Motor and Battery Characterization

ECE 482 Lecture 2
January 13, 2015

Lab 1

10Ah Li-ion ~26V
battery

500W Hub PM Motor

Introduction to Battery Modeling

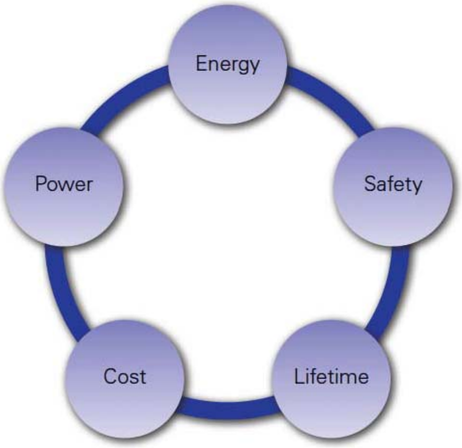
Battery Performance Metrics

Energy

- Available energy storage between charging cycles
- A*hr rating
- Specific energy, Wh/kg, energy density Wh/L

Power

- Instantaneous power available
- "C" rating: peak discharge current
- Specific power, W/kg, W/L



Cost

- Initial investment
- Total energy cost over life of battery

Safety

- Hazardous chemical content
- Outgassing
- Risk of fire from damage or heating

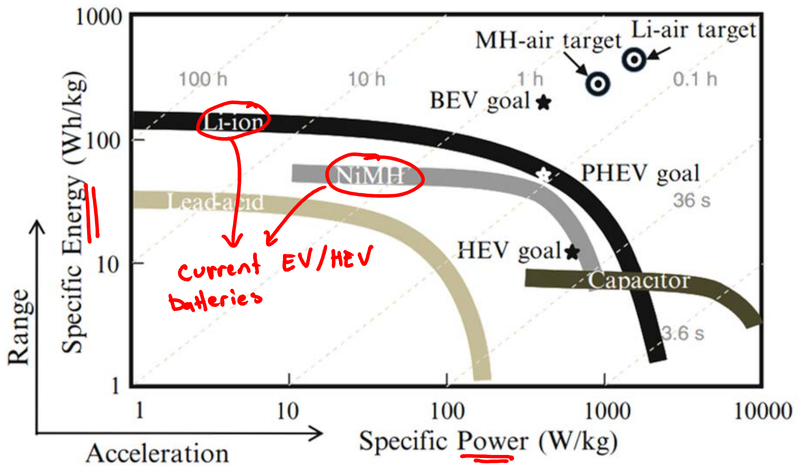
Lifetime

- Number of charge / discharge cycles to 80% capacity
- Dependence on % discharge and peak currents

Energy and Power Density of Storage

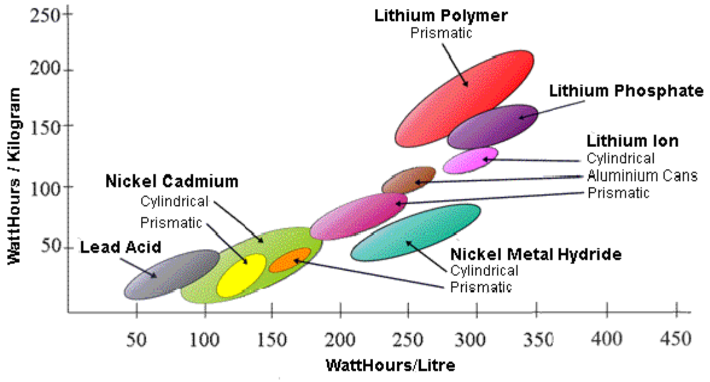
12000

↳ ≈ Gasoline Specific Energy

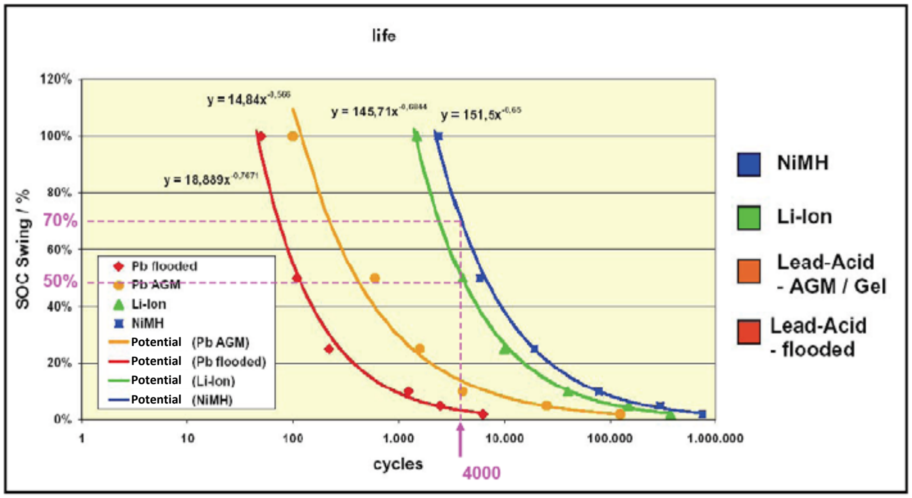


current EV/HEV batteries

Energy Density and Specific Energy



Cycle Life of EV Battery Packs



Data presented by Christian Rosenkranz (Johnson Controls) at EVS 20

Smaller SOC swing → Longer Life

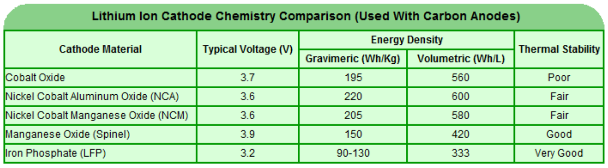
Li-ion Advantages and Disadvantages

Advantages

- Higher energy density, 150-200 Wh/kg, 250-500 Wh/l
- High power density, can be optimized for energy or power
- Higher voltage, approx. 3.2 V to 3.8 V
- Low self-discharge rate, retain charge for months
- No liquid electrolyte
- Relatively long cycle life (1,000-3,000 deep cycles)

Disadvantages

- More complex to manufacture, more expensive (0.5-1 $/Wh)
- Safety concerns: require circuitry to protect against overcharging or over-discharging



Lithium Ion Cathode Chemistry Comparison (Used With Carbon Anodes)

Cathode Material	Typical Voltage (V)	Energy Density		Thermal Stability
		Gravimeric (Wh/Kg)	Volumetric (Wh/L)	
Cobalt Oxide	3.7	195	560	Poor
Nickel Cobalt Aluminum Oxide (NCA)	3.6	220	600	Fair
Nickel Cobalt Manganese Oxide (NCM)	3.6	205	580	Fair
Manganese Oxide (Spinel)	3.9	150	420	Good
Iron Phosphate (LFP)	3.2	90-130	333	Very Good

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

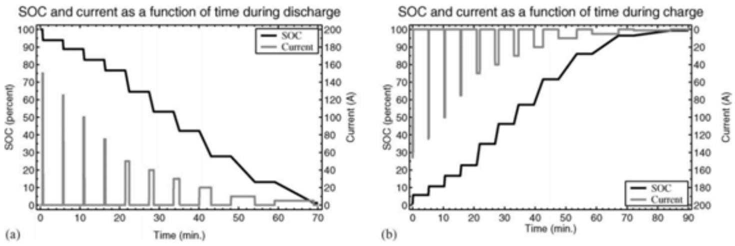
Objective:

- 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]

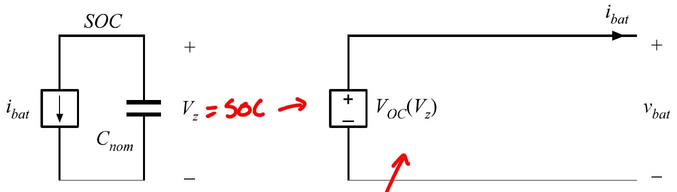
- Model parameters found using least-square estimation or Kalman filter techniques based on experimental test data
- Run-time estimation of state of charge (SOC)

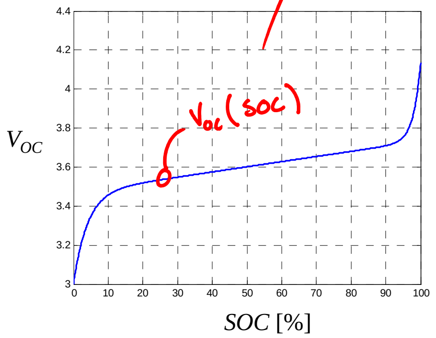
Approach: Pulsed current tests



[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.

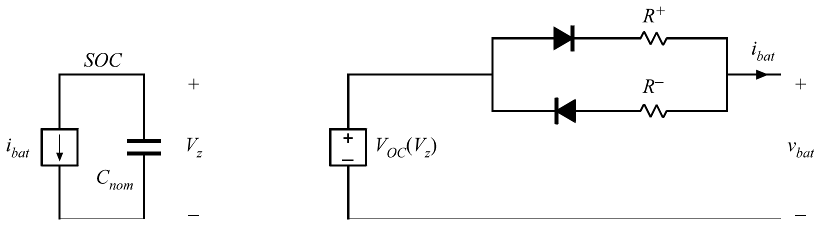
Model A: SOC and V_{oc}





example V_{oc}-SOC curve

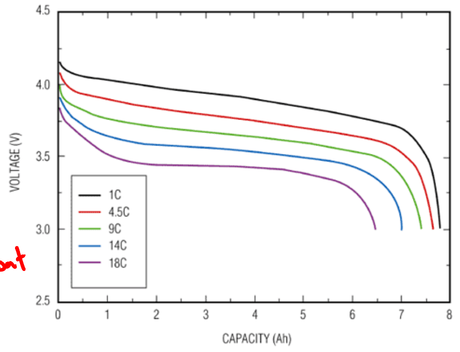
Model B: Series Resistance



C = capacity (in Amp-hrs)

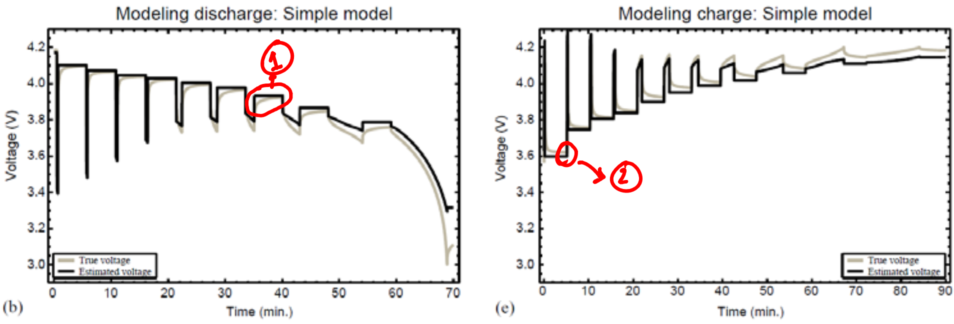
ex
C = 10 Ah

2C discharge means 20 A = i_{bat}



V_{bat} -vs- SOC & C change with discharge current

Model B Performance



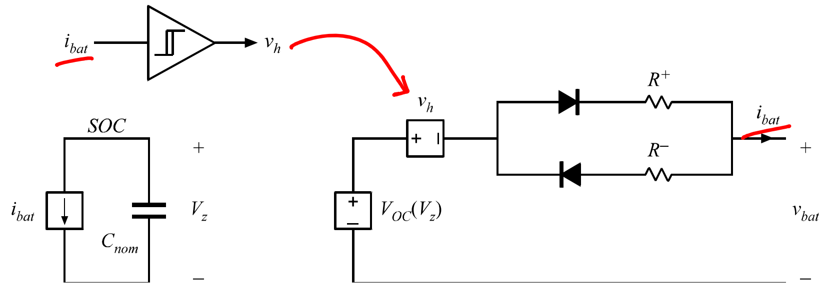
Missing :

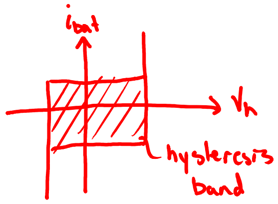
1 : Dynamics

2: Voltage offset

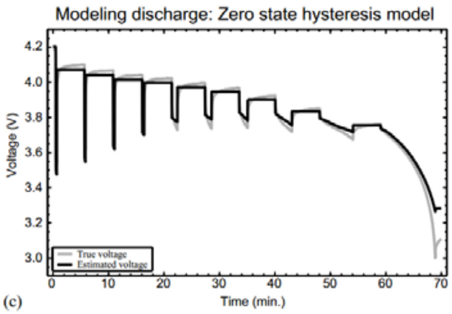
Model C: Zero-state Hysteresis

[Plett 2004] To address offset



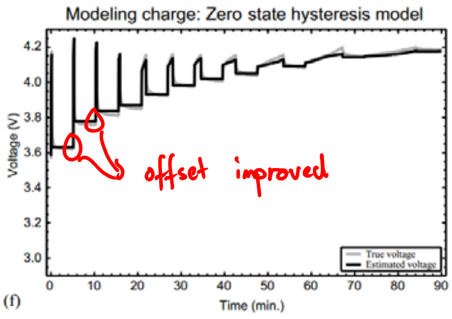


Model C Performance



Modeling discharge: Zero state hysteresis model

(c)



Modeling charge: Zero state hysteresis model

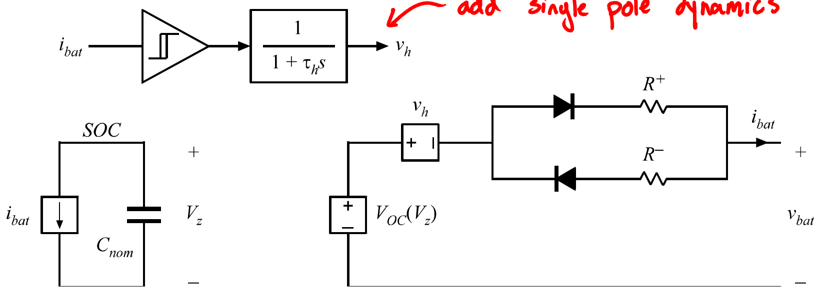
(f)

offset improved

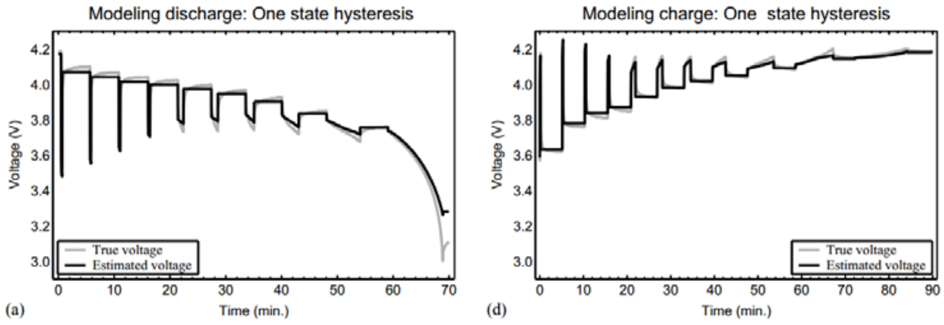
Model C1: One-state Hysteresis

[Plett 2004]

add single pole dynamics

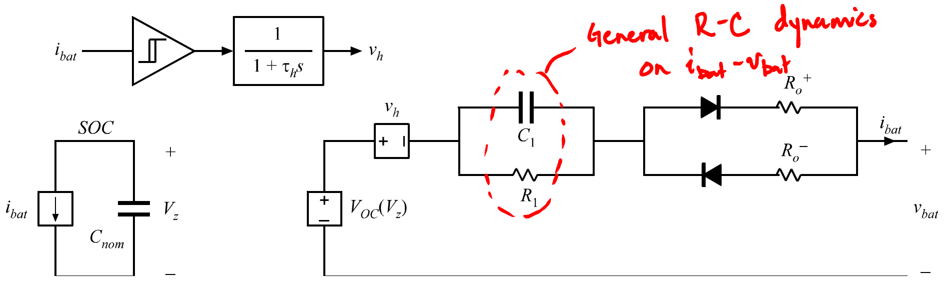


Model C1 Performance



Model D: Diffusion (one-state)

[Plett 2004]

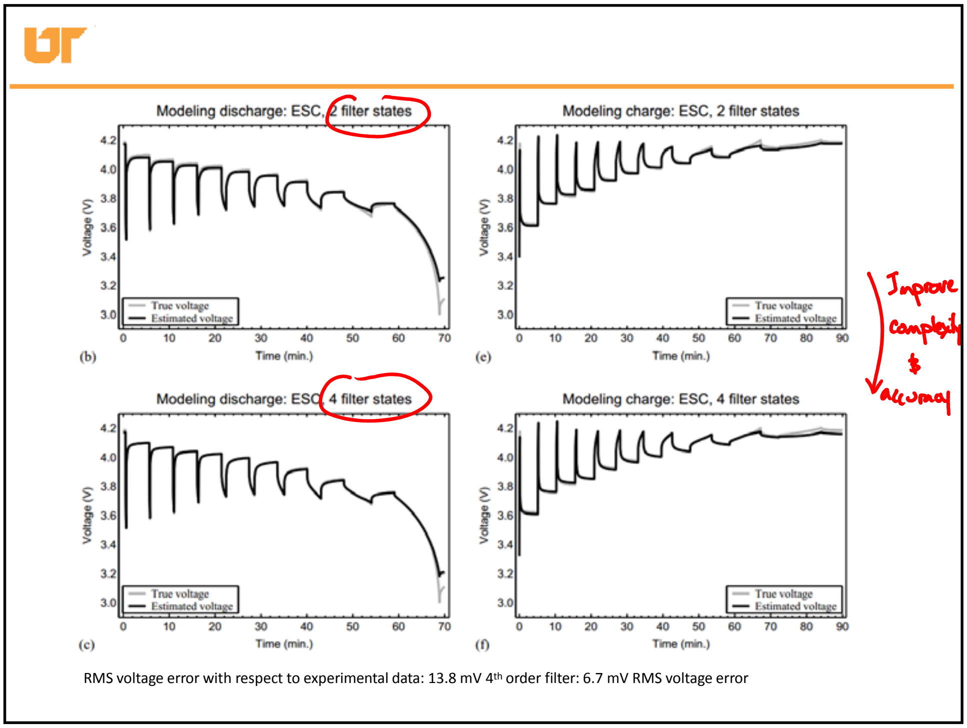


General R-C dynamics on i_{bat} - v_{bat}

Steady-state : $R_{charge} = R_1 + R_o^-$

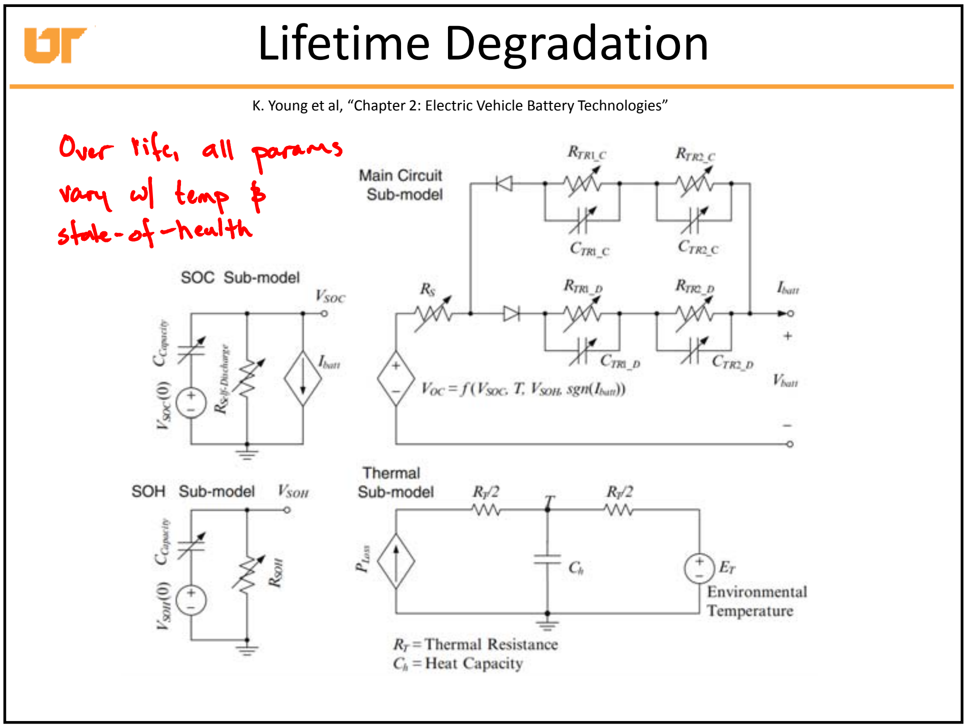
$R_{discharge} = R_1 + R_o^+$

C_1 set to get measured τ_{RC}



RMS voltage error with respect to experimental data: 13.8 mV 4th order filter: 6.7 mV RMS voltage error

Improve complexity & accuracy



Lifetime Degradation

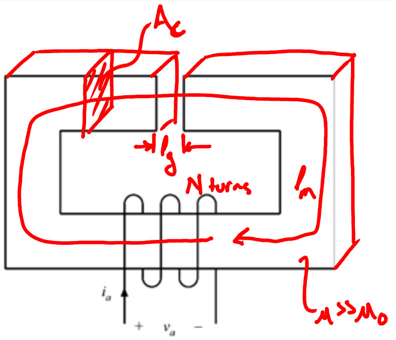
K. Young et al, “Chapter 2: Electric Vehicle Battery Technologies”

Over life, all params vary w/ temp & state-of-health

R_T = Thermal Resistance
C_h = Heat Capacity

PM Motor Operation

Magnetic Circuit



Assume:

- B & H are constant throughout the core
- Magnetic flux is contained entirely within the core (except at air gap)
- No fringing at air gap
- Material is linear, unsaturated; $B = \mu H$

Apply:

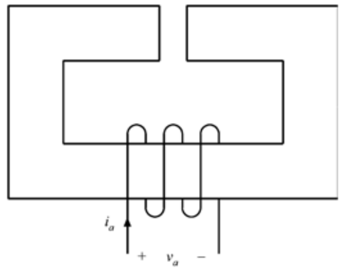
Ampere's Law : $N i_a = \oint_{l_m} H \cdot dl = \frac{B}{\mu}(l_m - l_g) + \frac{B}{\mu_0} l_g$

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

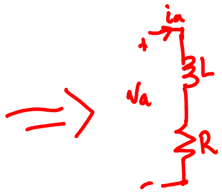
$v_a = \boxed{L} \frac{di_a}{dt}$

Combine : $v_a = N A_c \frac{d}{dt}\left(\frac{N i_a}{\frac{l_m - l_g}{\mu} + \frac{l_g}{\mu_0}} \right) = \boxed{\frac{N^2 A_c}{\frac{l_m - l_g}{\mu} + \frac{l_g}{\mu_0}}} \frac{di_a}{dt}$

Equivalent Circuit

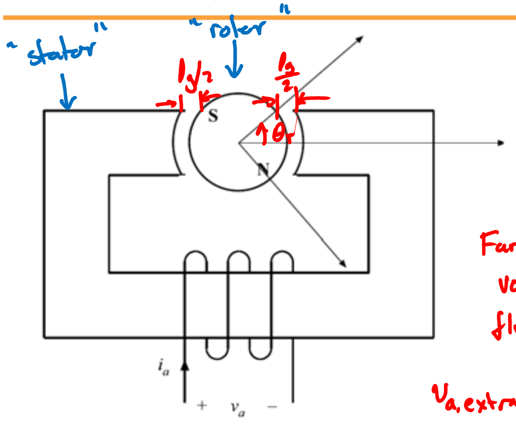


$$R_w = \rho \frac{N \cdot MLT}{A_w}$$



if $\mu >> \mu_0$ $\quad L \approx \frac{\mu_0 N^2 A_c}{l_g}$

Single Phase Motor (Simplified)



Assume magnet has flux Φ_m & $\mu >> \mu_0$

L & R still present, but by Faraday's Law to find additional voltage due to permanent magnet's flux

$$v_{a,extra} = \frac{d}{dt}\left(N \Phi_m \underbrace{f(\theta_r)}\right)$$

some function describing how much flux couples into core.

As an example (not inherently true)

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

define "flux linkage" $\lambda_m = N \Phi_m$, units of $\frac{V \cdot sec}{rad}$

Electromechanical Conversion

The power going into the winding is

$$P_a = i_a v_a = \underbrace{i_a^2 R_w}_{\text{winding DC copper loss}} + \underbrace{i_a L \frac{di_a}{dt}}_{\text{AC-only reactive current}} + \underbrace{i_a \lambda_m \omega_r \cos(\theta_r)}_{\text{power transferred to mechanical}}$$

In mechanical domain, instantaneous power of the rotor is

$$P_m = \underbrace{\omega_r}_{\text{speed}} \underbrace{\tau_r}_{\text{Torque}}$$

Assuming 100% conversion efficiency.

$$P_m = P_e = i_a \lambda_m \cancel{\omega_r} \cos(\theta_r) = \cancel{\omega_r} \tau_r$$

$$\boxed{\tau_r = i_a \lambda_m \cos(\theta_r)} \rightarrow$$

Problem: when $\theta_r \to \frac{\pi}{2}, \frac{3\pi}{2}$, $\tau_r \to 0$!

Winding Voltage Equation

$$V_{a,extra} = \lambda_m \frac{d}{dt} \sin(\theta_r) = \lambda_m \cos(\theta_r) \frac{d}{dt}\theta_r$$

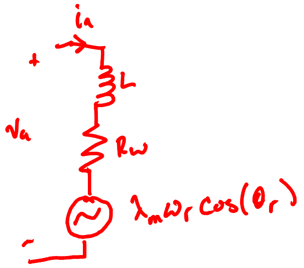
if spinning at a constant rate, $\frac{d}{dt}\theta_r = \omega_r$

$$v_{a,extra} = \lambda_m \omega_r \cos(\theta_r)$$

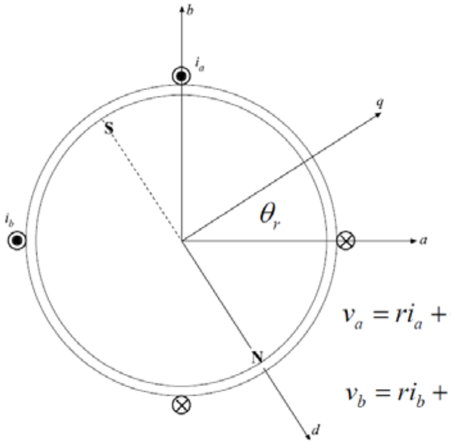
Total equation is then

$$\boxed{v_a = R_w i_a + L \frac{di_a}{dt} + \lambda_m \omega_r \cos(\theta_r)}$$

equivalent circuit:



2-Pole, 2-Phase PMSM



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

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

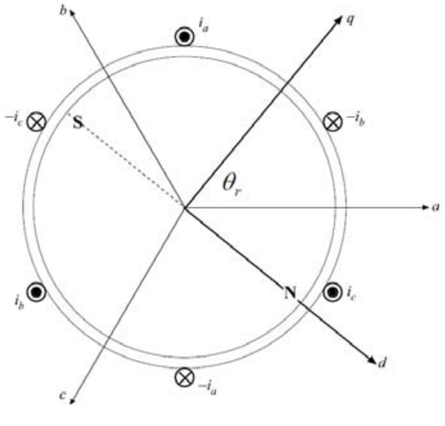
Same as before

$$v_a = ri_a + \frac{d\lambda_a}{dt} = ri_a + L\frac{di_a}{dt} + \lambda_M \omega_r \cos(\theta_r)$$
$$v_b = ri_b + \frac{d\lambda_b}{dt} = ri_b + L\frac{di_b}{dt} + \lambda_M \omega_r \sin(\theta_r)$$
$$T_m = \lambda_M (i_a \cos(\theta_r) + i_b \sin(\theta_r))$$

e.g. select $i_a = I\cos(\theta_r)$ $i_b = I\sin(\theta_r)$

$T_m = \lambda_m I(\cos^2\theta_r + \sin^2\theta_r) = \underline{\underline{\lambda_m I}}$ → constant!

3-Phase, 2-Pole PMSM



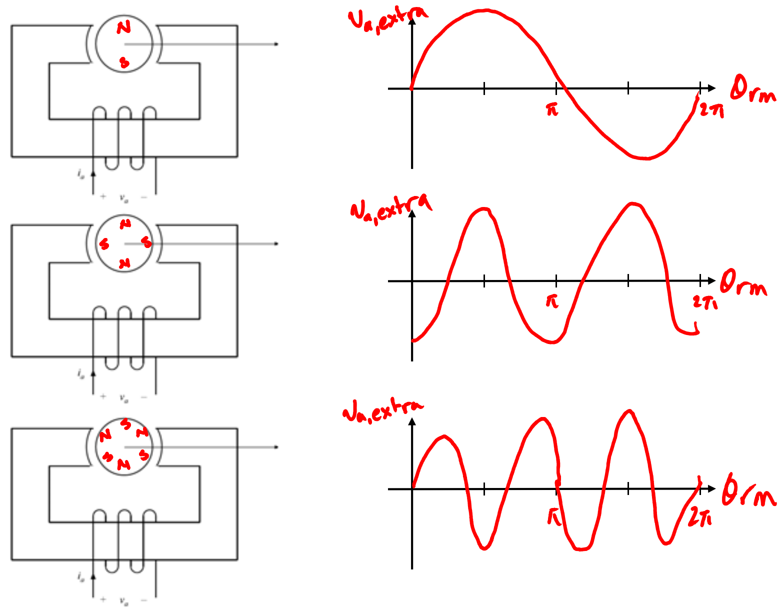
$$\lambda_a(\theta_r) = \lambda_m \sin(\theta_r)$$
$$\lambda_b(\theta_r) = \lambda_m \sin\left(\theta_r - \frac{2\pi}{3}\right)$$
$$\lambda_c(\theta_r) = \lambda_m \sin\left(\theta_r - \frac{4\pi}{3}\right)$$

$$\begin{cases} i_a = I\cos(\theta_r) \\ i_b = I\cos\left(\theta_r - \frac{2\pi}{3}\right) \\ i_c = I\cos\left(\theta_r - \frac{4\pi}{3}\right) \end{cases}$$

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

$= \frac{3}{2}\lambda_m I$

Different Number of Poles

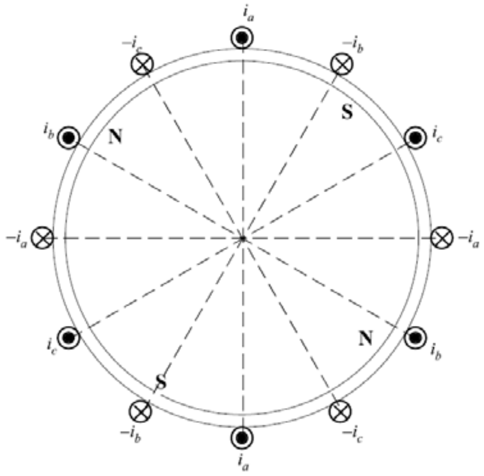


3-Phase, P-Pole PMSM

if $P \neq 2$ $\theta_r \neq \theta_{rm}$

electrical mechanical

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

$$T_m \leq \lambda_m \frac{P}{2}\frac{3}{2} I$$