Transportation Electrification

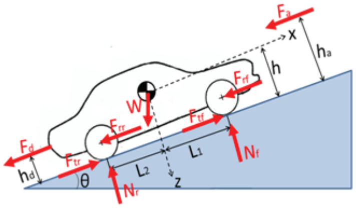
Motivation

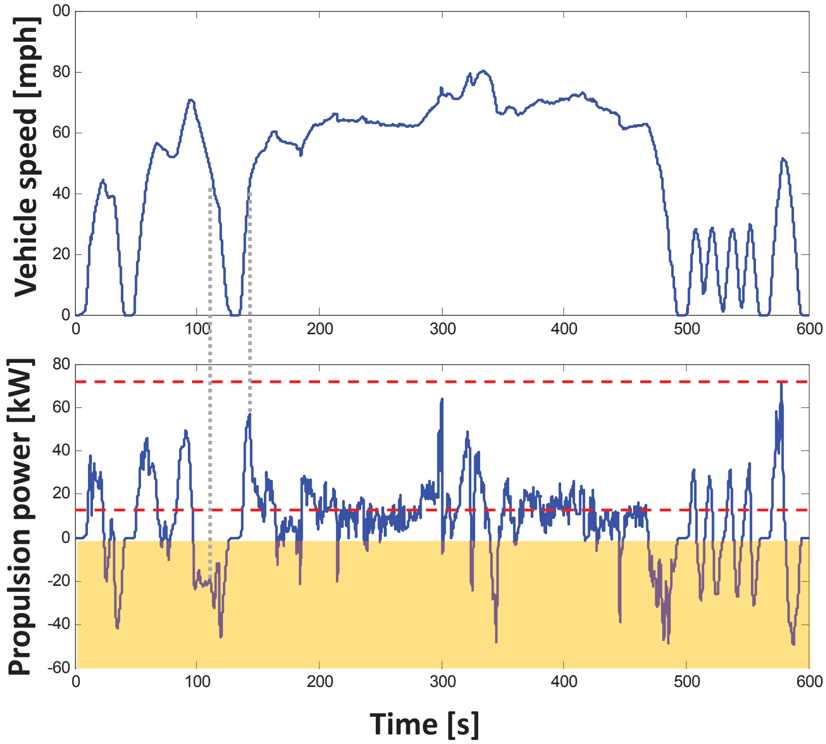
- Improve efficiency: reduce energy consumption
- Displace petroleum as primary energy source
- Reduce impact on environment
- Reduce cost

US Energy Information Administration:

- Transportation accounts for 28% of total U.S. energy use
- Transportation accounts for 33% of CO_2 emissions
- Petroleum comprises 90% of US transportation energy use

Example: US06 driving cycle

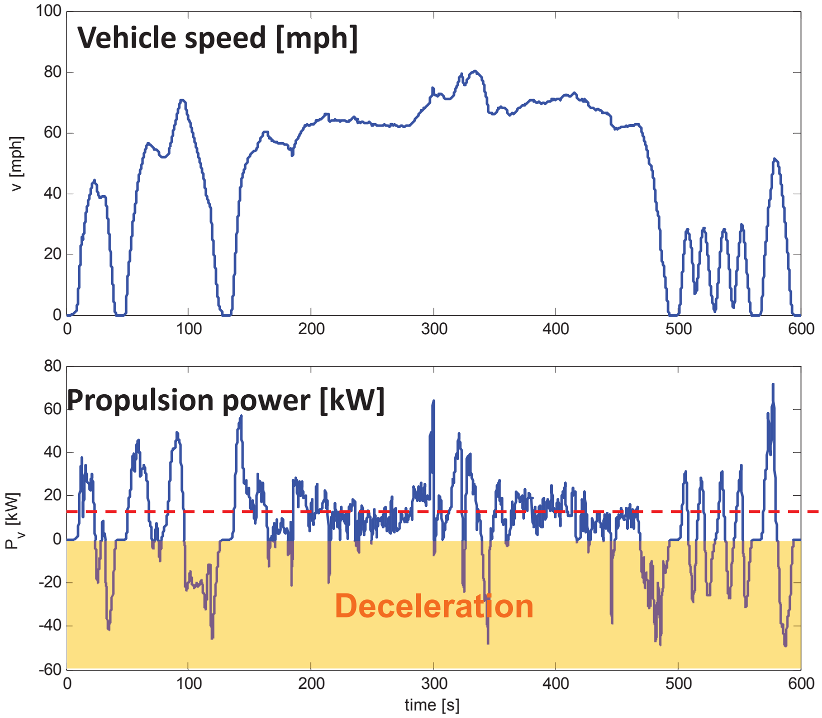




10-min
8 miles

Example:
Prius-sized
vehicle

Example: US06 driving cycle



10-min
8 miles

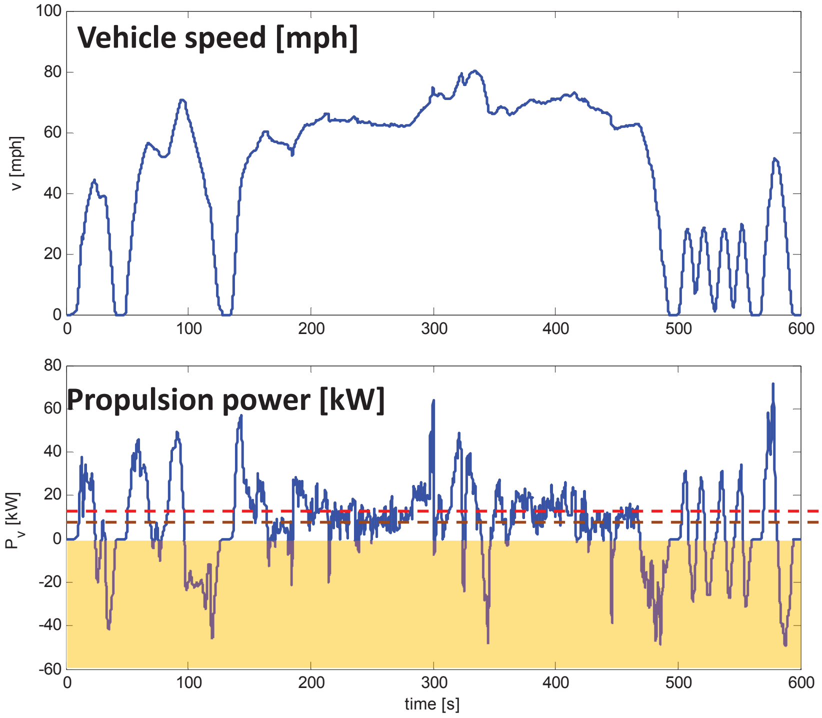
Prius-sized vehicle

Dissipative braking

P_{vavg} = 11.3 kW

235 Wh/mile

Average power and energy



Prius-sized vehicle

Dissipative braking

P_{vavg} = 11.3 kW

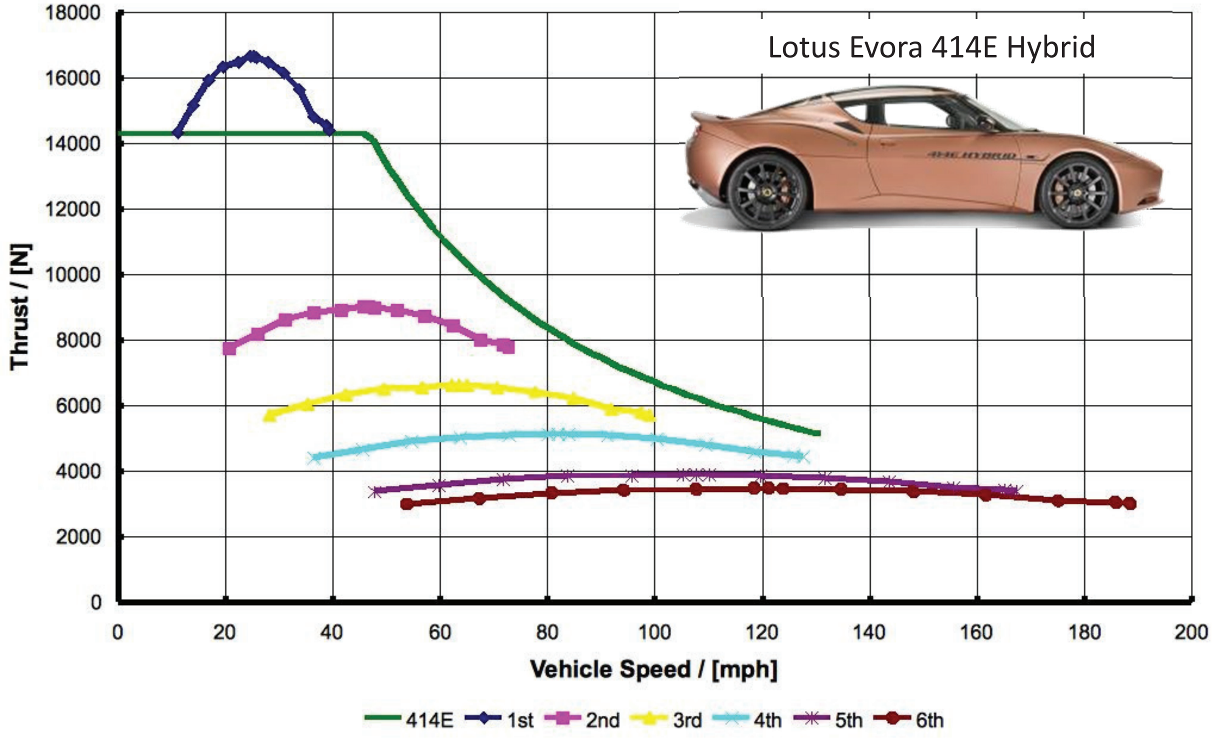
235 Wh/mile

Regenerative braking

P_{vavg} = 7.0 kW

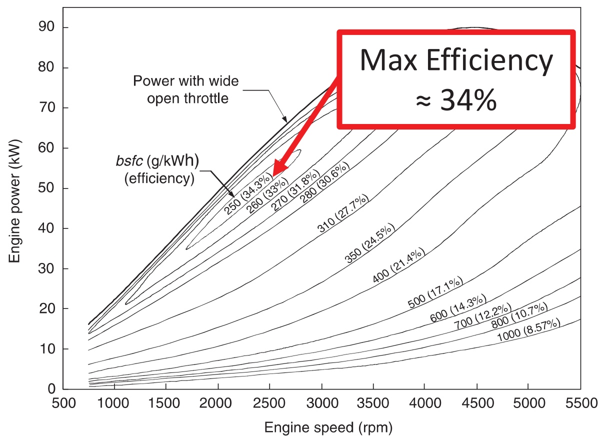
146 Wh/mile

ICE vs ED τ–ω



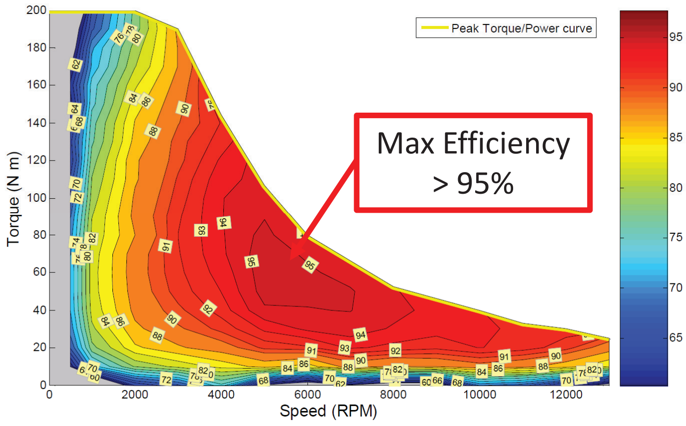
“Full Acceleration”, proactive Magazine, Oct. 2012

ICE vs. ED η



Max Efficiency ≈ 34%

Internal Combustion Engine (ICE)



Max Efficiency > 95%

Electric Drive (ED)

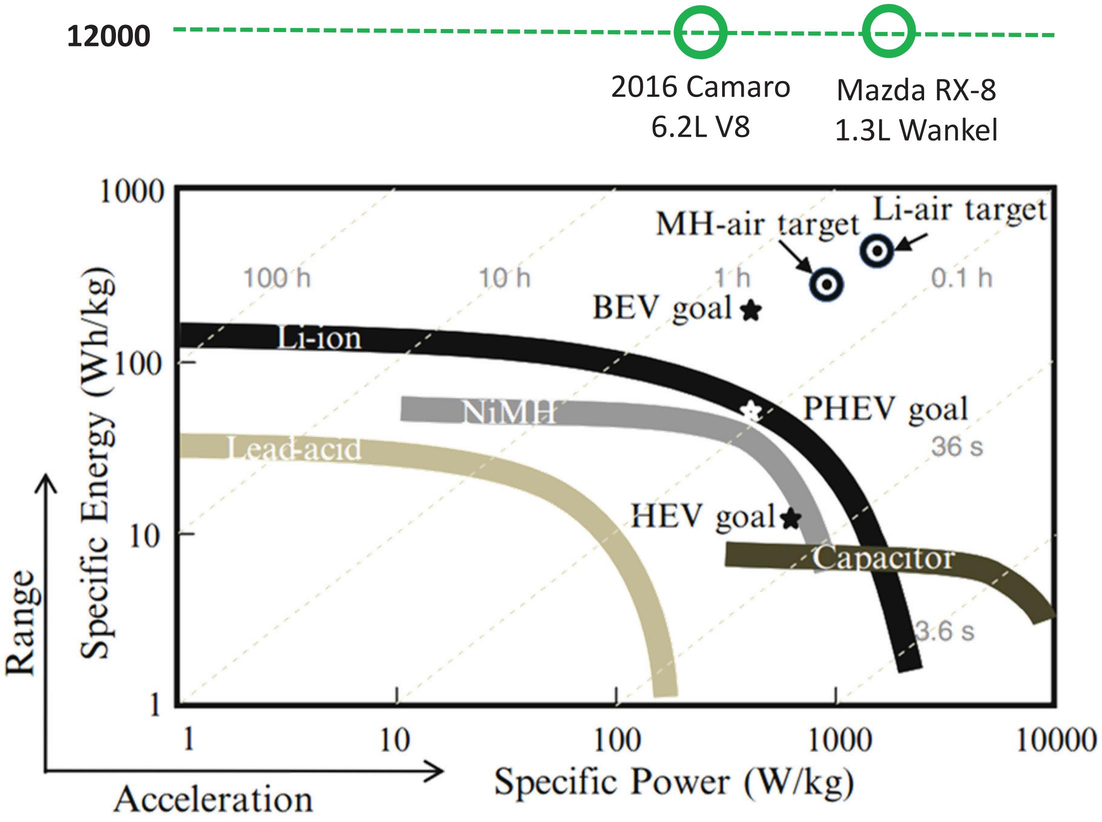
- $\eta_{ED,pk} \approx 95\%$; $\eta_{ICE,pk} \approx 35\%$
- ED offers full torque at zero speed
  - No need for multi-gear transmission

Conventional Vs. Electric Vehicle

(Commuter Sedan comparison)

	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.
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]
Energy Costs (10-yr, 15k mi/yr)	$18,000	$3,000

Energy and Power Density of Storage



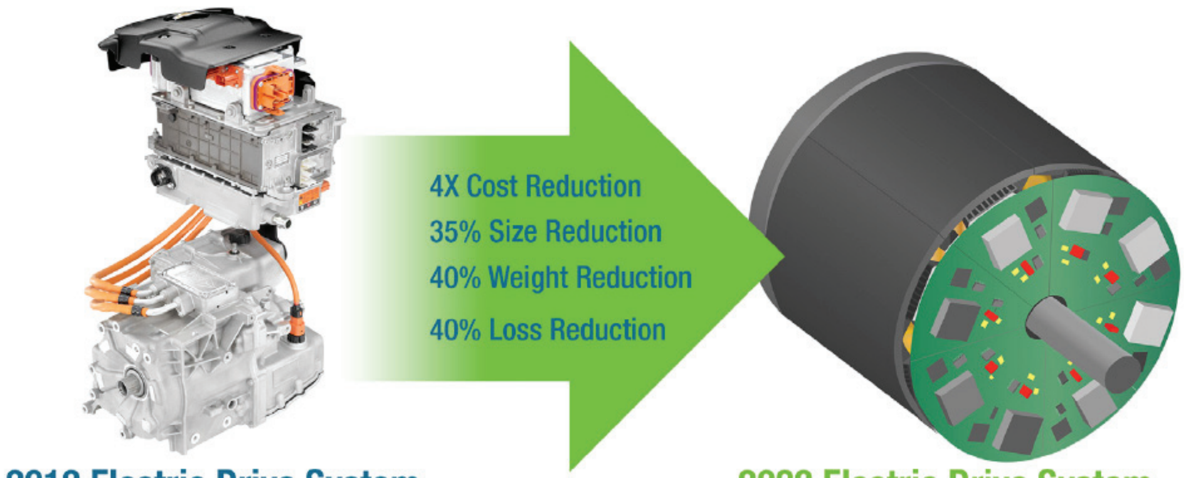
Conventional Vs. Electric Vehicle

(Commuter Sedan 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)	$13,500 (Battery Pack Replacement)
Range	> 350 mi	< 100 mi
Curb Weight	3,000 lb	3,700 lb
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

EV Everywhere Grand Challenge

Advancements needed for an electric drive system to support meeting *EV Everywhere* targets



4X Cost Reduction

35% Size Reduction

40% Weight Reduction

40% Loss Reduction

2012 Electric Drive System

$30/kW, 1.1 kW/kg, 2.6 kW/L

90% system efficiency

Today

$12/kW

1.2 kW/kg

3.5 kW/l

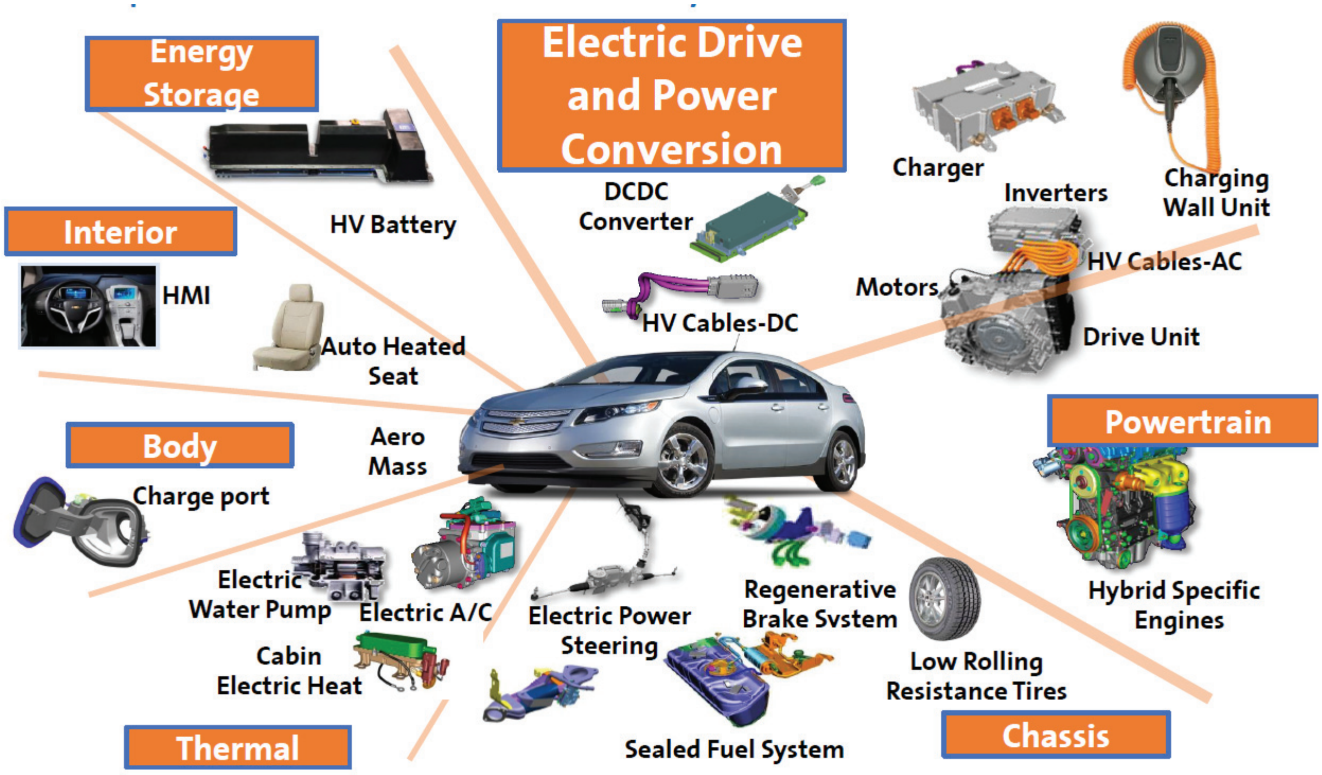
>93% efficiency

2022 Electric Drive System

$8/kW, 1.4 kW/kg, 4.0 kW/L

94% system efficiency

Power Electronics in Electric Vehicles



Energy Storage

HV Battery

Electric Drive and Power Conversion

DCDC Converter

HV Cables-DC

Charger

Inverters

Charging Wall Unit

Motors

HV Cables-AC

Drive Unit

Interior

HMI

Auto Heated Seat

Body

Aero Mass

Charge port

Powertrain

Hybrid Specific Engines

Thermal

Electric Water Pump

Electric A/C

Cabin Electric Heat

Electric Power Steering

Regenerative Brake Svstem

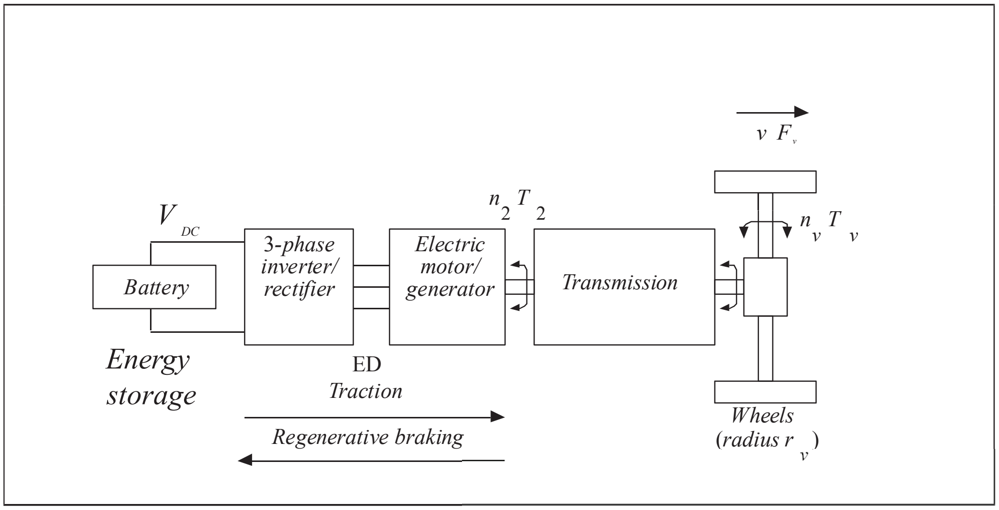
Sealed Fuel System

Low Rolling Resistance Tires

Chassis

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

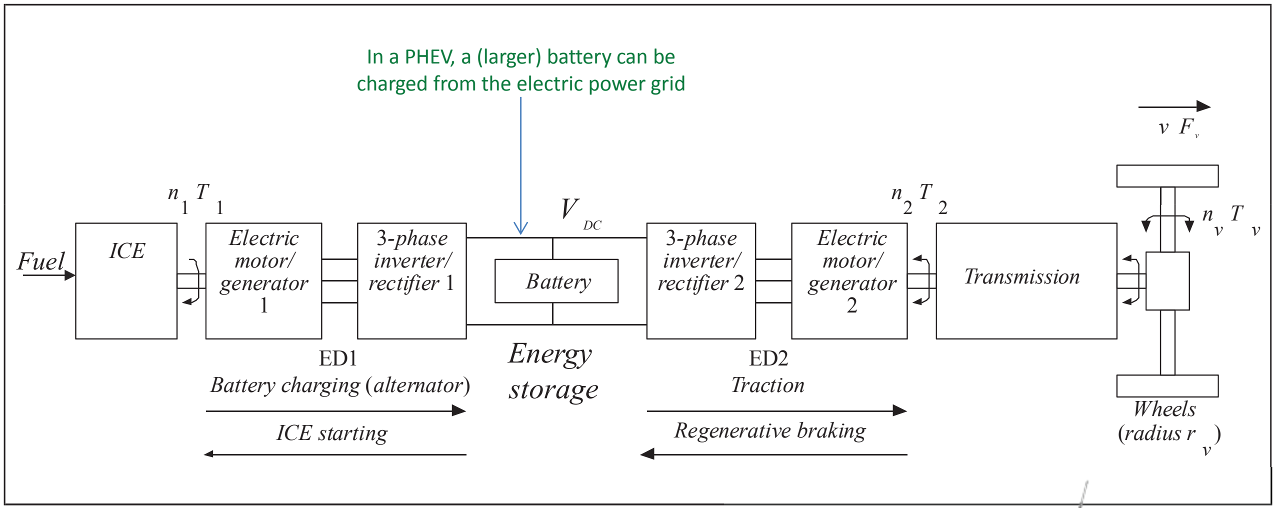
BEV Architecture



Example: Tesla Roadster

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

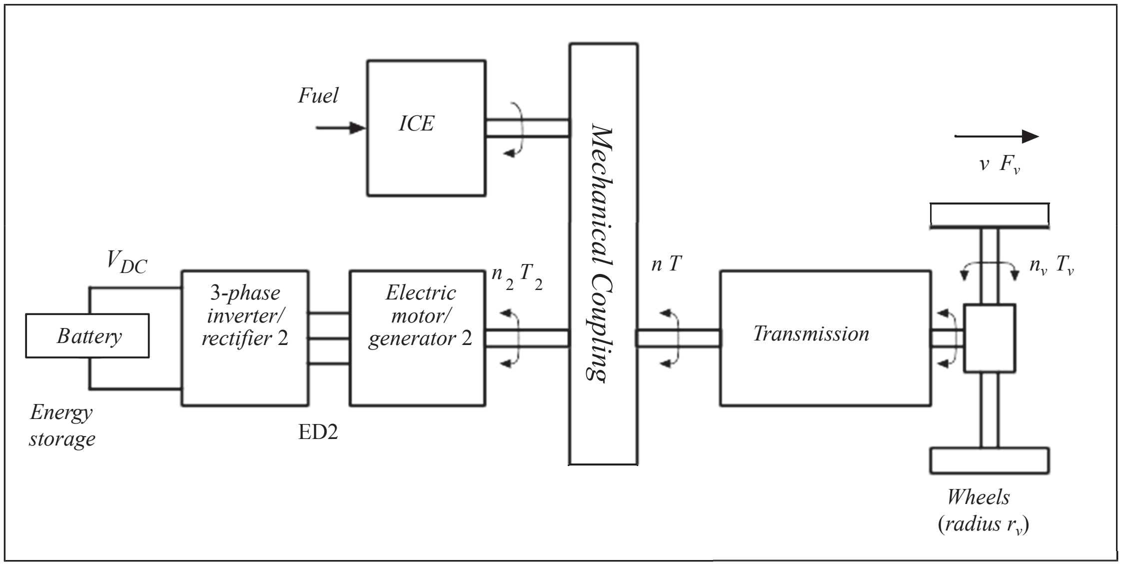
Series HEV Architecture


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

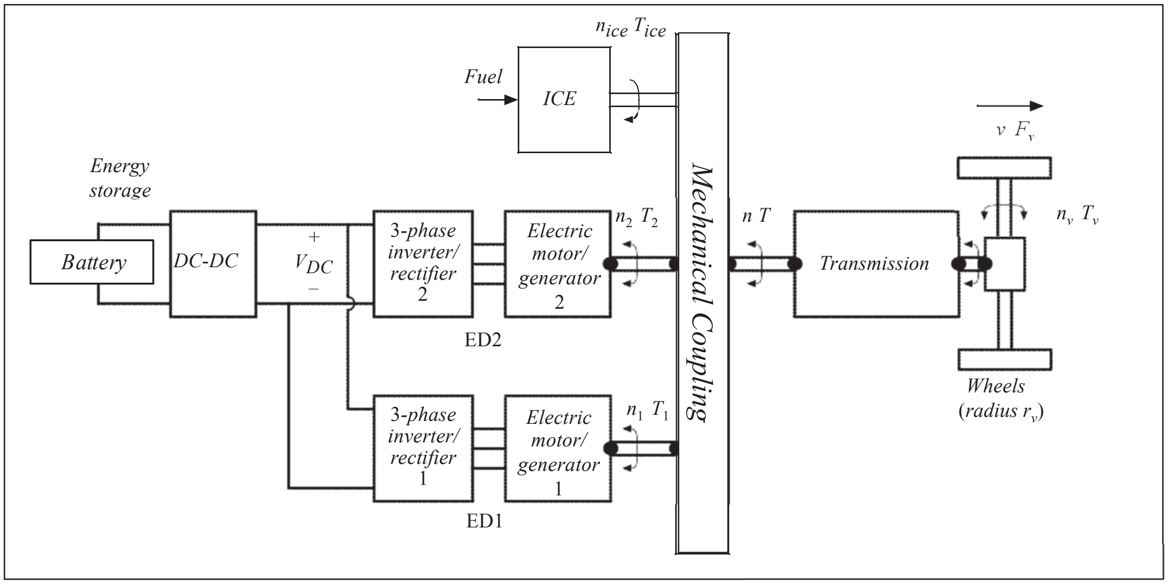
Parallel HEV



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

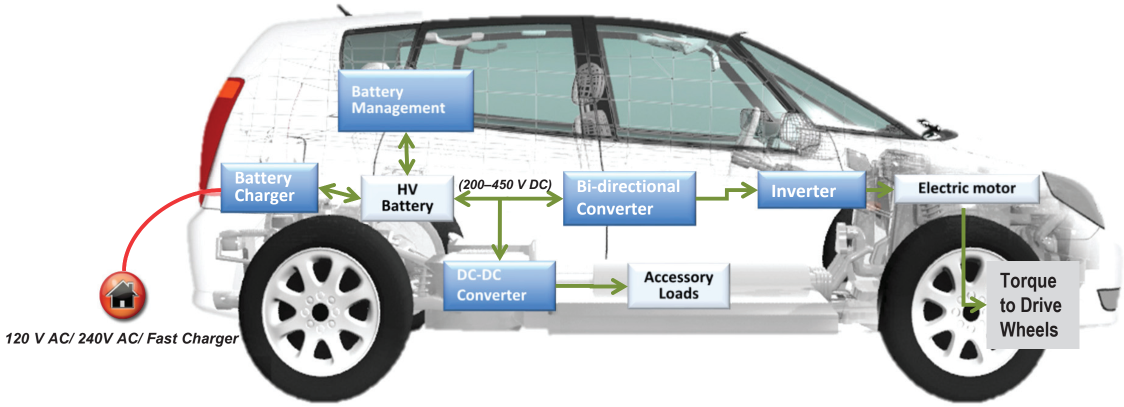
Series/Parallel HEV



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



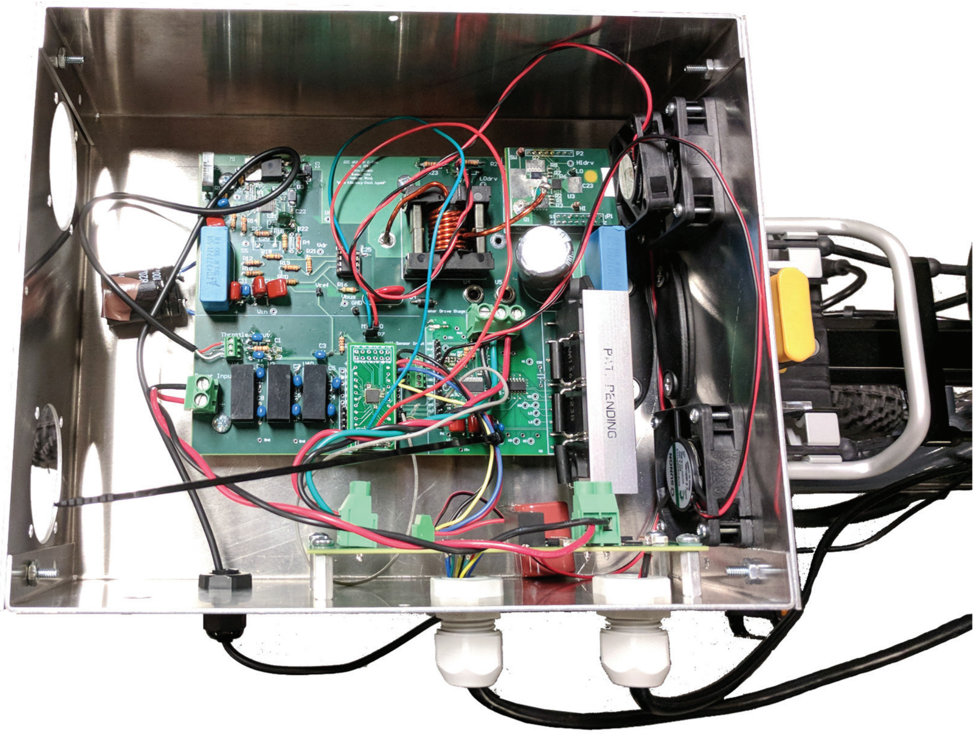
Electric Bicycle Platform

Power Conversion and Control

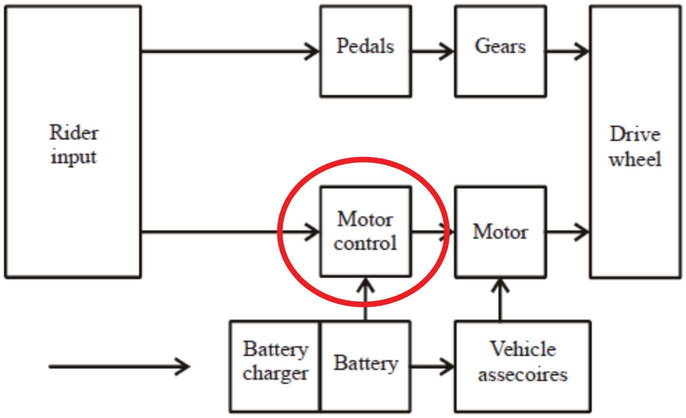
Battery

Electric Motor

Electrical Build Space

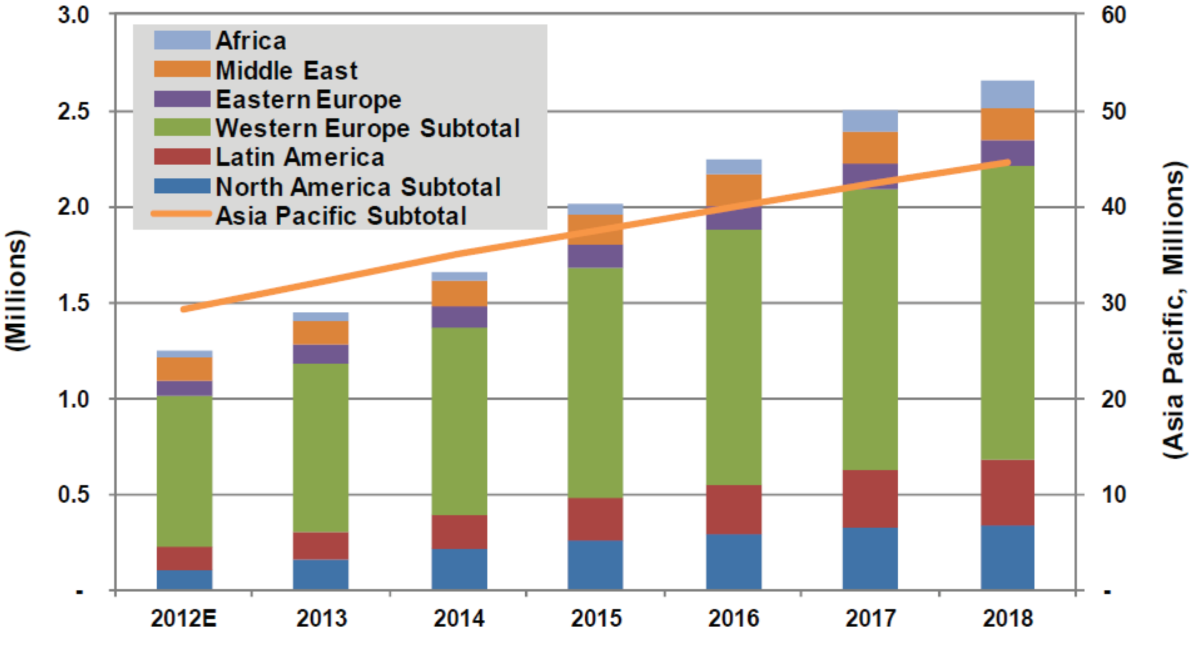


Electric Bicycle System



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

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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

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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; 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

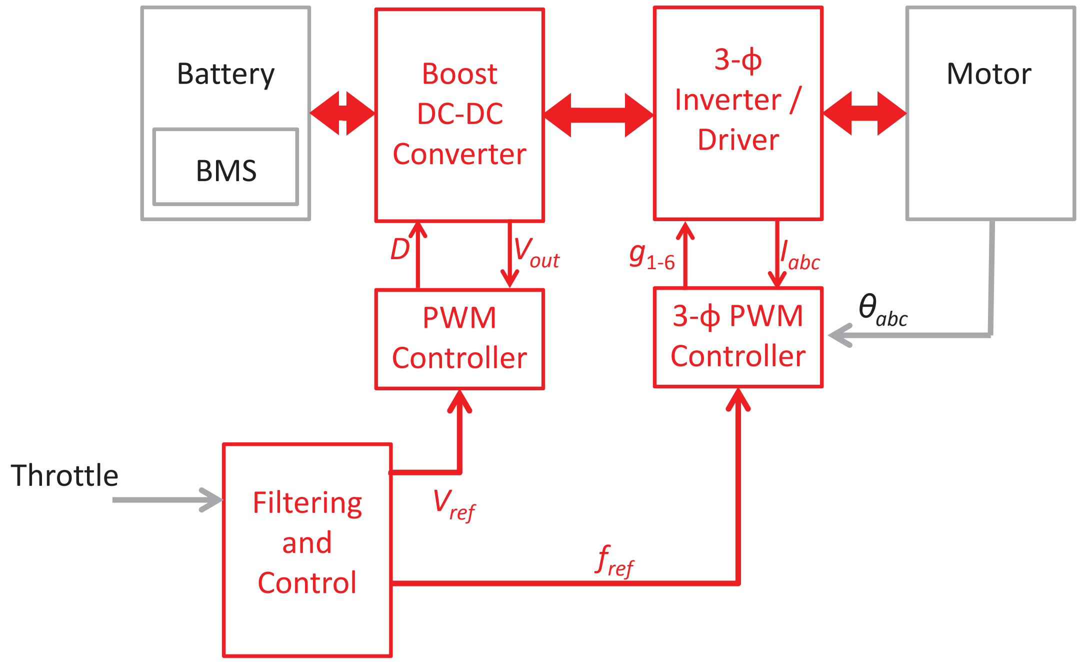
- Attendance is required during all lectures and scheduled lab time
  - Make use of designated time with Instructor present
  - Informal Q&A and end-of-experiment demonstrations
- Work efficiently but do not work independently
  - Understand all aspects of design
- Outside of normal lab hours, key access 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



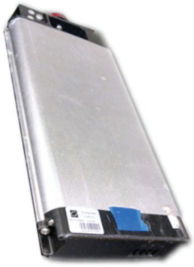
Experiment 1

Battery

BMS

Motor

θ_{abc}



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

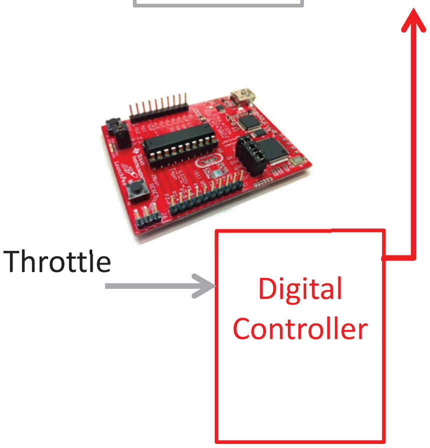
Experiment 2

Battery

BMS

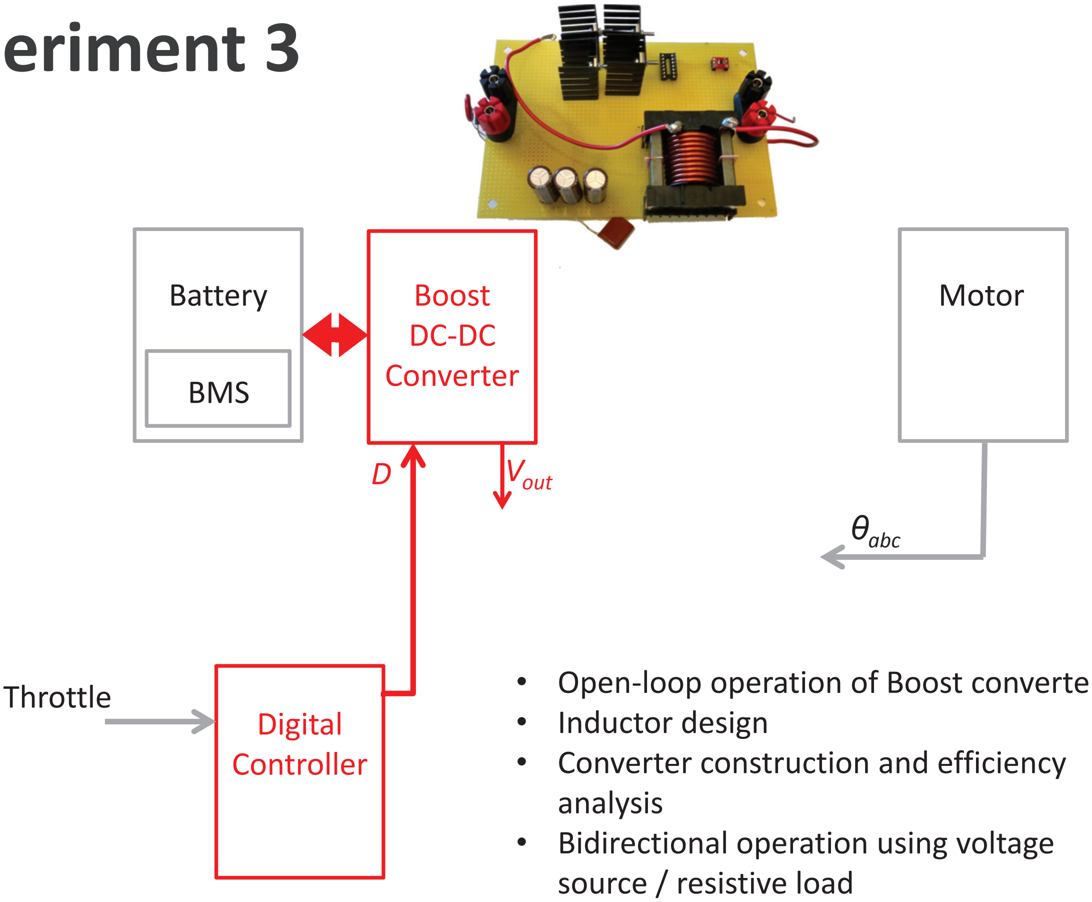
Motor

θ_{abc}



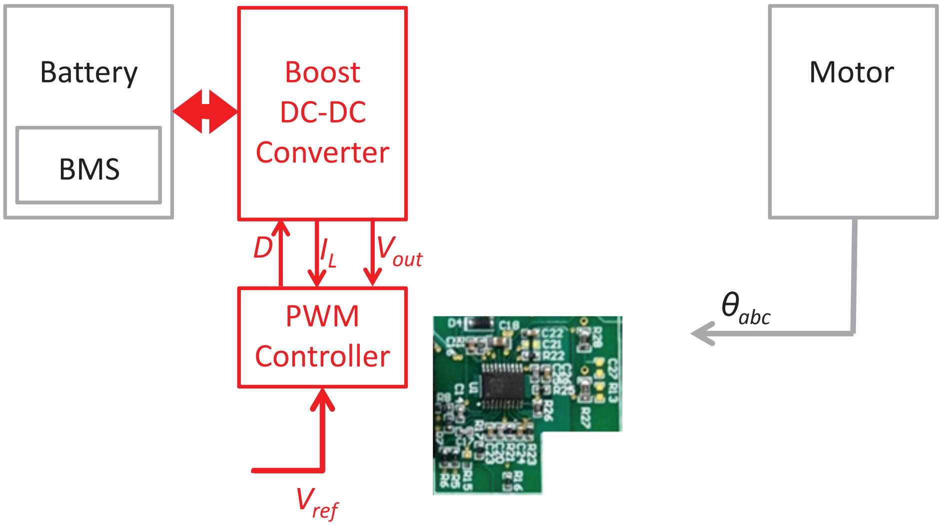
- Open-loop operation of Boost converter
- Inductor design
- Converter construction and efficiency analysis
- Bidirectional operation using voltage source / resistive load

Experiment 3



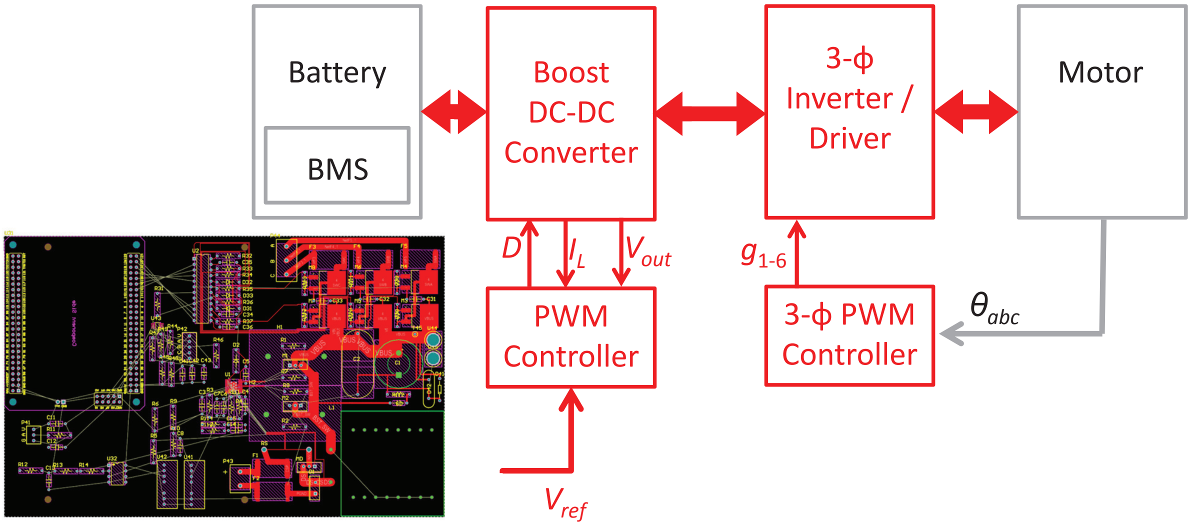
- Open-loop operation of Boost converter
- Inductor design
- Converter construction and efficiency analysis
- Bidirectional operation using voltage source / resistive load

Experiment 4



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

Experiment 5



Battery

BMS

Boost DC-DC Converter

3-ϕ Inverter / Driver

Motor

D

I_L

V_{out}

g_{1-6}

PWM Controller

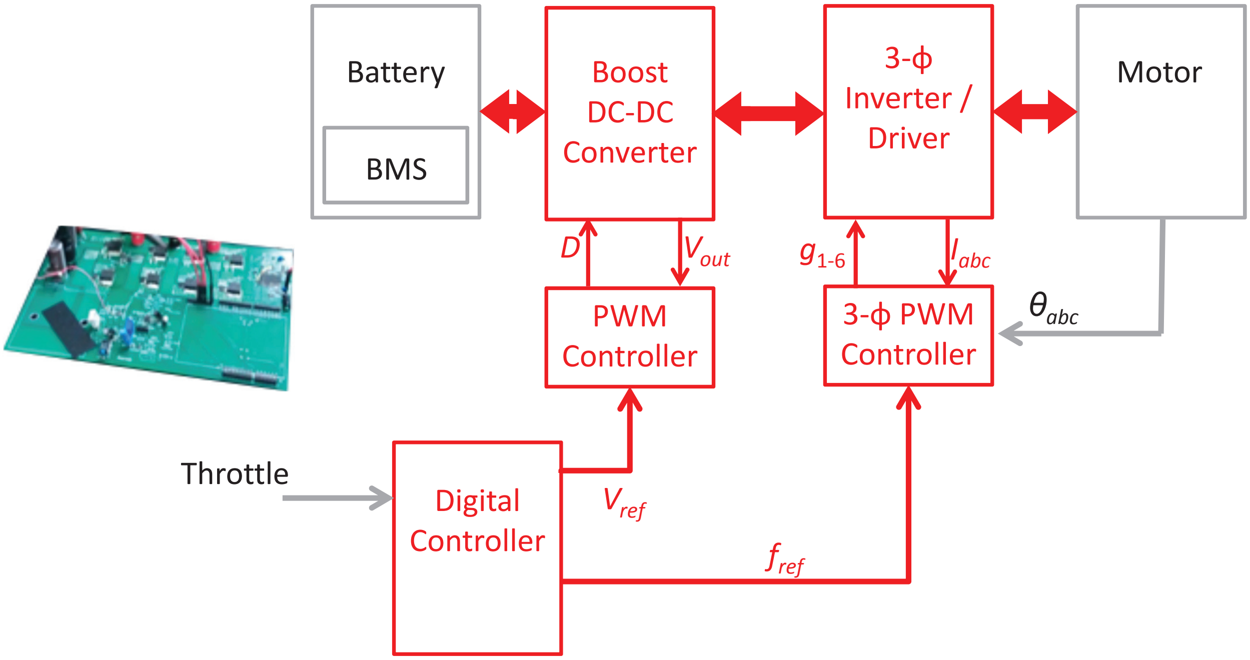
3-ϕ PWM Controller

θ_{abc}

V_{ref}

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

Experiment 6



Battery

BMS

Boost DC-DC Converter

3-ϕ Inverter / Driver

Motor

D

V_{out}

g_{1-6}

I_{abc}

PWM Controller

3-ϕ PWM Controller

θ_{abc}

Throttle

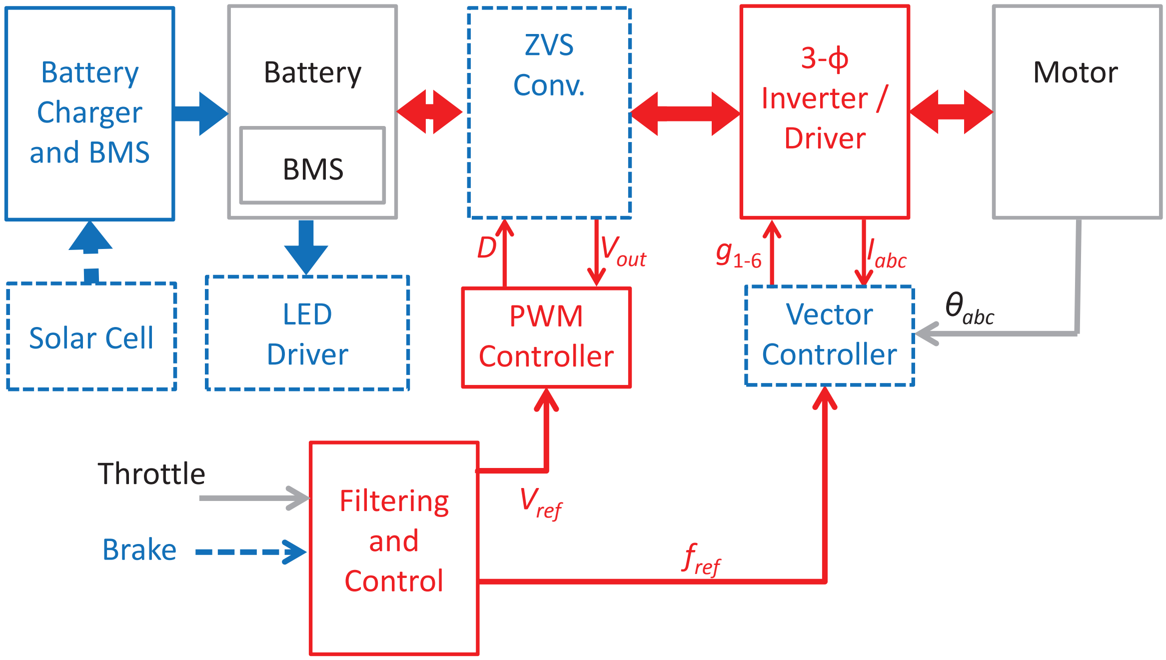
Digital Controller

V_{ref}

f_{ref}

- System-level control techniques

Experiment 7


Battery Charger and BMS

Battery

BMS

ZVS Conv.

3-ϕ Inverter / Driver

Motor

Solar Cell

LED Driver

D

V_{out}

PWM Controller

$g_{1\text{-}6}$

I_{abc}

Vector Controller

θ_{abc}

Throttle

Brake

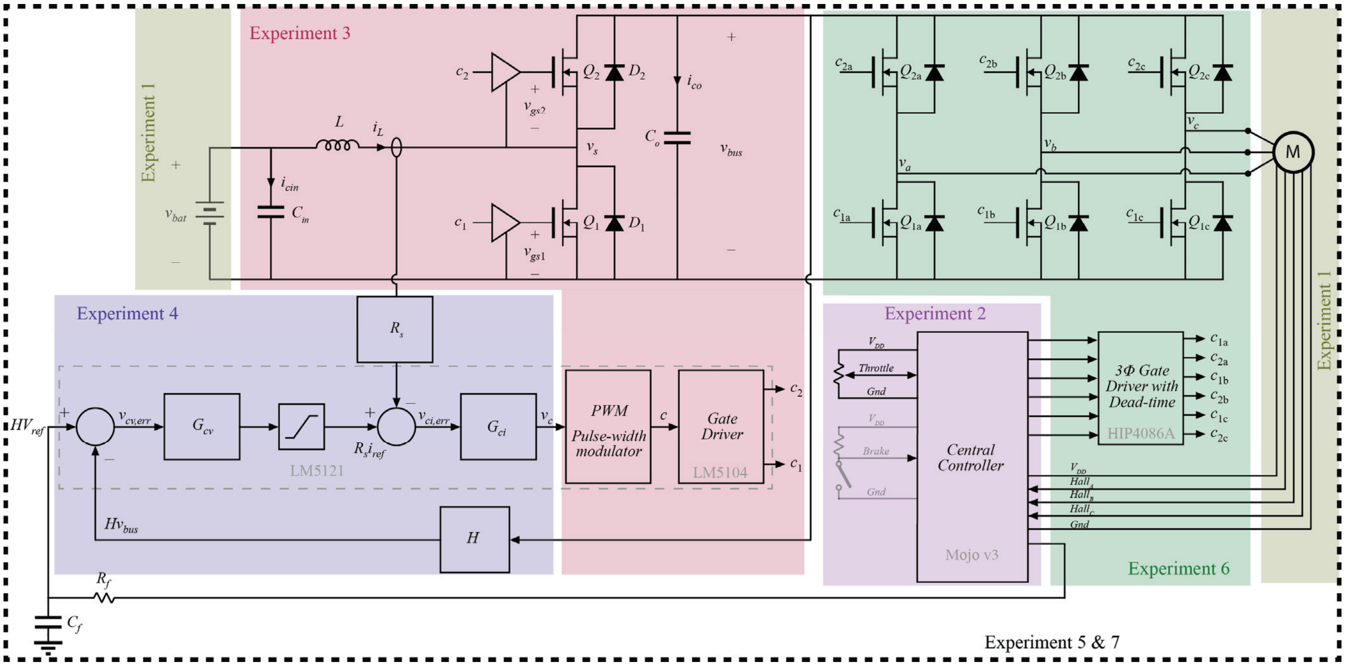
Filtering and Control

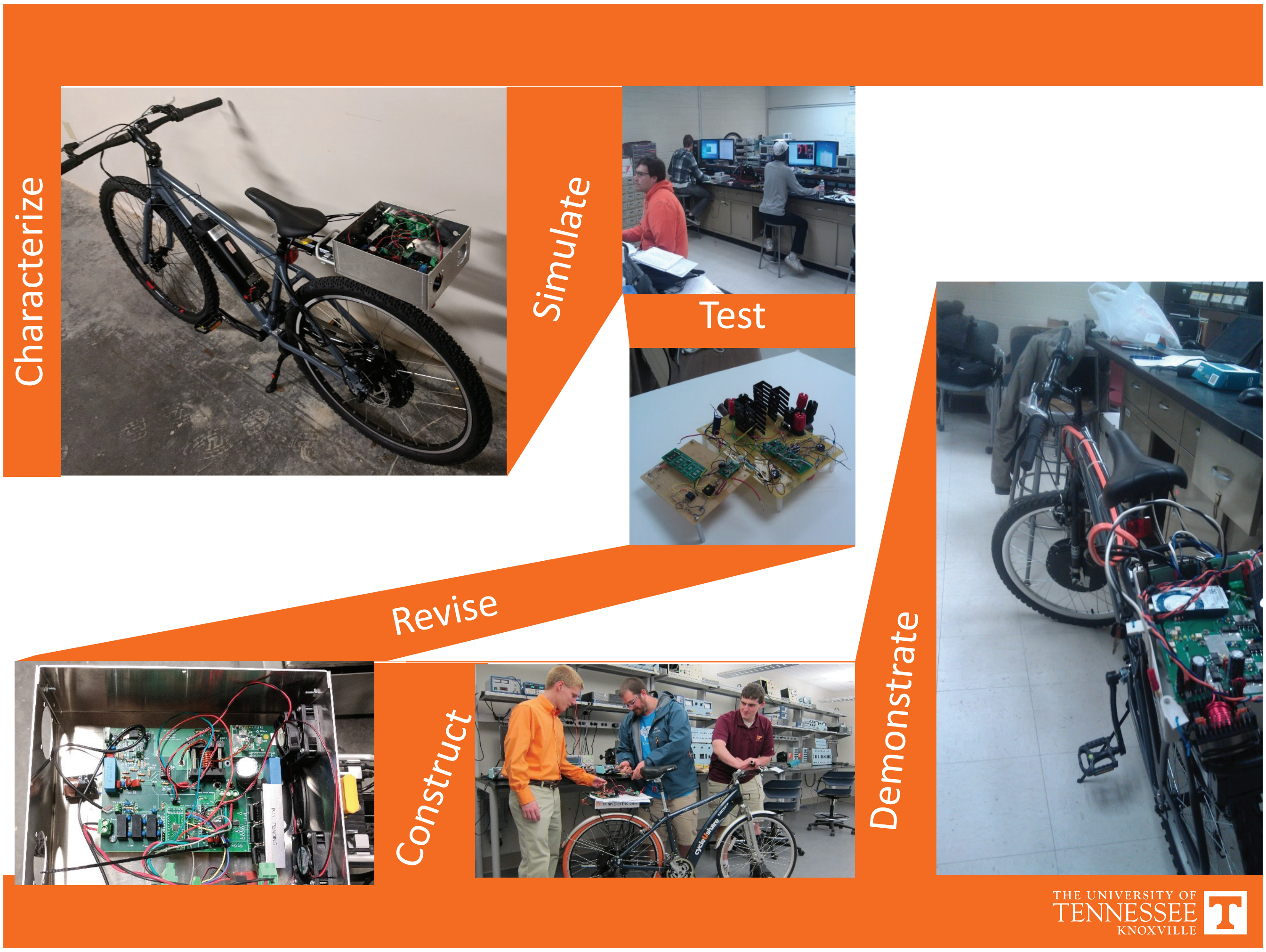
V_{ref}

f_{ref}

- 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

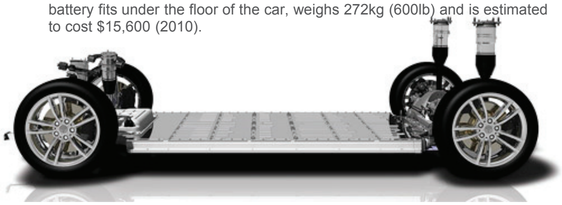
- Login to canvas at https://utk.instructure.com/courses/29416/modules
- Complete training modules
  - General Lab Safety
  - Hazardous Waste
  - Hazard Communication Training and GHS Updates
  - Fire Extinguisher Training
  - Fire Safety in Laboratories
  - Chemical Fume Hood Safety Training
  - Compressed 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

Lab 1

Introduction to Battery Modeling

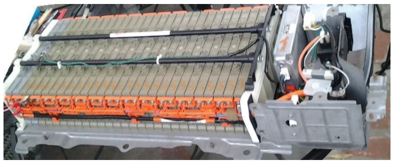
Example EV Batteries

Cutaway battery of Nissan Leaf electric vehicle. The Leaf includes a 24kWh 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 60-85kWh lithium-ion battery with a city driving range of 480km (300miles). 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

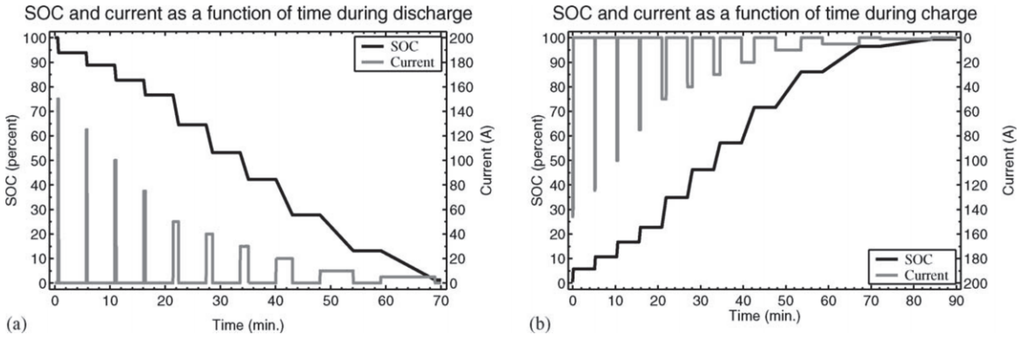
Objective:

- 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



[Plett 2004-2] G. Plett, “Extended Kalman Filtering for Battery Management Systems of LiPB-Based HEV Battery Packs—Part 2: Modeling and Identification,” Journal of Power Sources, Vol. 134, No. 2, August 2004, pp. 262–76.

Battery Nomenclature

- Known beforehand:

Capacity C [Ah]

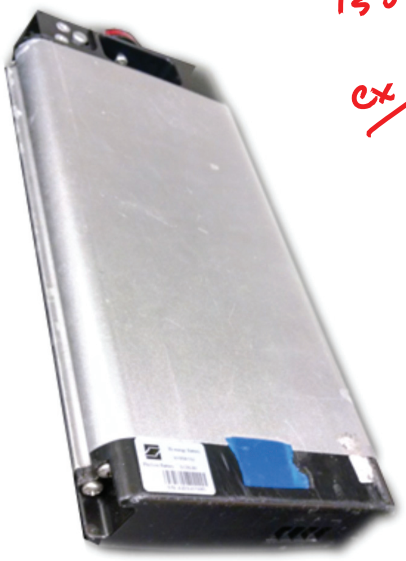
Nominal voltage V_{nom} [V]

Max Charge Rate
Max Discharge Rate } specified as $k \frac{C}{1\,hr}$

ex/
Max Charge = 1C
for 10Ah cell => 10A max charge

Max discharge = 5C
for 10Ah battery → 50A

Example Battery

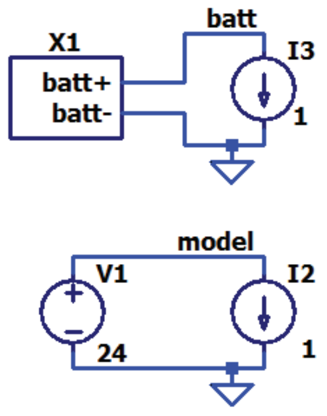


"7s5p" → 7 cells in series, 5 in parallel

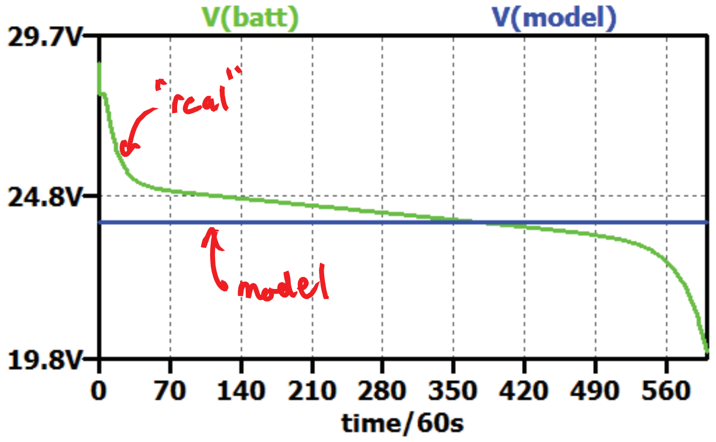
ex/ cells: { $V_{nom} = 3.4V$, C = 2Ah
max charge = 0.2C
max discharge = 1.9C

pack: { $V_{nom} = 24V$, C = 10Ah
Max charge = 1C
Max discharge = 10C

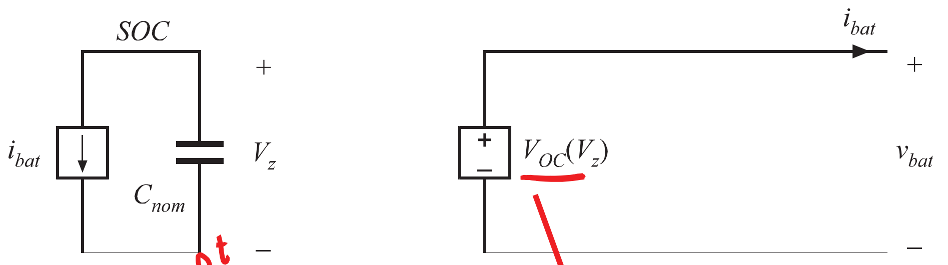
Model 0: Voltage Source



.tran 36000

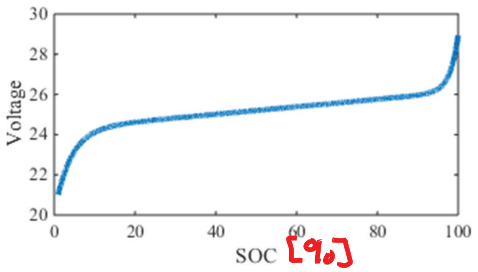


Model A: SOC and V_{oc}



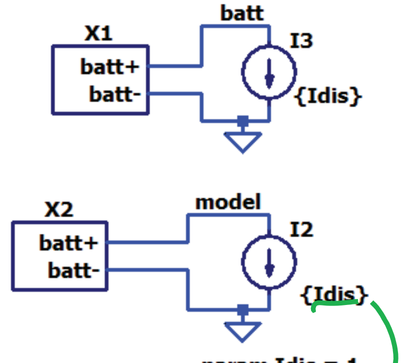
$$V_z = V_{z0} - \underbrace{\frac{1}{C_{nom}} \underbrace{\int_0^t i_{bat}\, dt}_{A \cdot s}}_{\frac{A \cdot h}{C} = \Delta SOC}$$

if I set $C_{nom} = C \cdot 3600$

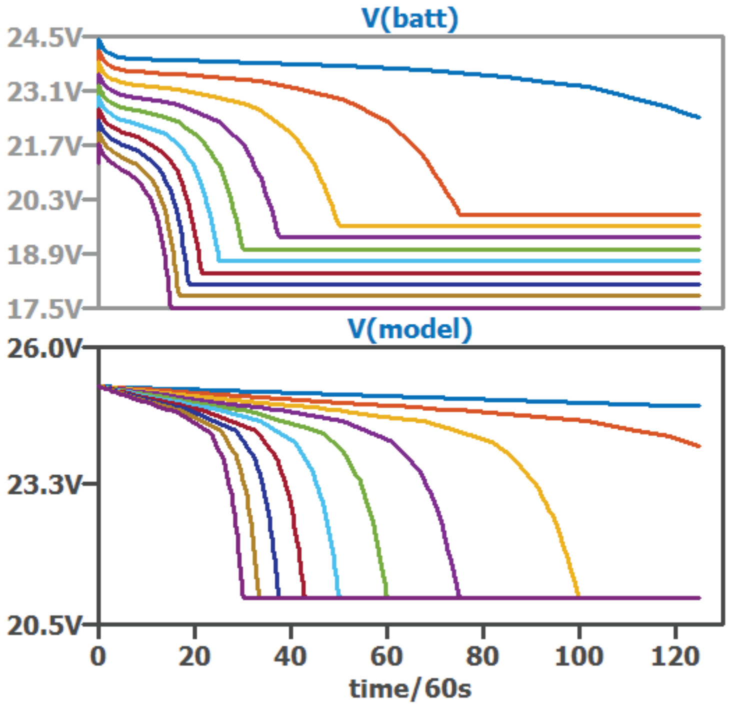


"state-of-charge"

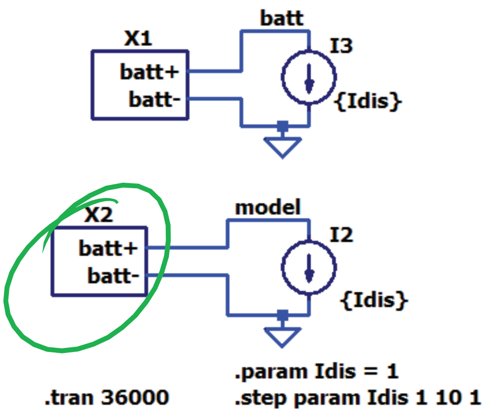
Model B: Series Resistance

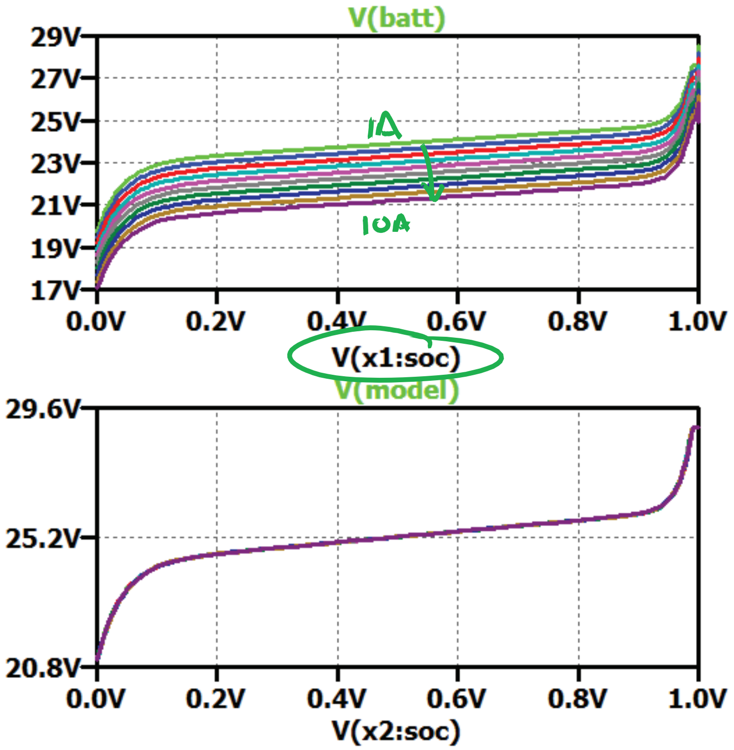


```
.tran 36000
.param Idis = 1
.step param Idis 1 10 1
```

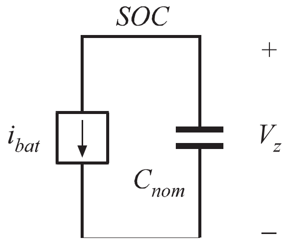


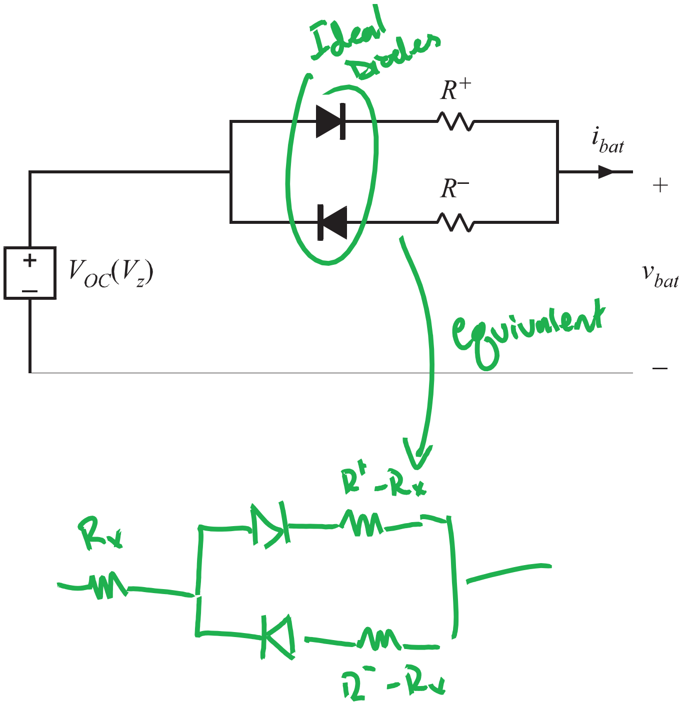
Model B: Series Resistance





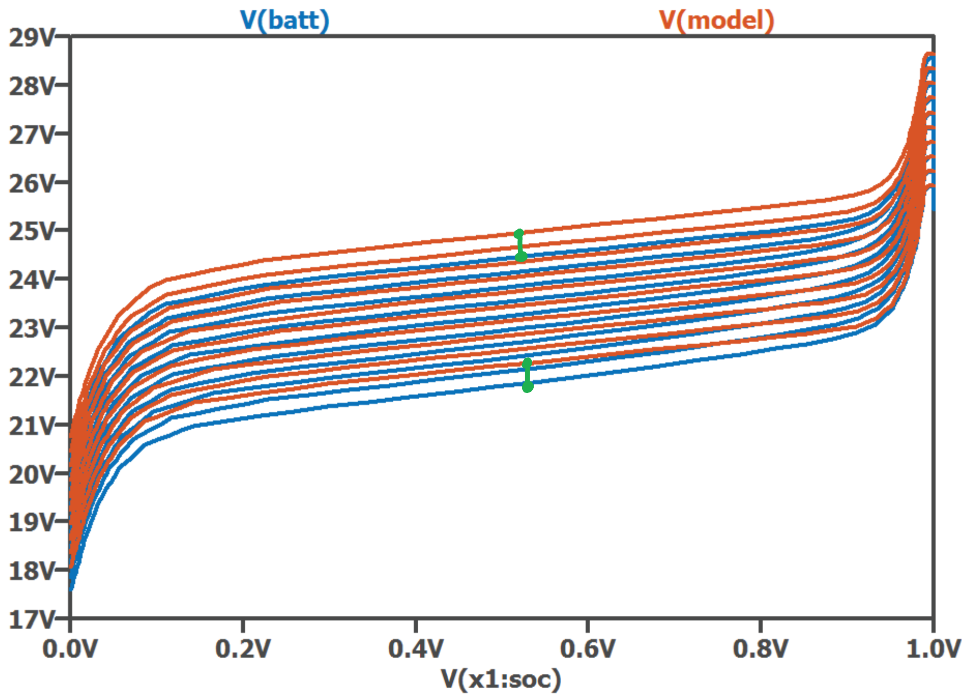
Model B: Series Resistance





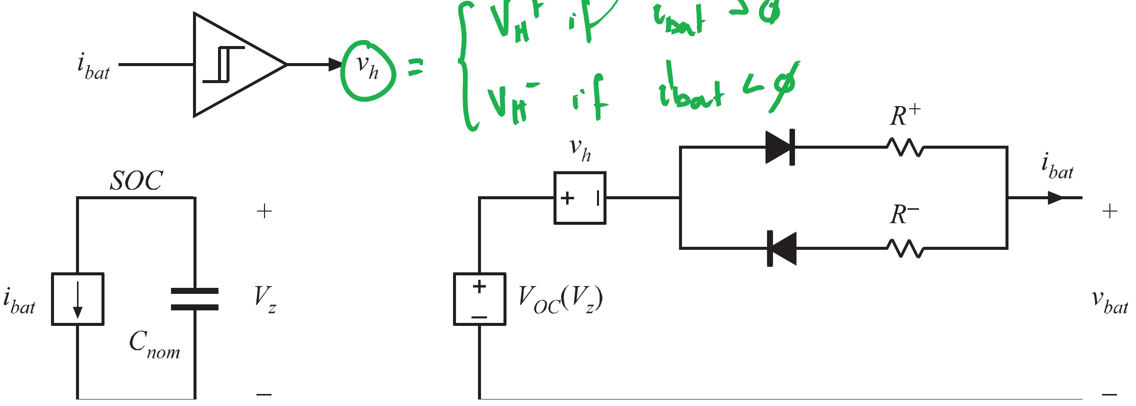
if $R_x \leq \min(R^+, R^-)$

Model B Performance



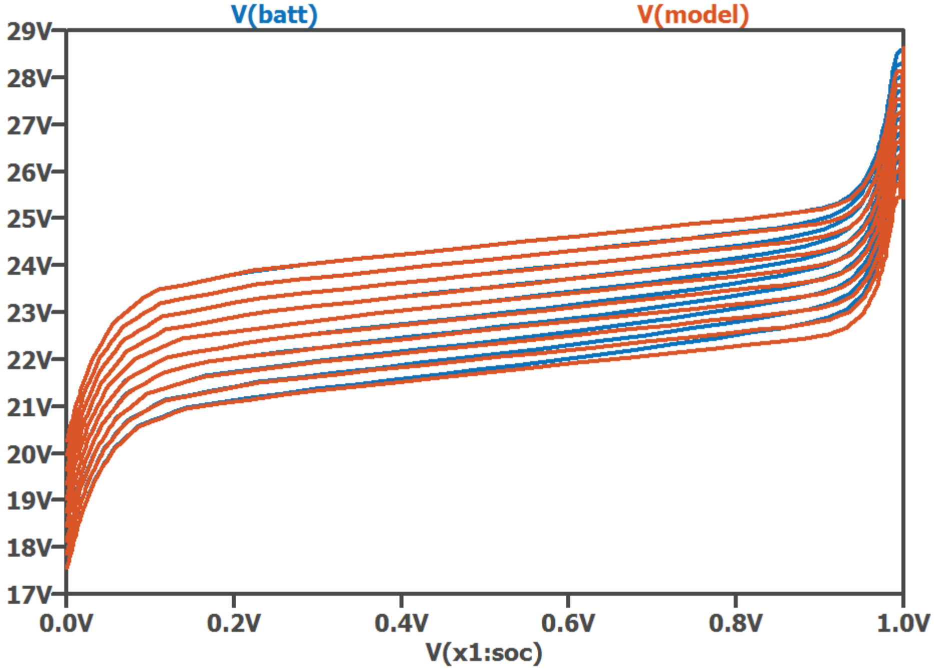
Model C: Zero-state Hysteresis

[Plett 2004]

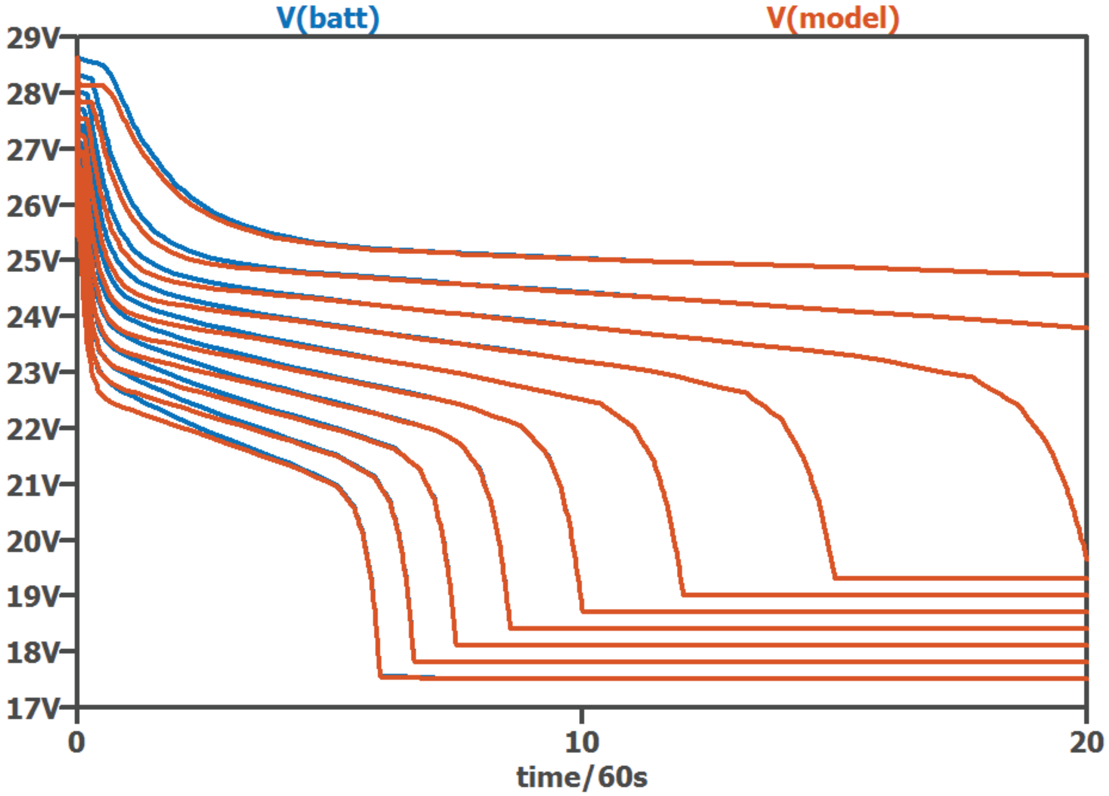


$$v_h = \begin{cases} V_H^+ & \text{if } i_{bat} > 0 \\ V_H^- & \text{if } i_{bat} < 0 \end{cases}$$

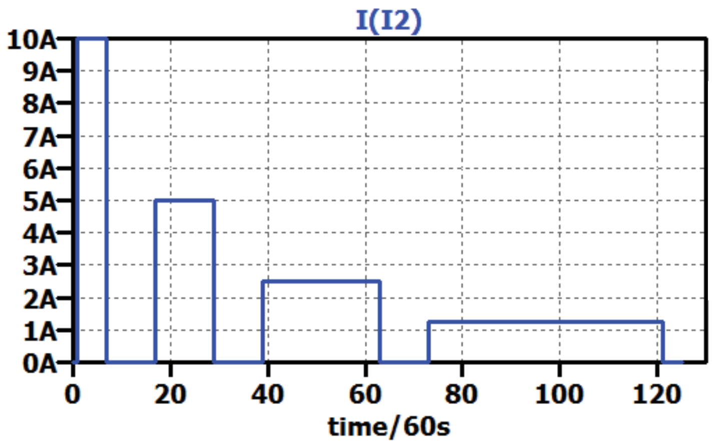
Model C Performance

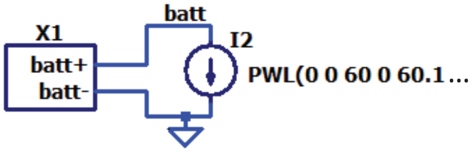


Model C Performance



Dynamic Performance

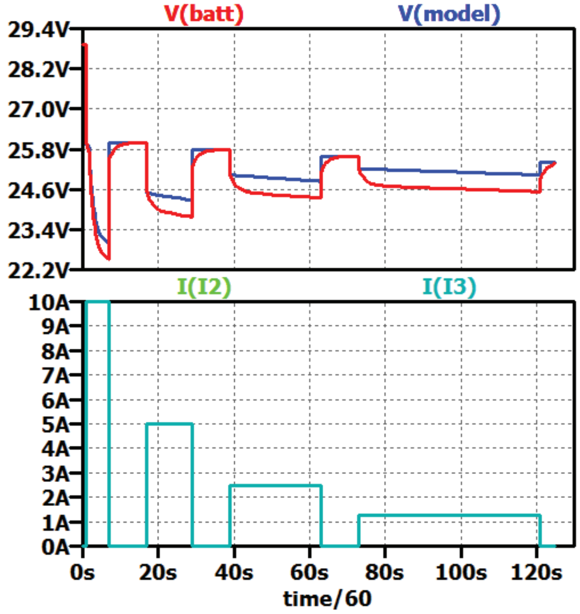




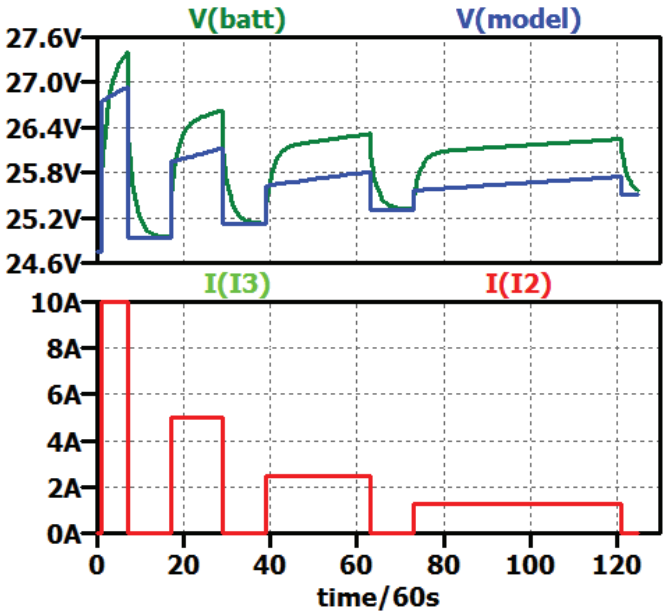
- Dynamic performance characterized by pulse train
- Constant percent of capacity per pulse [%Ahr] → not necessary

Dynamic Performance

Discharge

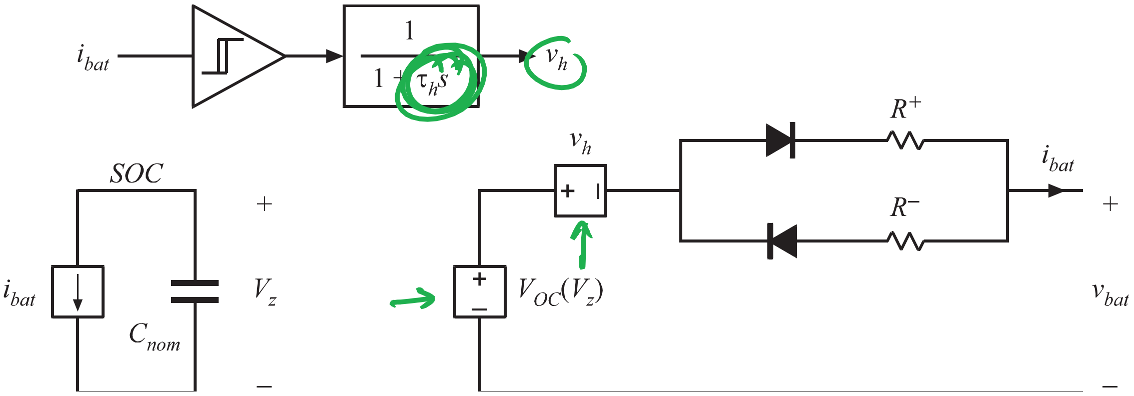


Charge

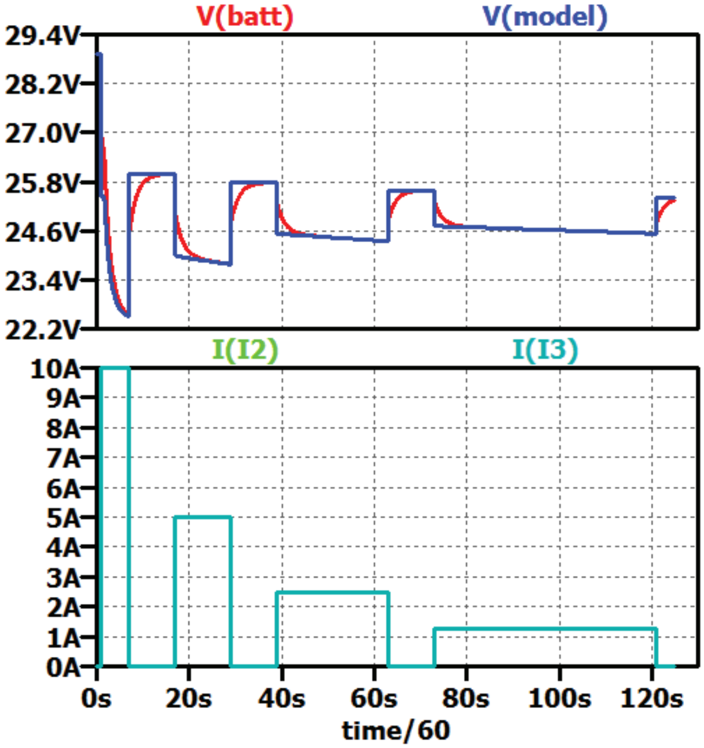


Model C1: One-state Hysteresis

[Plett 2004]

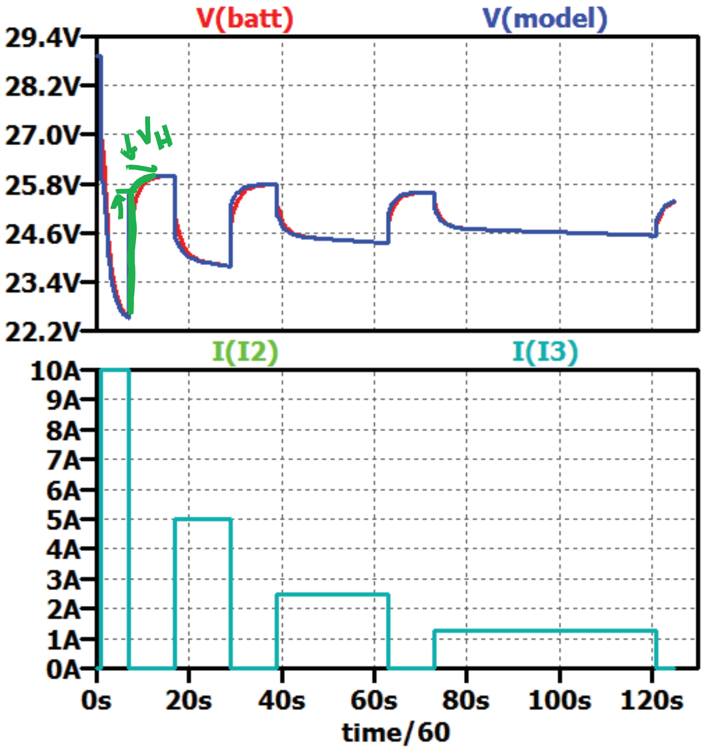


Model C~~1~~ Performance



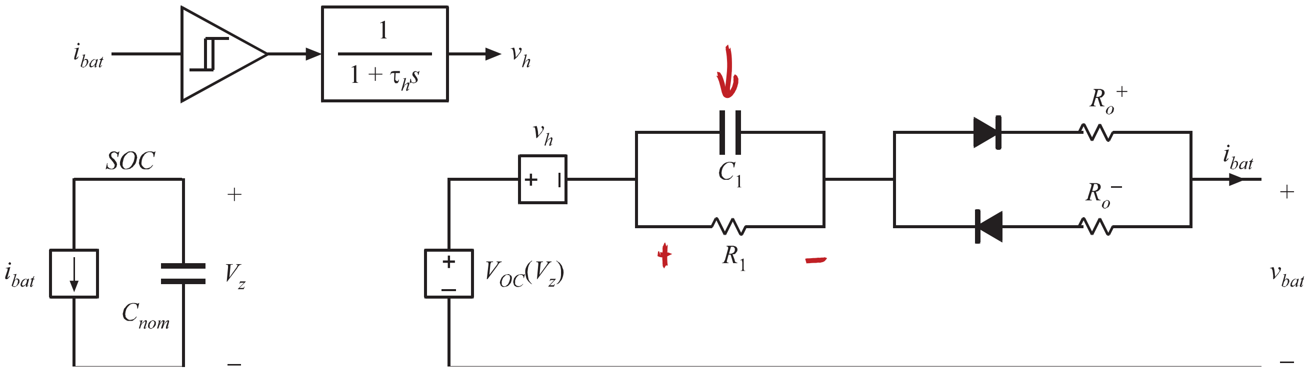
w/out dynamics of hysteresis

Model C1 Performance

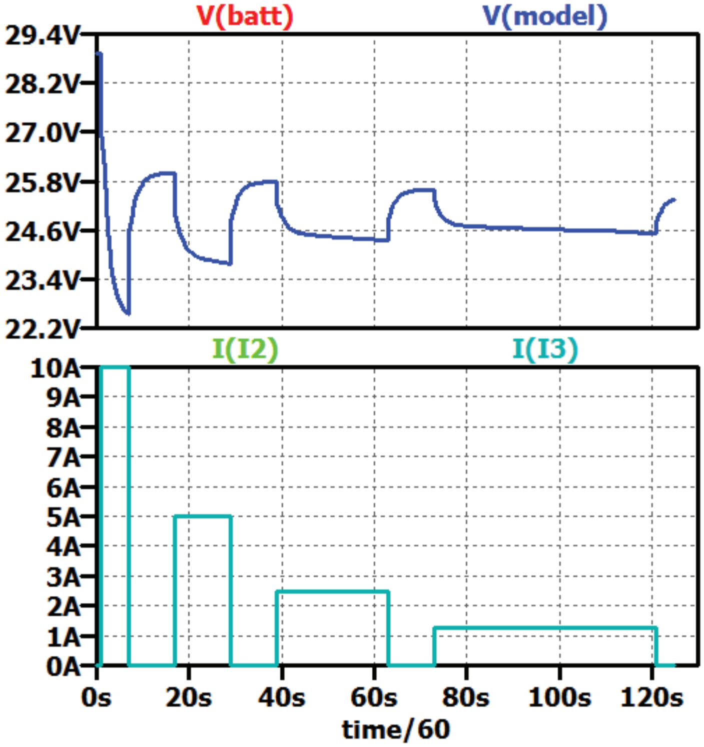


Model D: Diffusion (one-state)

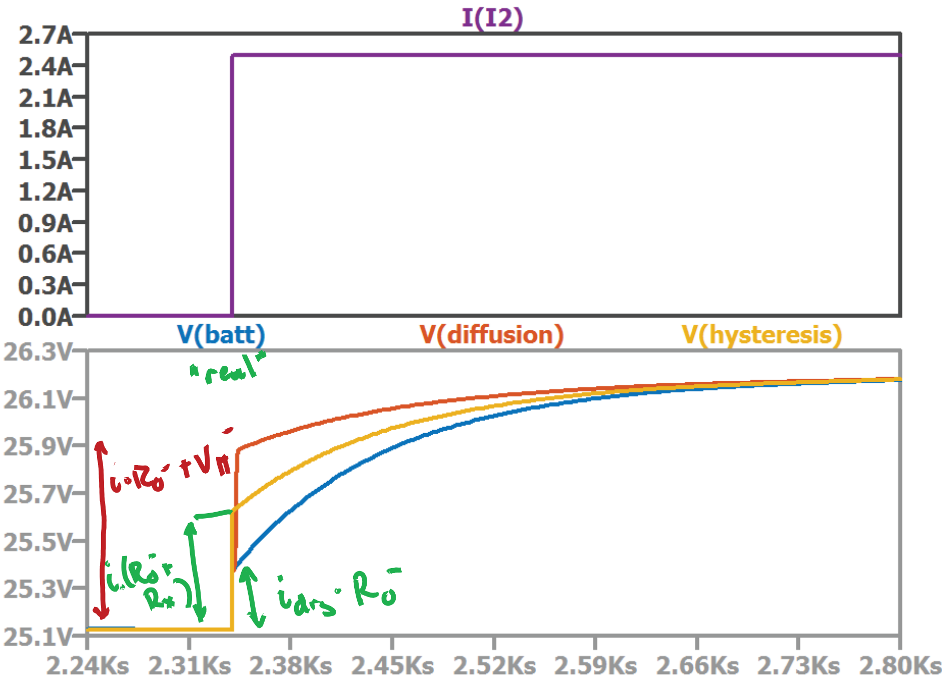
[Plett 2004]



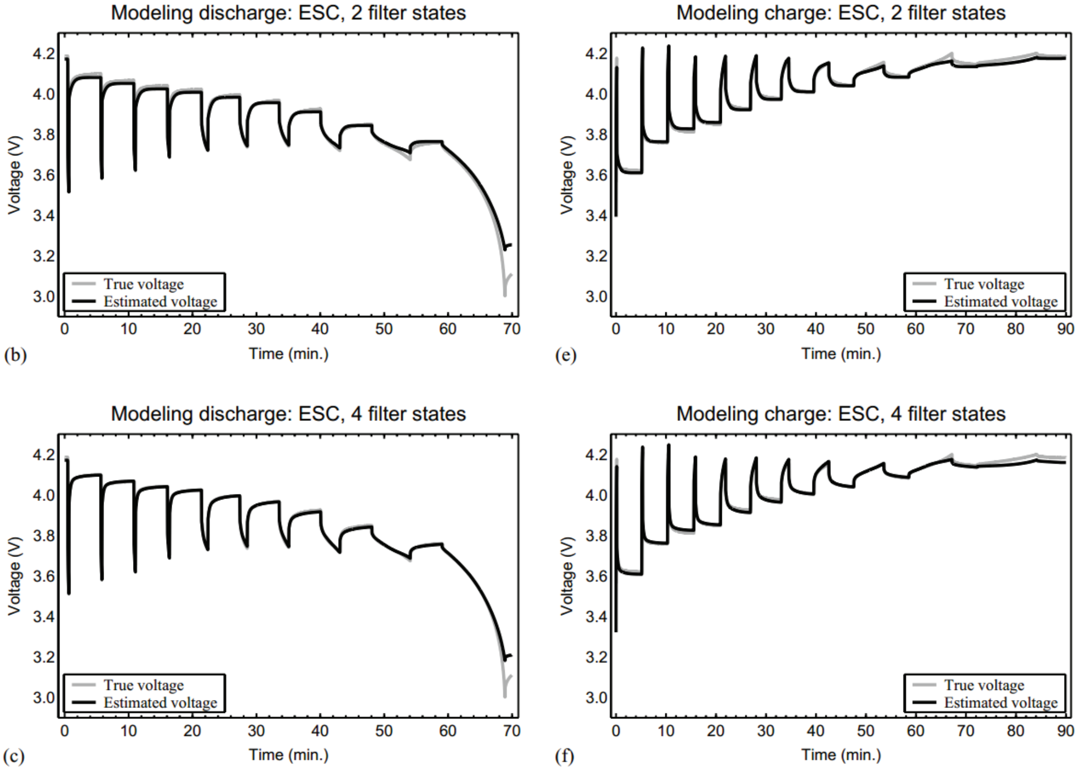
Model D Performance



Diffusion Vs Hysteresis

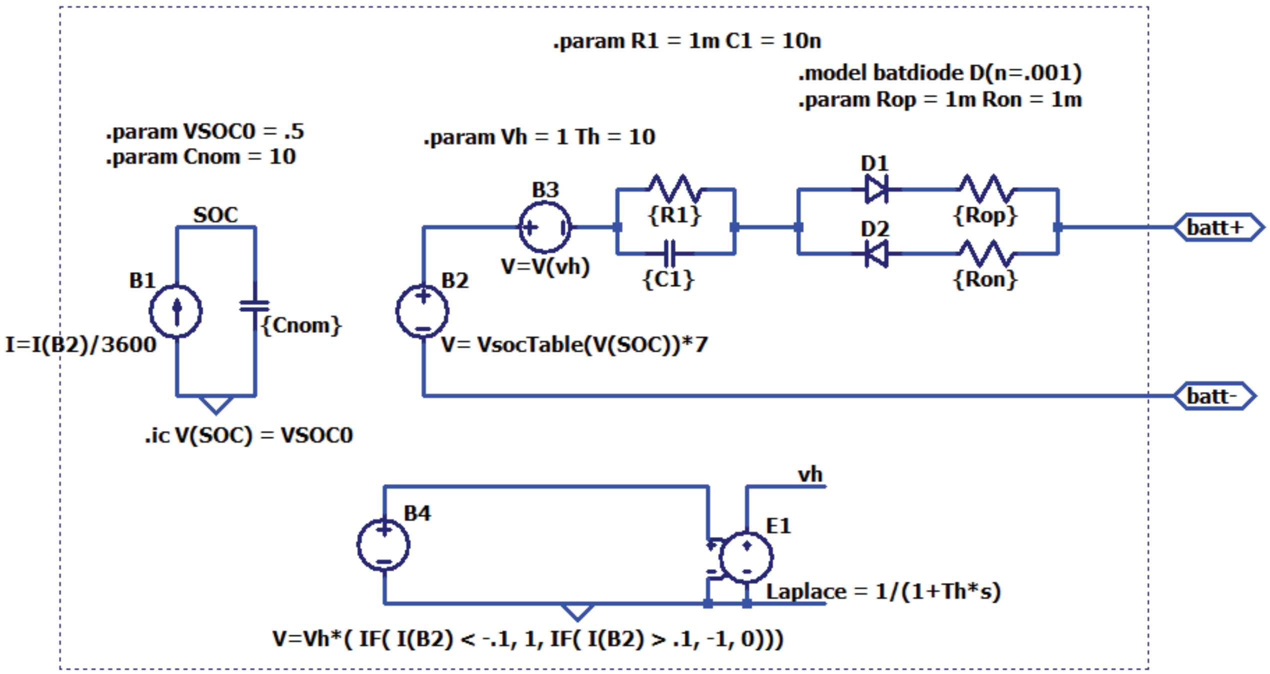


Experimental Results



[Plett 2004-2] G. Plett, "Extended Kalman Filtering for Battery Management Systems of LiPB-Based HEV Battery Packs—Part 2: Modeling and Identification," Journal of Power Sources, Vol. 134, No. 2, August 2004, pp. 262–76.

Implementation in LTSpice



```
.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

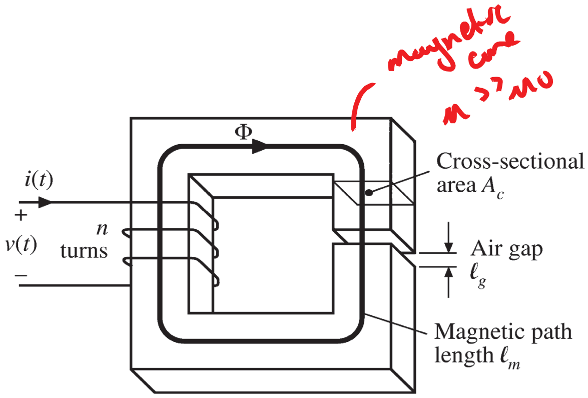
Battery BMS

- 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

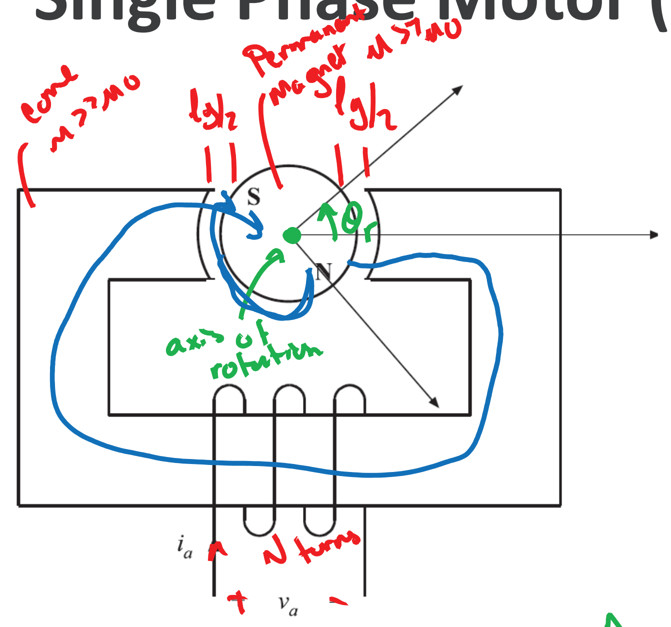
- http://web.eecs.utk.edu/~dcostine/ECE481/Fall2017/schedule.php
  - Lectures 35-36



$$L = \frac{\mu_0 l_g n^2}{A_c}$$

$$R = \frac{\rho n \, MLT}{A_w}$$

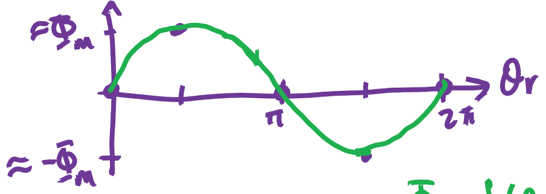
Single Phase Motor (Simplified)



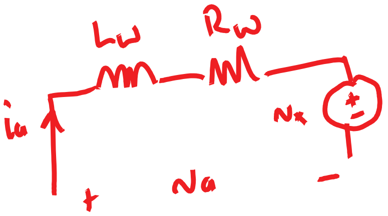
Assume magnet generates a peak flux Φ_m at $\theta_r = 90°$

if magnet rotates

$\Phi_{coil, magnet}$



Approximate $\Phi_{coil, magnet} = \Phi_m f(\theta_r)$ w/ $f(\theta_r) = \sin(\theta_r)$



if $\theta_r \to \theta_r(t)$

$$v_x = n \cdot \frac{d\Phi_{coil, magnet}}{dt} = n\Phi_m \frac{d}{dt}\sin(\theta_r(t))$$

Electromechanical Conversion

$$v_x = \underbrace{n\Phi_m}_{\lambda_m \text{ "flux linkage"}} \frac{d}{dt}\sin(\theta_r(t))$$

if magnet spins at constant rate

$$\frac{d\theta_r(t)}{dt} = \omega_r$$

$$v_x = \lambda_m \cos(\theta_r(t)) \frac{d\theta_r(t)}{dt}$$

$$\boxed{v_x = \lambda_m \omega_r \cos(\theta_r)}$$

look at power $P_a = i_a v_a$

$$P_a = \underbrace{i_a^2 R_w}_{\text{conduction Loss}} + \underbrace{i_a L_w \frac{di_a}{dt}}_{\text{reactive power}} + \underbrace{i_a \lambda_m \omega_r \cos\theta_r}_{\text{converted to mechanical power}}$$

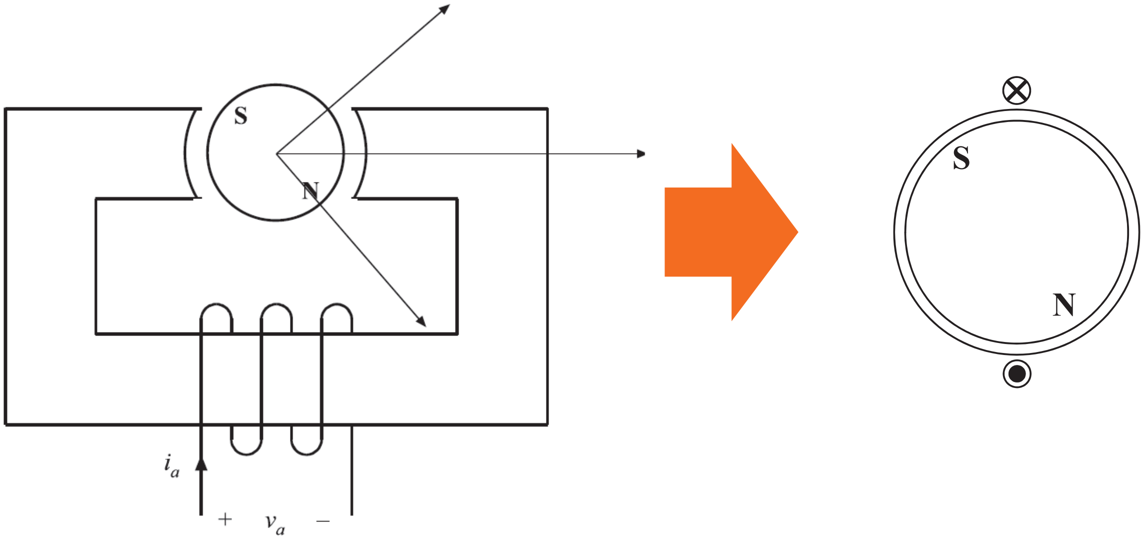
no matter how i_a is controlled $\tau_m \to \varnothing$ twice per period (bad)

$$\boxed{\tau_m = i_a \lambda_m \cos\theta_r}$$

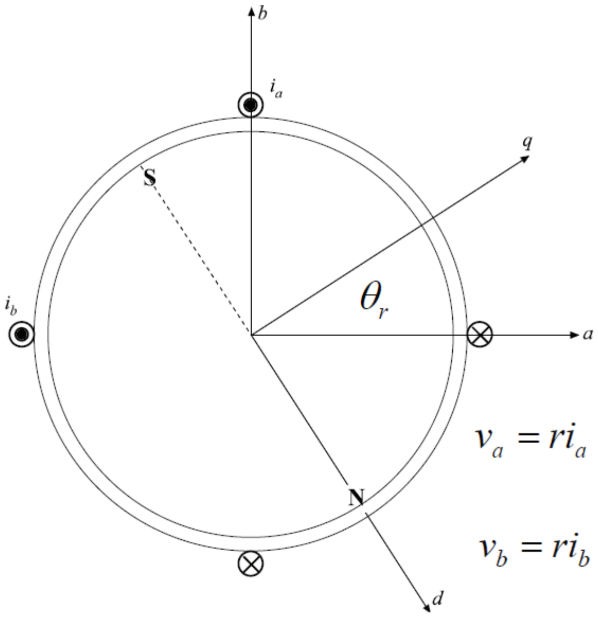
$$P_{mech} = \tau_m \omega_r$$

neglect friction / dynamics in motor

Alternative Diagram



2-Pole, 2-Phase PMSM



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

$$\lambda_a(\theta_r) = \lambda_M \sin(\theta_r)$$

$$\lambda_b(\theta_r) = -\lambda_M \cos(\theta_r)$$

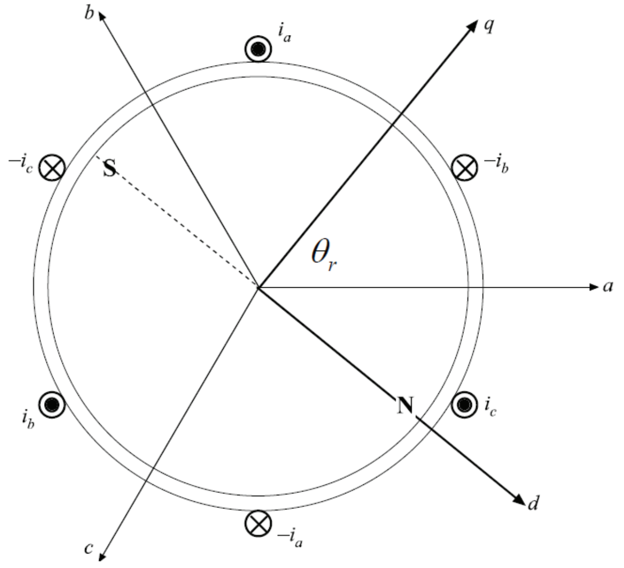
$$v_a = ri_a + \frac{d\lambda_a}{dt} = ri_a + L\frac{di_a}{dt} + \lambda_M \omega_r \cos(\theta_r)$$

$$v_b = ri_b + \frac{d\lambda_b}{dt} = ri_b + L\frac{di_b}{dt} + \lambda_M \omega_r \sin(\theta_r)$$

$$T_m = \lambda_M\left(i_a \cos(\theta_r) + i_b \sin(\theta_r)\right) = \lambda_m I_x$$

if $i_a = I_x \cos(\theta r)$
$i_b = I_x \sin(\theta r)$ → implies that currents need to be controlled to synchronize w/ motor

3-Phase, 2-Pole PMSM



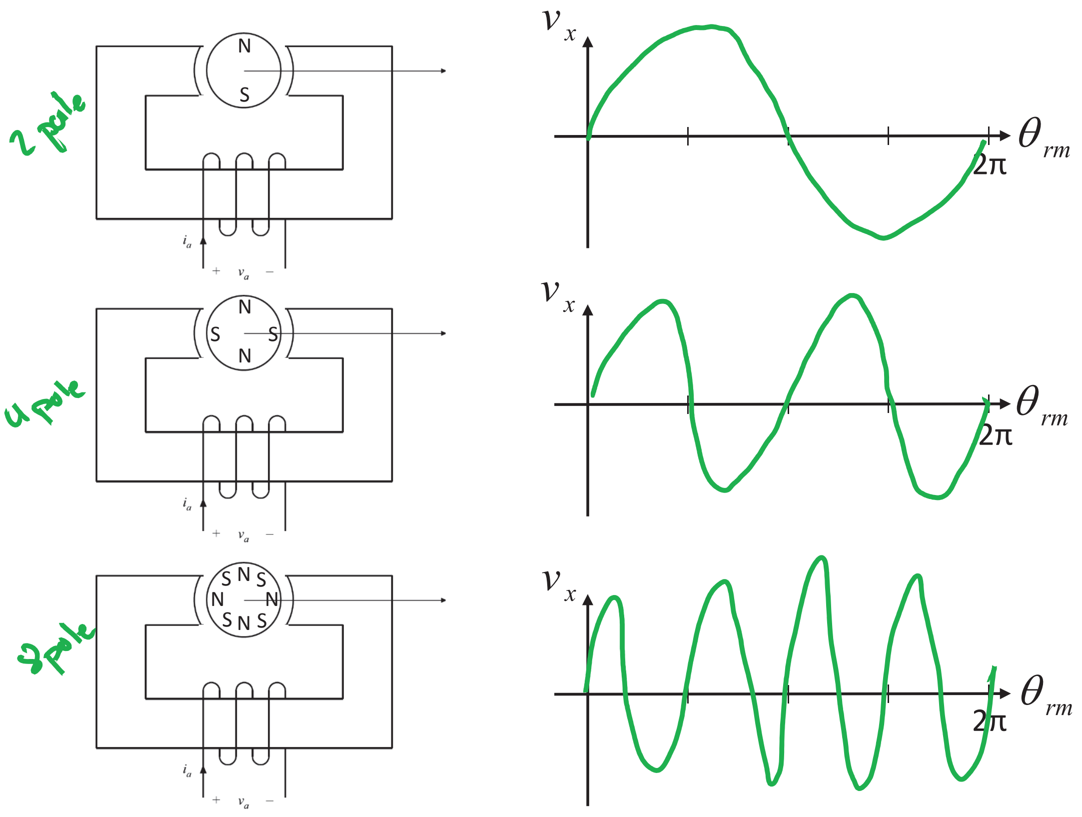
$$\lambda_a(\theta_r) = \lambda_m \sin(\theta_r)$$

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

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

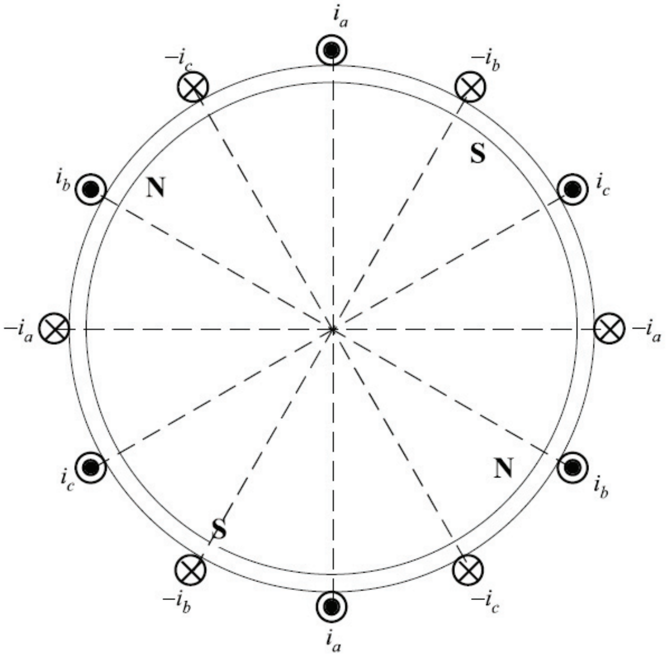
$$T_m = i_a \lambda_m \cancel{\omega_r} \cos(\theta_r) + i_b \lambda_m \cancel{\omega_r} \cos\left(\theta_r - \frac{2\pi}{3}\right) + i_c \lambda_m \cancel{\omega_r} \cos\left(\theta_r - \frac{4\pi}{3}\right)$$

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

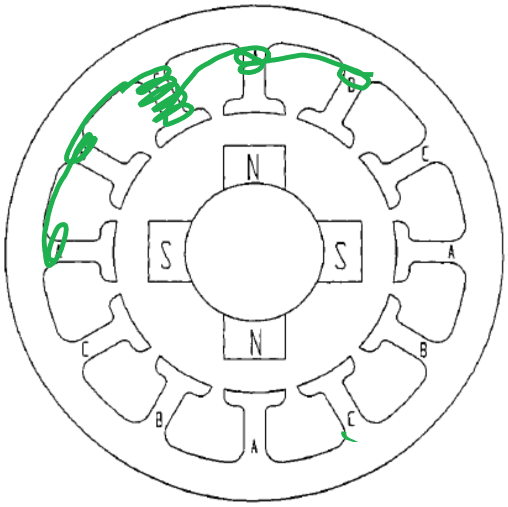
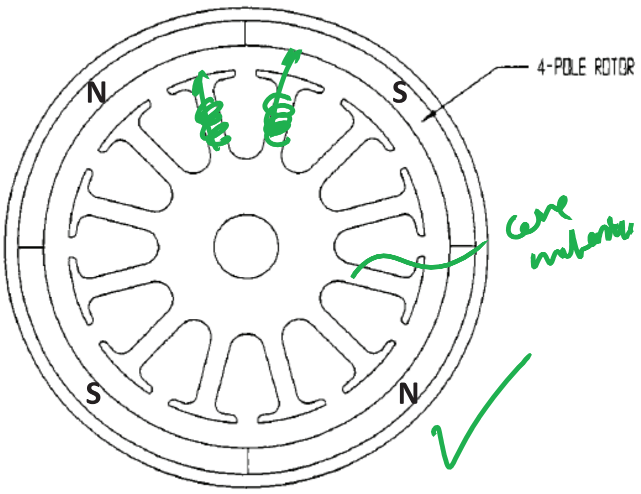


FIGURE 5.15 Multiphase inner-rotor motor.



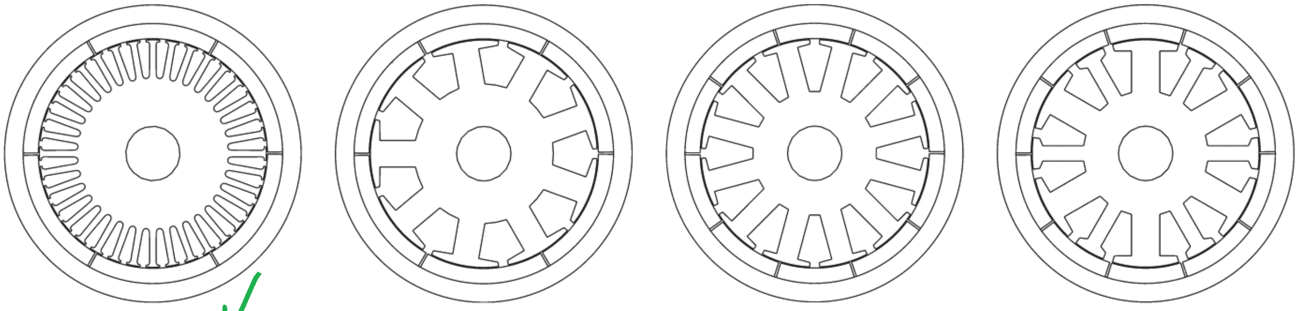
core material

✓

FIGURE 5.13 Multiphase outer-rotor motor.

- 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

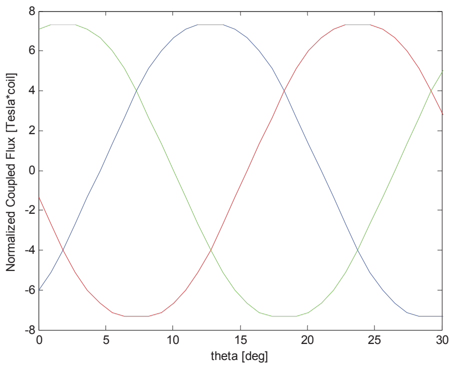
(c) 12–slot/10-pole (all teeth wound)

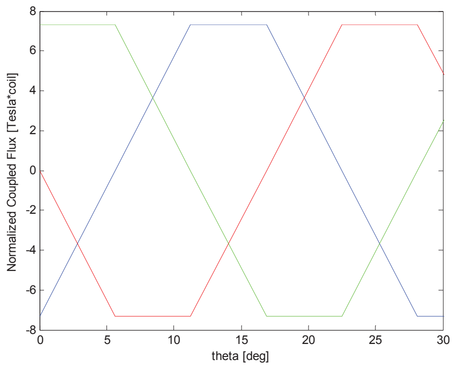
(d) 12-pole/10-pole (alternate teeth wound)

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

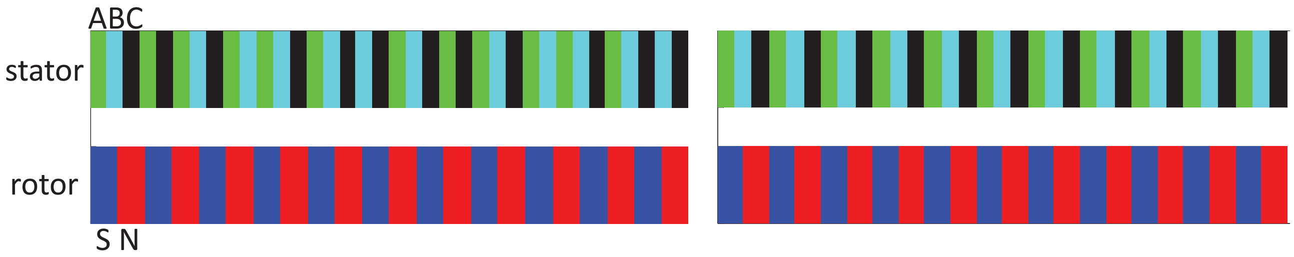
Shape of Back EMF



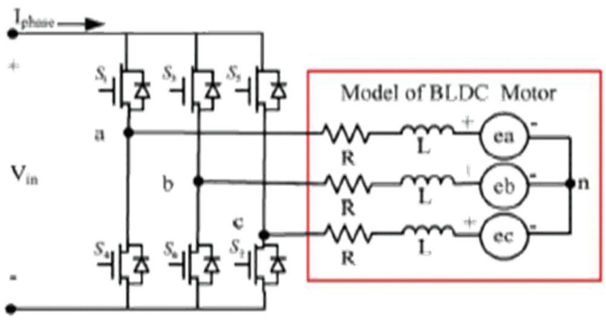


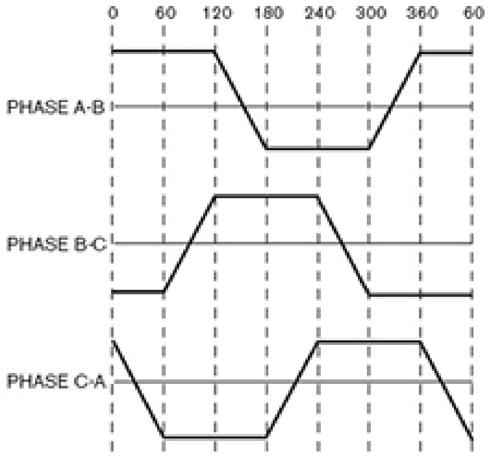
- 36 Teeth, 22 Poles
- Teeth/Pole/Phase = 0.5455

- 33 Teeth, 22 Poles
- Teeth/Pole/Phase = 0.5

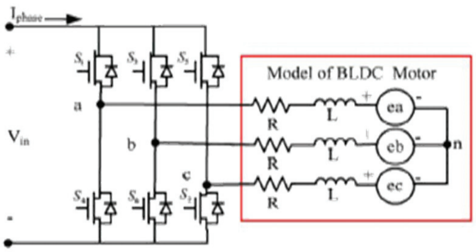


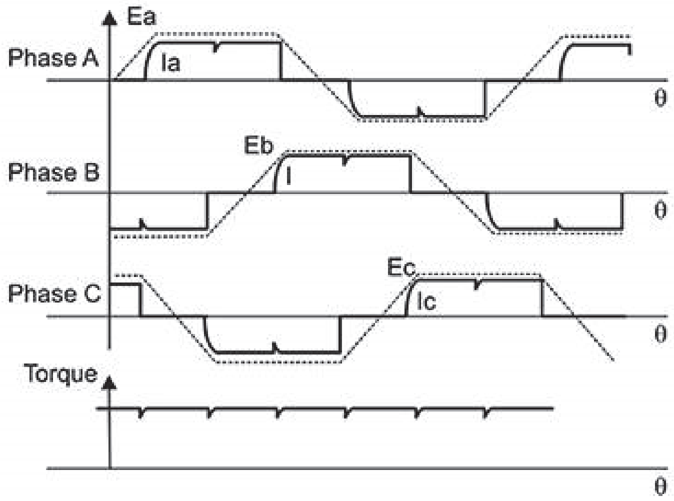
Motor Driver: Trapezoidal Control





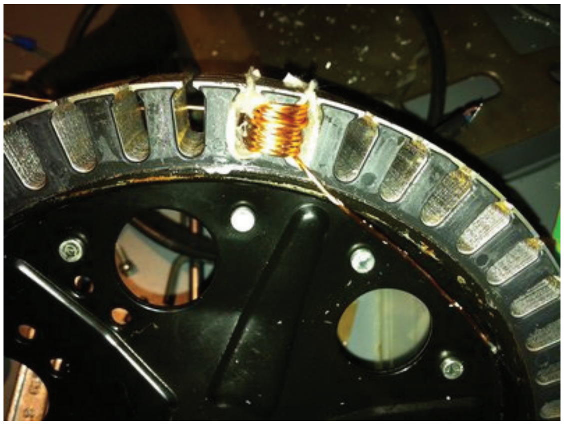
Torque Ripple





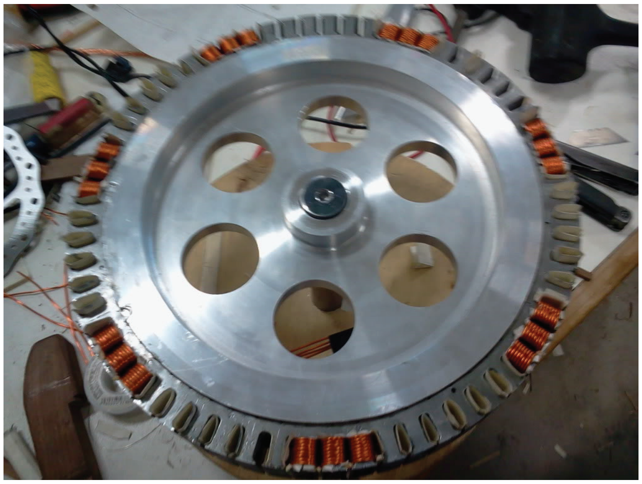
Example Front Wheel Hub Motor

E-bike hub (stator)

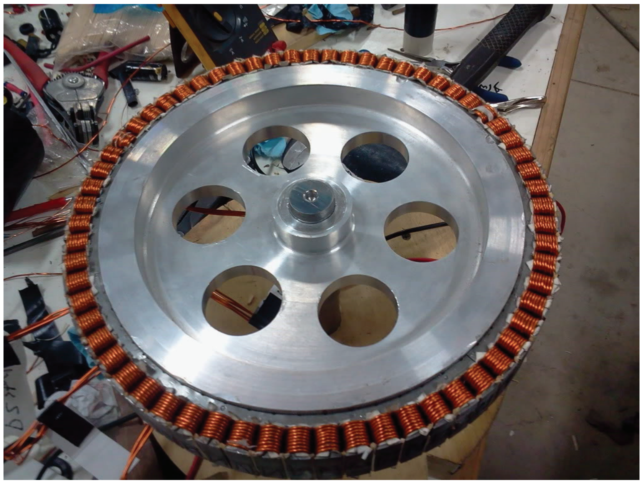


Single phase wound per tooth

Stator Winding



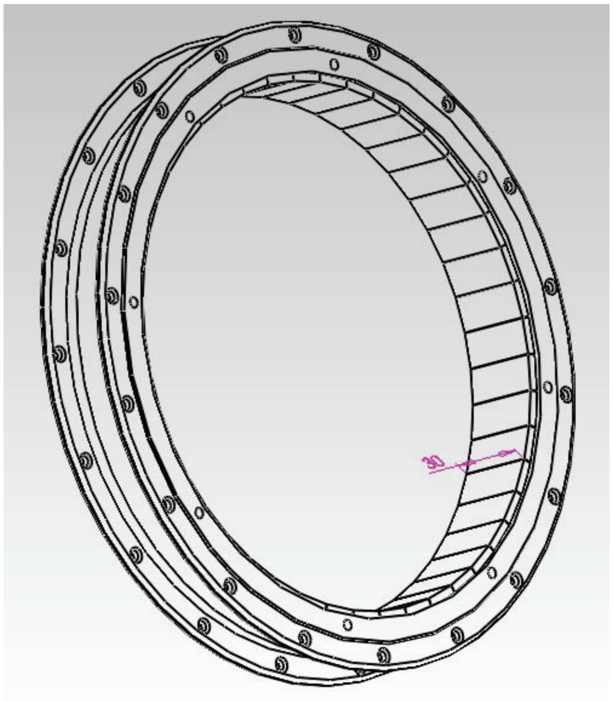
Complete winding of Phase A



Complete winding of all phases

56 pole
63 teeth

Rotor and Poles



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