Power Electronic Circuits

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ECE 482 Lecture 2
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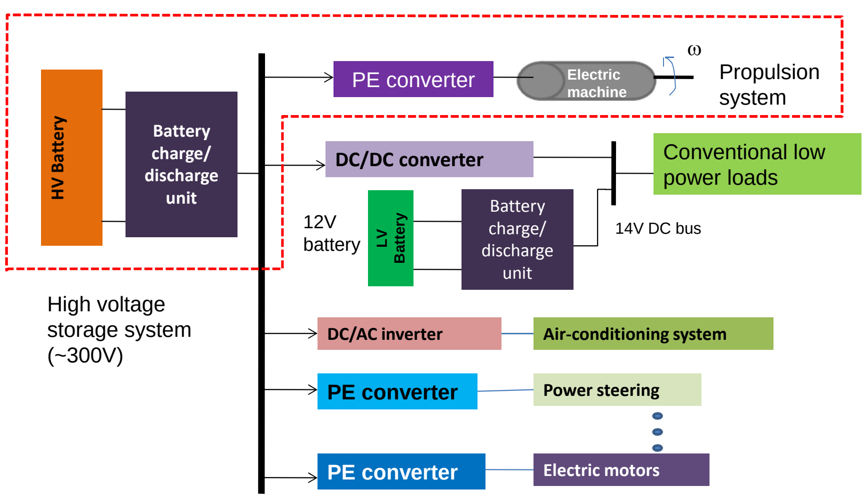
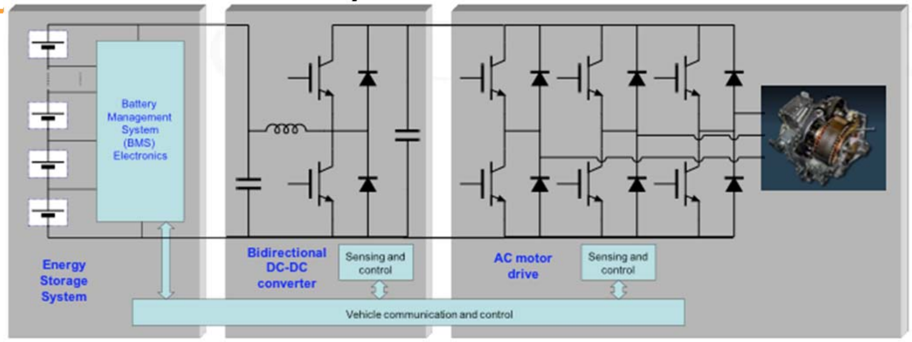
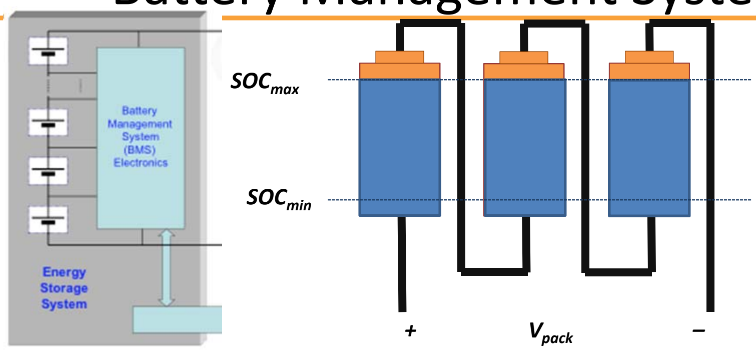
Power Electronics in EVs



PHEV/EV Drivetrain

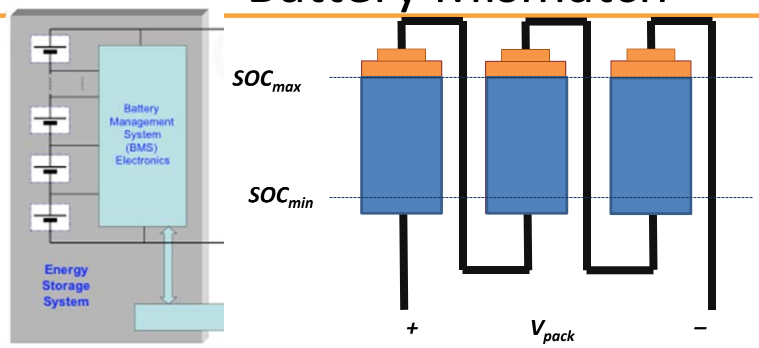


Battery Management System



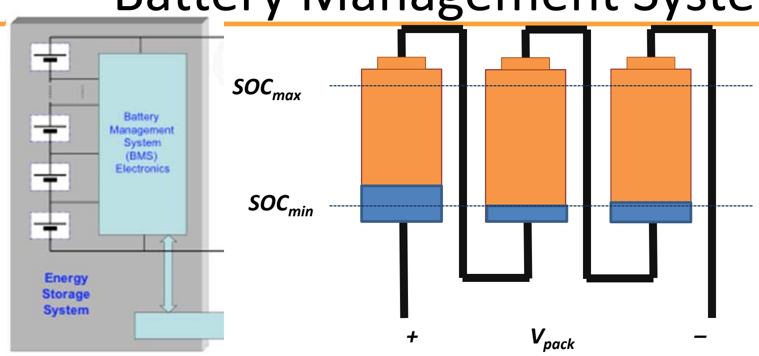
- BMS monitors batteries to ensure operation within safe limits of
  - Charge/discharge current
  - State-of-Charge (SOC)
  - (Temperature, SOH, …)

Battery Mismatch



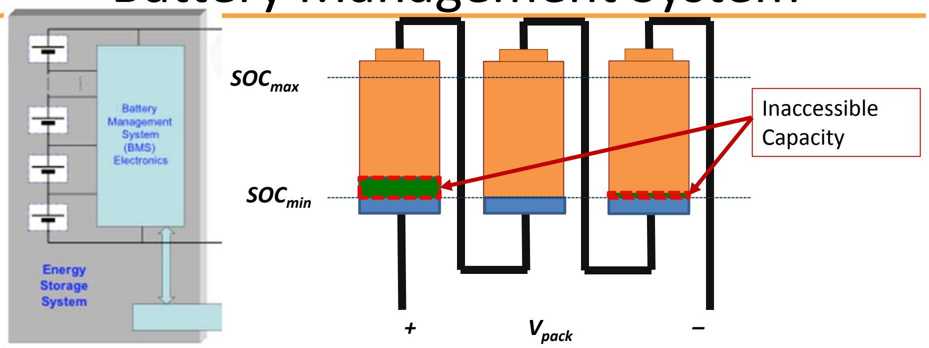
- EV battery consists of many (100's) series battery cells (LFP, Li-ion, NiMH)
- Cells share a charging and discharging current, but may have mismatches in series resistance, capacity, operating temperature, health, or dynamics
- Cells binned by manufacturer to limit mismatch at beginning-of-life

Battery Management System



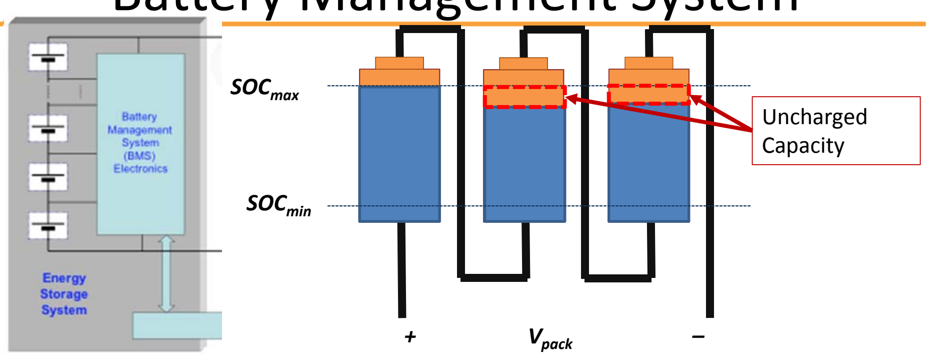
- Discharge is limited by the first cell to reach the minimum allowable State-of-Charge (SOC).

Battery Management System



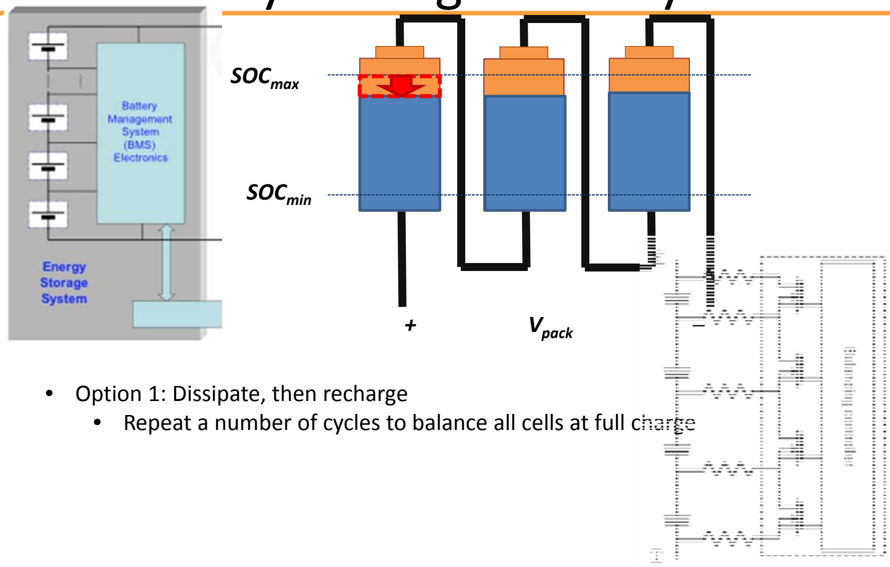
- Discharge is limited by the first cell to reach the minimum allowable State-of-Charge (SOC).
- Effective pack capacity limited to the capacity of the lowest cell (in Amp-hours)

Battery Management System



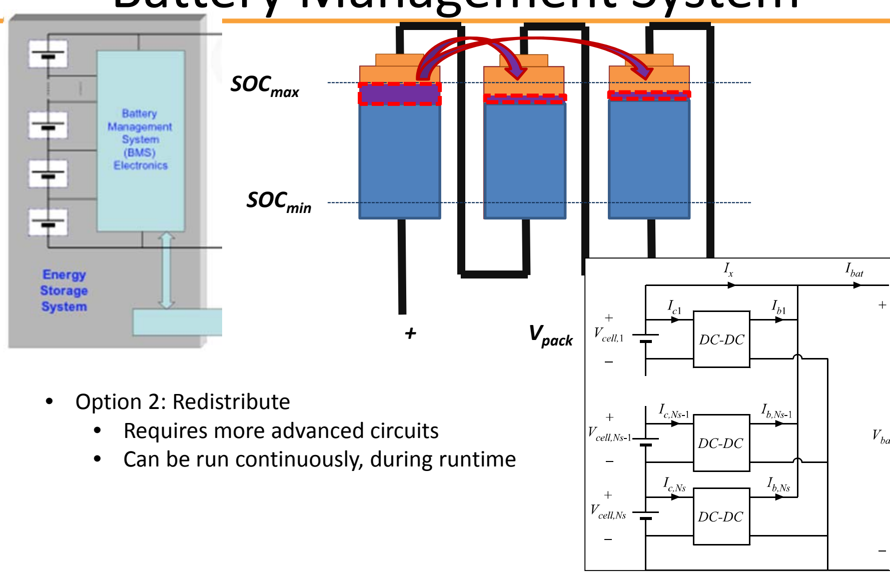
- When recharged, charging is stopped when the first cell reaches maximum capacity, leading to incomplete charging of some cells and lower total pack capacity

Battery Management System



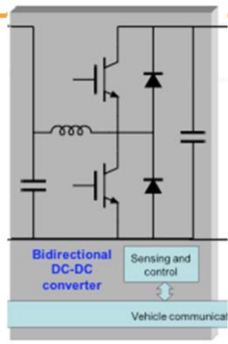
- Option 1: Dissipate, then recharge
  - Repeat a number of cycles to balance all cells at full charge

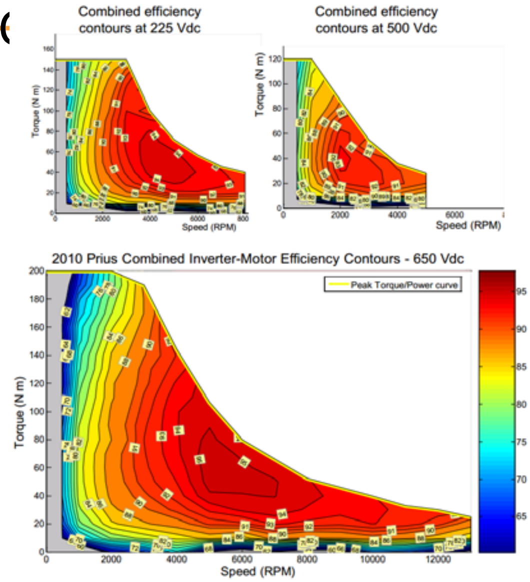
Battery Management System



- Option 2: Redistribute
  - Requires more advanced circuits
  - Can be run continuously, during runtime

(Optional) Bidirectional DC-DC

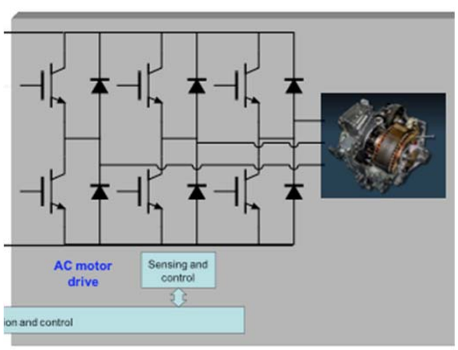


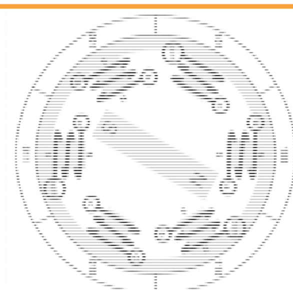


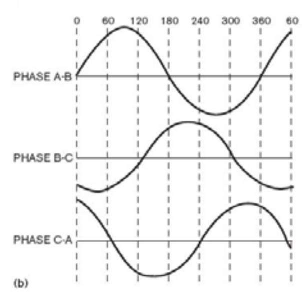
- A DC-DC converter to boost battery voltage is included in many EVs
  - Allows higher η operation of ED
  - Wider operating range
  - Lower pack voltage

Reference: Oak Ridge National Lab, "Benchmarking of Competitive Technologies"

DC-AC Motor Drive

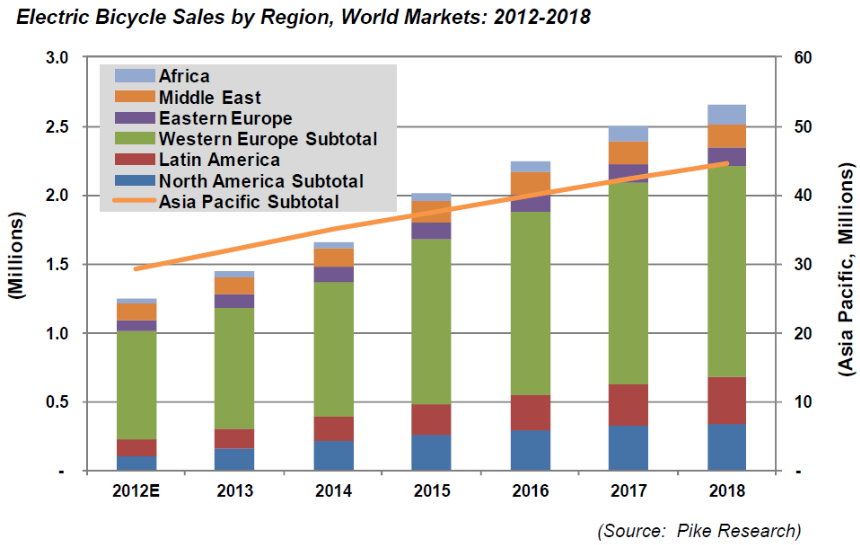






- Motor drive generates three, 120° out of phase signals to drive motor windings
- Individually operate as three individual electronic power converters

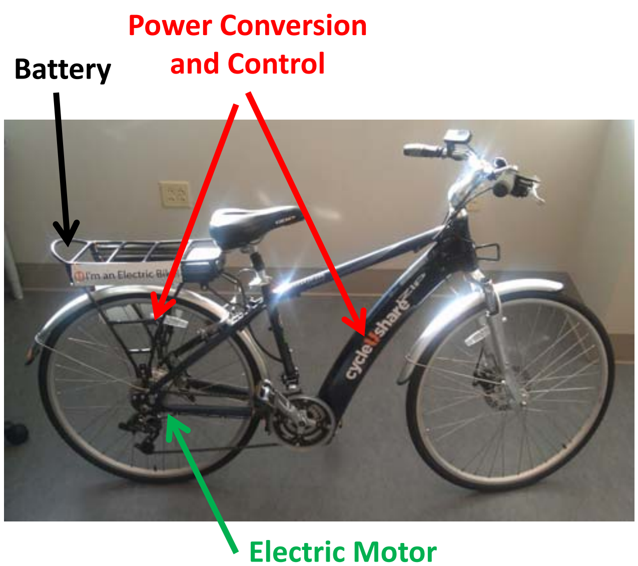
Growing Popularity of E-bikes



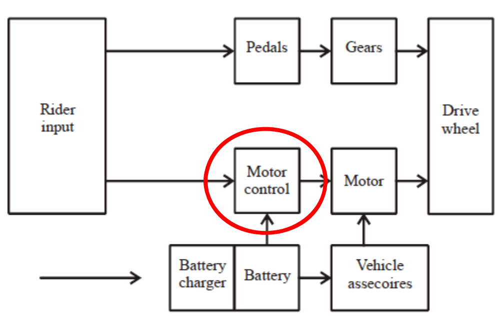
Electric Bicycles Worldwide

- 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

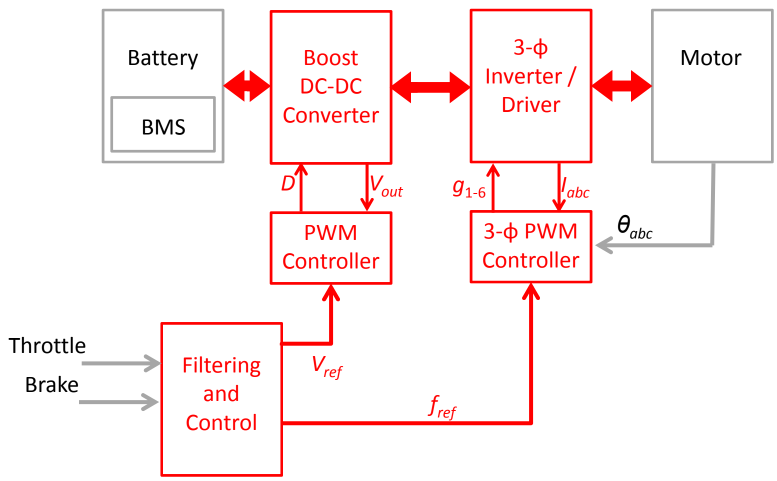
Electric Bicycle Platform



Electric Bicycle System



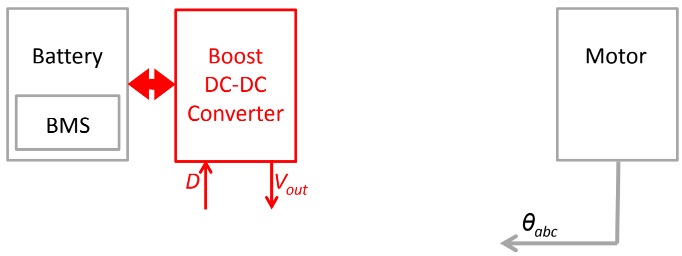
System Structure



Experiment 1

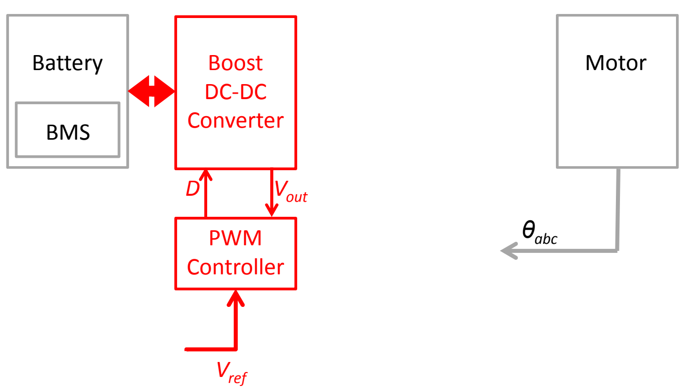
- Identification and characterization of motor
- Modeling of system using simulink
- Derivation of model parameters from experimental data
- Specification of performance for power electronics

Experiment 2



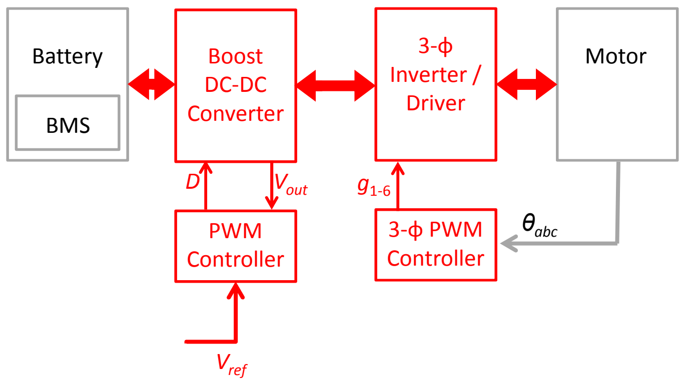
- Open-loop operation of Boost converter
- Inductor design
- Converter construction and efficiency analysis
- Bidirectional operation using voltage source / resistive load

Experiment 3



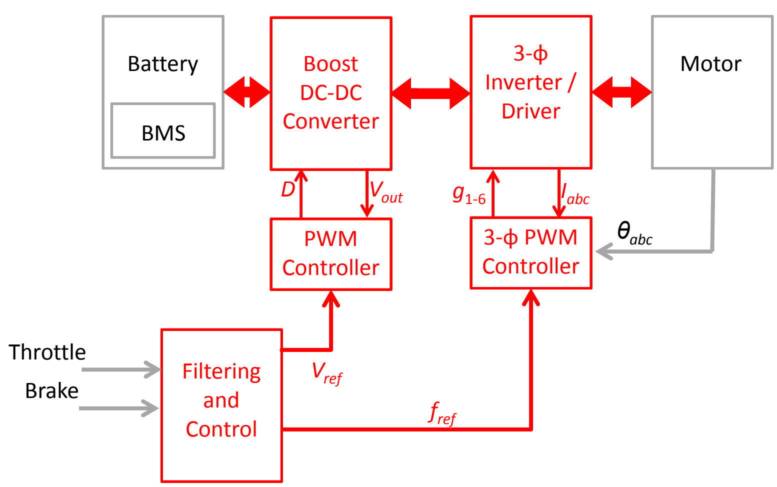
- Closed loop operation of boost converter
- Feedback loop design and stability analysis
- Analog control of PWM converters

Experiment 4/5



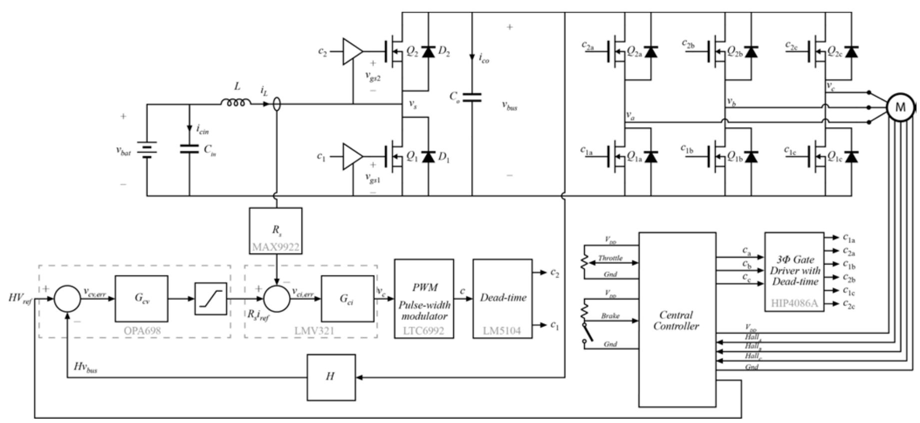
- Circuit layout and PCB design
- Device selection and implementation according to loss analysis
- Basic control of BLDC motors

Experiment 6

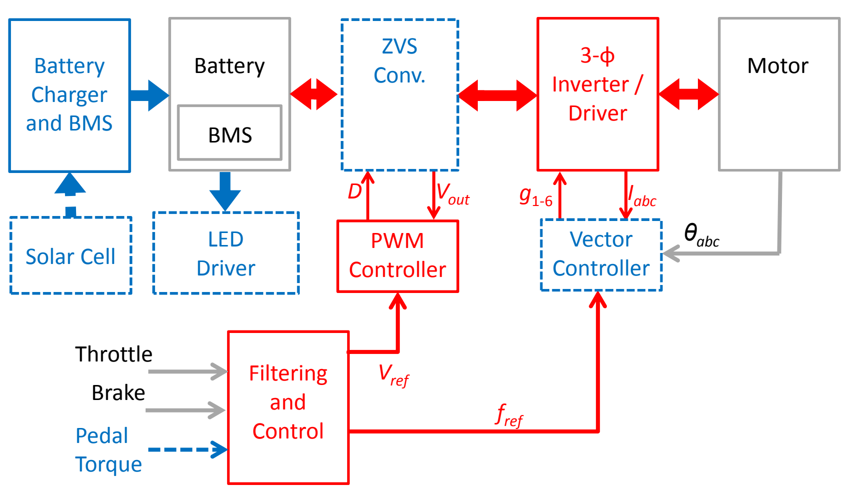


- System-level control techniques

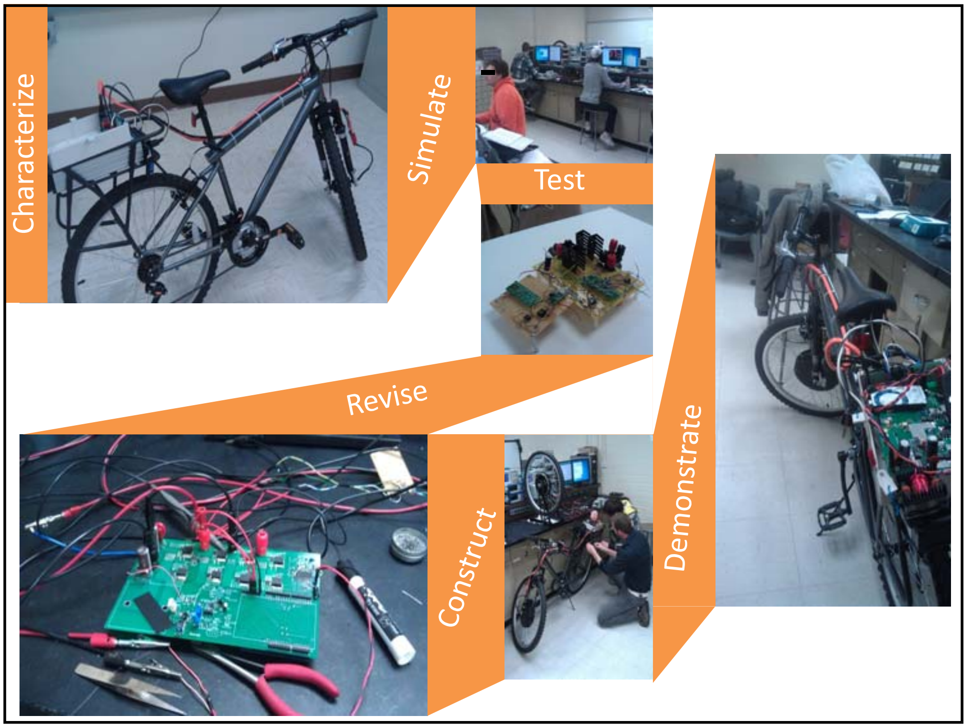
Example System Implementation



Experiment 7



- System improvements



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

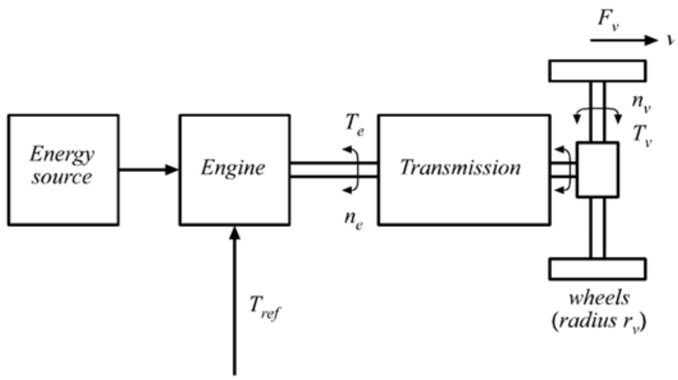
- Traffic Law:
  - Electric motor with power output not more than 1000 W
  - Not capable of propelling or assisting at greater than 20 mph
- No helmet laws for riders over age 16; you may request one at any time
- Read Tennessee bicycle safety laws on website

General Safety

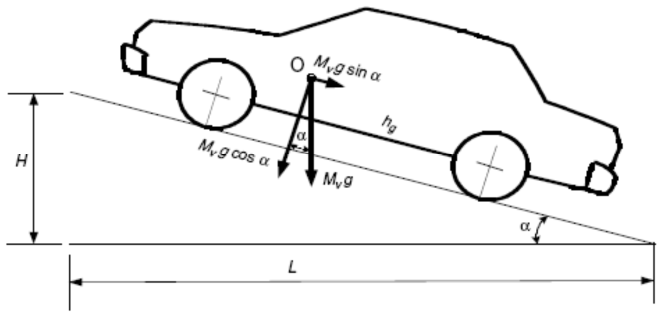
- Lab will work with high voltages (Up to 100 V)
- Will use various machinery with high power moving parts
- Use caution at all times

Introduction to Vehicle Dynamics

Vehicle as a Feedback Sytem



Basic Vehicle Dynamics



Angle of inclination

$$\alpha = \tan^{-1}\left(\frac{H}{L}\right)$$

Slope or "grade"

$$Z = \left(\frac{H}{L}\right)$$

$$g = 9.81 \text{ m/s}^2$$

Air density

$$\rho = 1.204 \text{ kg/m}^3$$

Rolling resistance coefficient C_r

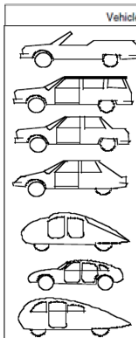
Aerodynamic drag coefficient C_d

Rolling resistance coefficient C_r

Rolling Resistance Coefficients

Conditions	Rolling resistance coefficient
Car tires on concrete or asphalt	0.013
Car tires on rolled gravel	0.02
Tar macadam	0.025
Unpaved road	0.05
Field	0.1–0.35
Truck tires on concrete or asphalt	0.006–0.01
Wheels on rail	0.001–0.002

Aerodynamic drag coefficient C_d



Vehicle Type	Coefficient of Aerodynamic Resistance
Open convertible	0.5–0.7
Van body	0.5–0.7
Ponton body	0.4–0.55
Wedge-shaped body; headlamps and bumpers are integrated into the body, covered underbody, optimized cooling air flow	0.3–0.4
Headlamp and all wheels in body, covered underbody	0.2–0.25
K-shaped (small breakway section)	0.23
Optimum streamlined design	0.15–0.20
Trucks, road trains	0.8–1.5
Buses	0.6–0.7
Streamlined buses	0.3–0.4
Motorcycles	0.6–0.7

Reference: Mehrdad Ehsani, Yimin Gao, Sebastien E .Gay, and Ali Emadi, Modern Electric, Hybrid Electric, and Fuel Cell Vehicles, CRC Press 2004.
Chapter 2

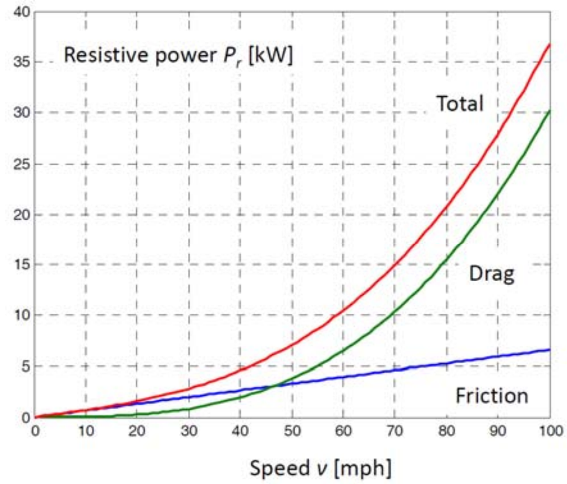
Typical Performance Specifications

- Cruising (v = const) specs
  - Top cruising speed on a flat road: v_{max}
  - Gradeability: ability to ascend a road of grade Z (in %) at a cruising speed v_{zmax}
- Acceleration specs
  - Time t_a it takes to accelerate from v_s to v_f Typical: v_s = 0 mph to v_f = 60 mph (100 km/h) in t_a seconds

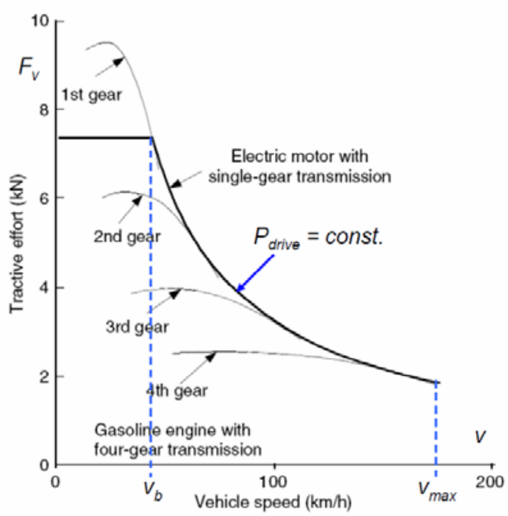
Cruising on a flat road

$$P_v = F_v v \approx \frac{1}{2}\rho C_d A_v v^3 + C_r M_v g v + M_v v \frac{dv}{dt}$$

Example
M_v = 1500 kg
r_w = 0.3 m
C_d = 0.26
C_r = 0.01
A_v = 2.16 m^2

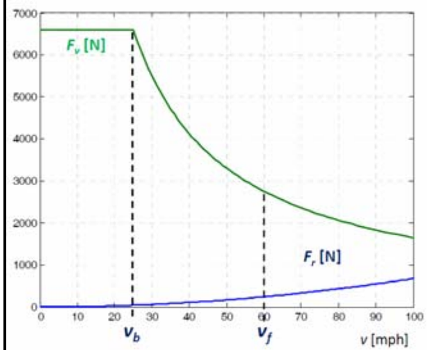


Engine Traction Characteristics



Acceleration Spec

$$M_v \frac{dv}{dt} \approx F_v - \frac{1}{2}\rho C_d A_v v^2 - C_r M_v g$$



Engine Power Rating

$$P_v \approx \frac{1}{2}\frac{M_v}{t_a}\left(v_b^2 + v_f^2\right) + \frac{1}{2}\rho C_d A_v v_f^3 + C_r M_v g v_f$$

Example
M_v = 1500 kg
C_d = 0.26
C_r = 0.01
A_v = 2.16 m^2
x = 4

Acc. performace spec: 0-60 mph in $t_a = 10$ s

$$(P_v)_{required} \approx 74 \text{ kW } (99 \text{ hp})$$