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 CO$_2$ emissions
• Petroleum comprises 90% of US transportation energy use
Example: US06 driving cycle

10-min 8 miles

Example: Prius-sized vehicle

Vehicle speed [mph]

Propulsion power [kW]

Dissipative braking

$P_{vavg} = 11.3 \text{ kW}$

235 Wh/mile
**Average power and energy**

![Image of vehicle speed and propulsion power graphs]

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

**ICE vs ED $\tau$–$\omega$**

- **Lotus Evora 414E Hybrid**

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 $\gt 95\%$

---

**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 c/mile [$3.50/gallon$]</td>
<td>2 c/mile [$0.12/kWh$]</td>
</tr>
<tr>
<td>CO$_2$ emissions (tailpipe, total)</td>
<td>$\approx (300, 350)$ g CO$_2$/mile</td>
<td>(0, $\approx 120$) g CO$_2$/mile [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**

![Graph showing energy storage and power density](image)

**Conventional Vs. Electric Vehicle**

(Commuter Sedan 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><strong>Purchase Price</strong></td>
<td>$24,495</td>
<td>$39,995</td>
</tr>
<tr>
<td><strong>Significant</strong></td>
<td>$5,000</td>
<td>$13,500</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td>(Major Engine Repair)</td>
<td>(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><strong>12.3 kWh/kg, 36.4 kWh/gallon</strong></td>
<td><strong>0.1 kWh/kg, 0.8 kWh/gallon</strong></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): <strong>100 kW, &lt;9 miles/minute</strong></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

Today
$12/kW
1.2 kW/kg
3.5 kW/L
>93% efficiency

2022 Electric Drive System
$8/kW, 1.4 kW/kg, 4.0 kW/L
94% system efficiency

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 Vehicle Components

Electric Bicycle Platform

Power Conversion and Control

Battery

Electric Motor
Electrical Build Space

Electric Bicycle System

Diagram of the electric bicycle system:
- Rider input
- Pedals
- Gears
- Drive wheel
- Motor control
- Motor
- Battery charger
- Battery
- Vehicle accessories
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
Course Details

Course Introduction

• Hands-on course in design and implementation of power converters
  • http://web.eecs.utk.edu/~dcostine/ECE482/Spring2018
  • http://web.eecs.utk.edu/courses/spring2018/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: MK502
  - 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

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
- 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

- Labs will be complete in groups of 3
  - Choose groups by Thursday, 1/18
- Late work will not be accepted except in cases of documented emergencies
- Due dates posted on website course schedule

**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

*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
- 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

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}

\phi_{1-6}

\theta_{abc}

\theta_{abc}

PWM Controller

Battery Motor

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

• Log in to K@TE at https://tennessee.csod.com/samldefault.aspx
• Complete training modules
  − Workplace safety orientation
  − PPE: Eye and Face Protection
  − NFPA 70E Electrical Safety in the Workplace 2012 Edition
  − Lockout/Tagout for Authorized Persons 2017
  − Job Hazard Analysis
  − Hazard Communication: An Employee’s Right to Know 2017
• 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
Training Modules

Lab 1

Old System (Skillsoft)

System (K@TE)

20187-18 System (K@TE)
Introduction to Battery Modeling

Example EV Batteries

Cutaway battery of Nissan Leaf electric vehicle. The Leaf includes a 24 kWh 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 60-85 kWh lithium-ion battery with a city driving range of 480km (300 miles). 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

![Battery Image]

```
.X1 batt+ batt-
.X2 model

.tran 36000

V(batt) 29.7V 24.8V 19.8V
V(model) 24.8V
```

![Graph Image]
Model A: SOC and $V_{oc}$

Model B: Series Resistance
Model B: Series Resistance

\[ V_{\text{batt}} \]

\[ V(x1:\text{soc}) \]

\[ V(x2:\text{soc}) \]

\[ i_{\text{bat}} \]

\[ v_{\text{bat}} \]

\[ V_{OC(V_z)} \]
Dynamic Performance

- Dynamic performance characterized by pulse train
- Constant percent of capacity per pulse [%Ahr]
Model C: Zero-state Hysteresis

Model C Performance
Model C1: One-state Hysteresis

\[ \frac{1}{1 + \tau_d s} \]

\[ V_{bat} \]

\[ C_{nom} \]

\[ SOC \]

\[ i_{bat} \rightarrow v_h \]

\[ R^+ \]

\[ R^- \]

\[ V_{OC}(V_z) \]

\[ V_{bat} \]

Model C1 Performance

![Graph showing performance comparison between V(batt) and V(model)]
Model D: Diffusion (one-state)

\[ i_{\text{bat}} \rightarrow \frac{1}{1 + r_p s} \rightarrow v_h \]

\[ S O C \]

\[ i_{\text{bat}} \rightarrow C_{\text{nom}} \rightarrow V_z \]

\[ v_h \] +

\[ + \]

\[ V_{O C}(V_z) \]

\[ R_1 \]

\[ C_1 \]

\[ R_o^+ \]

\[ R_o^- \]

\[ i_{\text{bat}} \rightarrow v_{\text{bat}} \]

[Model D Performance]

V(batt)  V(model)

<table>
<thead>
<tr>
<th>V(batt)</th>
<th>V(model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.4V</td>
<td></td>
</tr>
<tr>
<td>28.2V</td>
<td></td>
</tr>
<tr>
<td>27.0V</td>
<td></td>
</tr>
<tr>
<td>25.8V</td>
<td></td>
</tr>
<tr>
<td>24.6V</td>
<td></td>
</tr>
<tr>
<td>23.4V</td>
<td></td>
</tr>
<tr>
<td>22.2V</td>
<td></td>
</tr>
</tbody>
</table>

I(12)  I(13)

<table>
<thead>
<tr>
<th>I(12)</th>
<th>I(13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10A</td>
<td></td>
</tr>
<tr>
<td>9A</td>
<td></td>
</tr>
<tr>
<td>8A</td>
<td></td>
</tr>
<tr>
<td>7A</td>
<td></td>
</tr>
<tr>
<td>6A</td>
<td></td>
</tr>
<tr>
<td>5A</td>
<td></td>
</tr>
<tr>
<td>4A</td>
<td></td>
</tr>
<tr>
<td>3A</td>
<td></td>
</tr>
<tr>
<td>2A</td>
<td></td>
</tr>
<tr>
<td>1A</td>
<td></td>
</tr>
</tbody>
</table>

Time/60 0s 20s 40s 60s 80s 100s 120s
Experimental Results

Modeling discharge: ESC, 2 filter states

Modeling charge: ESC, 2 filter states

Modeling discharge: ESC, 4 filter states

Modeling charge: ESC, 4 filter states

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
  – Lectures 35-36
Single Phase Motor (Simplified)

Electromechanical Conversion
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

\[ \lambda_a(\theta_r) = \lambda_m \sin(\theta_r) \]
\[ \lambda_b(\theta_r) = \lambda_m \sin(\theta_r - \frac{2\pi}{3}) \]
\[ \lambda_c(\theta_r) = \lambda_m \sin(\theta_r - \frac{4\pi}{3}) \]

\[ T_m = i_a \lambda_m \omega_r \cos(\theta_r) + i_b \lambda_m \omega_r \cos(\theta_r - \frac{2\pi}{3}) + i_c \lambda_m \omega_r \cos(\theta_r - \frac{4\pi}{3}) \]
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

Shape of Back EMF

- 36 Teeth, 22 Poles
- Teeth/Pole/Phase = 0.5455

- 33 Teeth, 22 Poles
- Teeth/Pole/Phase = 0.5
Motor Driver: Trapezoidal Control

Torque Ripple