Power Electronic Circuits

Prof. Daniel Costinett

ECE 482 Lecture 1
January 8, 2014

• New course in design an implementation of power converters
  • Course website: http://web.eecs.utk.edu/courses/spring2014/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 three 1-hr lectures and one 1-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*
- Demonstrations each lab session: 10% of grade
  - Show functionality/progress and demonstrate understanding
- 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 (Wed, 9:05-11:55)
  – 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 US transportation energy use

Example: US06 driving cycle

- Vehicle speed [mph]
- Propulsion power [kW]

Example: Prius-sized vehicle

10-min
8 miles
Average power and energy

**Vehicle speed [mph]**

**Propulsion power [kW]**

- **Dissipative braking**
  \[ P_{\text{avg}} = 11.3 \text{ kW} \]
  \[ 235 \text{ Wh/mile} \]

- **Regenerative braking**
  \[ P_{\text{avg}} = 7.0 \text{ kW} \]
  \[ 146 \text{ Wh/mile} \]

---

**Conventional Vs. Electric Vehicle**

<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><strong>Regenerative braking</strong></td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Tank-to-wheel efficiency</strong></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><strong>Energy storage</strong></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><strong>Refueling</strong></td>
<td>5 gallons/minute</td>
<td>Level I (120Vac): 1.5 kW, &lt;8 miles/hour</td>
</tr>
<tr>
<td></td>
<td><strong>11 MW</strong>, 140 miles/minute</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><strong>Cost</strong></td>
<td>12 ¢/mile [$3.50/gallon]</td>
<td>2 ¢/mile [$0.12/kWh]</td>
</tr>
<tr>
<td><strong>CO₂ emissions (tailpipe, total)</strong></td>
<td>≈ (300, 350) g CO₂/mile</td>
<td>(0, ≈120) g CO₂/mile [current U.S. electricity mix]</td>
</tr>
</tbody>
</table>
Electric-Drive Vehicle Technologies

- **Hybrid Electric Vehicle (HEV)**
  - Combination of a gasoline-powered ICE and electric drive with a relatively small battery
  - HEV efficiency improvements
    - Regenerative braking
    - “Downsizing:” a smaller, more efficient ICE
    - ICE operated around the most efficient operating point, not directly tied to the required drive power & speed
    - No idling required when the vehicle stops, keep ICE off

- **Plug-in Hybrid Electric Vehicle (PHEV)**
  - Same efficiency improvements as HEV
  - Larger battery for an all-electric range

- **Electric Vehicle (EV)**
  - No ICE, (much) larger battery

---

**Series PHEV drive train example**

- In a PHEV, a (larger) battery can be charged from the electric power grid
- 62 kW (83 hp, 1.4 L) ICE
- 55 kW electric drive ED1
- 111 kW (149 hp) electric drive ED2
- 16 kWh Li-Ion battery pack (175 kg), 65% (10.5 kWh) usable, (approximately) 40 miles of EV range (0.26 kWh/mile)
- 37 mpg (hybrid), 99 mpg equivalent (electric)

Example: Chevy Volt, a PHEV
New EPA stickers: PHEV example

Chevy Volt

1720 kg
110 kW (149 hp) electric drive
62 kW (83 hp) ICE
16 kWh Li-ion battery
175 kg battery pack
(8 years, 100,000 miles warranty)

PHEV or EV drive train

- Plug-in hybrid electric vehicle (PHEV) has a driving range (X miles) as electric vehicle powered by batteries only (EV mode)
  - Example: Chevy Volt is a PHEV40, with a 16 kWh battery, 65% (10.5 kWh) usable, and (approximately) 40 miles of EV range (0.26 kWh/mile)
- Electric vehicle (EV), or Battery Electric Vehicle (BEV) does not include ICE at all
  - Example: Tesla Roadster has about 250 miles (400 km) EV range, with about 50 kWh battery, 75% (37.5 kWh) usable (0.15 kWh/mile)
New EPA stickers: EV example

Nissan Leaf

1527 kg
80 kW (110 hp) electric drive
24 kWh Li-ion battery

Cells: 140 Wh/kg
300 kg battery pack
(8 years, 100,000 miles warranty)

MPGequivalent = \frac{\text{Trip length [miles]}}{\text{Total energy consumed [kWh]}} \times 33.7 \text{ kWh/gallon}

CO₂ emissions

http://www.epa.gov/cleanenergy/energy-resources/calculator.html

Gasoline CO₂ emissions (tailpipe only)
8.89 \times 10^{-3} \text{ metric tons CO₂/gallon of gasoline} = 8892 \text{ g CO₂/gallon} = 264 \text{ g CO₂/kWh}

CO₂ emissions from electricity generation (average over year, average over US)
7.18 \times 10^{-4} \text{ metric tons CO₂/kWh} = 718 \text{ g CO₂/kWh}

t(eGRID2007 Version 1.1, U.S. annual non-baseload CO₂ output emission rate, year 2005 data)

<table>
<thead>
<tr>
<th></th>
<th>Conv. Gasoline V.</th>
<th>HEV</th>
<th>EV (zero tailpipe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPGequv.</td>
<td>20</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>kWh/mile</td>
<td>1.685</td>
<td>1.123</td>
<td>0.674</td>
</tr>
<tr>
<td>g CO₂/mile</td>
<td>445</td>
<td>296</td>
<td>178</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)

---

**Trends and Challenges**

- **Paths to electrified (personal) transportation**
  - Hybrid electric vehicles
  - Plug-in hybrid electric vehicles
  - Battery electric vehicles
  - Hydrogen + fuel cell electric vehicles
- **Electricity generation mix: shift to renewables**
- **Challenges**
  - Batteries
  - Engineering of electric drivetrain components, including efficient, high-density, reliable power electronics
  - Charging infrastructure
Vision: Renewable Sources + Battery Electric Vehicles

- Zero GHG emissions, zero-oil
- High efficiencies are feasible: 80% grid-to-wheel
- Challenges
  - Battery technology: cost, cycle life, power and energy density
  - Need for charging infrastructure
  - Limited $P_{chg}$, long charge-up times
    - At the gasoline pump: 10 gallons in 2 minutes, effective $P_{chg} = 10$ MW
    - Fastest electric chargers envisioned: $P_{chg}$: 0.1-0.2 MW

Growing Popularity of E-bikes

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

(Source: Pike Research)
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