Power Electronic Circuits

Prof. Daniel Costinett

ECE 482 Lecture 1
January 8, 2014

- New course in design an implementation of power converters
  - Course website: http://web.eecs.utk.edu/courses/spring2014/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 with relatively little new theory
- Goal of course is practical experience in designing, building, testing, and debugging power electronics; system, components, architectures can be modified based on student initiative
- Prerequisites: undergraduate Circuits sequence, Microelectronics, ECE 481 – Power Electronics

Instructor: Daniel Costinett

- Office: MK502
- OH during canceled lectures, in-lab
- 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 three 1-hr lectures and one 1-hr lab session per week
- Theory is presented as necessary for practical design
- Plan to spend ~10 hours per week on course; mostly lab time
- Lectures will only be used as needed – when no theory/review is necessary, lectures will give way to additional lab time
  - Check course website often for cancelled lectures
- Additional theory may be presented in brief sessions during 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, 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

Assignments

- Labs will be complete in groups of 2-3
- Lab Reports and Demonstrations (~7 labs total): 50% of total grade
  - Turn in one lab writeup *per group*
- Demonstrations each lab session: 10% of grade
  - Show functionality/progress and demonstrate understanding
- Pre-labs completed prior to starting each experiment: 20% of grade
  - Turn in one pre-lab assignment *per person*
- Midterm exam (open book/notes, in-class), 20% of the grade
- 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 (Wed, 9:05-11:55)
  - 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
- Build in stages; test one stage at a time
- Outside of normal lab hours, key access will be granted 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

Transportation Electrification

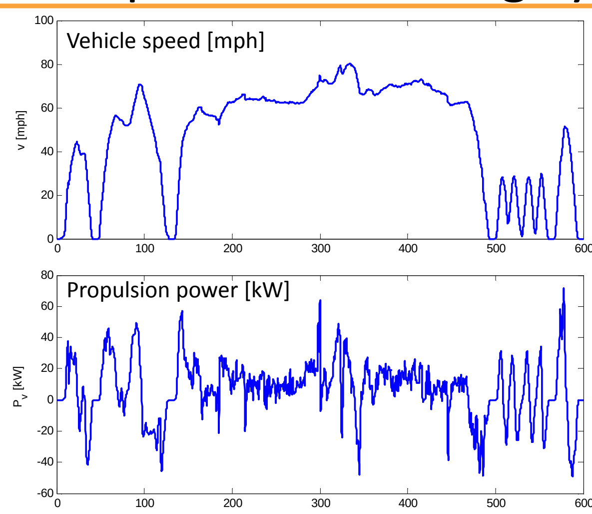
Motivation

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

EIA:

- Transportation accounts for 28% of total U.S. energy use
- Transportation accounts for 33% of CO_2 emissions
- Petroleum comprises 93% of US transportation energy use

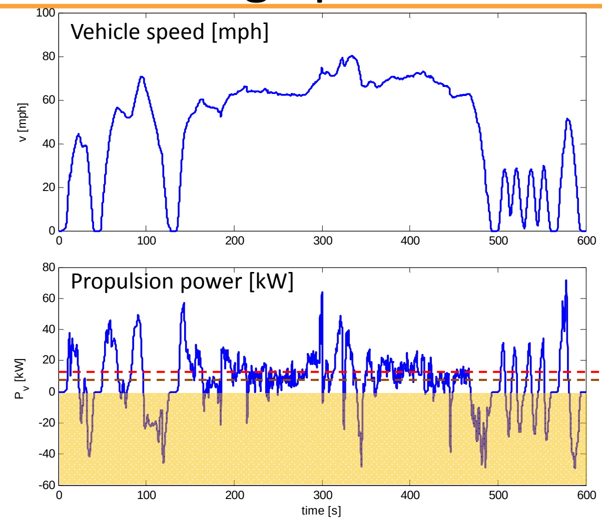
Example: US06 driving cycle



10-min
8 miles

Example:
Prius-sized vehicle

Average power and energy



Prius-sized vehicle example

Dissipative braking

P_{vavg} = 11.3 kW

235 Wh/mile

Regenerative braking

P_{vavg} = 7.0 kW

146 Wh/mile

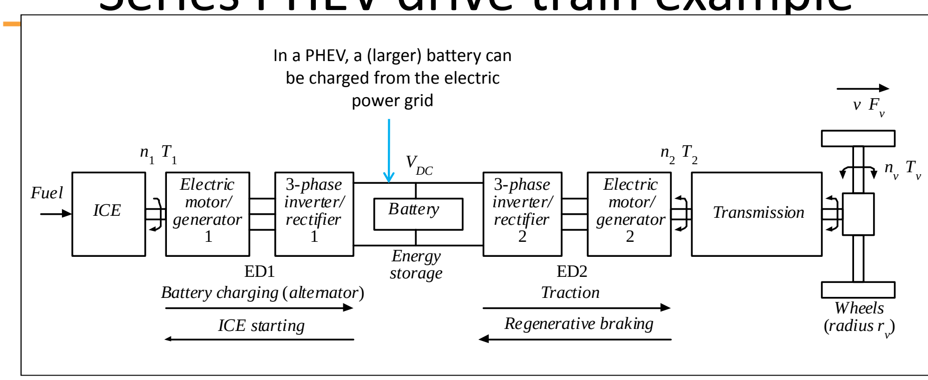
Conventional Vs. Electric Vehicle

	Tank + Internal Combustion Engine	Electric Vehicle (EV) Battery + Inverter + AC machine
Regenerative braking	NO	YES
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**	$LiFePO_4$ 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]
CO_2 emissions (tailpipe, total)	≈ (300, 350) g CO_2/mile	(0, ≈120) g CO_2/mile [current U.S. electricity mix]

Electric-Drive Vehicle Technologies

- **Hybrid Electric Vehicle (HEV)**
  - Combination of a gasoline-powered ICE and electric drive with a relatively small battery
  - HEV efficiency improvements
    - Regenerative braking
    - "Downsizing:" a smaller, more efficient ICE
    - ICE operated around the most efficient operating point, not directly tied to the required drive power & speed
    - No idling required when the vehicle stops, keep ICE off
- **Plug-In Hybrid Electric Vehicle (PHEV)**
  - Same efficiency improvements as HEV
  - Larger battery for an all-electric range
- **Electric Vehicle (EV)**
  - No ICE, (much) larger battery

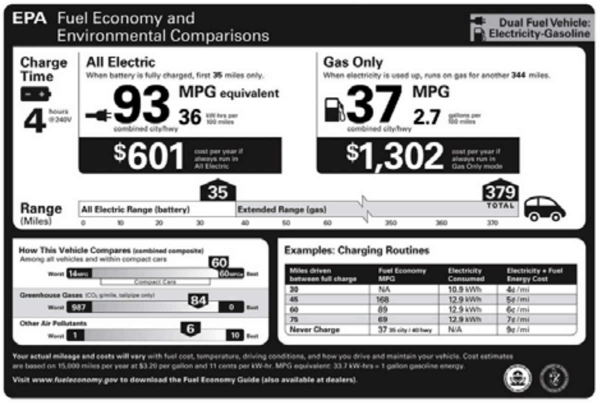
Series PHEV drive train example



- 62 kW (83 hp, 1.4 L) ICE
- 55 kW electric drive ED1
- 111 kW (149 hp) electric drive ED2
- 16 kWh Li-Ion battery pack (175 kg), 65% (10.5 kWh) usable, (approximately) 40 miles of EV range (0.26 kWh/mile)
- 37 mpg (hybrid), 99 mpg equivalent (electric)

Example: Chevy Volt, a PHEV

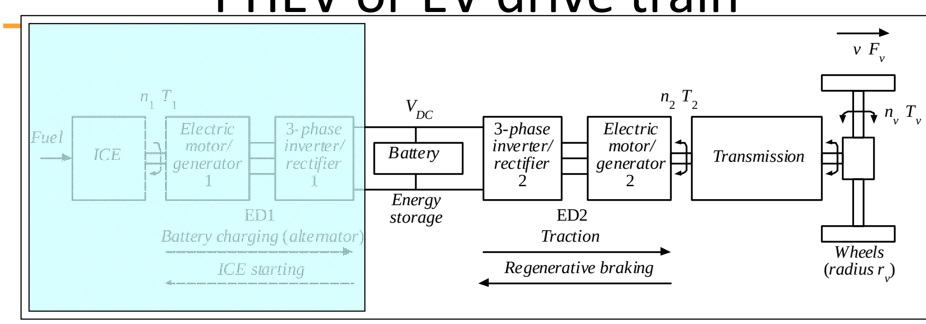
New EPA stickers: PHEV example



Chevy Volt

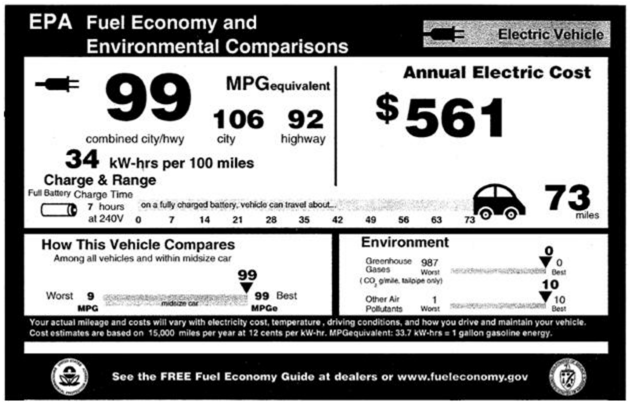
1720 kg
110 kW (149 hp) electric drive
62 kW (83 hp) ICE
16 kWh Li-Ion battery
175 kg battery pack
(8 years, 100,000 miles warranty)

PHEV or EV drive train



- Plug-in hybrid electric vehicle (PHEVX) has a driving range (X miles) as electric vehicle powered by batteries only (EV mode)
  - Example: Chevy Volt is a PHEV40, with a 16 kWh battery, 65% (10.5 kWh) usable, and (approximately) 40 miles of EV range (0.26 kWh/mile)
- Electric vehicle (EV), or Battery Electric Vehicle (BEV) does not include ICE at all
  - Example: Tesla Roadster has about 250 miles (400 km) EV range, with about 50 kWh battery, 75% (37.5 kWh) usable (0.15 kWh/mile)

New EPA stickers: EV example



Nissan Leaf

1527 kg
80 kW (110 hp) electric drive
24 kWh Li-Ion battery
- Cells: 140 Wh/kg
- 300 kg battery pack
- (8 years, 100,000 miles warranty)

EPA miles-per-gallon-equivalent calculation

$$MPG_{equivalent} = \frac{\text{Trip length [miles]}}{\text{Total energy consumed [kWh]}} \times 33.7 \text{ kWh/gallon}$$

CO_2 emissions

http://www.epa.gov/cleanenergy/energy-resources/calculator.html

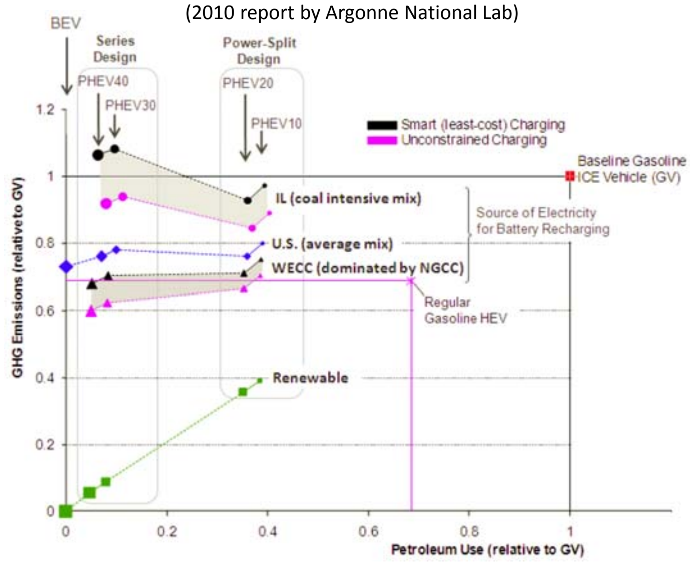
Gasoline CO_2 emissions (tailpipe only)
8.89×10^{-3} metric tons CO_2/gallon of gasoline = **8892 g CO_2 / gallon** = **264 g CO_2/kWh**

CO_2 emissions from electricity generation (average over year, average over US)
7.18 x 10^{-4} metric tons CO_2 / kWh = **718 g CO_2 / kWh**
(eGRID2007 Version 1.1, U.S. annual non-baseload CO_2 output emission rate, year 2005 data)

	Conv. Gasoline V.		HEV	EV (zero tailpipe)		
MPGequiv.	20	30	50	99	135	225
kWh/mile	1.685	1.123	0.674	0.340	0.250	0.150
g CO2/mile	445	296	178	244	179	108

CO_2 emissions and oil displacement study

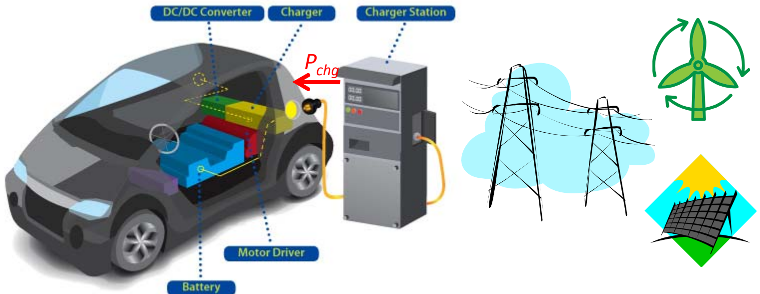
Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of PHEVs
(2010 report by Argonne National Lab)



Trends and Challenges

- Paths to electrified (personal) transportation
  - Hybrid electric vehicles
  - Plug-in hybrid electric vehicles
  - Battery electric vehicles
  - Hydrogen + fuel cell electric vehicles
- Electricity generation mix: shift to renewables
- Challenges
  - Batteries
  - Engineering of electric drivetrain components, including efficient, high-density, reliable power electronics
  - Charging infrastructure

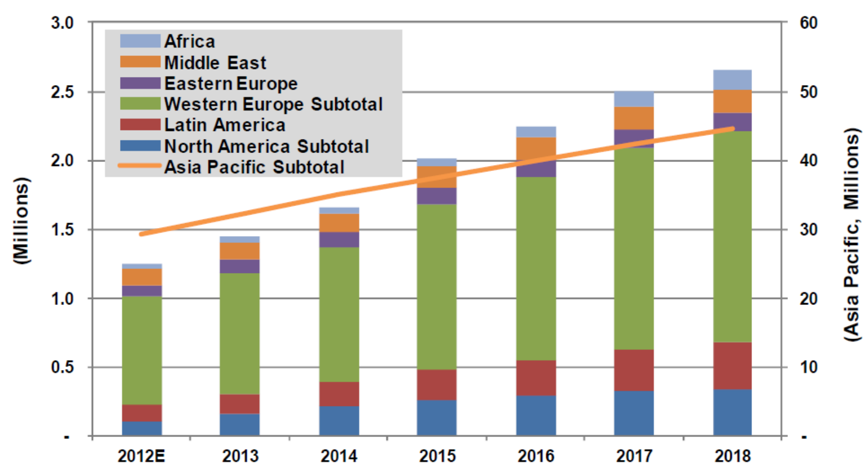
Vision: Renewable Sources + Battery Electric Vehicles



- Zero GHG emissions, zero-oil
- High efficiencies are feasible: 80% grid-to-wheel
- Challenges
  - Battery technology: cost, cycle life, power and energy density
  - Need for charging infrastructure
  - Limited P_{chg}, long charge-up times
    - At the gasoline pump: 10 gallons in 2 minutes, effective P_{chg} = 10 MW
    - Fastest electric chargers envisioned: P_{chg}: 0.1-0.2 MW

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