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

10-min 8 miles

**Prius-sized vehicle**

Dissipative braking

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

235 Wh/mile

Regenerative braking

$P_{\text{avg}} = 7.0$ 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

Internal Combustion Engine (ICE)

Electric Drive (ED)
## 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>≈ 20%</td>
<td>≈ 85%</td>
</tr>
<tr>
<td>1.2 kWh/mile, 28 mpg</td>
<td>0.17 kWh/mile, 200 mpg equiv.</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>12 ¢/mile [$3.50/gallon]</td>
<td>2 ¢/mile [$0.12/kWh]</td>
</tr>
<tr>
<td>CO₂ emissions (tailpipe, total)</td>
<td>≈ (300, 350) g CO₂/mile</td>
<td>(0, ≈120) g CO₂/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

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

![Energy and Power Density of Storage Graph](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>Purchase Price</td>
<td>$24,495</td>
<td>$39,995</td>
</tr>
<tr>
<td>Significant</td>
<td>$5,000 (Major Engine Repair)</td>
<td>$13,500 (Battery Pack Replacement)</td>
</tr>
<tr>
<td>Maintenance</td>
<td></td>
<td></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
- **2022 Electric Drive System**: $8/kW, 1.4 kW/kg, 4.0 kW/L, 94% system efficiency

**Today**
- $12/kW
- 1.2 kW/kg
- 3.5 kW/L
- >93% efficiency
Power Electronics in Electric Vehicles

BEV Architecture

Example: Tesla Roadster
- 215 kW electric drive ED1 (sport model)
- 53 kWh Li-ion battery
Series HEV Architecture

In a PHEV, a (larger) battery can be charged from the electric power grid.

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

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
  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

• Labs will be complete in groups of 2-3
  • Choose groups by Tuesday, 1/15
• Late work will not be accepted except in cases of documented emergencies
• Due dates posted on website course schedule
• All assignments turned in via Canvas

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
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 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:**

  - Capacity $C$ [Ah]
  - Nominal voltage $V_{nom}$ [V]
  - Max Charge Rate
  - Max Discharge Rate

  Specified as $\frac{C}{10}$ hr

  Example:
  - Max Charge = 1C
    - for 10Ah cell $\Rightarrow$ 10A max charge
  - Max discharge = 5C
    - for 10Ah battery $\Rightarrow$ 50A

---

Example Battery

\[ 7s_5p \rightarrow 7 \text{ cells in series, 5 in parallel} \]

\[ \text{Ex: cells:} \quad \begin{cases} V_{\text{nom}} = 3.4\, \text{V}, & C = 2\, \text{Ah} \\ \text{max charge} = 0.2\, C \\ \text{max discharge} = 1.9\, C \end{cases} \]

\[ \text{Poth:} \quad \begin{cases} V_{\text{nom}} = 2\, \text{V}, & C = 10\, \text{Ah} \\ \text{max charge} = 1\, C \\ \text{max discharge} = 10\, C \end{cases} \]

Model 0: Voltage Source

![Diagram of circuit model](image)

\[ V_{\text{batt}}(t) \quad \text{and} \quad V_{\text{model}}(t) \]
Model A: SOC and $V_{oc}$

\[ V_c = V_{zd} - \frac{1}{C_{nom}} \int i_{bat} \, dt \]

if \( I \) set 
\[ C_{nom} = C \times 3600 \]

Model B: Series Resistance

\begin{verbatim}
.tran 36000
.param Idis = 1
.step param Idis 1 10 1
.end
\end{verbatim}
Model B: Series Resistance

\[ i_{bat} \quad V_z \quad C_{nom} \]

\[ i_{bat} \quad V_{OC}(V_z) \quad v_{bat} \]

\[ R^+ \quad R^- \]

\[ R_x \leq \min(R^+, R^-) \]
Model B Performance

[Graph showing voltage characteristics]

Model C: Zero-state Hysteresis

\[ v_h = \begin{cases} 
V_H^+ & \text{if } i_{bat} > 0 \\
V_H^- & \text{if } i_{bat} < 0 
\end{cases} \]

[Plett 2004]
Model C Performance

![Graph showing voltage performance over time for Model C. The graph compares the actual battery voltage (V(batt)) with the model prediction (V(model)). The x-axis represents time in 60-second intervals, while the y-axis shows voltage levels.]
Dynamic Performance

- Dynamic performance characterized by pulse train
- Constant percent of capacity per pulse [%Ahr] → not necessary

Dynamic Performance

Discharge

Charge
Model C1: One-state Hysteresis

[Model diagram with mathematical equations and components]

Model C1 Performance

[Graph showing comparison between V(batt) and V(model) over time, with notes on dynamics of hysteresis]
Model C1 Performance

Model D: Diffusion (one-state)

[Plott 2004]
Model D Performance

Diffusion Vs Hysteresis
Experimental Results

[Image 89x431 to 502x726]

Implementation in LTSpice

```
.param R1 = 1m C1 = 10n
.param VSOC0 = .5
.param Cnom = 10

.b1 SOC
.I=I(B2)/3600
.jc V(SOC) = VSOC0

.b2 V=B3(1+R1/C1)
.V = VsocTable(V(SOC)+7)

.b3
.model bmdatodiode D(n=0.01)
.param Rop = 1m Ron = 1m

.b4
.Laplace = 1/(1+Th+s)
.V = Vh*(IF(I(B2)<.1, 1, IF(I(B2)>.1, -1, 0)))

.func VsocTable(x) = {table(x,0,3.0021, 0.01, 3.108, 0.02, 3.191, 0.03, 3.257, 0.04, 3.308, 0.05, 3.3...}
```

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

\[ V_x = n \frac{d}{dt} \Phi_m \sin(\theta_r(t)) \]

\[ \lambda_m \text{ "flux linkage"} \]

\[ V_x = \lambda_m \cos(\theta_r(t)) \frac{d\theta_r(t)}{dt} \]

\[ V_x = \lambda_m \omega_r \cos(\theta_r) \]

Look at power

\[ P_a = i_a v_a \]

\[ P_a = i_a^2 R_w + i_a \frac{di_a}{dt} + i_a \lambda_m \omega_r \cos \theta_r \]

\[ \text{Power loss} \]

\[ \text{Power output} \]

\[ P_{\text{mech}} = T_m \omega_r \]

\[ T_m = i_a \lambda_m \cos \theta_r \]

\[ \text{Mechanical torque} \]

\[ \text{Converted to mechanical power} \]

\[ \text{Neglect friction/dynamics in this analysis} \]
Alternative Diagram

2-Pole, 2-Phase PMSM

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

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

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

If \( i_a = I_x \cos(\theta_r) \) and \( i_b = I_x \sin(\theta_r) \), implies that currents need to be controlled to synchronize motor.
3-Phase, 2-Pole PMSM

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

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

Different Number of Poles
3-Phase, P-Pole PMSM

$P = 4$ 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

Example Front Wheel Hub Motor

E-bike hub (stator)

Single phase wound per tooth
Stator Winding

Complete winding of Phase A

Complete winding of all phases

56 pole
63 teeth

Rotor and Poles

- Outer rotor (to which spokes/wheel are attached)
- Magnets alternate N-S

www.leafmotor.com