Power Electronics Program at CU Boulder

ECEN 4/5797
Introduction to Power Electronics
Fall semesters

ECEN 4/5517 Power Electronics Lab
Spring semesters

ECEN5807
Modeling and Control of PE Systems
Alternate Spring semesters (2019)

ECEN5817
Resonant and Soft-Switching Techniques in PE
Alternate Spring semesters (2020)

Professional Certificate in Power Electronics

ECEN5807, Spring 2007
Power Electronics Courses at the University of Colorado, Boulder

undergraduate

ECEN 2250 Circuits 1

ECEN 3250 Circuits 3

ECEN 2260 Circuits 2

ECEN 3170 Energy Conversion

ECEN 4797/5797 Intro to Power Electr.

ECEN 4517/5517 Power Electronics Lab

ECEN 4827/5827 Analog IC Design

ECEN 4167/5737 Energy Conversion 2

graduate

ECEN 4507 Modeling and Control of Power Electronics Systems

ECEN 5817 Res. and Soft-Sw. Tech

ECEN 5837 Mixed-Signal IC Design

ECEN 5737 AC Drives

ECEN 5017 Pwr Elect for Electric Drive Vehicles

Professional certificate in power electronics

Power management

Graduate certificate in electric drivetrain technology

Coursera (MOOC): Introduction to Power Electronics

Prerequisite for either ECEN 5807 or ECEN 5817: ECEN 5797
• Photovoltaic power systems
• Power conversion and control electronics

Prerequisite: ECEN 4797 or ECEN 5797

Instructor: Roger Bell
Spring 2019
Experiment 1
Direct Energy Transfer System

- Model PV panel
- Investigate direct energy transfer system behavior
- Investigate effects of shading
- Observe behavior of lead-acid battery
Experiments 2 and 3
Maximum Power Point Tracking

- Design and construct dc-dc converter
- Employ microcontroller to achieve maximum power point tracking (MPPT) and battery charge control
Experiments 4 and 5
Add Inverter to System

- Build your own inverter system to drive AC loads from your battery
- Step up the battery voltage to 200 VDC as needed by inverter
- Regulate the 200 VDC with an analog feedback loop
- Change the 200 VDC into 120 VAC
Mini-Project
ECEE Expo Competition

- Operate your complete system
- Competition during ECEE Expo: capture the most energy with your system outside

A previous year’s competition poster
ECEN 5807 Topics
Spring 2019      Instructor: Prof. Dragan Maksimovic

1. Simulation and averaged switch modeling
   • CCM, DCM, and other examples
   • Simulation

2. Techniques of design-oriented analysis, with application to switched-mode converter systems
   • Middlebrook’s feedback and extra-element theorems
   • Input filter design
   • Writing complex transfer function expressions by inspection

3. Current-programmed control of PWM converters

4. Introduction to digital control of PWM converters

5. Rectifiers
   • Rectifier harmonics in power systems
   • Low-harmonic rectifiers and power factor correction converters
1. Simulation and Averaged Switch Modeling

- Additional notes, Section 7.4, Chapter 11, and Appendix B
- Averaged switch modeling is another approach to derive the averaged model of a PWM converter.
  - Well suited to Spice modeling of PWM converters
  - We will use this approach to model CCM, DCM, and current-programmed converters
  - Also useful for incorporation of ac losses (switching loss, core loss) into averaged models of PWM converters

- Computer simulation of small-signal transfer functions
  - Objectives of simulation
  - Spice models
  - Matlab/Simulink models
Averaged Switch Modeling and Simulation

Switching converter circuit

Switching network

averaging

Large-signal averaged circuit model

Averaged switch model

simulation model

Model implementation for simulation

linearization

DC and small-signal averaged circuit model

\[ G_c(s) = \frac{1 - s/w_c}{1 + (1/Q)s/w_o + (s/w_o)^2} \]

Analytical results:

steady-state characteristics

and small-signal dynamics

DC, AC and Transient simulation
2. Techniques of Design-Oriented Analysis

Chapter 10, Appendix C, and supplementary notes on website

Null double injection methods for analysis of complex analog systems

• Converter applications
  
  Input filter design
  
  Exact analysis of a fifth-order converter system

• Middlebrook's extra element theorem
  
  How to easily determine the effect of an added element on a circuit transfer function, without starting the analysis all over again

• The $n$ extra element theorem
  
  How to write complicated transfer functions by inspection, in rational form

• Middlebrook's feedback theorem
  
  How to easily construct the loop gain and transfer functions of a complex feedback circuit
Middlebrook’s Extra Element Theorem

Appendix C

How a transfer function $G(s)$ is modified by addition of an extra element $Z(s)$:

$$\frac{v_{\text{out}}(s)}{v_{\text{in}}(s)} = \left( G(s) \right)_{Z(s)\to\infty} \cdot \left( 1 + \frac{Z_N(s)}{Z(s)} \right) \left( 1 + \frac{Z_D(s)}{Z(s)} \right)$$

Simple methods to find $Z_N(s)$ and $Z_D(s)$ using null double injection

How to design circuits so that the extra element doesn’t significantly change $G(s)$:

$$||Z(j\omega)|| \gg ||Z_N(j\omega)||$$

$$||Z(j\omega)|| \gg ||Z_D(j\omega)||$$

Design-oriented result: construct Bode plots of above equations, and use to shape $Z(s)$
Input Filter Design

- Input filter can seriously degrade control system behavior and cause instability
- Use Extra Element Theorem to derive conditions that ensure that input filter does not disrupt dynamics of control system
- Must design input filter having adequate damping
Design of Input Filters that Do Not Degrade Converter Transfer Functions

Design criteria derived via Extra Element Theorem:

\[ Z(j\omega) \gg Z_N(j\omega) \]
\[ Z(j\omega) \gg Z_D(j\omega) \]

Two-section damped input filter design:

- \( R_2 = 0.65 \, \Omega \)
- \( n_2L_2 = 2.9 \, \mu H \)
- \( R_1 = 1.9 \, \Omega \)
- \( n_1L_1 = 15.6 \, \mu H \)
- \( L_2 = 5.8 \, \mu H \)
- \( L_1 = 31.2 \, \mu H \)
- \( C_2 = 11.7 \, \mu F \)
- \( C_1 = 6.9 \, \mu F \)
Write the line-to-output transfer function by inspection

Example: buck-boost with input filter

Solution: use \( n \) extra element theorem
3. Current-Programmed Control

- Chapter 12
- A very popular method for controlling PWM converters
- Transistor turns off when its current $i_s(t)$ is equal to a control signal $i_c(s)$
- Simpler dynamics, more robust compensator
Effect of current programming on converter transfer functions
Buck converter example

Comparison of control-to-output transfer functions

Averaged switch model used in spice simulations

![Graph of control-to-output transfer functions](image)

![Averaged switch model diagram](image)
Digitally Controlled Buck Converter
Simulink Model

- Buck converter block is same as in continuous-time system
- Note the parts of the system that model the digital controller, including:
  - A/D converter
  - Discrete-time compensator
  - Digital PWM
4. Modern Rectifiers, Power System Harmonics, and Low-Harmonic Rectifiers

- The traditional peak-detection rectifier injects very large harmonic currents into the ac power line.
- At substantial power levels, this type of rectifier is not allowed
The Ideal Rectifier

Modeling the basic functions of ideal converters

**DC-DC converter:**
- **DC transformer**

**AC-DC rectifier:**
- "Loss-free resistor"

\[
\begin{align*}
V_g & \quad + \quad - \\
R & \quad + \quad V \\
- & \quad + \\
\end{align*}
\]

**Ideal rectifier (LFR)**

\[
p(t) = \frac{v_{ac}^2}{R_e}
\]

\[
\begin{align*}
i_{ac}(t) & \quad + \quad - \\
v_{ac}(t) & \quad + \quad - \\
R_e(v_{control}) & \quad + \quad - \\
v_{control} & \quad + \quad - \\
v(t) & \quad + \quad -
\end{align*}
\]
Controller varies $d(t)$ as necessary, to cause $i_g(t)$ to be proportional to $v_g(t)$.