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

Example: Prius-sized vehicle

Dissipative braking

\[ P_{\text{dissip}} = 11.3 \, \text{kW} \]

235 Wh/mile

Deceleration
Average power and energy

**Vehicle speed [mph]**

**Propulsion power [kW]**

- **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**

ICE vs. ED $\eta$

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

Electric Drive (ED)
- $\eta_{\text{ED,pk}} \approx 95\%$
- 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 ¢/mile [$3.50/gallon]</td>
<td>2 ¢/mile [$0.12/kWh]</td>
</tr>
<tr>
<td>CO$_2$ emissions</td>
<td>$\approx (300, 350)$ g CO$_2$/mile</td>
<td>(0, $\approx120$) g CO$_2$/mile</td>
</tr>
<tr>
<td>(tailpipe, total)</td>
<td>[current U.S. electricity mix]</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

Conventional Vs. Electric Vehicle

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Electric Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank + Internal Combustion Engine (Ford Focus ST)</td>
<td>Electric Vehicle (EV) Battery + Inverter + AC machine (Ford Focus Electric)</td>
<td></td>
</tr>
<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>$13,500 (Battery Pack Replacement)</td>
</tr>
<tr>
<td>Range</td>
<td>&gt; 350 mi</td>
<td>&lt; 100 mi</td>
</tr>
<tr>
<td>Curb Weight</td>
<td>3,000 lb</td>
<td>3,700 lb</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</td>
<td>Level I (120Vac): 1.5 kW, &lt;8 miles/hour</td>
</tr>
<tr>
<td></td>
<td>11 MW, 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>
</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

4X Cost Reduction
35% Size Reduction
40% Weight Reduction
40% Loss Reduction

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

Battery

Power Conversion and Control

Electric Motor
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
  - http://web.eecs.utk.edu/courses/spring2017/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

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 of system structure with Battery, BMS, Boost DC-DC Converter, 3-phase PWM Controller, 3-phase Inverter/Driver, Motor, Filtering and Control, Vref, fref, D, Vout, gL+6, abc, θabc, and Throttle connections.]
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 100 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 SkillSoft at https://oit2.utk.edu/cbt/login.php
- Once all training is completed print your Skillsoft Learner Records Progress Report and send it to Dr. Costinett
- Must complete with passing scores before Thursday 1/21
Lab 1

Introduction to Battery Modeling
Example EV Batteries

Cutaway battery of Nissan Leaf electric vehicle. The Leaf includes a 30-kWh lithium-ion battery with a city driving range of 100km (60 miles). The battery fits under the floor of the car, weighs 272kg (600lb), and is estimated to cost $30,000 (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 $51,600 (2010).

Cutaway battery of Tesla electric vehicle. The Tesla includes a 80-kWh lithium-ion battery with a city driving range of 330km (200 miles). The battery weighs 544kg (1200lb) and is estimated to cost $71,600 (2015).

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:
  
  * Capacity: \( C \) [Ah]
  * Nominal Voltage: \( V_{oc} \) [V]
  * Max rate: \( 0.5C \)
  * Max discharge: \( 10C \)
  
  - If \( C = 10Ah \):
    - 0.5C rate \( \rightarrow 5A \)
    - 10C rate \( \rightarrow 100A \)

Example Battery

- Example:
  - 7-series Li-ion cells
  - 3.4V nominal cell voltage
  - \( \cong 24V \) nominal pack voltage
  - \( C = 10Ah \)
  - Max charge: 0.2C
  - Max discharge: 1.9C
Model 0: Voltage Source

Model A: SOC and $V_{oc}$

$V_e = V_{2o} - \frac{1}{C_{nom}} \int_{0}^{t} i_{bat} dt$

$V_e = V_{soe}$

set $C_{nom} = \frac{3600}{t_{capacity}}$
Model B: Series Resistance

Diagram showing a circuit model with a battery and a model connected in series, along with voltage over time graphs.
Model B: Series Resistance

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

Discharge

Charge

Model C: Zero-state Hysteresis

[Plett 2004]
Model C Performance

Model C1: One-state Hysteresis

[Model C1 Diagram]

Model C1: One-state Hysteresis

[Plett 2004]
Model C1 Performance

Model D: Diffusion (one-state) [Plett 2004]
Model D Performance

Experimental Results

Reference:
**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
PM Motor Operation

Basic Magnetics Relationships

Faraday’s law

B(t), \Phi(t)

Core characteristics

H(t), \mathcal{F}(t)

Ampere’s law

Fundamentals of Power Electronics

Chapter 13: Basic Magnetics Theory
Core Material Characteristics

\[ B = \mu_0 H \]

\[ \mu_0 = \text{permeability of free space} = 4\pi \cdot 10^{-7} \text{Henries per meter} \]

A magnetic core material

Highly nonlinear, with hysteresis and saturation

Basic Magnetics

Simplifying Assumptions:
1. Field contained entirely within core
2. Uniform field distribution throughout core
3. Material unsaturated \( B = NA \)

Ampere's Law:
\[ n_i(t) = \oint \mathbf{H} \cdot d\mathbf{l} = H_{\text{core}}(l_m - l_g) + H_{\text{gap}}(l_g) \]

Faraday's Law:
\[ \oint \mathbf{E} \cdot d\mathbf{l} = -\frac{\partial \mathbf{B}}{\partial t} \]

\[ \mathbf{v}(t) = \frac{\partial \mathbf{B}}{\partial t} \cdot \mathbf{A} \]
**Equivalent Circuit**

1. \[ B = \frac{n_i i(t)}{\ln \left( \frac{L_g}{L_o} \right) + \frac{L_g}{L_o}} \]

2. \[ v(t) = n \frac{dB}{dt} A_c \]

Effect of Air Gap:

- **Decrease inductance**
- **Increase saturation current**
- **Inductance is less dependent on core permeability**

\[ ni = \Phi \left( \mathcal{R}_c + \mathcal{R}_s \right) \]

\[ L = \frac{n^2}{\mathcal{R}_c + \mathcal{R}_s} \]

\[ \Phi_{sat} = B_{sat} A_c \]

\[ I_{sat} = \frac{B_{sat} A_c}{n} \left( \mathcal{R}_c + \mathcal{R}_s \right) \]

\[ \Phi = B A_c \]

**Fundamentals of Power Electronics**

Chapter 13: Basic Magnetics Theory
Single Phase Motor (Simplified)

Assume magnet produces a constant total flux $\Phi_m$

$\Phi_{coil} =$ flux from magnet which goes through the coil

$\Phi_{coil} = f(\Theta_r) \Phi_m$

$-1 \leq f(\Theta_r) \leq 1$

$\Theta_r = f(\Theta)$

$v_x = n \frac{d\Phi_{coil}}{dt} = n \frac{d}{dt} (\Phi_m f(\Theta_r))$

Winding Voltage Equation

$v_x = n \Phi_m \frac{d}{dt} f(\Theta_r)$

$\lambda_m = $ flux linkage

$f(\Theta_r) = \sin \Theta_r$

Assuming constant angular speed

$\lambda_m \cos \Theta_r$:

$\lambda_m \omega_r \cos \Theta_r$

Look at $P_a = N_a i_a$

$P_a = i_a^2 R_w + i_a \frac{d}{dt} L + i_a \lambda_m \omega_r \cos \Theta_r$

Conversion:

- Conduction loss
- Reactive only
- Converted to mechanical
Electromechanical Conversion

\[ r_a \lambda_m \omega_r \]

2-Pole, 2-Phase PMSM
Two-pole, two-phase PMSM terminal characteristics in stator reference frame:

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

\[ v_a = r_i_a + \frac{d\lambda_a}{dt} = r_i_a + L \frac{di_a}{dt} + \lambda_M \omega_r \cos(\theta_r) \]
\[ v_b = r_i_b + \frac{d\lambda_b}{dt} = r_i_b + L \frac{di_b}{dt} + \lambda_M \omega_r \sin(\theta_r) \]

\[ T_m = \lambda_M (i_a \cos(\theta_r) + i_b \sin(\theta_r)) \]
\[ d = \lambda_M I = \text{constant}! \]

3-Phase, 2-Pole PMSM:

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

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

\[ \tau = \frac{3}{2} I \lambda_m \]
Different Number of Poles

3-Phase, P-Pole PMSM

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

\[ T_m \leq \lambda_m \frac{P}{2} \frac{3}{2} I \]