V

-140 W

-70 W

0 W

70 W

140 W

210 W

280 W

350 W

420 W

490 W

560 W

630 W
Low Power Operation

Synchronous Operation

[Diagram of Low Power Operation with graphs and equations]

[Diagram of Synchronous Operation with circuit diagram]
Synchronous Simulation

Switching Transitions
Low Power Operation

Resonant Operation

<table>
<thead>
<tr>
<th>Switching</th>
<th>$L$</th>
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<th>$f_s$</th>
<th>Diode</th>
<th>$\eta$ (Sim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard</td>
<td>22uH</td>
<td>22uF</td>
<td>202k</td>
<td>Si (FR)</td>
<td>93.9%</td>
</tr>
<tr>
<td>Hard</td>
<td>22uH</td>
<td>22uF</td>
<td>202k</td>
<td>Si Schottky</td>
<td>95.8%</td>
</tr>
<tr>
<td>Soft</td>
<td>4.65uH</td>
<td>22uF</td>
<td>202k</td>
<td>Si Schottky</td>
<td>98.4%</td>
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<tr>
<td>Soft</td>
<td>710nH</td>
<td>4.4uF</td>
<td>1 MHz</td>
<td>Si Schottky</td>
<td>98.2%</td>
</tr>
<tr>
<td>Soft</td>
<td>710nH</td>
<td>4.4uF</td>
<td>1 MHz</td>
<td>MOSFET</td>
<td>99.6%</td>
</tr>
<tr>
<td>Resonant</td>
<td>10uH + 2.4uH</td>
<td>1uF + 10nF</td>
<td>225 kHz</td>
<td>Si Schottky</td>
<td>98.6%</td>
</tr>
<tr>
<td>Resonant</td>
<td>10uH + 2.4uH</td>
<td>1uF + 10nF</td>
<td>225 kHz</td>
<td>MOSFET</td>
<td>99.96%</td>
</tr>
</tbody>
</table>
Resonant Boost Converter

![Graph showing waveforms for I(D1), V(out), V(vds), I(L1), V(out)*I(R1), and V(g)*I(L1).]

Resonant Circuits

![Diagram of a resonant circuit with components L, C, and R.]
Resonant Circuit Analysis

Soft Switching

• Advantages
  - Reduced switching loss
  - Possible operation at higher switching frequency
  - Lower EMI

• Disadvantages
  - Increased current and/or voltage stresses due to circulating current
  - Higher peak and rms current values
  - Complexity of analysis and modeling
Limitations: Gate Drive

Limitations: $t_d/T_s$
Limitations: Thermal

(a)

(b)

Limitations: Magnetics Design
Limitations: Circuit Modeling