ECE 481: Power Electronics

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University of Tennessee Knoxville
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ECE 481: Power Electronics

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    - Please use [ECE481] in the subject line for all course-related e-mails.
  - Office Hours: W 12:30-1:30pm, T 3:00-4:00pm
Course Materials

• Textbook:
  - Available through campus bookstore, online vendors, or online through UT libraries

• Course Website
  - http://web.eecs.utk.edu/~dcostine/ECE481
  - Includes lectures slides, handouts, supplemental notes, homework assignments, course announcements

Assignments

• Homework (35%)
  - Due at *beginning* of class on date listed on Lecture Schedule web page (Fridays)
  - No late work accepted except in cases of documented emergencies
  - Collaboration is encouraged on all homework assignments but must turn in *your own* work

• Midterms and Labs (35%)

• Final (30%)
Lab Sequence

- Hands-on experience testing and controlling GaN-based converter
- 3-lab sequence in modeling, open-loop control and analysis, and closed-loop control
- Completed in groups of 2-3 outside of normal lecture hours

ECE 481 vs ECE 599

- Students enrolled in ECE 599 will have additional homework and exam problems
- Grading
  - Separate curving for ECE 481 and ECE 599
  - Extra credit is added to final grade after any curving
How to Succeed in ECE 481

• Attend all lectures
  – Participate; ask questions or ask for clarification
• Read textbook for additional explanation
• Complete all homework assignments
  – Attempt homework alone prior to collaborating
  – Review and understand mistakes
  – ~12 assignments for 35% of the grade

Power Electronics Courses at UTK

<table>
<thead>
<tr>
<th>Junior</th>
<th>Senior</th>
<th>Graduate</th>
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</thead>
<tbody>
<tr>
<td>ECE 325 Electric Energy System Components</td>
<td>ECE 481 Power Electronics</td>
<td>ECE 623 Advanced Power Electronics and Drives</td>
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<td>ECE 481 Power Electronics</td>
<td>ECE 523 Power Electronics and Drives</td>
<td>ECE 625 Utility Applications of Power Electronics</td>
</tr>
<tr>
<td>ECE 482 Power Electronic Circuits</td>
<td>ECE 525 Alternative Energy Sources</td>
<td>ECE 626 Solid State Power Semiconductors</td>
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Undergraduate Research in Power Electronics

• Opportunity for paid (hourly) undergraduate research developing SiC microgrid converters
  o Testing of high voltage transistors and controllers
  o Software for controlling microgrid converters
• Timeframe: immediate start, continues through Spring semester
• Contact Professor Fred Wang for details
• Fred.wang@utk.edu

Introduction to Power Conversion

Dc-dc conversion: Change and control voltage magnitude
Ac-dc rectification: Possibly control dc voltage, ac current
Dc-ac inversion: Produce sinusoid of controllable magnitude and frequency
Ac-ac cycloconversion: Change and control voltage magnitude and frequency
Example Server Power Distribution

Example VRM Design
Example VRM Design

\[ V_{\text{out}} = V_g - I_{\text{out}} R \]

\[ R = \frac{V_g - V_{\text{out}}}{I_{\text{out}}} \]

\[ R_{eq} = \frac{V_{\text{out}}}{I_{\text{out}}} = 150 \text{m}\Omega \]
Variations in Load

\[ V_{out} = V_g - I_{out} R \]
\[ V_{out} = 12V - (5A)(1.05\Omega) \]
\[ V_{out} = 6.75V \]

Control is Invariably Required
Linear Regulator

\[ V_{g} \quad 12V \]

\[ \eta = \frac{P_{out}}{P_{in}} = \frac{7.5W}{60W} = 12.5\% \]
A High Efficiency Converter

A goal of current converter technology is to construct converters of small size and weight, which process substantial power at high efficiency.

Devices Available to the Circuit Designer

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<th>Resistors</th>
<th>Capacitors</th>
<th>Magnetics</th>
<th>Linear-mode</th>
<th>Switched-mode</th>
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Semiconductor devices
Devices Available to the Circuit Designer

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Signal processing: avoid magnetics

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Power processing: avoid lossy elements
Power Loss in an Ideal Switch

Switch closed: \( v(t) = 0 \)

Switch open: \( i(t) = 0 \)

In either event: \( p(t) = v(t) i(t) = 0 \)

Ideal switch consumes zero power

Use of SPDT Switch

\[ V_g \]

\[ V_g \]

\[ V_g = D V_g \]

\[ \text{switch position:} \]

\[ 1 \quad 2 \quad 1 \]

\[ DT_s \quad (1 - D) T_s \quad t \]
Controlling Duty Cycle

The figure illustrates the duty cycle of a switch, where $v_s(t)$ represents the input voltage, and $V_s$ is the average value. The duty cycle $D$ is defined as:

$$D = \frac{D T_s}{T_s}$$

Where $D \leq 1$. The switching period $T_s$ and the switching frequency $f_s = \frac{1}{T_s}$ are also defined.

DC component of $v_s(t)$ is the average value:

$$V_s = \frac{1}{T_s} \int_0^{T_s} v_s(t) \, dt = D V_s$$

Addition of Low Pass Filter

The addition of an ideally lossless $L$-$C$ low-pass filter is shown for the purpose of removing switching harmonics. The filter configuration includes an inductor $L$ and a capacitor $C$, connected in series with the load $R$. The circuit is used to control the duty cycle by filtering out high-frequency noise.

- Choose filter cutoff frequency $f_0$ much smaller than switching frequency $f_s$.
- This circuit is known as the “buck converter.”
Duty Cycle Control

\[ V_s = \frac{1}{T_s} \int_0^{T_s} v_s(t) \, dt = DV_g \]

Control System for Voltage Regulation
Dynamic Performance

Single Phase Inverter

"H-bridge"
Modulate switch duty cycles to obtain sinusoidal low-frequency component
Power Electronics Overview

Some Power Electronics Applications
Power Transmission: Saturable Reactor

V \downarrow \quad L_{ac} \downarrow \quad N_{ac}\quad (\text{controlled circuit})

\begin{align*}
\text{ac circuit inductance: } \\
L_{ac} &= \frac{\mu \cdot N_{ac}^2 \cdot A}{l} = \text{const} \cdot \mu \\
\mu &= f(I_{dc})
\end{align*}

\text{dc bias flux control circuit}

EVs: Integrated Converter

Traditional 2-stage drivetrain topology

Combined isolated/non-isolated topology

5kW Scaled-Down Converter Prototype

Full Power, 3D-Printed Module
Renewables: 2kW Power Dense Solar Inverter

- CAD Model of Power-Dense Design
- Thermal Test at Full Power

Prototype 2kW Solar Inverter

Commercial Product Size Comparison

Medical Devices: RF Energy Harvesting

- Powered entirely by commercial 5.8GHz WiFi adapter
- Able to operate with ~5μW power using only off-the-shelf components
- Able to operate down to 100nW using a custom IC

Wireless Sensor Block Diagram

5.8 GHz patch rectenna

OTS Power Converter Design

Custom harvester IC implementation

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Mobile Electronics

- Major power consumers: baseband digital, display, multiple radio channels
- Power supply demands: small footprint area & integration, high efficiency over wide range of loads, power management interface
Wearable Electronics: Medical Sensor

- Various biological markers can now be sensed through noninvasive methods
- Pulse, water content, GSR, blood glucose levels, oxygen content, etc.
- Precision integrated power electronics and low power circuit design techniques needed for future implementations

Part I: Converters in Equilibrium

2. Principles of steady state converter analysis
3. Steady-state equivalent circuit modeling, losses, and efficiency
4. Switch realization
5. The discontinuous conduction mode
6. Converter circuits
Part I: Converters in Equilibrium

Inductor waveforms

Averaged equivalent circuit

Predicted efficiency

Discontinuous conduction mode
Transformer isolation

Switch Realization: Semiconductor Devices

The IGBT

Switching loss
Part II: Converter Dynamics and Control

7. Ac modeling
8. Converter transfer functions
9. Controller design
10. Input filter design
11. Ac and dc equivalent circuit modeling of the discontinuous conduction mode
12. Current-programmed control
Part III: Magnetics

13. Basic magnetics theory
14. Inductor design
15. Transformer design