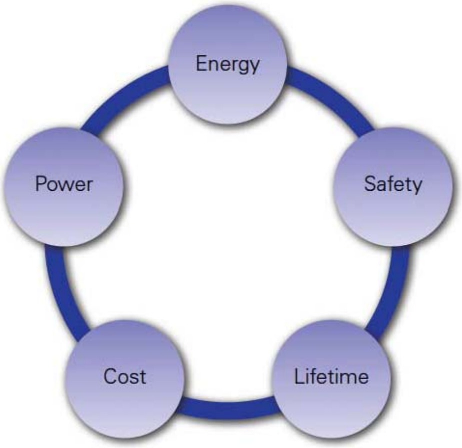
Lab 1

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



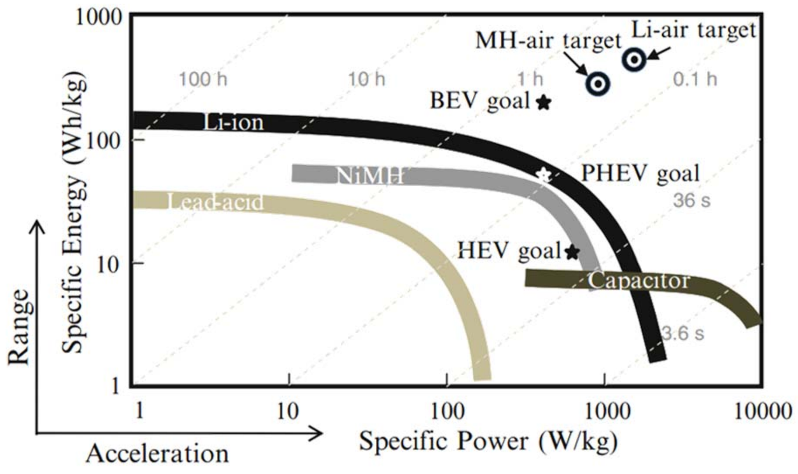
Cost
- Initial investment
- Total energy cost over life of battery

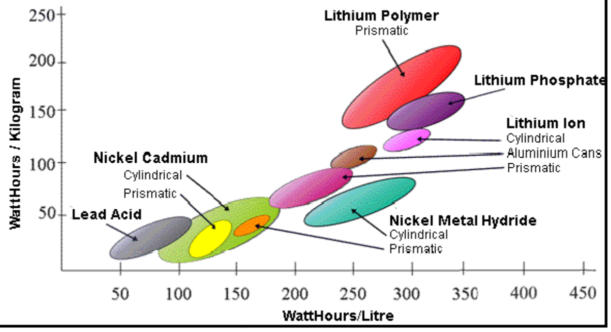
Safety
- Hazardous chemical content
- Outgassing
- Risk of fire from damage or heating

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

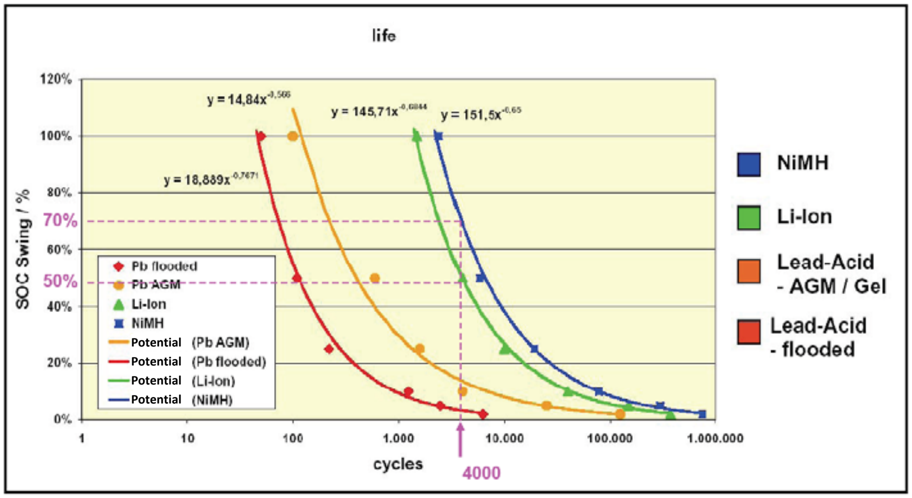
Energy and Power Density of Storage

12000





Cycle Life of EV Battery Packs



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

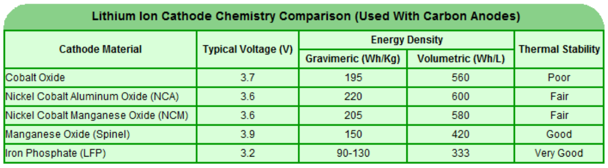
Li-ion Advantages and Disadvantages

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 544*kg (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

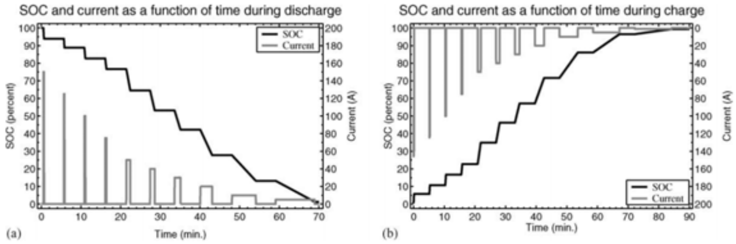
Objective:

- 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]

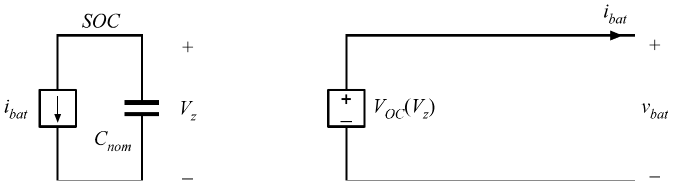
- Model parameters found using least-square estimation or Kalman filter techniques based on experimental test data
- Run-time estimation of state of charge (SOC)

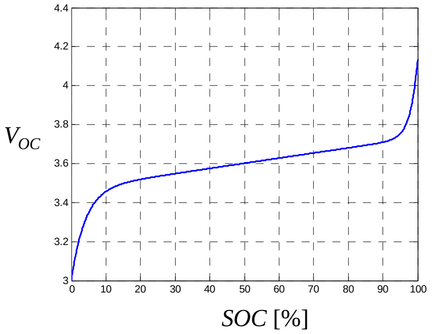
Approach: Pulsed current tests



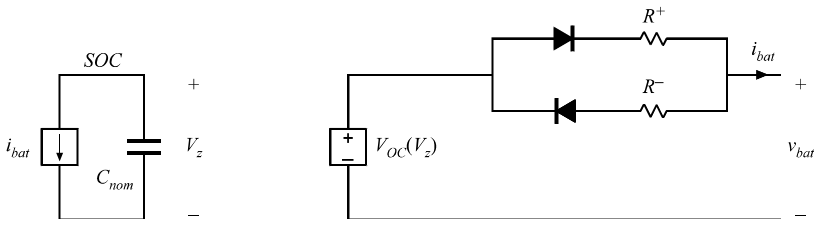
[Plett 2004-2] G. Plett, "Extended Kalman Filtering for Battery Management Systems of LiPB-Based HEV Battery Packs—Part 2: Modeling and Identification," Journal of Power Sources, Vol. 134, No. 2, August 2004, pp. 262–76.

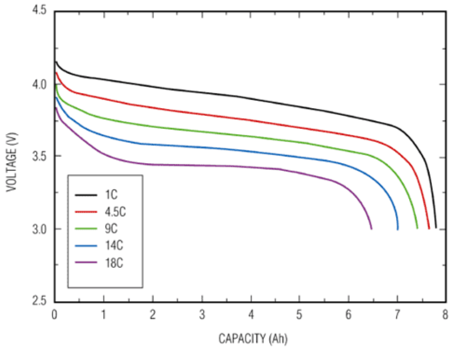
Model A: SOC and V_{oc}



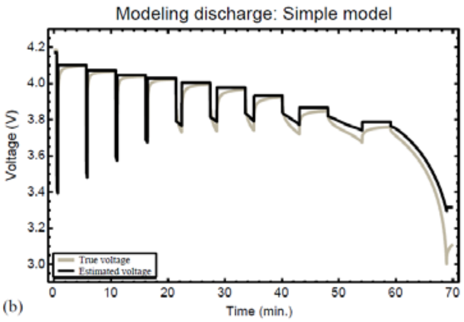


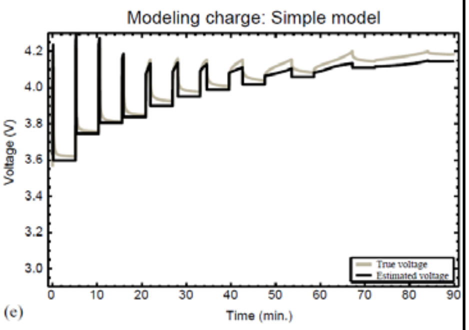
Model B: Series Resistance





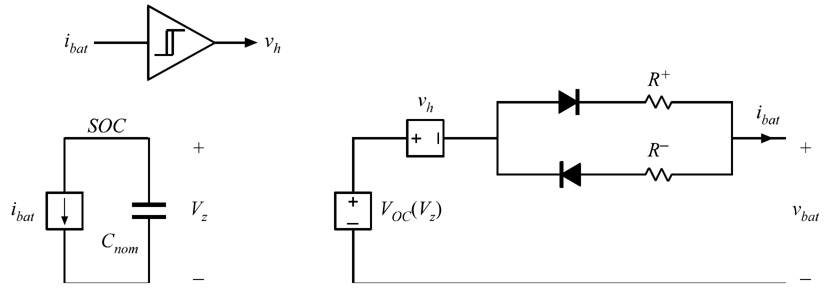
Model B Performance



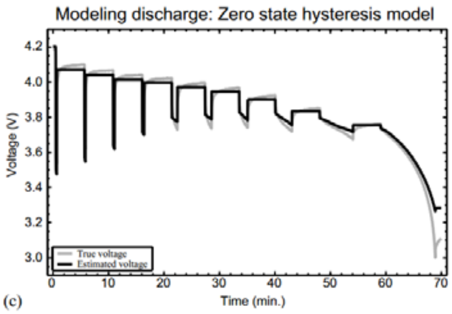


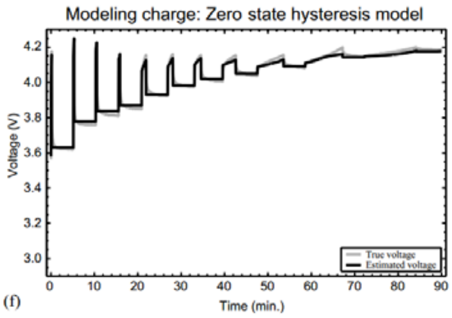
Model C: Zero-state Hysteresis

[Plett 2004]



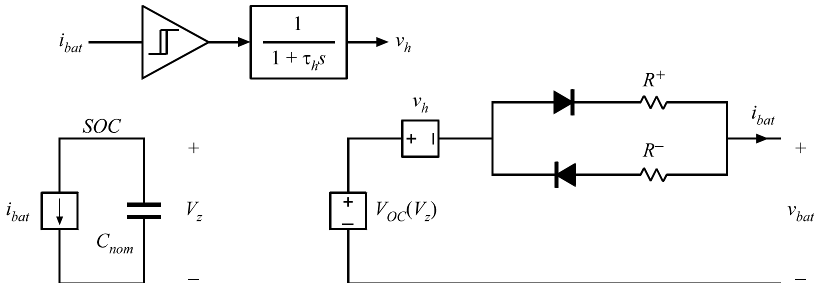
Model C Performance



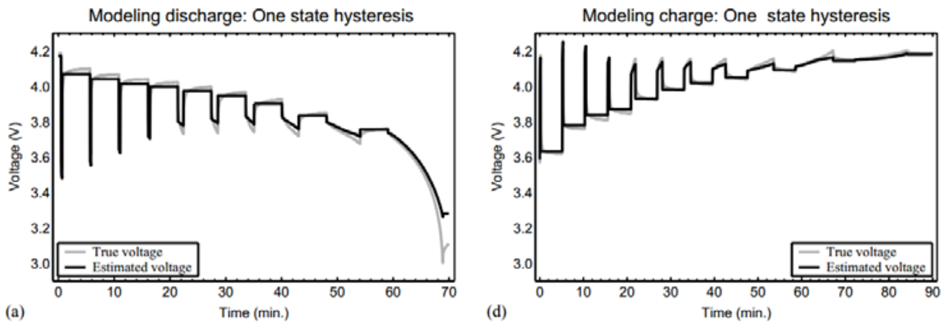


Model C1: One-state Hysteresis

[Plett 2004]

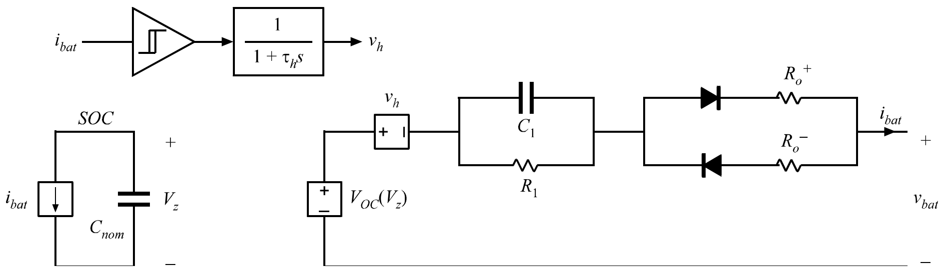


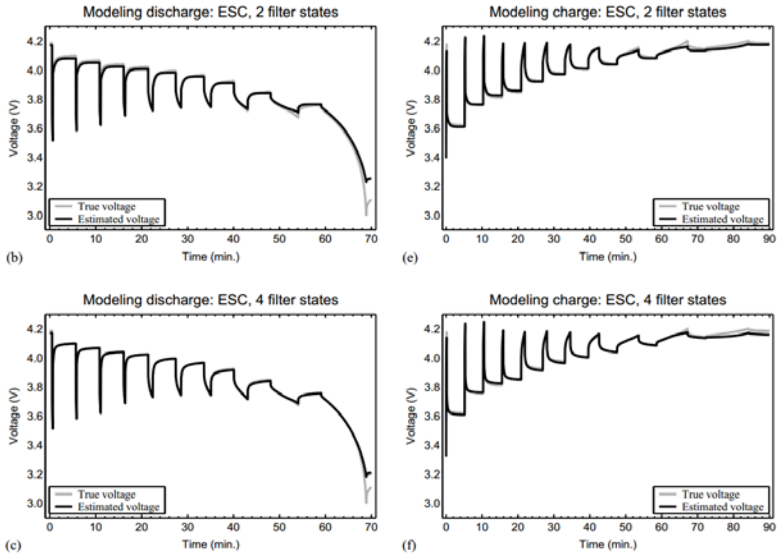
Model C1 Performance



Model D: Diffusion (one-state)

[Plett 2004]




Modeling discharge: ESC, 2 filter states

Modeling charge: ESC, 2 filter states

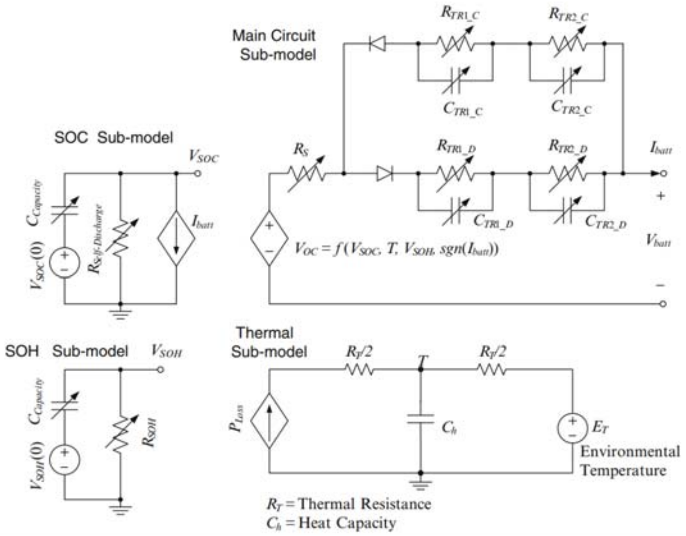
Modeling discharge: ESC, 4 filter states

Modeling charge: ESC, 4 filter states

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

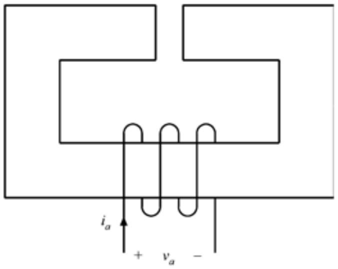
Lifetime Degradation

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

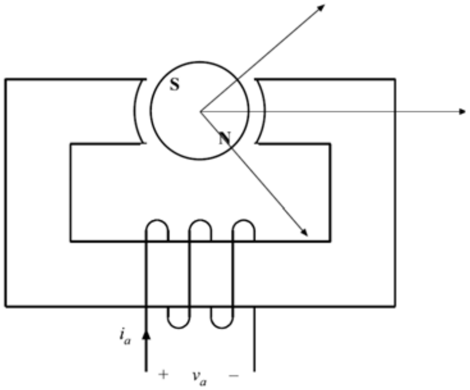


PM Motor Operation

Magnetic Circuit



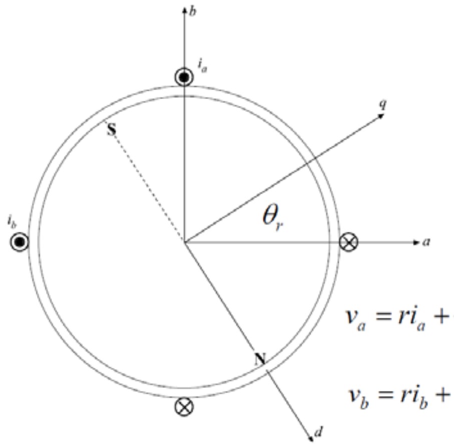
Single Phase Motor (Simplified)



Winding Voltage Equation

Electromechanical Conversion

2-Pole, 2-Phase PMSM

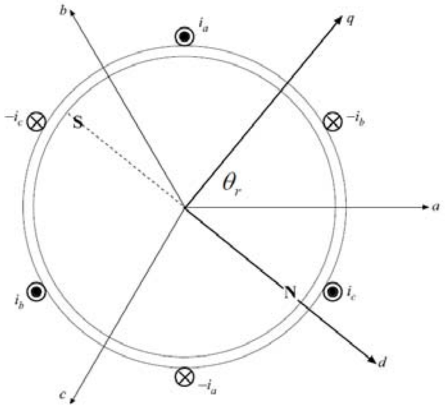


Two-pole, two-phase PMSM terminal characteristics in stator reference frame

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

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

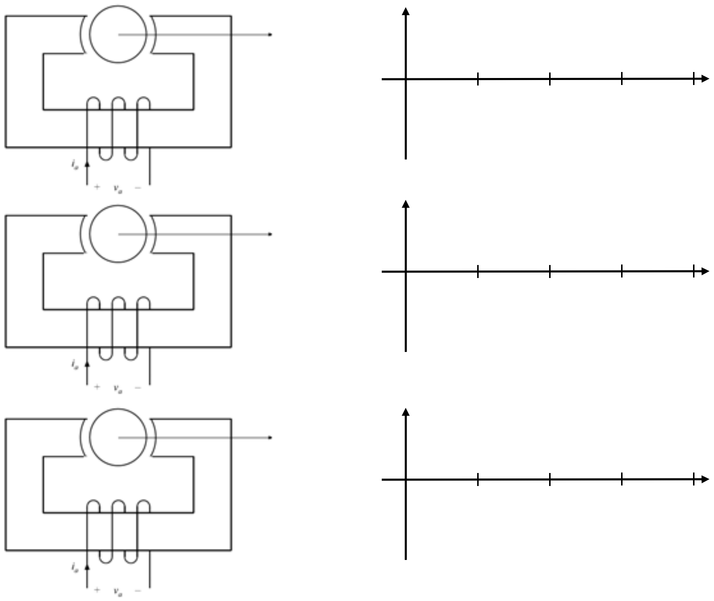
3-Phase, 2-Pole PMSM



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

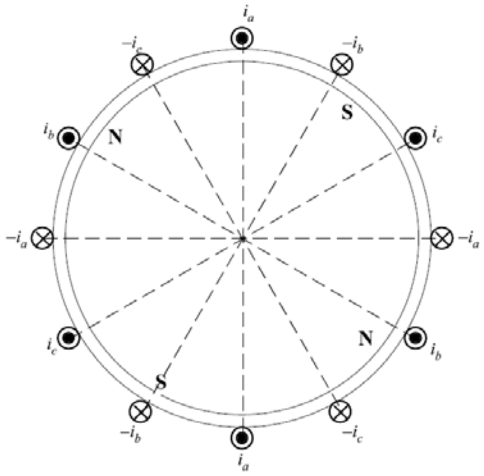
$$T_m = i_a \lambda_m \omega_r \cos(\theta_r) + i_b \lambda_m \omega_r \cos\left(\theta_r - \frac{2\pi}{3}\right) + i_c \lambda_m \omega_r \cos\left(\theta_r - \frac{4\pi}{3}\right)$$

Different Number of Poles



3-Phase, P-Pole PMSM

P = 4 example



Electrical and mechanical angle

$$\theta_r = \frac{P}{2}\theta_{rm}$$

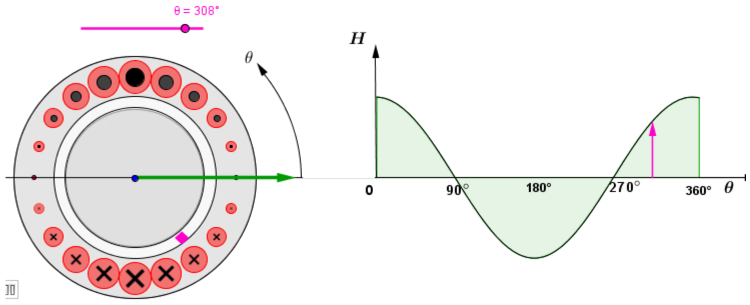
Electrical and mechanical speed

$$\omega_r = \frac{P}{2}\omega_{rm}$$

Max torque per amp

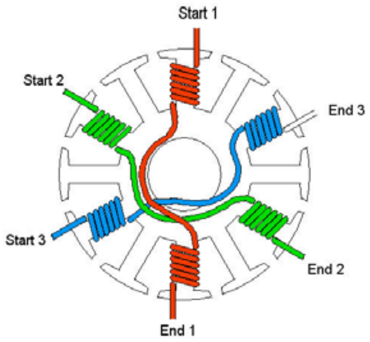
$$T_m \le \lambda_m \frac{P}{2}\frac{3}{2} I$$

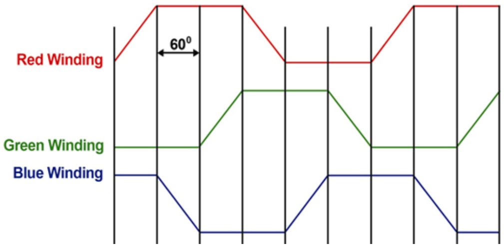
Shape of Back EMF



- Sinusoidal back EMF desirable for low-torque operation
- Can be achieved with sinusoidal winding distribution

BLDC Motor Winding





http://web.eecs.utk.edu/courses/spring2015/ece482/materials/brushless-motor.swf