Power Electronic Circuits

Prof. Daniel Costinett

ECE 482 Lecture 1
January 8, 2015

• New course in design an implementation of power converters
  • Course website: http://web.eecs.utk.edu/courses/spring2015/ece482/
  • Course uses electric bicycle platform as framework for the investigation of practical issues in SMPS construction
• Unlike ECE 481, this is not a theory-focused course; expect to spend most of your effort on construction/debugging with relatively little new theory
• Goal of course is practical experience in designing, building, testing, and debugging power electronics; system, components, architectures can be modified based on student initiative
• Prerequisites: undergraduate Circuits sequence, Microelectronics, ECE 481 – Power Electronics
Instructor: Daniel Costinett

- Office: MK502
- OH during canceled lectures, in-lab
- E-mail: Daniel.Costinett@utk.edu
- Email questions will be answered within 24 hours (excluding weekends)
- Please use ECE 482 in the subject line

Course Structure

- Scheduled for one lecture and one 3-hr lab session per week
- Theory is presented as necessary for practical design
- Plan to spend ~10 hours per week on course; mostly lab time
- Lectures will only be used as needed – when no theory/review is necessary, lectures will give way to additional lab time
  - Check course website often for cancelled lectures
- Additional theory may be presented in brief sessions during lab time
Textbook and materials

- Portions of the Textbook
  will be used. The textbook is available on-line from campus network
- MATLAB/Simulink, LTSpice, Altium Designer, Xilinx ISE will be used; All installed in MK227 and in the Tesla Lab
- Lecture slides and notes, additional course materials, prelabs, experiments, etc. posted on the course website

Assignments

- Labs will be complete in groups of 2-3
- Lab Reports and Demonstrations (~7 labs total): 50% of total grade
  - Turn in one lab writeup per group
  - Submit electronically via e-mail to Daniel.Costinett@utk.edu
- Demonstrations each lab session: 10% of grade
  - Show functionality/progress and demonstrate understanding
  - Questions asked to each individual group member
- Pre-labs completed prior to starting each experiment: 20% of grade
  - Turn in one pre-lab assignment per person
- Midterm exam (open book/notes, in-class), 20% of the grade
- Late work will not be accepted except in cases of documented emergencies
- Due dates posted on website course schedule
# Use of Lab Time

- Attendance is required during all lectures and scheduled lab time
  - Make use of designated time with Instructor present
  - Informal Q&A and end-of-experiment demonstrations
- Work efficiently but do not work independently
  - Understand all aspects of design
- Build in stages; test one stage at a time
- Outside of normal lab hours, key access will be granted per group

# Topics Covered

- **Course Topics**
  - Battery Modeling
  - Modeling and Characterization of AC Machines
  - DC/DC Converter Analysis and Design
  - Loss Modeling of Power Electronics
  - Basic Magnetics and Transformers
  - Feedback Loop Design
  - Layout of Power Electronics Circuits
  - Electric Motor Drivers
  - BLDC and PMSM Control Methods
  - System-Level Control Design
Transportation Electrification

Motivation

- Improve efficiency: reduce energy consumption
- Displace petroleum as primary energy source
- Reduce impact on environment
- Reduce cost

EIA:
- Transportation accounts for 28% of total U.S. energy use
- Transportation accounts for 33% of CO2 emissions
- Petroleum comprises 93% of U.S. transportation energy use

Example: US06 driving cycle

Vehicle speed [mph]

Propulsion power [kW]

10-min
8 miles

Example: Prius-sized vehicle
Average power and energy

**Vehicle speed [mph]**

**Propulsion power [kW]**

Prius-sized vehicle
- **Dissipative braking**
  \[ P_{\text{avg}} = 11.3 \text{ kW} \]
  235 Wh/mile
- **Regenerative braking**
  \[ P_{\text{avg}} = 7.0 \text{ kW} \]
  146 Wh/mile

ICE vs ED \( \tau - \omega \)

Lotus Evora 414E Hybrid

Vehicle speed / [mph]

Propulsion power / [kW]

Thread / [kW]
ICE vs. ED $\eta$

- ED offers full torque at zero speed
- $\eta_{ED, pk} \approx 95\%$; $\eta_{ICE, pk} \approx 35\%$

Transmissions in Conventional Vehicles

ICE with multi-gear transmission

Electric motor with single gear
Conventional Vs. Electric Vehicle

(Prius-sized vehicle example)

<table>
<thead>
<tr>
<th></th>
<th>Tank + Internal Combustion Engine</th>
<th>Electric Vehicle (EV) Battery + Inverter + AC machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regenerative braking</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Tank-to-wheel efficiency</td>
<td>≈ 20%</td>
<td>≈ 85%</td>
</tr>
<tr>
<td></td>
<td>1.2 kWh/mile, 28 mpg</td>
<td>0.17 kWh/mile, 200 mpg equiv.</td>
</tr>
<tr>
<td>Energy storage</td>
<td>Gasoline energy content</td>
<td>LiFePO4 battery</td>
</tr>
<tr>
<td></td>
<td>12.3 kWh/kg, 36.4 kWh/gallon</td>
<td>0.1 kWh/kg, 0.8 kWh/gallon</td>
</tr>
<tr>
<td>Refueling</td>
<td>5 gallons/minute, 11 MW, 140 miles/minute</td>
<td>Level I (120Vac): 1.5 kW, &lt;8 miles/hour</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Level II (240Vac): 6 kW, &lt;32 miles/hour</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Level III (DC): 100 kW, &lt;9 miles/minute</td>
</tr>
<tr>
<td>Cost</td>
<td>12 ¢/mile [$3.50/gallon]</td>
<td>2 ¢/mile [$0.12/kWh]</td>
</tr>
<tr>
<td>CO₂ emissions (tailpipe, total)</td>
<td>≈ (300, 350) g CO₂/mile</td>
<td>(0, ~120) g CO₂/mile</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[current U.S. electricity mix]</td>
</tr>
</tbody>
</table>

CO₂ emissions and oil displacement study

Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of PHEVs
(2010 report by Argonne National Lab)
## CO₂ emissions Over Full Lifetime

Preparing for a Life Cycle CO₂ Measure (2011 report by Ricardo)

![CO₂ emissions chart]

### Conventional vs. Electric Vehicle

*(Ford Focus comparison)*

<table>
<thead>
<tr>
<th></th>
<th>Tank + Internal Combustion Engine (Ford Focus ST)</th>
<th>Electric Vehicle (EV) Battery + Inverter + AC machine (Ford Focus Electric)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase Price</td>
<td>$24,495</td>
<td>$39,995</td>
</tr>
<tr>
<td>Significant Maintenance</td>
<td>$5,000 (Major Engine Repair)</td>
<td>$50 - 13,500 (Battery Pack Replacement)</td>
</tr>
<tr>
<td>Energy Costs (10-year, 15k mi/yr)</td>
<td>$18,000</td>
<td>$3,000</td>
</tr>
<tr>
<td>Range</td>
<td>&gt; 350 mi</td>
<td>&lt; 100 mi</td>
</tr>
<tr>
<td>Performance</td>
<td>160 hp @ 6500 rpm 0-60 mph: 8.7 sec ¼ mile: (16.4 sec @ 85.4 mph)</td>
<td>123 hp, 2000-12000 rpm 0-60 mph: 9.6 sec ¼ mile: (17.2 sec @ 82.1 mph)</td>
</tr>
<tr>
<td>Curb Weight</td>
<td>3,000 lb</td>
<td>3,700 lb</td>
</tr>
</tbody>
</table>
The Price of Batteries

- Estimates of electric-vehicle battery costs ($ per kWh)-hour

- Additional cost of a plug-in hybrid electric vehicle (PHEV) over a conventional vehicle

- Market share of hybrid and electric vehicles

Sources: Accelerate Automotive Batteries, Boston Consulting Group, Deutsche Bank, Electrification Coalition, National Research Council, and Pike Research

Note: "EVs estimations for cars with at or 50mile the electric range. Source: National Research Council

Peter Savagian, "Barriers to the Electrification of the Automobile," Plenary session, ECCE 2014

The Impact of Policy

- Gasoline Price — USD$ per Gallon

- Electricity Price — USD $ per kWh

- Range of Policy

- Electric Driving Make Economic Sense

Range: $600 per kWh, $400 per kWh, $200 per kWh, Free Battery Pack - $0 per kWh

Peter Savagian, "Barriers to the Electrification of the Automobile," Plenary session, ECCE 2014
A Vision: Renewable Sources + Battery Electric Vehicles

• Zero GHG emissions, no petroleum
• High efficiencies are feasible: 80% grid-to-wheel
• Challenges
  • Battery technology: cost, cycle life, power and energy density
  • Efficient, reliably and cost-effective drivetrain components
  • Need for charging infrastructure
  • Limited charging power, long charge-up times

Power Electronics in Electric Vehicles

Peter Savagian, “Barriers to the Electrification of the Automobile,” Plenary session, ECCE 2014
BEV Architecture

Example: Tesla Roadster
- 215 kW electric drive ED1 (sport model)
- 53 kWh Li-ion battery

Series HEV Architecture

Example: Chevy Volt, a PHEV with a drive-train based on the series architecture:
- 62 kW (83 hp, 1.4 L) ICE
- 55 kW electric drive ED1
- 111 kW (149 hp) electric drive ED2
Parallel HEV

Example: 2011 Sonata HEV with a drive-train based on the parallel architecture:
• 121 kW (163 hp, 2.0 L) ICE
• 30 kW electric drive ED1
  • 8.5 kW hybrid starter/generator connected to crankshaft

Series/Parallel HEV

Example: 2010 Prius HEV with a drive-train based on the series/parallel architecture:
• 73 kW (98 hp, 1.8 L) ICE
• 60 kW electric drive ED2
  • 100 kW total power
  • 42 kW (149 hp) electric drive ED1
Electric Bicycle Platform

Battery

Power Conversion and Control

Electric Motor

Electric Bicycle System
Growing Popularity of E-bikes

Electric Bicycle Sales by Region, World Markets: 2012-2018

Electric Bicycles Worldwide

- E-bikes accounted for $6.9 billion in revenue in 2012
- By utilizing sealed lead-acid (SLA) batteries, the cost of e-bicycles in China averages about $167 (compared to $815 in North America and $1,546 in Western Europe)
- China accounts for 90% of world market
- Western Europe accounts for majority of remaining 10% despite $1,546 average cost
- North America: 89,000 bicycles sold in 2012
System Structure

- Battery
- BMS
- Boost DC-DC Converter
- PWM Controller
- 3-φ PWM Controller
- Motor
- Filtering and Control
- Throttle
- Brake
- V_ref
- f_ref
- θ_abc
- D
- V_out
- \( g_{L6} \)
- \( I_{abc} \)
- \( 3 \)-φ Inverter / Driver
- BMS

Experiment 1

- Battery
- BMS
- Motor
- θ_abc

- Identification and characterization of motor
- Modeling of motor using simulink
- Derivation of model parameters from experimental data
Experiment 2-3

- Open-loop operation of Boost converter
- Inductor design
- Converter construction and efficiency analysis
- Bidirectional operation using voltage source / resistive load

Experiment 4

- Closed loop operation of boost converter
- Feedback loop design and stability analysis
- Analog control of PWM converters
Experiment 5

- Circuit layout and PCB design
- Device selection and implementation according to loss analysis
- Basic control of BLDC motors

Experiment 6

- System-level control techniques
**Experiment 7**

- System improvements

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**Example System Implementation**
Design Expo

- No final exam
- Demo operational electric bicycles with system improvements
- Competition to determine the most efficient and well-controlled system
Electric Bicycle Safety and Law

• Traffic Law:
  • Electric motor with power output not more than 1000 W
  • Not capable of propelling or assisting at greater than 20 mph
  • No helmet laws for riders over age 16; you may request one at any time
  • Read Tennessee bicycle safety laws on website

General Safety

• Lab will work with high voltages (Up to 100 V)
• Will use various machinery with high power moving parts
• Use caution at all times