Power Electronic Circuits

Prof. Daniel Costinett

ECE 482 Lecture 1
January 8, 2015

- New course in design an implementation of power converters
  - Course website: http://web.eecs.utk.edu/courses/spring2015/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 one lecture and one 3-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*
  - Submit electronically via e-mail to Daniel.Costinett@utk.edu
- Demonstrations each lab session: 10% of grade
  - Show functionality/progress and demonstrate understanding
  - Questions asked to each individual group member
- 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
  - 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

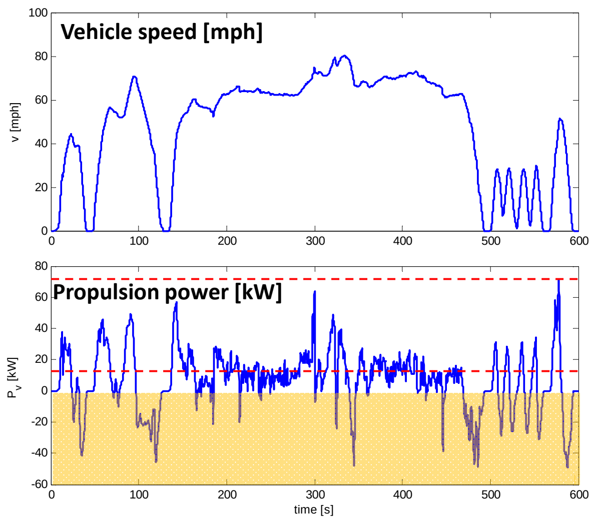
Motivation

- 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

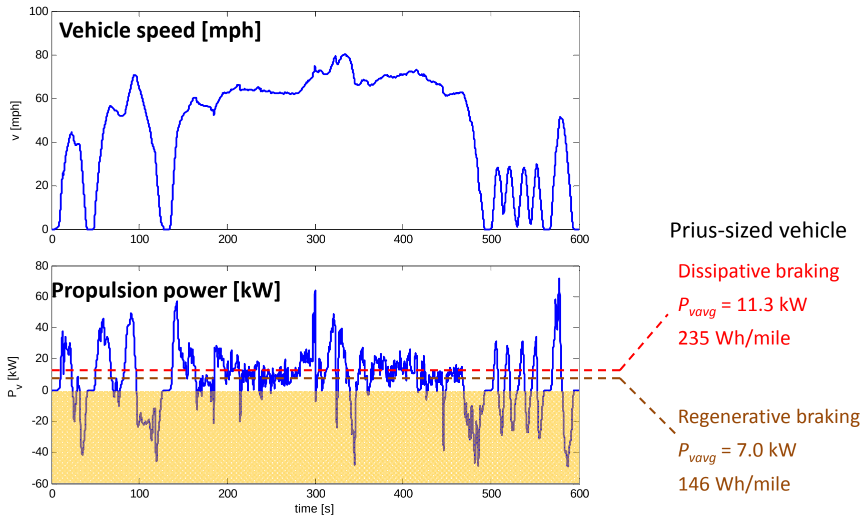
Example: US06 driving cycle



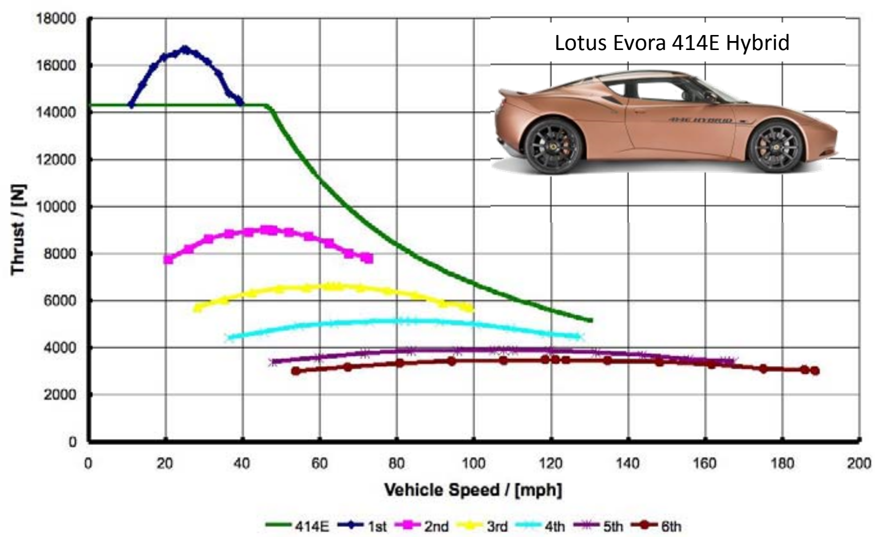
10-min
8 miles

Example:
Prius-sized
vehicle

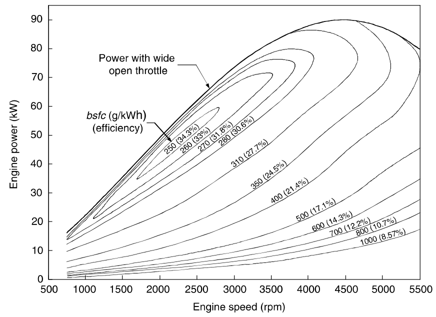
Average power and energy



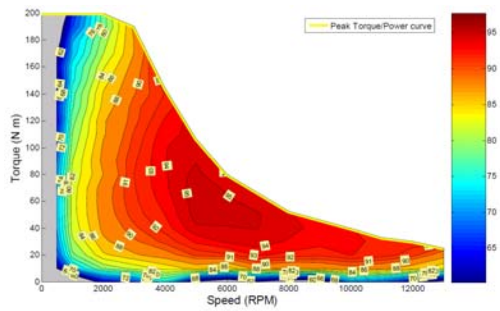
ICE vs ED τ–ω



ICE vs. ED η



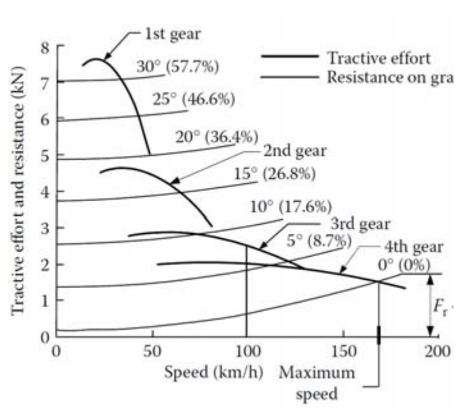
Internal Combustion Engine (ICE)



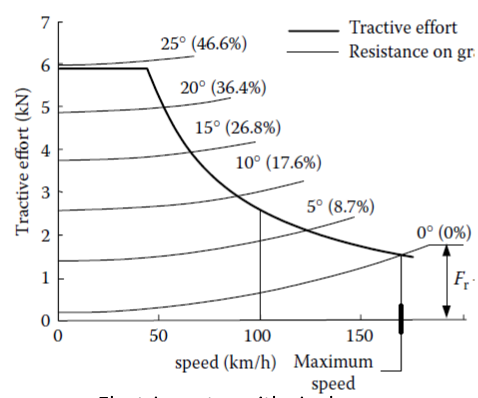
Electric Drive (ED)

- ED offers full torque at zero speed
- $\eta_{ED,pk} \approx 95\%$; $\eta_{ICE,pk} \approx 35\%$

Transmissions in Conventional Vehicles



ICE with multi-gear transmission



Electric motor with single gear

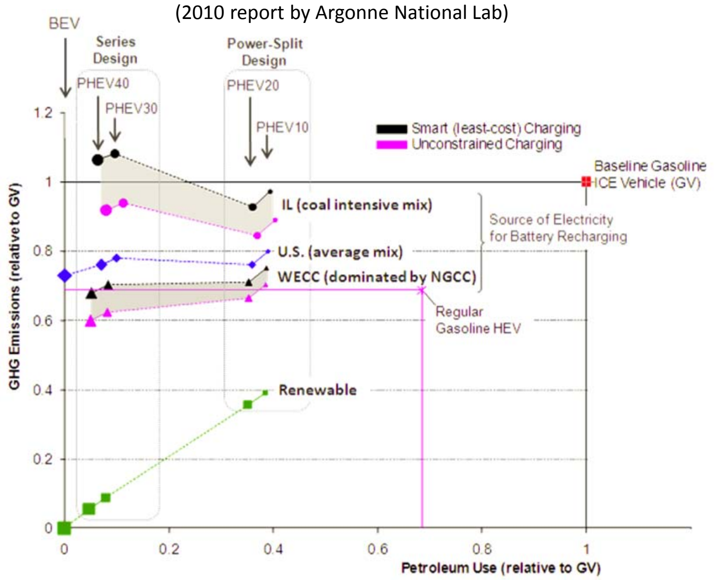
Conventional Vs. Electric Vehicle

(Prius-sized vehicle example)

	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]

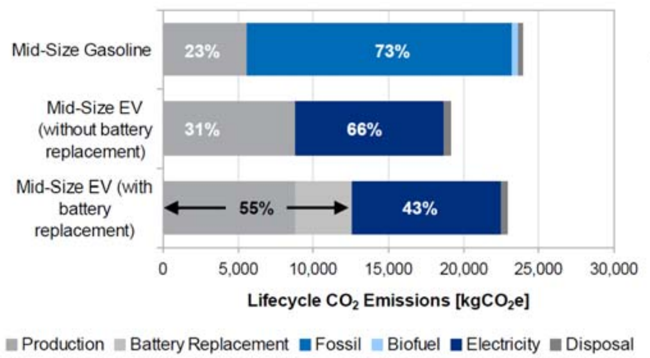
CO_2 emissions and oil displacement study

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



CO_2 emissions Over Full Lifetime

Preparing for a Life Cycle CO_2 Measure (2011 report by Ricardo)

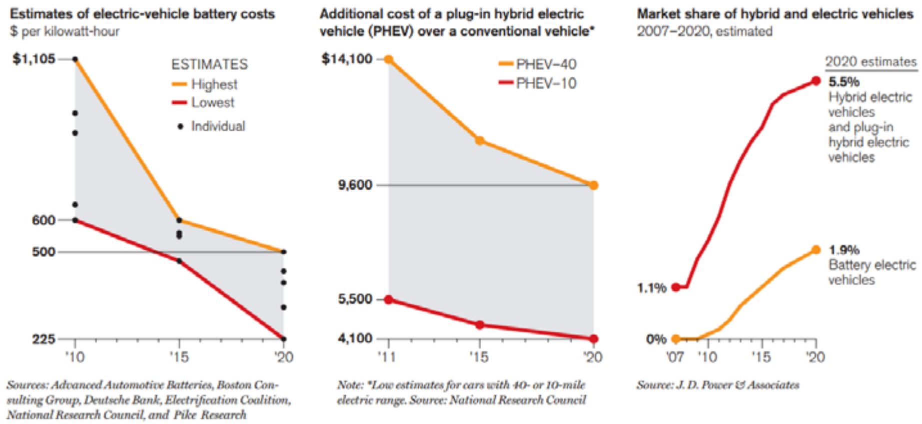


Conventional Vs. Electric Vehicle

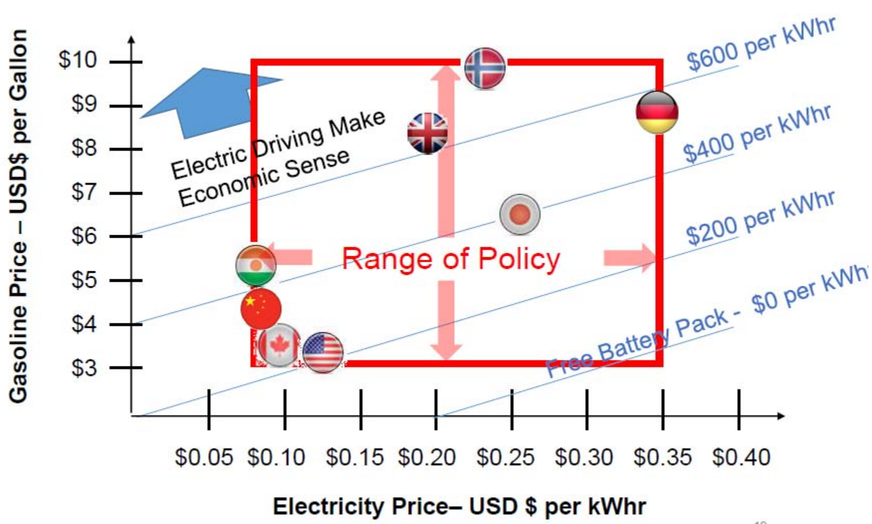
(Ford Focus comparison)

	Tank + Internal Combustion Engine (Ford Focus ST)	Electric Vehicle (EV) Battery + Inverter + AC machine (Ford Focus Electric)
Purchase Price	$24,495	$39,995
Significant Maintenance	$5,000 (Major Engine Repair)	$0 - 13,500 (Battery Pack Replacement)
Energy Costs (10-year, 15k mi/yr)	$18,000	$3,000
Range	> 350 mi	< 100 mi
Performance	160 hp @ 6500 rpm 0-60 mph : 8.7 sec ¼ mile: (16.4 sec @ 85.4 mph)	123 hp, 2000-12000 rpm 0-60 mph: 9.6 sec ¼ mile: (17.2 sec @ 82.1 mph)
Curb Weight	3,000 lb	3,700 lb

The Price of Batteries



The Impact of Policy

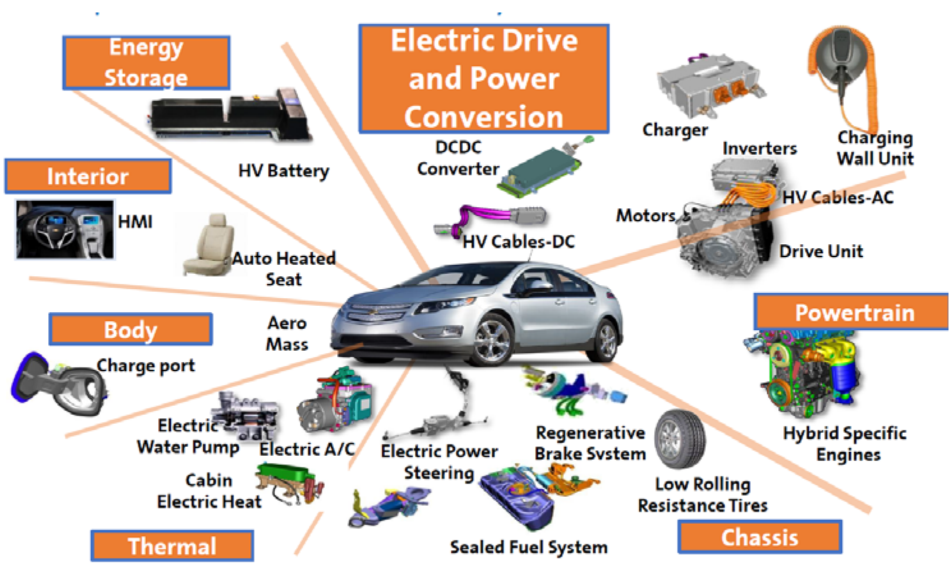


Peter Savagian, "Barriers to the Electrification of the Automobile," Plenary session, ECCE 2014

A Vision: Renewable Sources + Battery Electric Vehicles

- Zero GHG emissions, no petroleum
- High efficiencies are feasible: 80% grid-to-wheel
- Challenges
  - Battery technology: cost, cycle life, power and energy density
  - Efficient, reliably and cost-effective drivetrain components
  - Need for charging infrastructure
  - Limited charging power, long charge-up times

Power Electronics in Electric Vehicles



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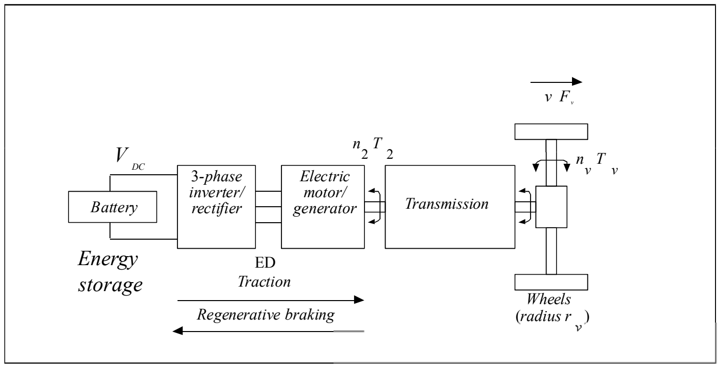
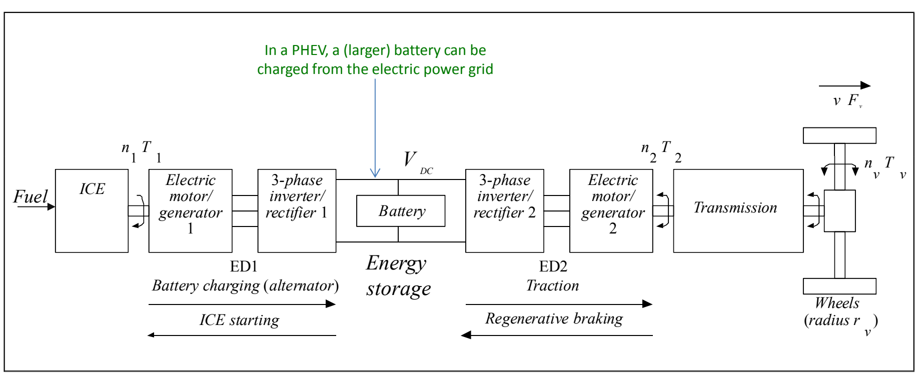
BEV Architecture



Example: Tesla Roadster

- 215 kW electric drive ED1 (sport model)
- 53 kWh Li-ion battery

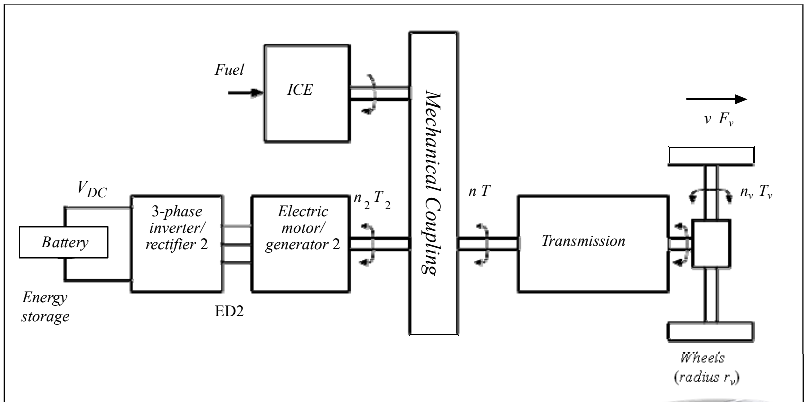
Series HEV Architecture



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

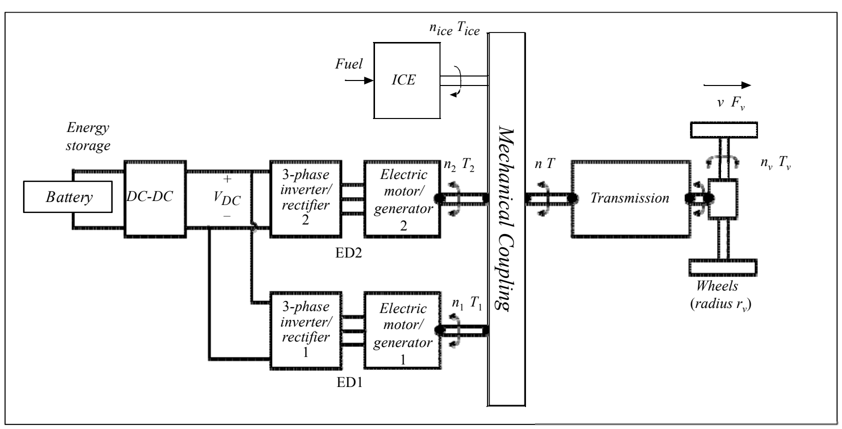
Parallel HEV



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

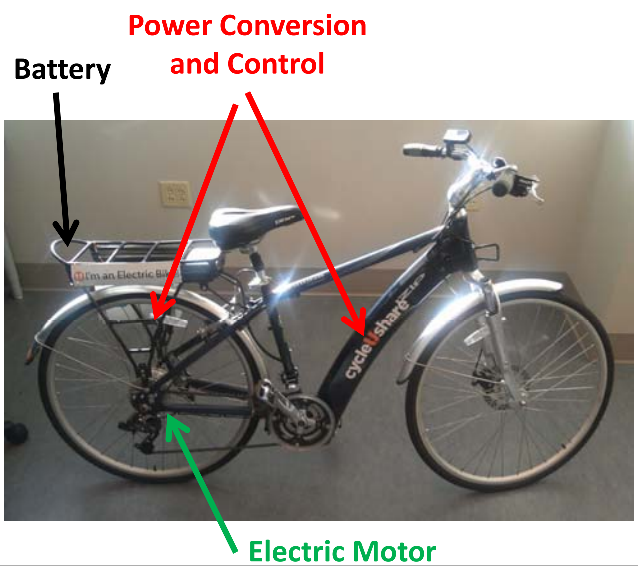
Series/Parallel HEV



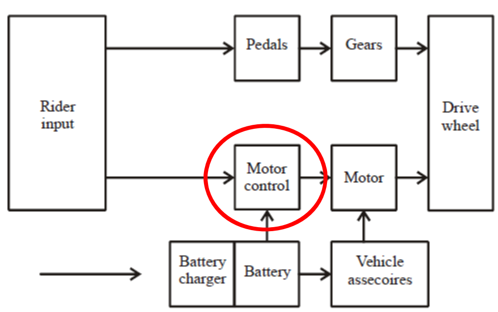
Example: 2010 Prius HEV with a drive-train based on the series/parallel architecture :

- 73 kW (98 hp, 1.8 L) ICE
- 60 kW electric drive ED2
  - 100 kW total power
  - 42 kW (149 hp) electric drive ED1

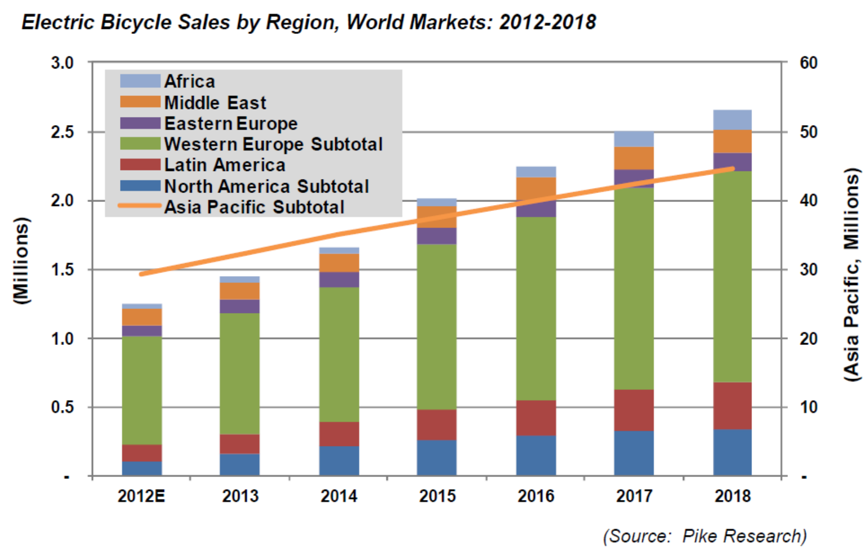
Electric Bicycle Platform



Electric Bicycle System



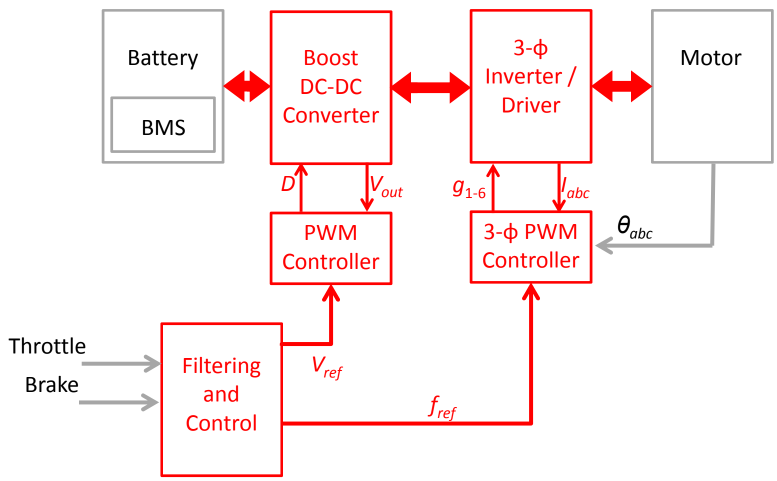
Growing Popularity of E-bikes



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

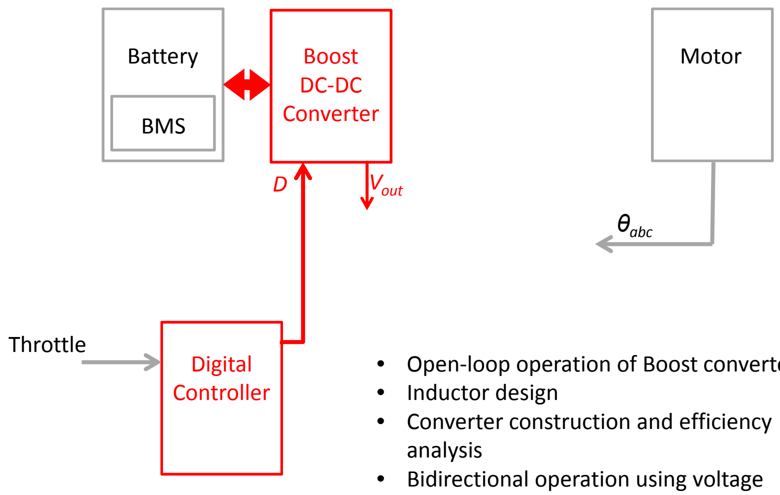
System Structure



Experiment 1

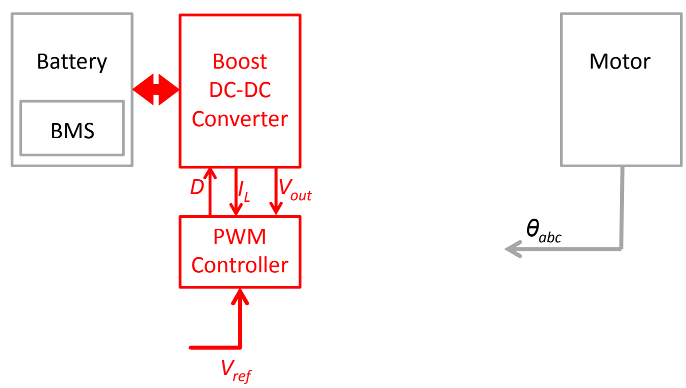
- Identification and characterization of motor
- Modeling of motor using simulink
- Derivation of model parameters from experimental data

Experiment 2-3



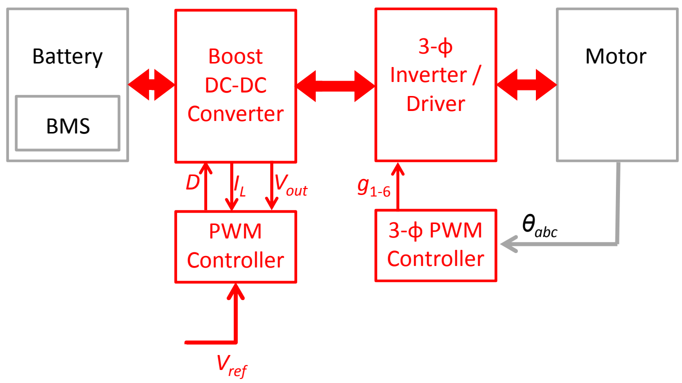
- Open-loop operation of Boost converter
- Inductor design
- Converter construction and efficiency analysis
- Bidirectional operation using voltage source / resistive load

Experiment 4



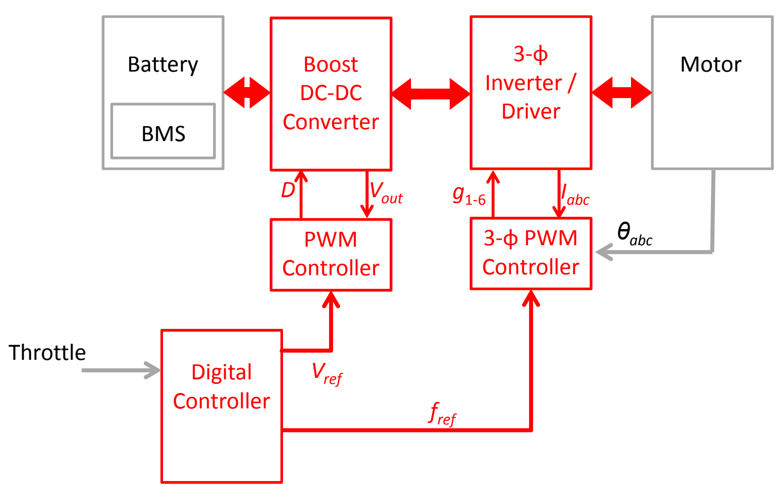
- Closed loop operation of boost converter
- Feedback loop design and stability analysis
- Analog control of PWM converters

Experiment 5



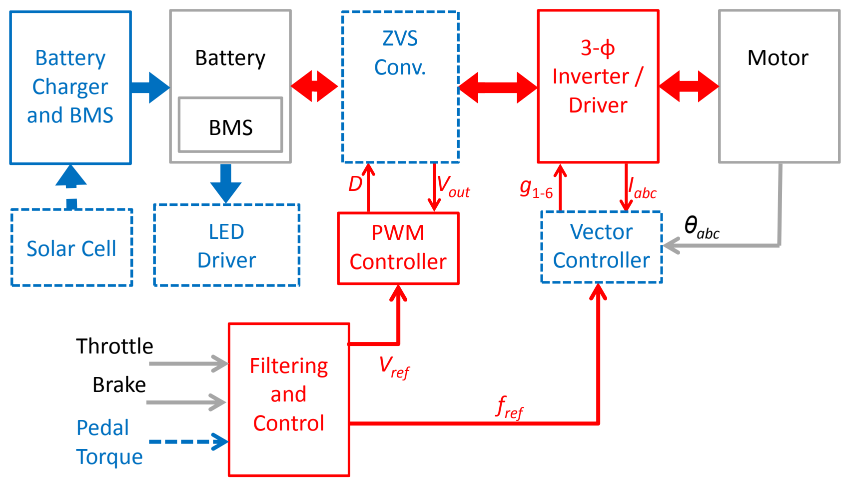
- Circuit layout and PCB design
- Device selection and implementation according to loss analysis
- Basic control of BLDC motors

Experiment 6



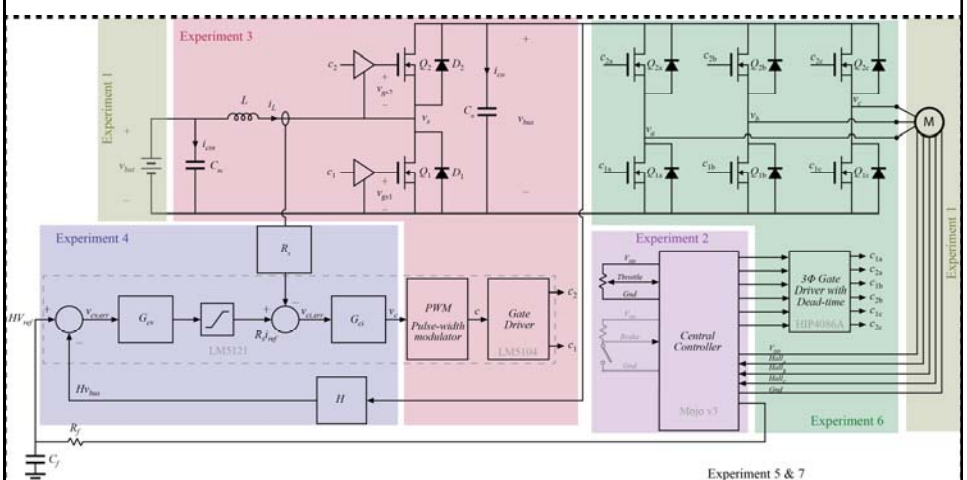
- System-level control techniques

Experiment 7



- System improvements

Example System Implementation



Design Expo

- No final exam
- Demo operational electric bicycles with system improvements
- Competition to determine the most efficient and well-controlled 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
- Use caution at all times