Transportation Electrification

Motivation

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

US Energy Information Administration:
• Transportation accounts for 28% of total U.S. energy use
• Transportation accounts for 33% of CO₂ emissions
• Petroleum comprises 90% of US transportation energy use

Example: US06 driving cycle

Example: Prius-sized vehicle
Example: US06 driving cycle

**Vehicle speed [mph]**

**Propulsion power [kW]**

**Prius-sized vehicle**

Dissipative braking

\[ P_{\text{avg}} = 11.3 \text{ kW} \]

235 Wh/mile

**Deceleration**

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 $\tau - \omega$


ICE vs. ED $\eta$

Internal Combustion Engine (ICE)
- $\eta_{ED,pk} \approx 95\%$; $\eta_{ICE,pk} \approx 35\%$
- ED offers full torque at zero speed
  - No need for multi-gear transmission

Electric Drive (ED)
- Max Efficiency $\approx 34\%$
- Max Efficiency $> 95\%$
Conventional Vs. Electric Vehicle  
(Commuter Sedan comparison)

<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>( \approx 20% )</td>
<td>( \approx 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>Cost</td>
<td>12 ( \cent/mile ) [$3.50/gallon]</td>
<td>2 ( \cent/mile ) [$0.12/kWh]</td>
</tr>
<tr>
<td>( \text{CO}_2 ) emissions</td>
<td>( \approx (300, 350) ) g ( \text{CO}_2 )/mile</td>
<td>(0, ( \approx 120 ) g ( \text{CO}_2 )/mile</td>
</tr>
<tr>
<td>(tailpipe, total)</td>
<td></td>
<td>[current U.S. electricity mix]</td>
</tr>
<tr>
<td>Energy Costs (10-yr, 15k mi/yr)</td>
<td>$18,000</td>
<td>$3,000</td>
</tr>
</tbody>
</table>

Energy and Power Density of Storage

- **2016 Camaro 6.2L V8**
- **Mazda RX-8 1.3L Wankel**

![Diagram showing Energy and Power Density of Storage](image)
## Conventional Vs. Electric Vehicle

*(Commuter Sedan comparison)*

<table>
<thead>
<tr>
<th></th>
<th>Tank + Internal Combustion Engine <em>(Ford Focus ST)</em></th>
<th>Electric Vehicle (EV) Battery + Inverter + AC machine <em>(Ford Focus Electric)</em></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purchase Price</strong></td>
<td>$24,495</td>
<td>$39,995</td>
</tr>
<tr>
<td><strong>Significant</strong></td>
<td>$5,000 (Major Engine Repair)</td>
<td>$13,500 (Battery Pack Replacement)</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>&gt; 350 mi</td>
<td>&lt; 100 mi</td>
</tr>
<tr>
<td><strong>Curb Weight</strong></td>
<td>3,000 lb</td>
<td>3,700 lb</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, 140 miles/minute</strong></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>
</tbody>
</table>

---

## EV Everywhere Grand Challenge

*Advancements needed for an electric drive system to support meeting *EV Everywhere* targets*

**2012 Electric Drive System**

- $30/kW, 1.1 kW/kg, 2.6 kW/L
- 90% system efficiency

**2022 Electric Drive System**

- $8/kW, 1.4 kW/kg, 4.0 kW/L
- 94% system efficiency

---

*4X Cost Reduction
35% Size Reduction
40% Weight Reduction
40% Loss Reduction*
Power Electronics in Electric Vehicles

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

Electric Vehicle Components
Electric Bicycle Platform

Power Conversion and Control

Battery

Electric Motor

Electrical Build Space
Electric Bicycle System

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

Course Details
Course Introduction

• Hands-on course in design and implementation of power converters
  • http://web.eecs.utk.edu/~dcostine/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
• Goal of course is practical experience in designing, building, testing, and debugging power electronics
• System, components, architectures can be modified based on student initiative
• Course is difficult; will require design effort and significant hands-on time outside of class. Expect to experience circuit failures.
• Prerequisites: undergraduate circuits sequence, Microelectronics, ECE 481 – Power Electronics

Contact Information

• Instructor: Daniel Costinett
  • Office: MK504
  • OH during canceled lectures, in-lab, individually scheduled
  • 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
  - Lectures as needed; many weeks will have two lab sessions
  - Check course website often for schedule
• Theory is presented as necessary for practical design
• Additional theory may be presented in brief sessions during lab time
• Plan to spend 9-12 hours per week on course; mostly lab time

Textbook and materials

• Portions of the Textbook
  R.Erickson, D.Maksimovic, Fundamentals of Power Electronics, Springer 2001
  will be used. The textbook is available on-line from campus network
• MATLAB/Simulink, LTSpice, Altium Designer; All installed in MK227 and in the Tesla Lab
• Lecture slides and notes, additional course materials, prelabs, experiments, etc. posted on the course website
• Lab kit is required (purchased from circuits store) in ~1-2 weeks
  - Price: $150-200 per group
  - Additional resistors and capacitors, etc. purchased as needed
  - Need to buy any replacement parts
Grading

Group
• Lab Completion and Reporting
  – 50% of total grade
  – Turn in one per group

Individual
• Pre-Lab Assignments
  – 15% of total grade
  – Turn in one per individual
• In-lab Demo and Participation
  – 20% of total grade
  – Questions asked to each group member
• Midterm Exam
  – 15% of total grade
  – Open book/notes, in-class
  – Covers material from experiments

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
• Outside of normal lab hours, key access will be granted (one 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
• Debugging and prototyping techniques
• Current-mode Control
• Feedback Loop Design
• Layout of Power Electronics Circuits
• BLDC and PMSM Control Methods
• System-Level Control Design

System Structure

[Diagram showing the system structure with labels for Battery, BMS, Boost DC-DC Converter, PWM Controller, 3-ϕ Inverter/Driver, 3-ϕ PWM Controller, Motor, Throttle, Filtering and Control, V_{ref}, f_{ref}, D, V_{out}, g_{1-6}, i_{abc}, \theta_{abc}, V_ref, f_ref]
Experiment 1

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

Experiment 2

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

Example System Implementation
Design Expo

• No final exam
• Demo operational electric bicycles
• Competition to determine the most efficient and robust 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 ~75 V)
• Will use various machinery with high power moving parts
• High temperatures for soldering
• Use caution at all times
• You may not work with electrical power alone in the lab
• No food or drink allowed in the lab
Safety training Requirements

- Login to canvas at https://utk.instructure.com/courses/29416/modules
- Complete training modules
  - General Lab Safety
  - Hazardous Waste
  - Hazard Communication Training and GHS Updates
  - Fire Extinguisher Training
  - Fire Safety in Laboratories
  - Chemical Fume Hood Safety Training
  - Compressed Gas Cylinder Training
  - Laboratory Safety for Undergraduates and Minors (required only if UG or minor)
  - Personal Protective Equipment
  - Electrical Safety, Orientation Level
  - Lead Awareness Training
- Once all training is completed print your “Completed” Transcript and turn it in to Dr. Costinett by e-mail
- Must complete with passing scores before Thursday 1/18
Introduction to Battery Modeling

Example EV Batteries

Cutaway battery of Nissan Leaf electric vehicle. The Leaf includes a 24kWh lithium-ion battery with a city driving range of 160km (100 miles). The battery fits under the floor of the car, weighs 272kg (600lb) and is estimated to cost $15,600 (2010).

Tesla Model S frame-integrated battery. The Model S includes a 60-85kWh lithium-ion battery with a city driving range of 480km (300miles). The battery weighs 544kg (1200lb) and is estimated to cost $24-34,000.

Toyota Prius HEV Battery. The 2004 Prius included a 1.3 kWh NiMH battery consisting of 168 cells and with a $3K retail replacement cost.
Cell Equivalent-Circuit Models

Objective:
• Dynamic circuit model capable of predicting cell voltage in response to charge/discharge current, temperature

Further key techniques discussed in [Plett 2004-Part 2] and [Plett 2004-Part 3]
• Model parameters found using least-square estimation or Kalman filter techniques based on experimental test data
• Run-time estimation of state of charge (SOC)

Approach: Pulsed current tests

Battery Nomenclature

• Known beforehand:
Example Battery

Model 0: Voltage Source

![](image)

`.tran 36000`
Model A: SOC and $V_{oc}$

Model B: Series Resistance
Model B: Series Resistance

\[ \text{SOC} \]

\[ i_{bat} \]

\[ V_z \]

\[ C_{nom} \]

\[ V_{OC}(V_z) \]

\[ i_{bat} \]

\[ + \]

\[ + \]

\[ - \]

\[ - \]
Model B Performance

Model C: Zero-state Hysteresis

[Plett 2004]
Model C Performance
Dynamic Performance

- Dynamic performance characterized by pulse train
- Constant percent of capacity per pulse [%Ahr]

Model C1: One-state Hysteresis

[Plett 2004]
Model C1 Performance

![Graph showing Model C1 Performance with voltage (V(batt)) and model voltage (V(model)) over time with current (I(12) and I(13)) change.]
Model D: Diffusion (one-state)

[Plett 2004]

Model D Performance
Diffusion Vs Hysteresis

Experimental Results

Implementation in LTSpice

Modeling in Experiment 1

- Batteries have internal Battery Management System (BMS)
  - Limit over-current, over-discharge
  - **Do not** connect directly to battery cell
- Never leave charging or discharging batteries unattended
- You determine necessary model complexity
  - Model A – Model D or other
- Not entirely analytical and solution may not be unique
  - Guess and check is fine, where appropriate
Battery BMS

- Insert batteries into BMS in correct polarity
  - Use voltmeter to be sure
- Never short leads of battery or BMS
- BMS will cut off with sustained, large current (>~2A)
- After BMS cutoff, connect leads to charger to reset BMS

PM Motor Operation
Review of Basic Magnetics

- [http://web.eecs.utk.edu/~dcostine/ECE481/Fall2017/schedule.php](http://web.eecs.utk.edu/~dcostine/ECE481/Fall2017/schedule.php)
  - Lectures 35-36

---

**Single Phase Motor (Simplified)**
Electromechanical Conversion

Alternative Diagram
2-Pole, 2-Phase PMSM

Two-pole, two-phase PMSM terminal characteristics in stator reference frame

\[
\lambda_a(\theta_r) = \lambda_m \sin(\theta_r) \\
\lambda_b(\theta_r) = -\lambda_m \cos(\theta_r)
\]

\[
v_a = ri_a + \frac{d\lambda_a}{dt} = ri_a + L \frac{di_a}{dt} + \lambda_m \omega_r \cos(\theta_r)
\]

\[
v_b = ri_b + \frac{d\lambda_b}{dt} = ri_b + L \frac{di_b}{dt} + \lambda_m \omega_r \sin(\theta_r)
\]

\[
T_m = \lambda_m (i_a \cos(\theta_r) + i_b \sin(\theta_r))
\]

3-Phase, 2-Pole PMSM

\[
\lambda_a(\theta_r) = \lambda_m \sin(\theta_r)
\]

\[
\lambda_b(\theta_r) = \lambda_m \sin \left( \theta_r - \frac{2\pi}{3} \right)
\]

\[
\lambda_c(\theta_r) = \lambda_m \sin \left( \theta_r - \frac{4\pi}{3} \right)
\]

\[
T_m = i_a \lambda_m \omega_r \cos(\theta_r) + i_b \lambda_m \omega_r \cos \left( \theta_r - \frac{2\pi}{3} \right) + i_c \lambda_m \omega_r \cos \left( \theta_r - \frac{4\pi}{3} \right)
\]
Different Number of Poles

3-Phase, P-Pole PMSM

\[ P = 4 \text{ example} \]

Electrical and mechanical angle

\[ \theta_r = \frac{P}{2} \theta_{rm} \]

Electrical and mechanical speed

\[ \omega_r = \frac{P}{2} \omega_{rm} \]

Max torque per amp

\[ T_m \leq \lambda_m \frac{P}{2} \frac{3}{2} I \]
Outer- vs. Inner-Rotor

- Traditional motors are inner-rotor
- On e-bike, need hub to remain stationary and outer wheel to spin

Motor Teeth/Poles Example

(a) 36-slot/6-pole
(b) 9-slot/6-pole
(c) 12-slot/10-pole (all teeth wound)
(d) 12-pole/10-pole (alternate teeth wound)
Shaping Back-EMF

• Earlier, assumed \( f(\theta_r) = \sin(\theta_r) \) resulting in sinusoidal back-EMF

• Ways to achieve:
  1. Sinusoidal distribution of windings
  2. Altering slot/pole/phase

• #2 is used in our motor
Motor Driver: Trapezoidal Control

Torque Ripple