Power Electronics Circuits

Prof. Daniel Costinett

ECE 482 Lecture 1
January 14, 2016

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TENNESSEE
KNOXVILLE

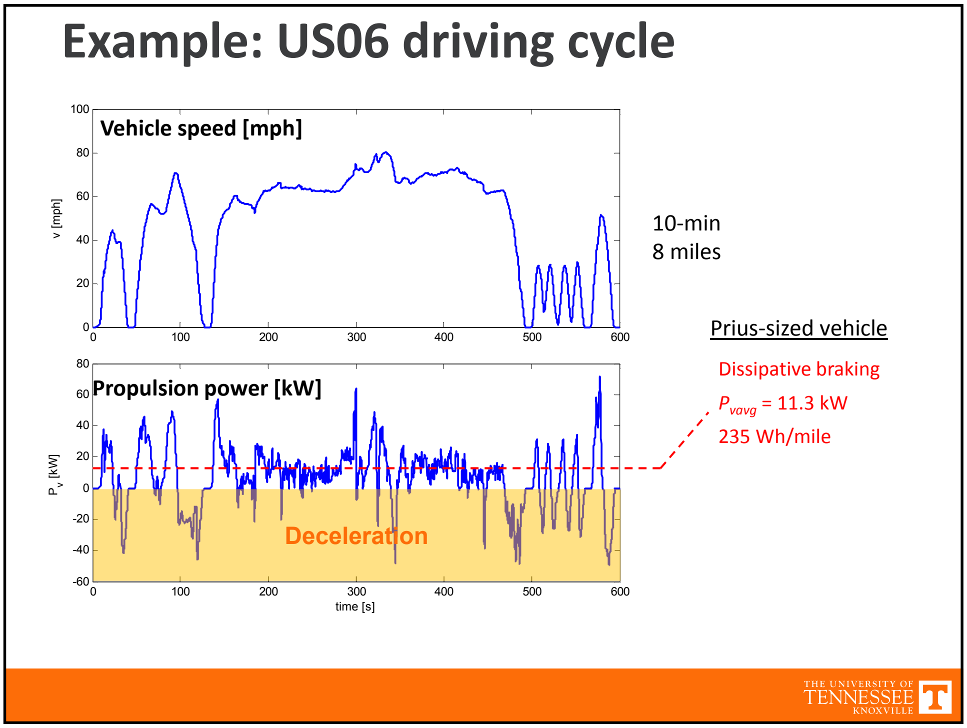
Transportation Electrification

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

Prius-sized vehicle

Dissipative braking

P_{vavg} = 11.3 kW

235 Wh/mile

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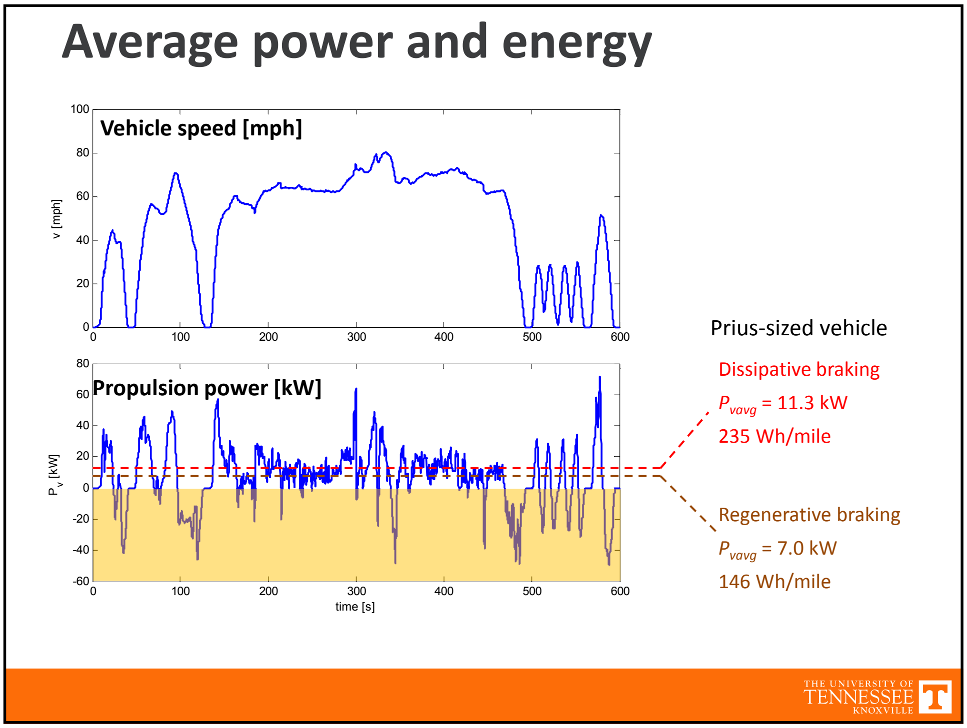

Average power and energy

Prius-sized vehicle

Dissipative braking

P_{vavg} = 11.3 kW

235 Wh/mile

Regenerative braking

P_{vavg} = 7.0 kW

146 Wh/mile

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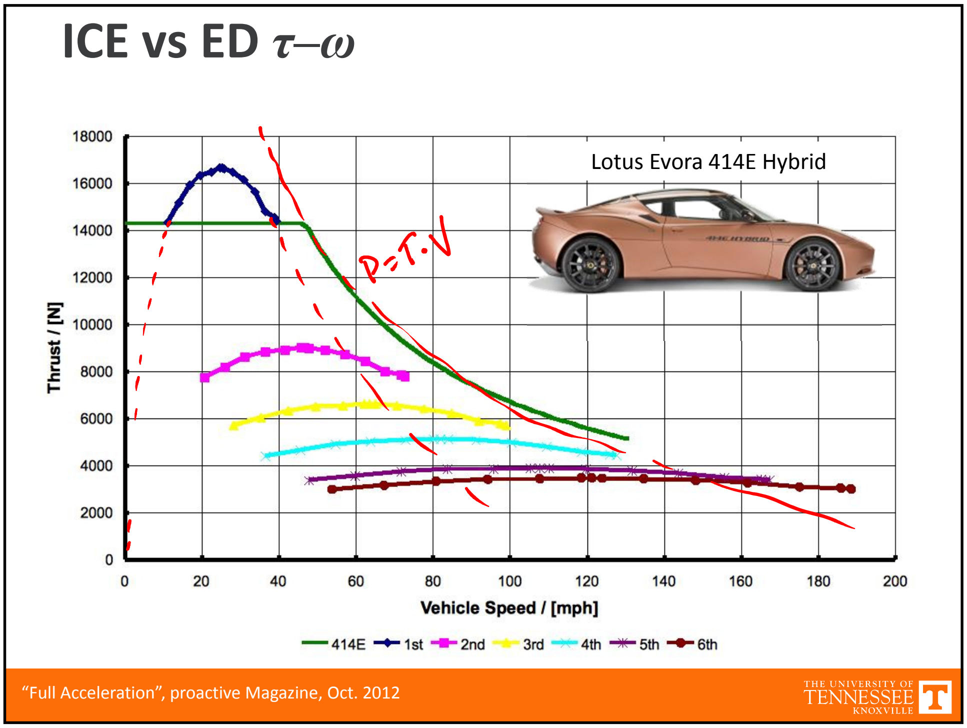
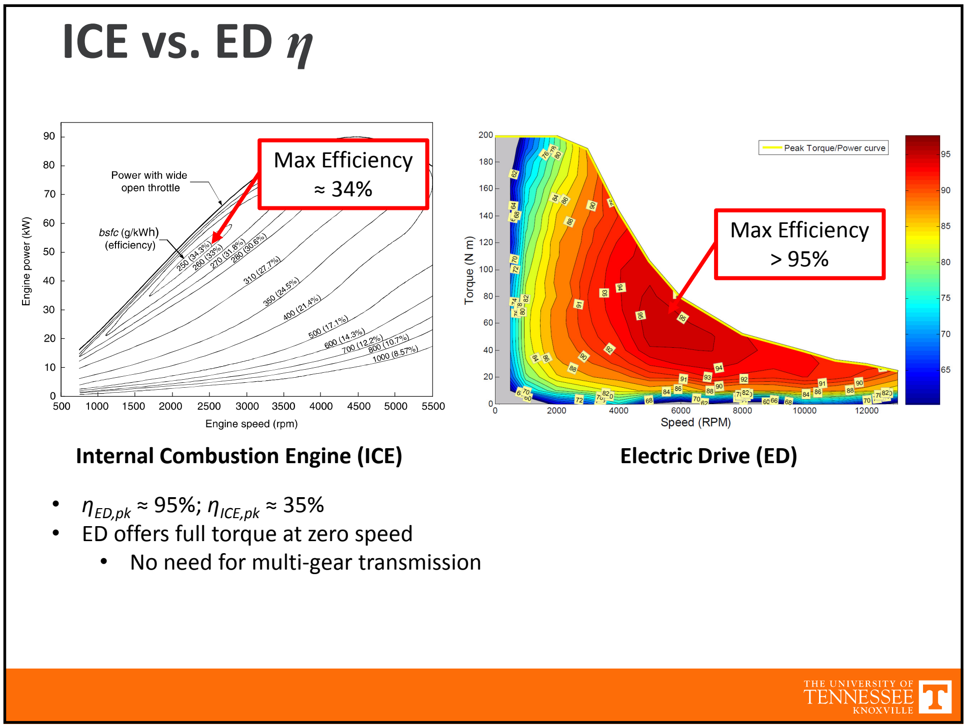


ICE vs ED τ–ω

“Full Acceleration”, proactive Magazine, Oct. 2012



ICE vs. ED η

Internal Combustion Engine (ICE)

Electric Drive (ED)

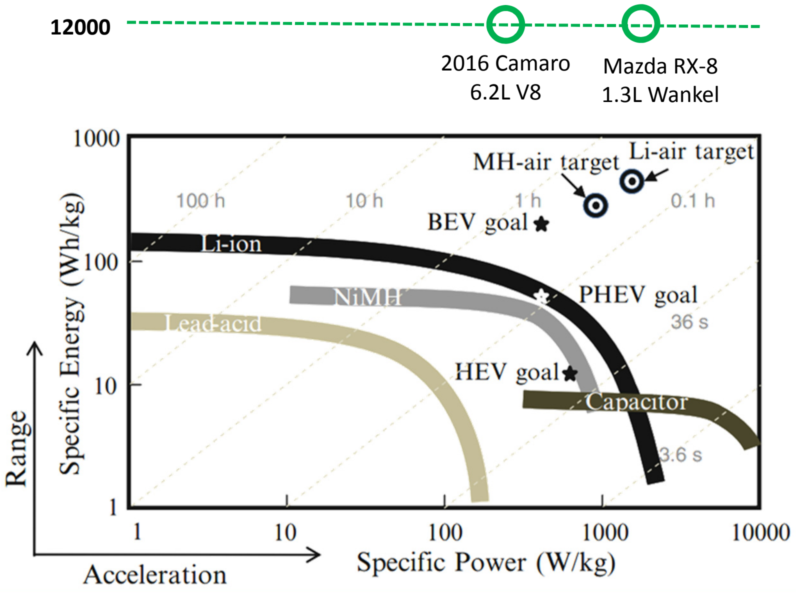
- $\eta_{ED,pk} \approx 95\%$; $\eta_{ICE,pk} \approx 35\%$
- ED offers full torque at zero speed
  - No need for multi-gear transmission

Conventional Vs. Electric Vehicle

(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]

Energy and Power Density of Storage

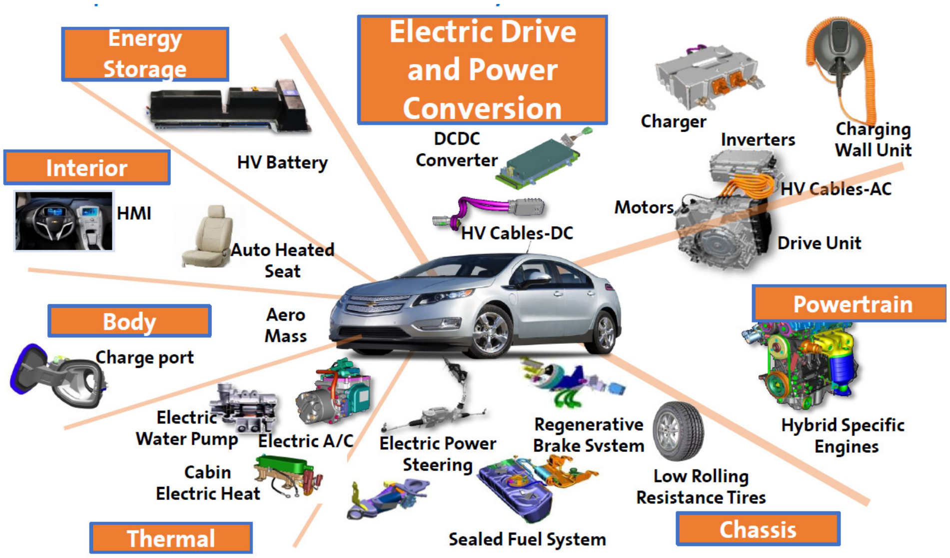


Conventional Vs. Electric Vehicle

(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

Power Electronics in Electric Vehicles



Energy Storage

HV Battery

Electric Drive and Power Conversion

DCDC Converter

HV Cables-DC

Charger

Inverters

Charging Wall Unit

HV Cables-AC

Motors

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

Chassis

Electric Power Steering

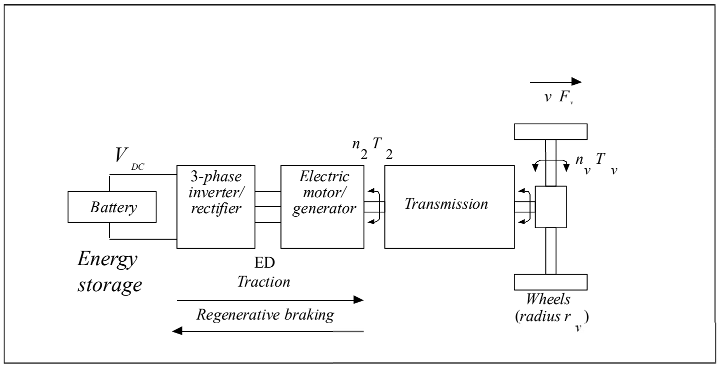
Regenerative Brake System

Low Rolling Resistance Tires

Sealed Fuel System

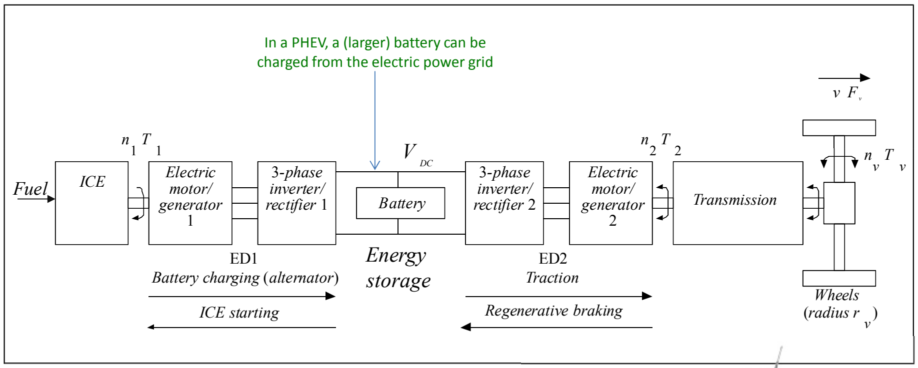
Peter Savagian, “Barriers to the Electrification of the Automobile,” Plenary session, ECCE 2014

BEV Architecture



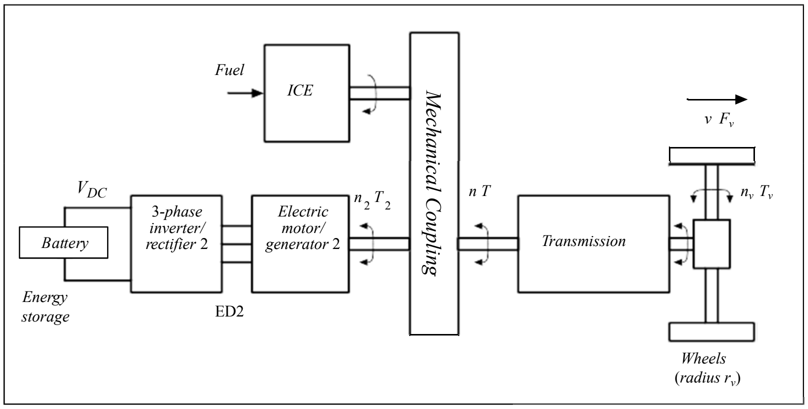
Example: Tesla Roadster
- 215 kW electric drive ED1 (sport model)
- 53 kWh Li-ion battery

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

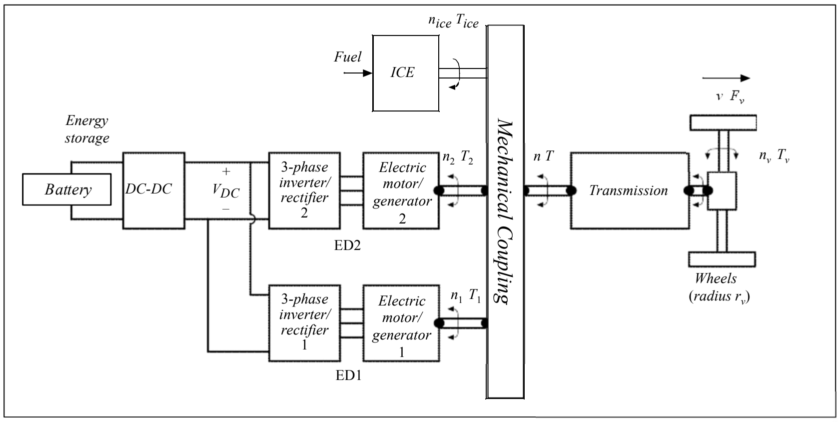
Parallel HEV



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

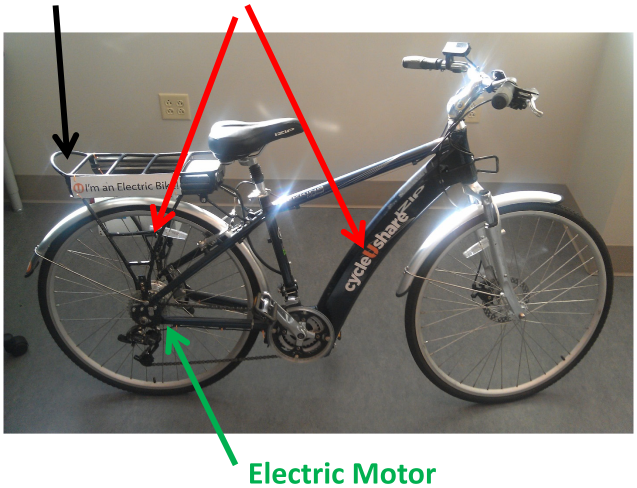
Series/Parallel HEV



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 Bicycle Platform

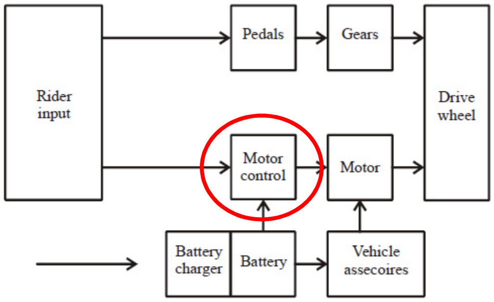


Battery

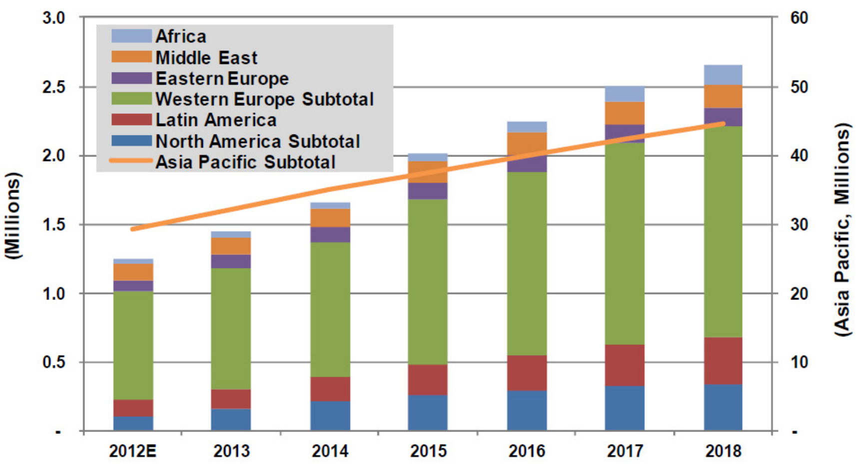
Power Conversion and Control

Electric Motor

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
  - http://web.eecs.utk.edu/courses/spring2016/ece482/

either

- 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: MK502
  - 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

  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
- Lab kit is required (purchased from circuits store) in ~1-2 weeks
  - Price: $100-150 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, 1/19
- Late work **will not** be accepted except in cases of documented emergencies
- Due dates posted on website course schedule

Individual

- Pre-Lab Assignments
  - 15% of total grade
  - Turn in one per individual
- In-lab Demonstrations
  - 10% of total grade
  - Questions asked to each group member
- Midterm Exam
  - 15% of total grade
  - Open book/notes, in-class
  - Covers material from experiments
- Peer Evaluation
  - 10% of total grade

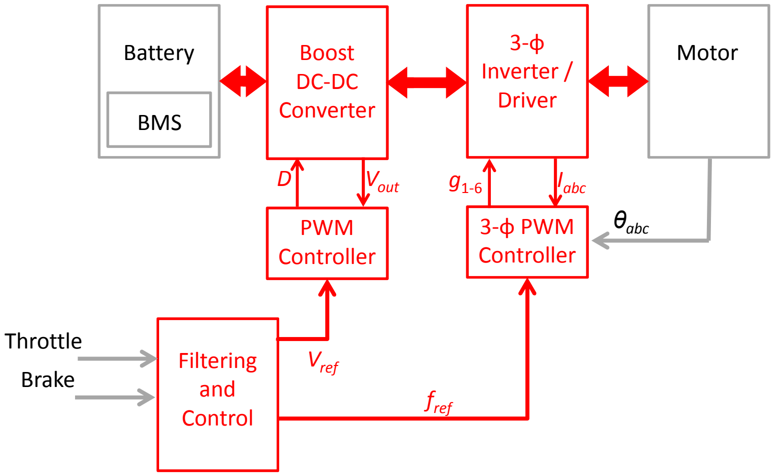
Use of Lab Time

- 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
  - Feedback Loop Design
  - Layout of Power Electronics Circuits
  - Electric Motor Drivers
  - BLDC and PMSM Control Methods
  - System-Level Control Design

System Structure



Battery

BMS

Boost DC-DC Converter

3-ϕ Inverter / Driver

Motor

D

V_{out}

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

I_{abc}

PWM Controller

3-ϕ PWM Controller

θ_{abc}

Throttle

Brake

Filtering and Control

V_{ref}

f_{ref}

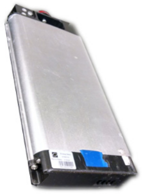
Experiment 1

Battery

BMS

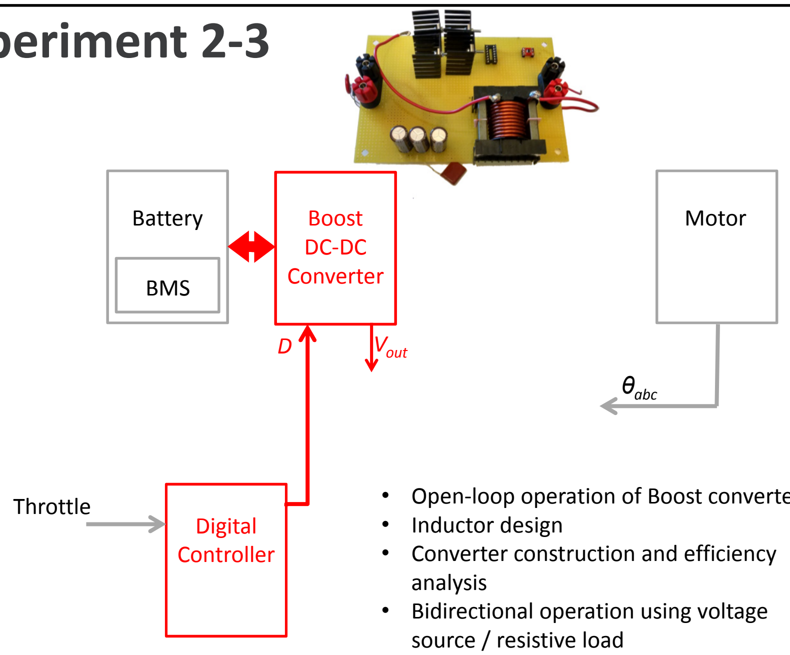
Motor

θ_{abc}



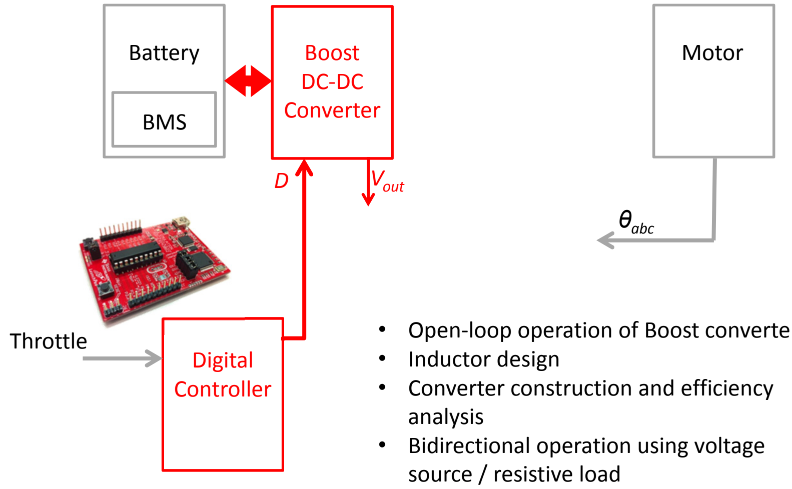
- Identification and characterization of motor
- Modeling of motor using simulink
- Derivation of model parameters from experimental data

Experiment 2-3



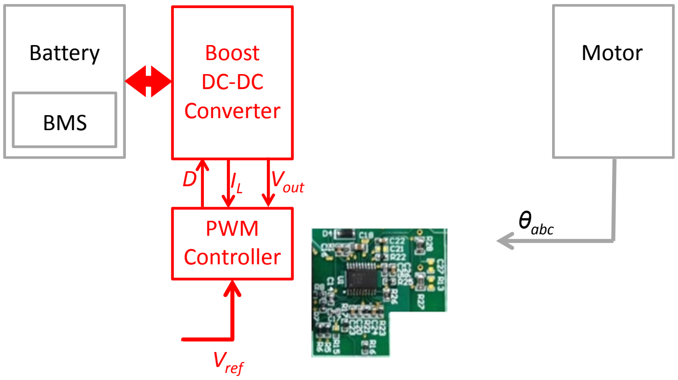
- Open-loop operation of Boost converter
- Inductor design
- Converter construction and efficiency analysis
- Bidirectional operation using voltage source / resistive load

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



Battery

BMS

Boost DC-DC Converter

Motor

D

I_L

V_{out}

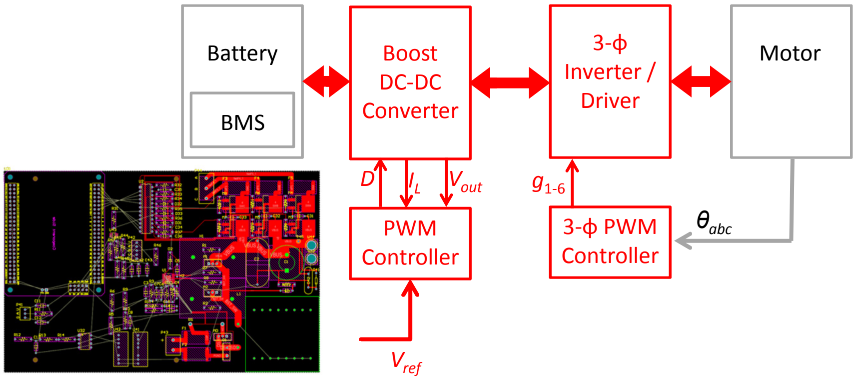
PWM Controller

θ_{abc}

V_{ref}

- 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}

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

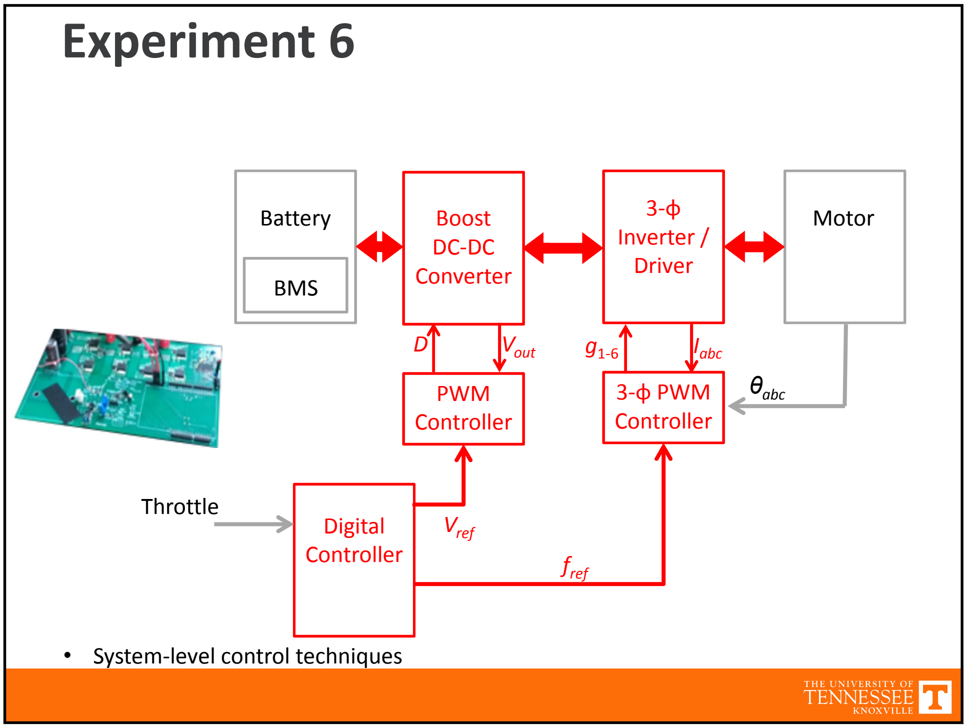
PWM Controller

3-ϕ PWM Controller

θ_{abc}

V_{ref}

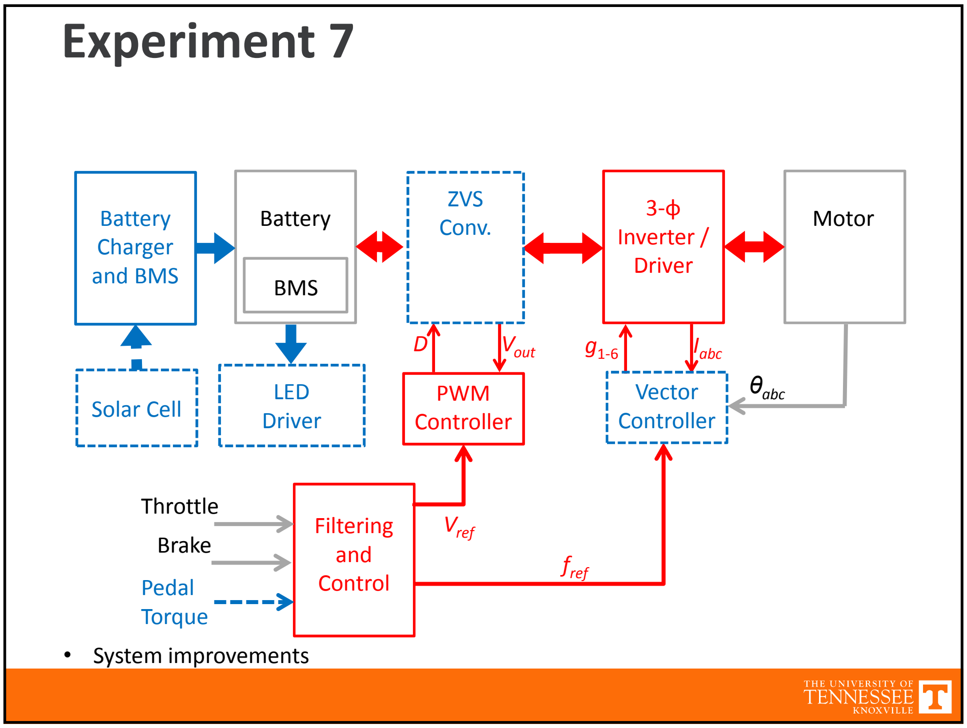
- Circuit layout and PCB design
- Device selection and implementation according to loss analysis
- Basic control of BLDC motors



Experiment 6

Battery
BMS
Boost DC-DC Converter
3-ϕ Inverter / Driver
Motor
D
V_{out}
$g_{1\text{-}6}$
I_{abc}
θ_{abc}
PWM Controller
3-ϕ PWM Controller
Throttle
Digital Controller
V_{ref}
f_{ref}

- System-level control techniques

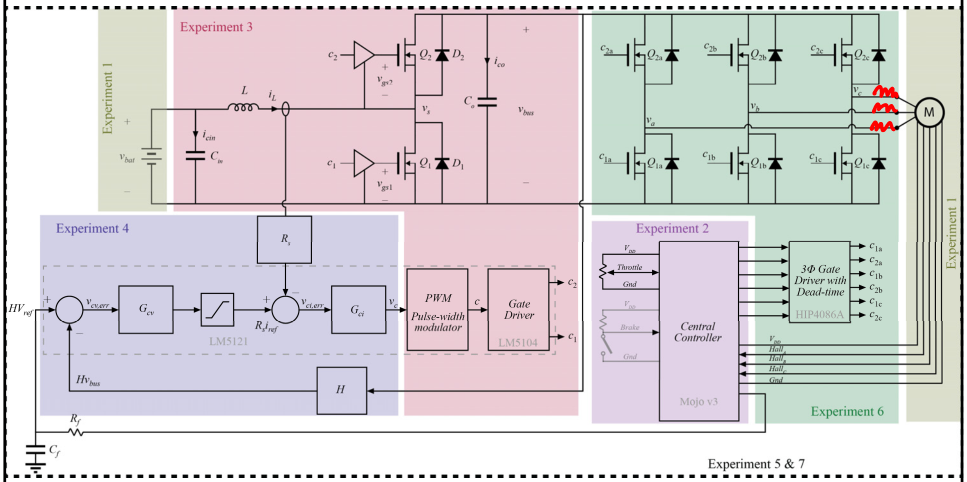


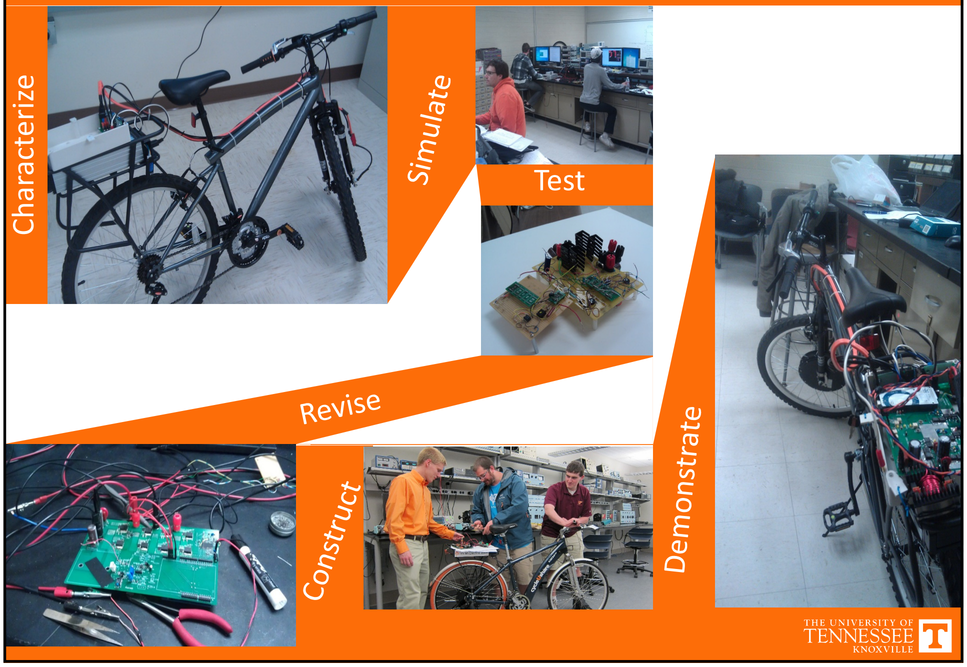
Experiment 7

Battery Charger and BMS
Battery
BMS
ZVS Conv.
3-ϕ Inverter / Driver
Motor
Solar Cell
LED Driver
D
V_{out}
$g_{1\text{-}6}$
I_{abc}
θ_{abc}
PWM Controller
Vector Controller
Throttle
Brake
Pedal Torque
Filtering and Control
V_{ref}
f_{ref}

- System improvements

Example System Implementation





Characterize

Simulate

Test

Revise

Construct

Demonstrate

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 100 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

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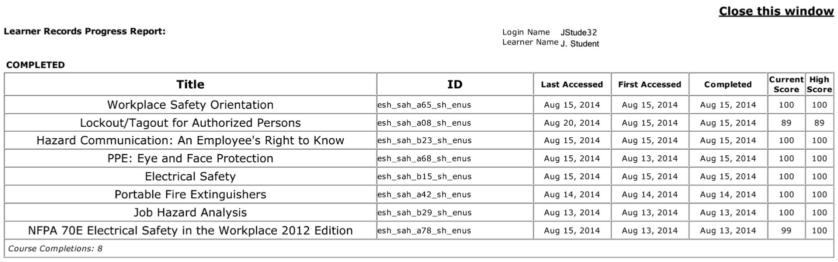
Safety training Requirements

- Log in to SkillSoft at https://oit2.utk.edu/cbt/login.php
- Once all training is completed print your Skillsoft Learner Records Progress Report and send it to Dr. Costinett
- Must complete with passing scores before Thursday 1/21



Learner Records Progress Report:

Login Name JStude32
Learner Name J. Student

COMPLETED

Title	ID	Last Accessed	First Accessed	Completed	Current Score	High Score
Workplace Safety Orientation	esh_sah_a65_sh_enus	Aug 15, 2014	Aug 15, 2014	Aug 15, 2014	100	100
Lockout/Tagout for Authorized Persons	esh_sah_a08_sh_enus	Aug 20, 2014	Aug 15, 2014	Aug 15, 2014	89	89
Hazard Communication: An Employee's Right to Know	esh_sah_b23_sh_enus	Aug 15, 2014	Aug 15, 2014	Aug 15, 2014	100	100
PPE: Eye and Face Protection	esh_sah_a68_sh_enus	Aug 15, 2014	Aug 13, 2014	Aug 15, 2014	100	100
Electrical Safety	esh_sah_b15_sh_enus	Aug 15, 2014	Aug 15, 2014	Aug 15, 2014	100	100
Portable Fire Extinguishers	esh_sah_a42_sh_enus	Aug 14, 2014	Aug 14, 2014	Aug 14, 2014	100	100
Job Hazard Analysis	esh_sah_b29_sh_enus	Aug 13, 2014	Aug 13, 2014	Aug 13, 2014	100	100
NFPA 70E Electrical Safety in the Workplace 2012 Edition	esh_sah_a78_sh_enus	Aug 15, 2014	Aug 13, 2014	Aug 13, 2014	99	100

Course Completions: 8

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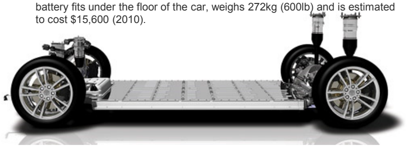
Lab 1

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

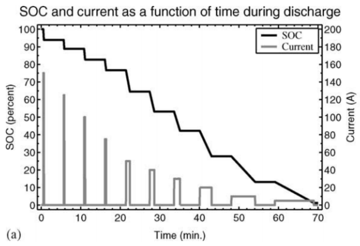
Objective:

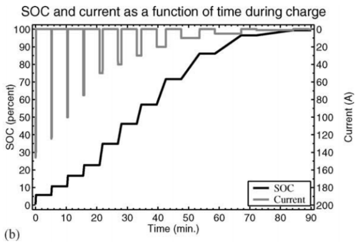
- Dynamic circuit model capable of predicting cell voltage in response to charge/discharge current, temperature

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 Capacity and C-rate

- Known beforehand:

→ Nominal Capacity : 10 A·hr

Nominal Voltage : 25.9V

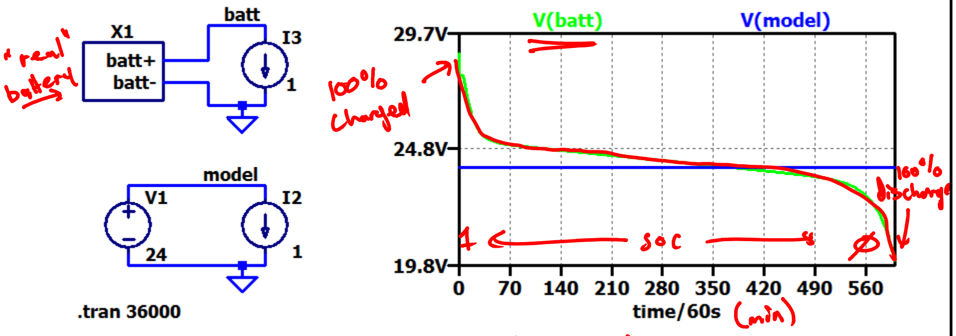
Maximum discharge rate : 1.9C → 19A

Maximum charge rate : 0.2C → 2A

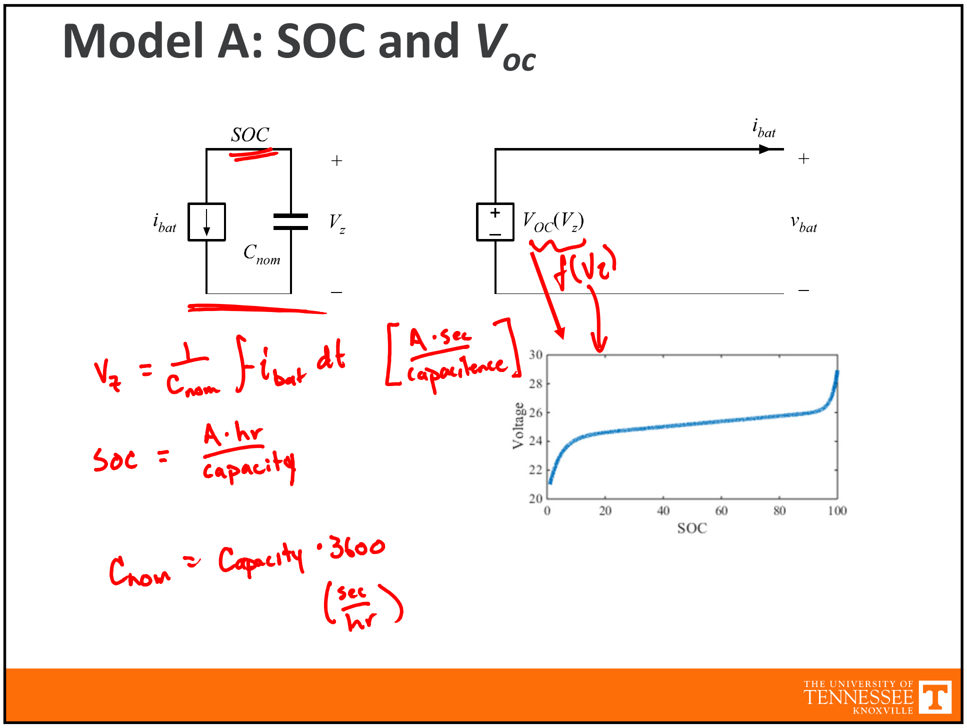
↕ "capacity"

In Exp 1 don't use more than 10A

Model 0: Voltage Source



"State of Charge" (soc)

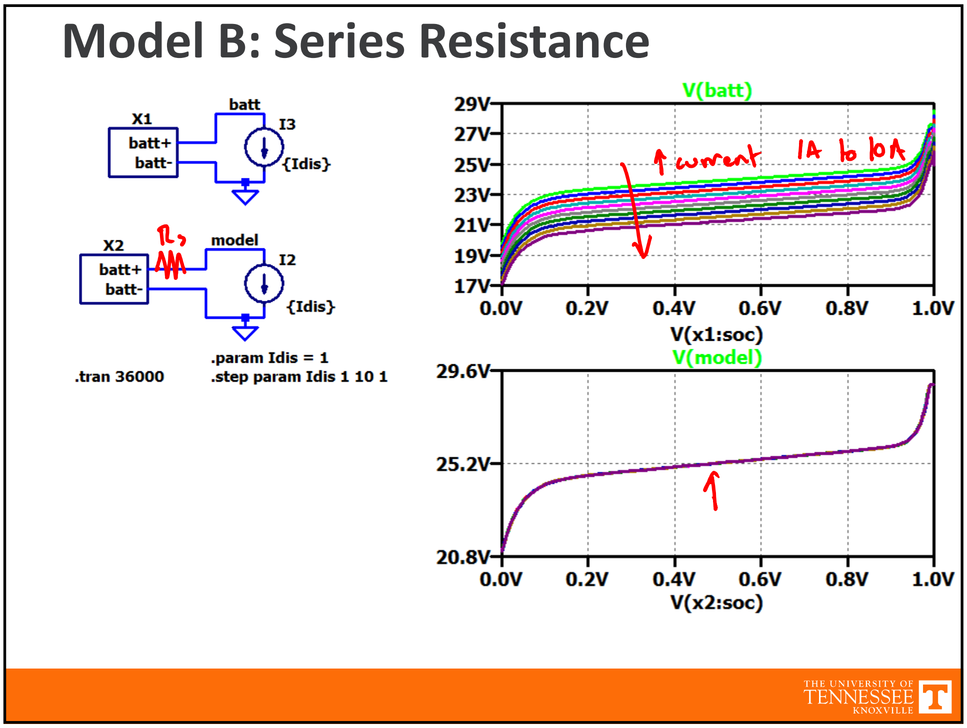


Model A: SOC and V_{oc}

$V_z = \frac{1}{C_{nom}} \int i_{bat}\, dt$ $\left[\frac{A \cdot sec}{capacitance}\right]$

$SOC = \frac{A \cdot hr}{capacity}$

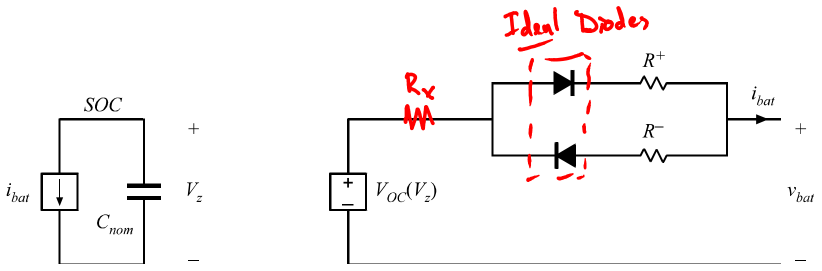
$C_{nom} = Capacity \cdot 3600$
$\left(\frac{sec}{hr}\right)$



Model B: Series Resistance

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

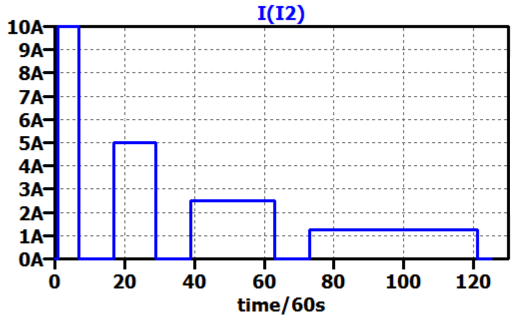
Model B: Series Resistance

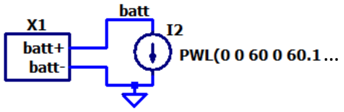


$R_{discharging}$: $R_x + R^+$

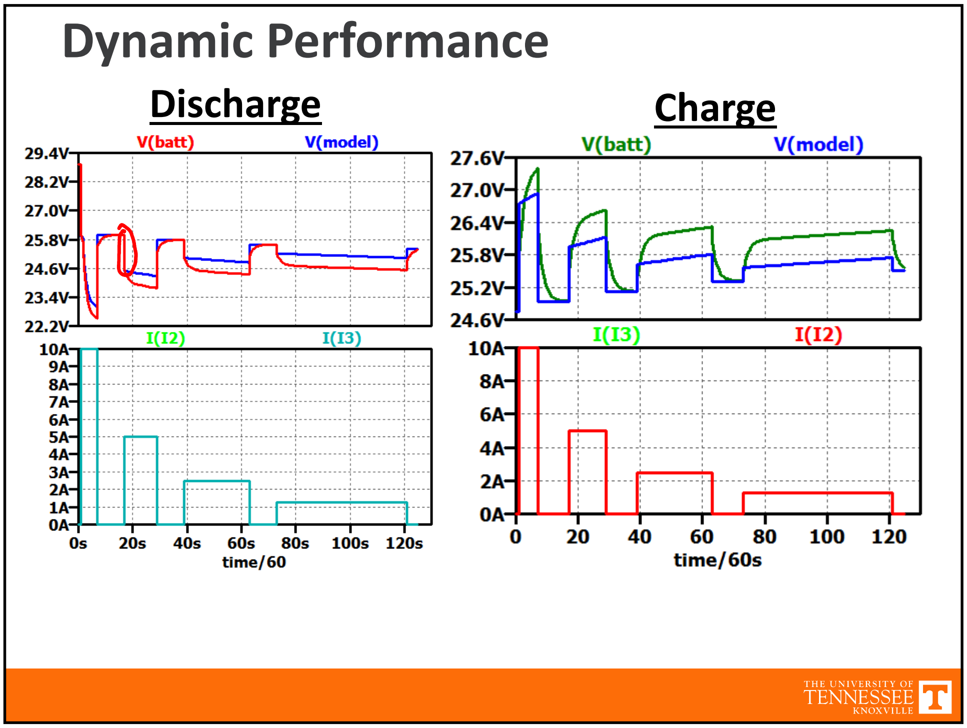
$R_{charging}$: $R_x + R^-$

Dynamic Performance





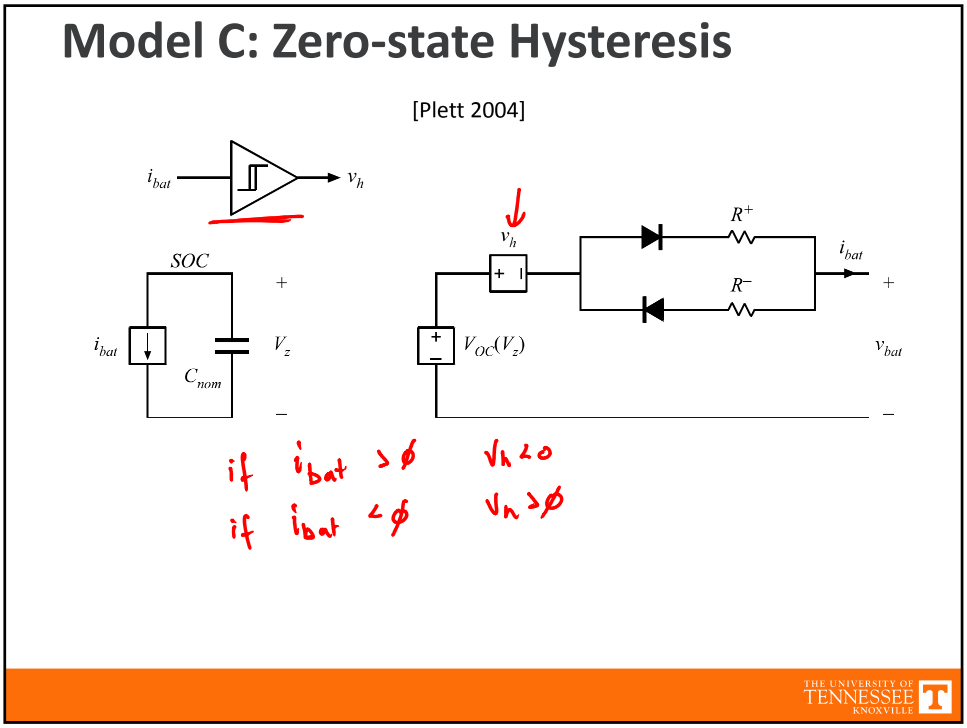
- Dynamic performance characterized by pulse train
- Constant percent of capacity per pulse [%Ahr]



Dynamic Performance

Discharge

Charge



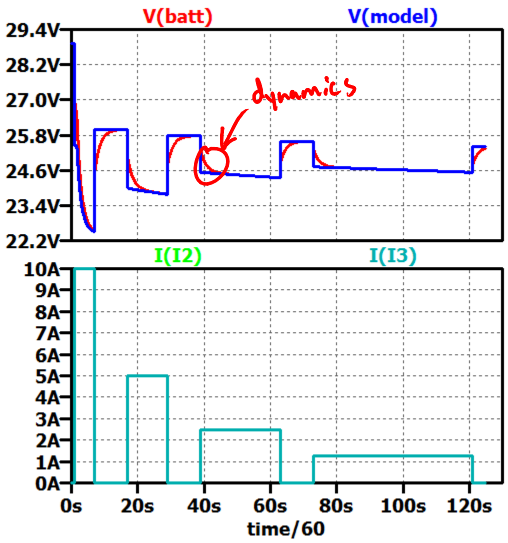
Model C: Zero-state Hysteresis

[Plett 2004]

if $i_{bat} > 0$ $v_h < 0$

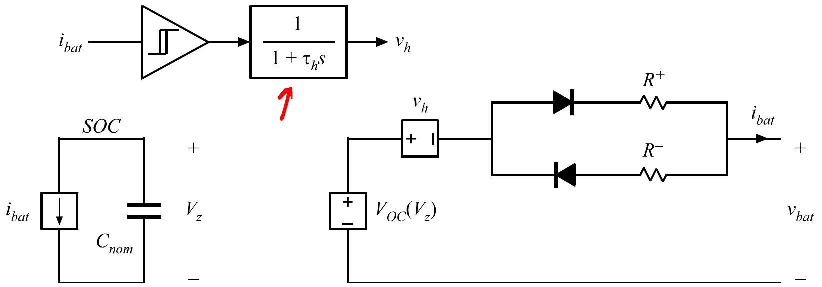
if $i_{bat} < 0$ $v_h > 0$

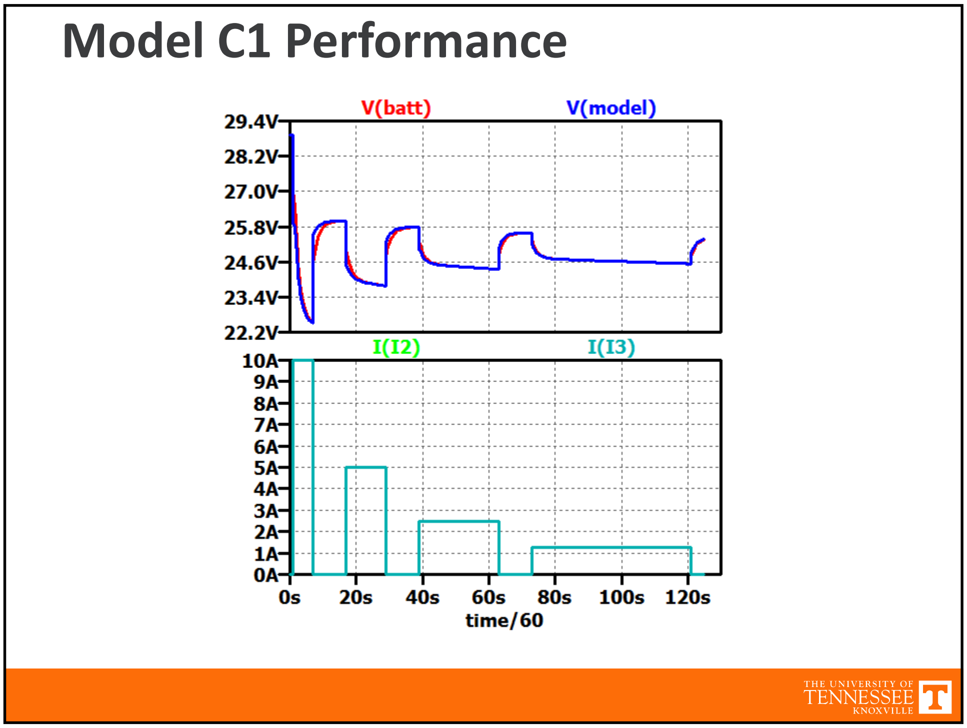
Model C Performance



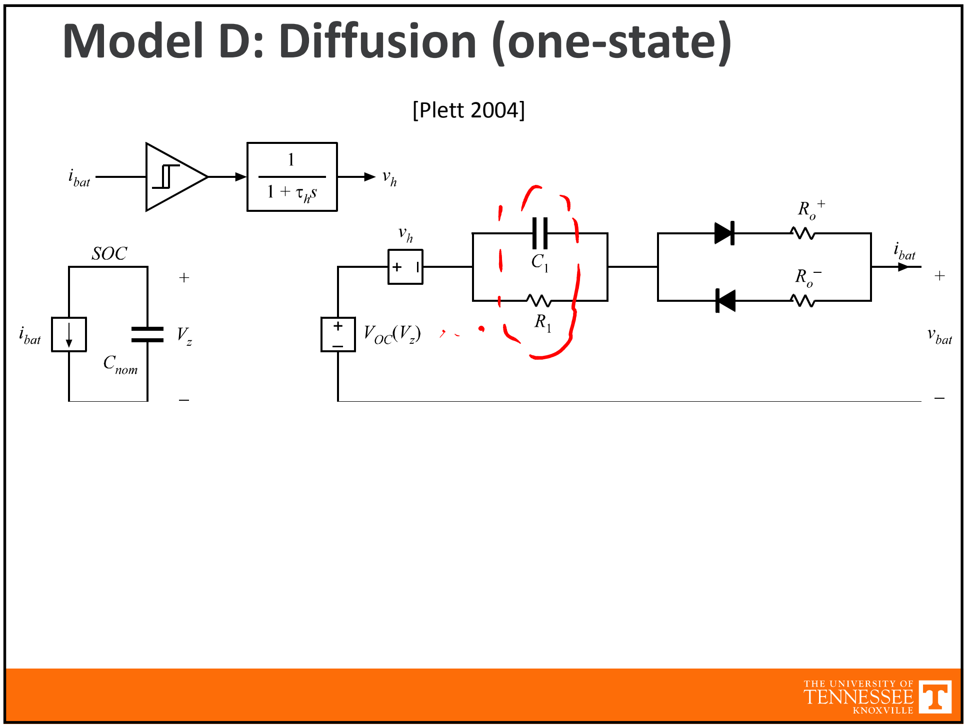
Model C1: One-state Hysteresis

[Plett 2004]





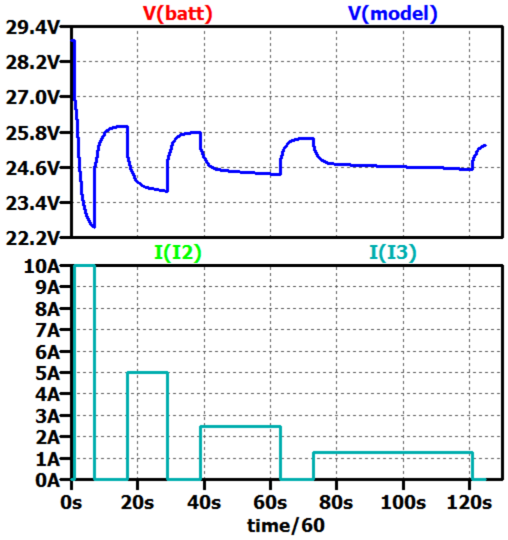
Model C1 Performance



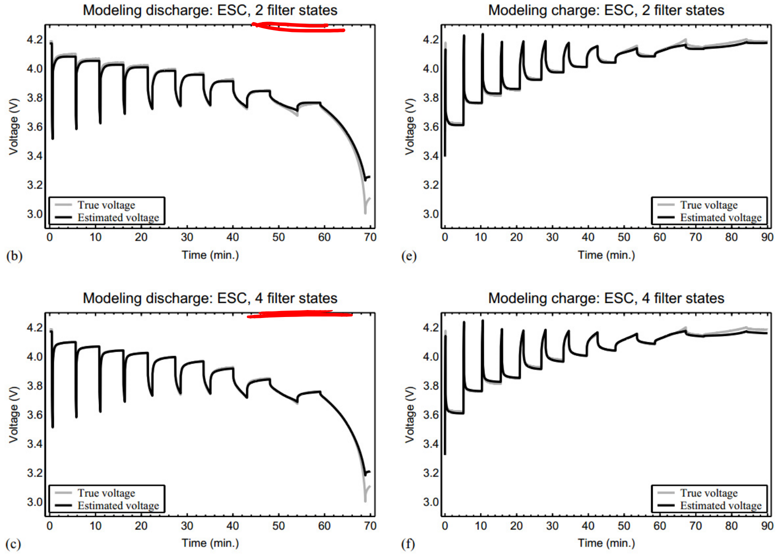
Model D: Diffusion (one-state)

[Plett 2004]

Model D Performance



Experimental Results


Modeling discharge: ESC, 2 filter states

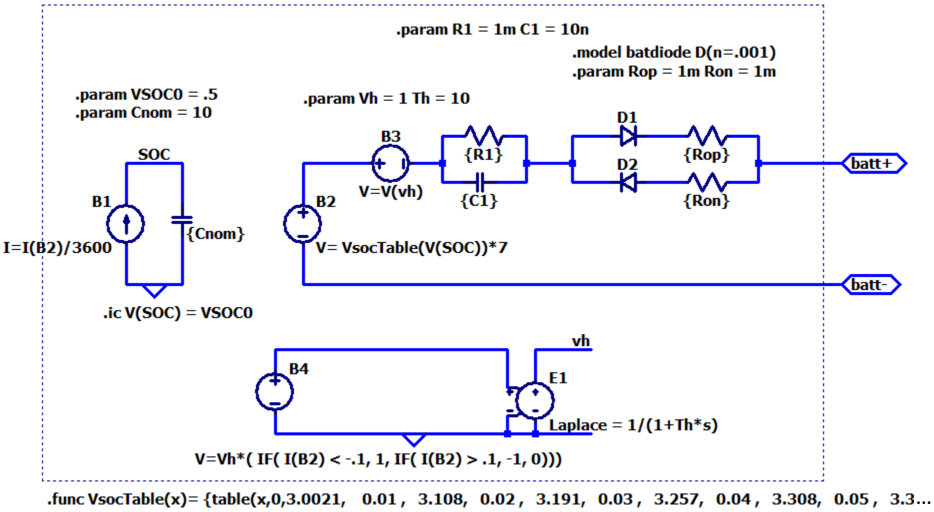
Modeling charge: ESC, 2 filter states

Modeling discharge: ESC, 4 filter states

Modeling charge: ESC, 4 filter states

[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.

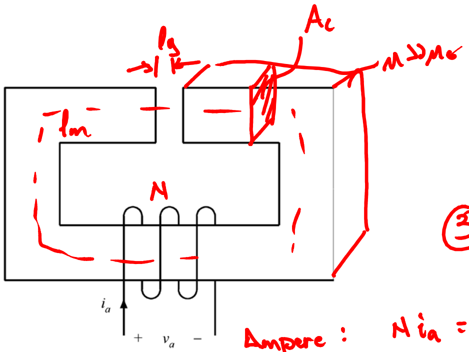
Implementation in LTSpice



```
.param R1 = 1m C1 = 10n
.model batdiode D(n=.001)
.param Rop = 1m Ron = 1m
.param VSOC0 = .5
.param Cnom = 10
.param Vh = 1 Th = 10
.ic V(SOC) = VSOC0
.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…
```

PM Motor Operation

Magnetic Circuit



Assume:

① field is uniform inside material

② No field outside material except air gap & no fringing

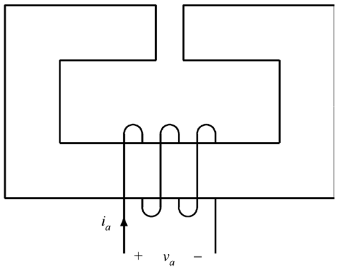
③ Material is linear & unsaturated $B = \mu H$

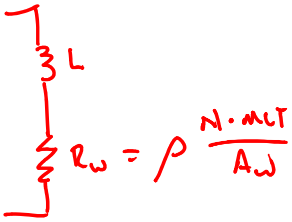
Ampere: $N i_a = \oint H \cdot dl = \frac{B}{\mu}(l_m - l_g) + \frac{B}{\mu_0} l_g$

Faraday's law: $v_a = N \frac{d\Phi}{dt} = N \frac{d}{dt} B A_c$

$$v_a = N A_c \frac{d}{dt}\left(\frac{N i_a}{\frac{l_m - l_g}{\mu} + \frac{l_g}{\mu_0}}\right) = \frac{N^2 A_c}{\underbrace{\frac{l_m - l_g}{\mu} + \frac{l_g}{\mu_0}}_{L \approx \frac{N^2 A_c \mu_0}{l_g}}} \frac{d i_a}{dt}$$

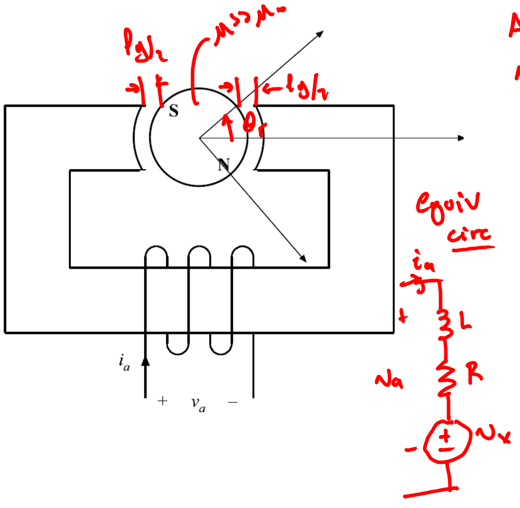
Equivalent Circuit





$R_w = \rho \frac{N \cdot MLT}{A_w}$

Single Phase Motor (Simplified)



Assume:

Magnet generates a constant flux Φ_m

$$v_x = N \frac{\partial \Phi_{\text{from magnet}}}{dt}$$

$$= \underbrace{N\Phi_m}\frac{d}{dt} f(\theta_r)$$

$$N\Phi_m \equiv \lambda_m \quad \text{"flux linkage"} \quad \left[\frac{V \cdot sec}{rad}\right]$$

Guess:

$$f(\theta_r) = \sin(\theta_r)$$

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Winding Voltage Equation

$$v_x = \lambda_m \frac{d}{dt} \sin\theta_r$$

$$v_x = \lambda_m \cos\theta_r \frac{\partial\theta_r}{\partial t}$$

$$\downarrow$$

ω_r → angular speed

$$v_x = \lambda_m \omega_r \cos\theta_r$$

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Electromechanical Conversion

Power into "A" winding

$$P = v_a i_a = \underbrace{i_a L \frac{di_a}{dt}}_{\text{Ac reactive power}} + \underbrace{i_a^2 R}_{\text{Resistive loss}} + \underbrace{i_a \lambda_m \omega_r \cos\theta_r}_{\text{power transferred to mechanical}}$$

Mechanical Power

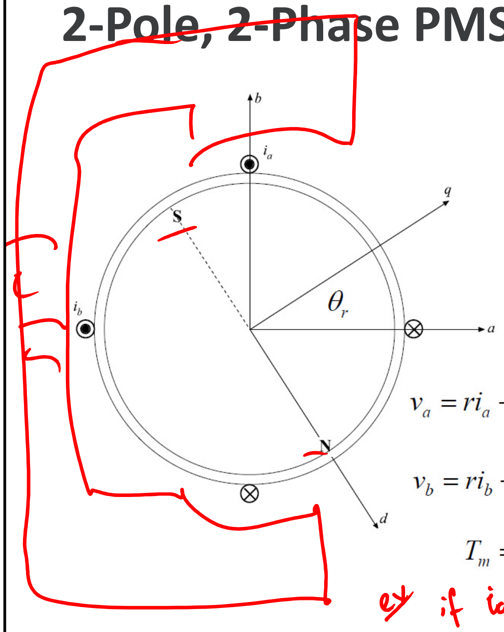
$$P_{mech} = \underset{\text{torque}}{\tau}\,\underset{\text{speed of rotation}}{\cancel{\omega_r}} = i_a \lambda_m \cancel{\omega_r} \cos\theta_r$$

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

$\tau \to 0$ @ $\theta_r = \frac{\pi}{2}$ & $\frac{3\pi}{2}$

regardless of i_a

2-Pole, 2-Phase PMSM



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

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

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

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

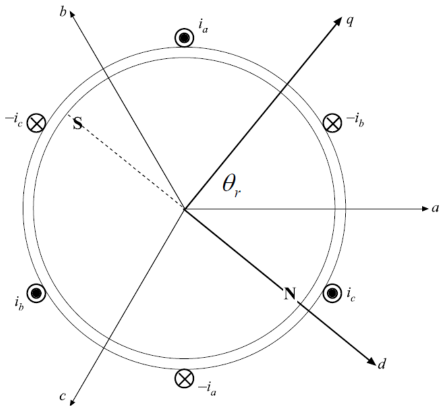
$$v_b = ri_b + \frac{d\lambda_b}{dt} = ri_b + L\frac{di_b}{dt} + \lambda_M \omega_r \sin(\theta_r)$$

$$T_m = \lambda_M (i_a \cos(\theta_r) + i_b \sin(\theta_r))$$

ex if $i_a = I_{ph} \cos\theta_r$, $i_b = I_{ph} \sin\theta_r$

$$T_m = \lambda_m I_{ph} (\cancel{\cos^2\theta_r + \sin^2\theta_r})$$

3-Phase, 2-Pole PMSM



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

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

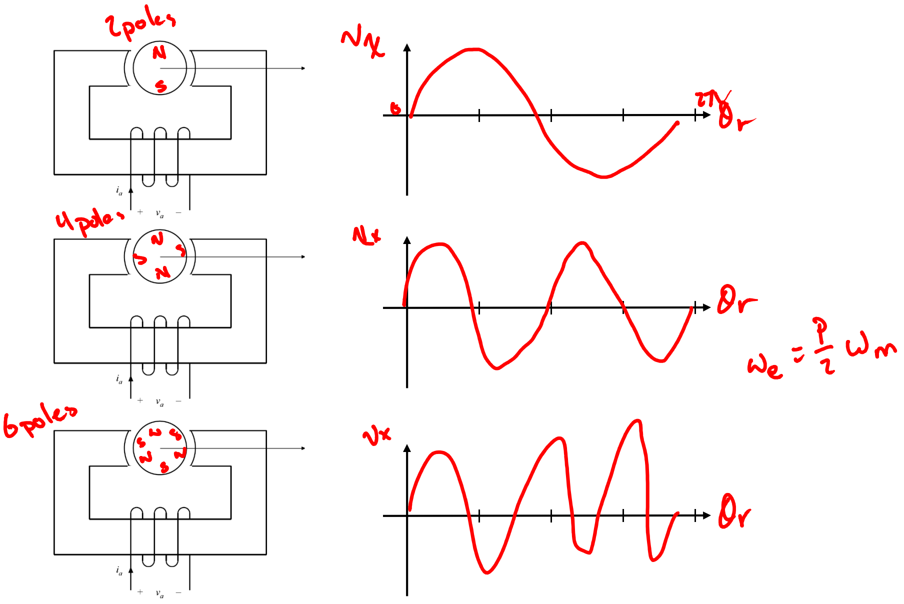
$$\lambda_c(\theta_r) = \lambda_m \sin\left(\theta_r - \frac{4\pi}{3}\right)$$

if i_a, i_b, i_c 120° out of phase sinusoids

$$T_m = \frac{3}{2} I_{pk} \lambda_m$$

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

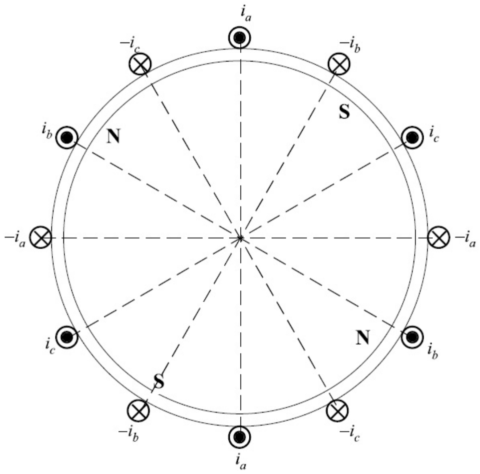
Different Number of Poles



$$\omega_e = \frac{P}{2} \omega_m$$

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

$$\boxed{T_m \le \lambda_m \frac{P}{2}\frac{3}{2} I}$$