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

10-min 8 miles

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

Dissipative braking
$P_{\text{avg}} = 11.3 \text{ kW}$
235 Wh/mile

Regenerative braking
$P_{\text{avg}} = 7.0 \text{ kW}$
146 Wh/mile

Average power and energy
ICE vs ED $\tau - \omega$

Lotus Evora 414E Hybrid

**ICE vs ED $\eta$**

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

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>
</tbody>
</table>
| Tank-to-wheel efficiency | ≈ 20%  
1.2 kWh/mile, 28 mpg             | ≈ 85%  
0.17 kWh/mile, 200 mpg equiv. |
| Energy storage         | Gasoline energy content  
12.3 kWh/kg, 36.4 kWh/gallon   | LiFePO4 battery  
0.1 kWh/kg, 0.8 kWh/gallon     |
| Refueling              | 5 gallons/minute  
11 MW, 140 miles/minute    | Level I (120Vac): 1.5 kW, <8 miles/hour  
Level II (240Vac): 6 kW, <32 miles/hour  
Level III (DC): 100 kW, <9 miles/minute |
| Cost                   | 12 ¢/mile [$3.50/gallon]          | 2 ¢/mile [$0.12/kWh]                               |
| CO₂ emissions (tailpipe, total) | ≈ (300, 350) g CO₂/mile | (0, ≈120) g CO₂/mile  
[current U.S. electricity mix] |

Energy and Power Density of Storage

![Diagram showing energy and power density of storage.](image)

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

![Graph showing energy and power density.](image)
Conventional Vs. Electric Vehicle

(Ford Focus comparison)

<table>
<thead>
<tr>
<th>Purchase Price</th>
<th>$24,495</th>
<th>$39,995</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significant Maintenance</td>
<td>$5,000 (Major Engine Repair)</td>
<td>$0 - 13,500 (Battery Pack Replacement)</td>
</tr>
<tr>
<td>Energy Costs</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 ¾ mile: (16.4 sec @ 85.4 mph)</td>
<td>123 hp, 2000-12000 rpm 0-60 mph: 9.6 sec ¾ 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>

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

- Rider input
- Pedals
- Gears
- Drive wheel
- Motor control
- Motor
- Battery charger
- Battery
- Vehicle

1/14/2016
Growing Popularity of E-bikes

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

- 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/spring2016/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: $100-150 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 Demonstrations
  - 10% of total grade
  - Questions asked to each group member
- Midterm Exam
  - 15% of total grade
  - Open book/notes, in-class
  - Covers material from experiments
- Peer Evaluation
  - 10% of total grade

- Labs will be complete in groups of 2-3
  - Choose groups by Tuesday, 1/19
  - 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

• 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
  – Feedback Loop Design
  – Layout of Power Electronics Circuits
  – Electric Motor Drivers
  – BLDC and PMSM Control Methods
  – System-Level Control Design
**System Structure**

![Diagram of system structure](image)

- Battery
- BMS
- Boost DC-DC Converter
- PWM Controller
- 3-φ Inverter / Driver
- 3-φ PWM Controller
- Motor

**Experiment 1**

- 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

**Diagram:**
- Battery
- Boost DC-DC Converter
- Motor
- Digital Controller
- Throttle
- V_out
- \( \theta_{abc} \)
**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

**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 fits under the floor of the car, weighs 544kg (1200 lb), and is estimated to cost $24,000 (2010).

**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).

**Toyota Prius HEV Battery.** The 2004 Prius included a 1.3 kWh NiMH battery consisting of 168 cells and with a $3000 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 Capacity and C-rate

- Known beforehand:
  - Nominal Capacity: 10A·hr
  - Nominal Voltage: 25.9 V
  - Maximum discharge rate: 1.9 C → 19 A
  - Maximum charge rate: 0.2 C → 2 A

In Exp 1 don't use more than 10A

Model 0: Voltage Source

[Diagram showing a model of a voltage source with a graph illustrating voltage over time and state of charge (SOC)].
**Model A: SOC and $V_{oc}$**

$V_t = \frac{1}{C_{nom}} \int i_{bat} \, dt$  \hspace{1cm} $\left[ \frac{A \cdot sec}{\text{capacity}} \right]$  

$SOC = \frac{A \cdot hr}{\text{capacity}}$  

$C_{nom} = \text{Capacity} \cdot 3600 \left( \frac{\text{sec}}{\text{hr}} \right)$

**Model B: Series Resistance**

[Diagrams and graphs showing battery models and voltage vs. current relationships]
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

[Figure showing a model with equations and components]

[Plett 2004]
Model C1 Performance

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

![Graph of Model D Performance](image)

Experimental Results

![Graph of Experimental Results](image)

Implementation in LTSpice

PM Motor Operation
Magnetic Circuit

Assume:
1. Field is uniform inside material
2. No field outside material except air gap & no fringing
3. Material is linear & no hysteresis

\[ B = \mu H \]

Ampere's law:
\[ \nabla \cdot \mathbf{B} = \mu \nabla \cdot \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J} \]

Faraday's law:
\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{D}}{\partial t} - \nabla \times \mathbf{J} \]

\[ N_a = N A_c \frac{d}{dt} \left( \frac{N \Delta a}{\mu} + \frac{\Delta a}{\mu_0} \right) = \frac{N^2 A_c}{\mu} \frac{d}{dt} \left( \frac{1}{L} + \frac{1}{L_0} \right) \]

Equivalent Circuit

\[ L = \frac{N^2 A_c}{\mu} \frac{1}{\frac{1}{L} + \frac{1}{L_0}} \]

\[ R_L = \rho \frac{N \cdot \Delta L}{A_w} \]
Single Phase Motor (Simplified)

Assume:
- Magnet generates a constant flux $\Phi_m$
- $e_x = N \frac{d\Phi_m}{dt}$ from magnet
- $e_x = N \frac{d\Phi_m}{dt} \cdot f(\theta_r)$
- $N \Phi_m \equiv \lambda_m$ "flux linkage"
- Guess: $f(\theta_r) = \sin(\theta_r)$

Winding Voltage Equation

$e_x = \lambda_m \frac{d}{dt} \sin \theta_r$

$e_x = \lambda_m \cos \theta_r \frac{d\theta_r}{dt}$

$\omega_r \rightarrow$ angular speed

$e_x = \lambda_m \omega_r \cos \theta_r$
Electromechanical Conversion

Power into "A" winding

\[ P = v_a i_a = i_a \frac{dL}{dt} + i_a^2 R + i_a \lambda_a \omega \cos \theta_r \]

\[ \text{AC reactive power} \]
\[ \text{Reactive loss} \]
\[ \text{Power transferred to mechanical} \]

Mechanical Power

\[ P_{mech} = J \frac{d\omega}{dt} = i_a \lambda_a \omega \cos \theta_r \]

\[ \tau = \frac{\omega}{\omega_r} \]

\[ \tau = \lambda_a i_a \cos \theta_r \]

2-Pole, 2-Phase PMSM

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

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

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

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

\[ \text{If } i_a = I_a \cos \theta_r, \quad i_b = I_b \sin \theta_r \]
\[ T_m = \lambda_M I_a I_b (\cos^2 \theta_r + \sin^2 \theta_r) \]
3-Phase, 2-Pole PMSM

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

If $i_a, i_b, i_c$ are out of phase

$$T_m = \frac{3}{2} \text{Ip} \lambda_m$$

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

Different Number of Poles

\[ N_p \]

\[ v_c \]

\[ \Omega_r = \frac{p}{2} \omega_m \]
3-Phase, P-Pole PMSM

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

Electrical and mechanical angle

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

Electrical and mechanical speed

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

Max torque per amp:

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