

EE155/255 Green Electronics

Electric Motors
10/16/17

Prof. William Dally
Computer Systems Laboratory
Stanford University

Course Logistics

- Solar day is Monday 10/23
- HW 3 is due today
- HW 4 out, due next Monday 10/23
- Lab 3 must be checked off this week
- Lab 4 out this week



No	Date	Topic	HW out	HW in	Lab out	Lab ck	Lab	HW
1	9/25/17	Intro (basic converters)	1		1		Intro to ST32F3	Periodic Steady State
2	9/27/17	Embedded Prog/Power Elect.						
3	10/2/17	Power Electronics - 1 (switches)	2	1	2	1	AC Energy Meter	Power Devices
4	10/4/17	Power Electronics - 2 (circuits)						
5	10/9/17	Photovoltaics	3	2	3	2	PV MPPT	Motor control Matlab
6	10/11/17	Feedback Control						
7	10/16/17	Electric Motors	4	3	4	3	Motor control - Lab/	Feedback
8	10/18/17	Isolated Converters						
9	10/23/17	Solar Day	5/PP	4	5	4	PS	Isolated Converters
10	10/25/17	Magnetics						
11	10/30/17	Soft Switching	6	5/PP	6	5	Magnetics	Magnetics and Inverters
12	11/1/17	Project Discussions						
13	11/6/17	Inverters, Grid, PF, and Batteries		6	P	6	Project	
14	11/8/17	Thermal & EMI						
15	11/13/17	Quiz Review				C1		
16	11/15/17	Grounding, and Debugging						
Q	11/15/17	Quiz - in the evening						
	11/20/17	Thanksgiving Break				C2		
	11/22/17	Thanksgiving Break						
17	11/27/17	Guest Lecture						
18	11/29/17	Martin Fornage - Enphase				C3		
19	12/4/17	Colin Campbell - Tesla						
20	12/6/17	No Class						
	TBD	Project presentations			P			
	12/15/17	Project webpage due						

Course to Date

- We need sustainable energy systems
- Voltage converters PSSA, buck and boost
- Real circuits: losses, dead-time, snubbers
- PV cells characterized by a diode-like I-V curve
- PV systems – 1ϕ store energy, MPPT and invert
- Feedback control - PID
 - Derivative looks ahead – stabilizes
 - Integral cancels residual error
 - Actuators have limits

Agenda

- Motor Operation
- Motor Model
- Steady State and Transient Response
- Motor control with buck/boost
- Types of Motors
 - Permanent magnet (PM) (brushed)
 - Brushless permanent magnet (BLPM)
 - AC Induction
 - Radial vs axial flux
 - Poles and phases

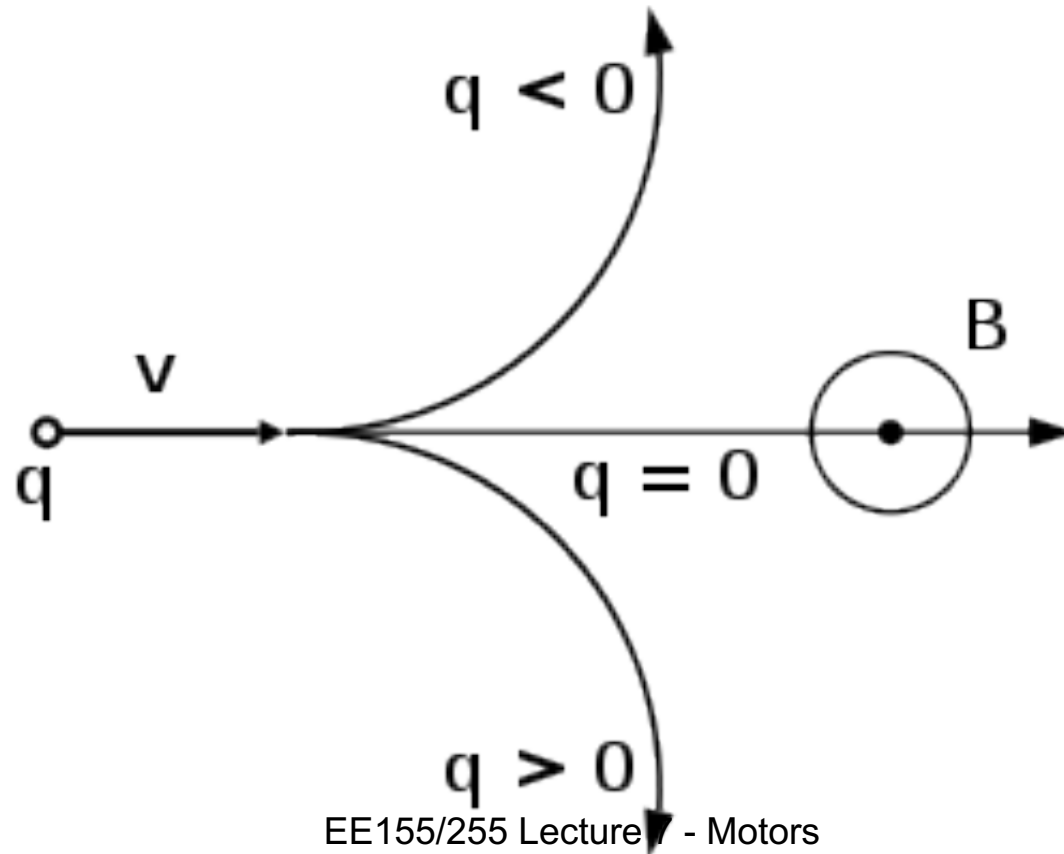
Motors and Generators are Everywhere

- Electric and Hybrid Cars
- Windmills and Hydro-Power
- Windows, door locks, ...
- Camera focus
- Printers

- Anywhere you need to convert between mechanical and electrical energy

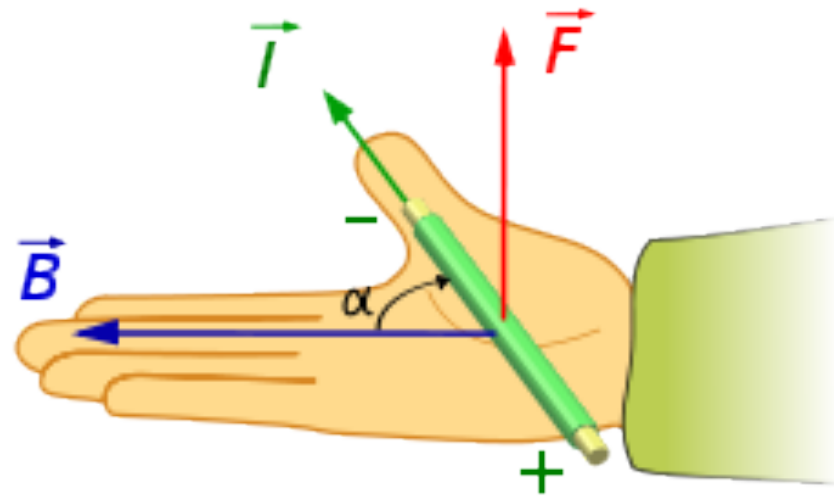
Lorentz Force

$$F = q(\mathbf{v} \times \mathbf{B})$$



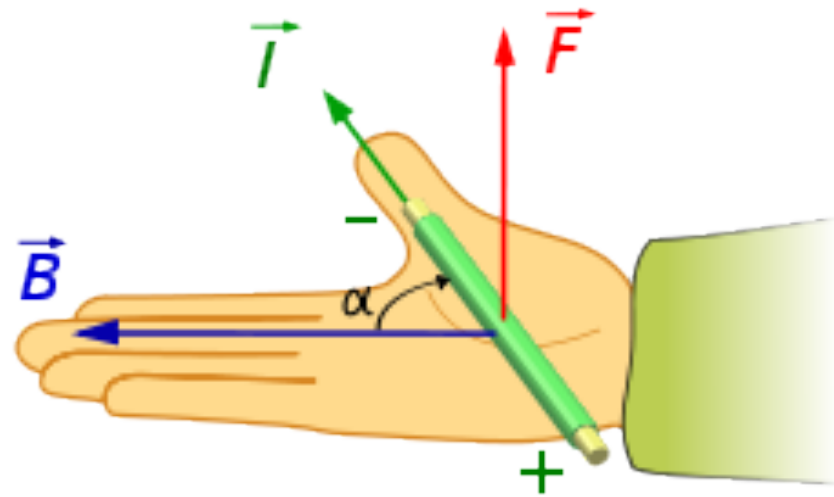
In a Wire

$$\vec{F} = i(\vec{L} \times \vec{B})$$



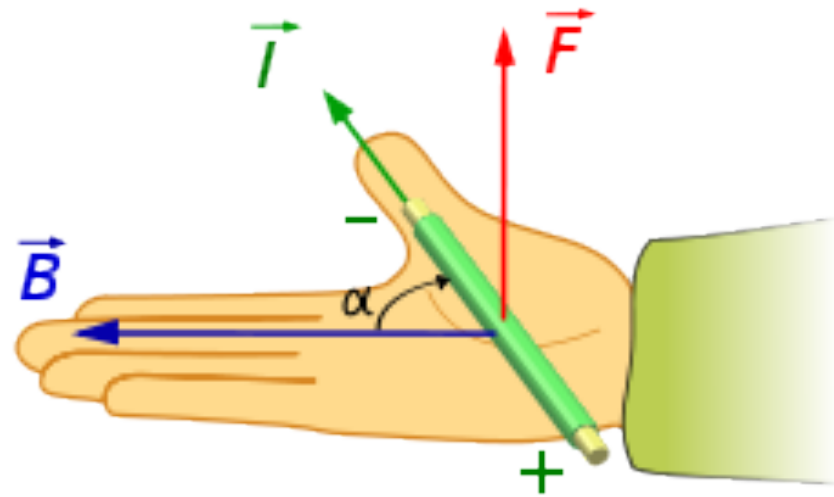
Force is proportional to Current

$$\vec{F} = i(\vec{L} \times \vec{B})$$



Faraday Induction

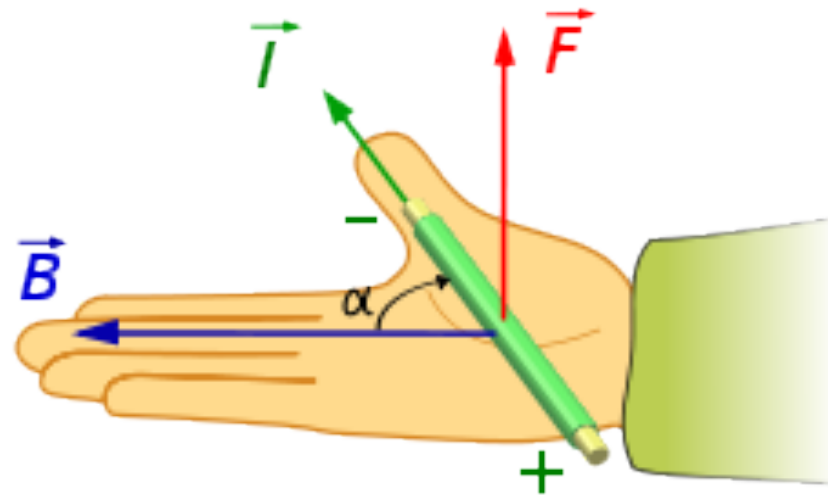
$$V = |L|(v \times B)$$



Voltage is proportional to velocity

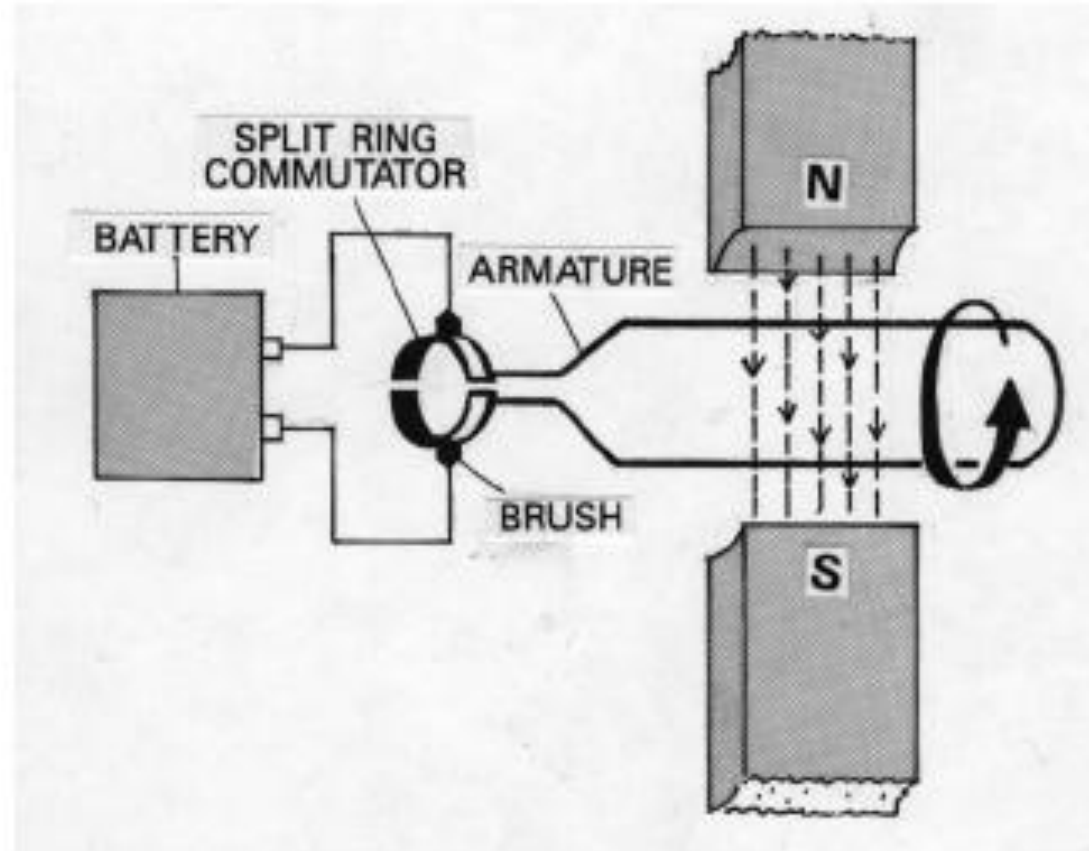
$$V = |L|(v \times B)$$

This voltage *pushes back* on the current



Motors

Just do this in a circle



Motor Equations

$$V = |L|(v \times B)$$

$$V = K_M \omega$$

$$F = i(L \times B)$$

$$\tau = K_M i$$

$$\tau = \mathcal{I}_M(d\omega/dt)$$

Simultaneously both a motor and a generator

Power is Conserved (mostly)

$$P = VI$$

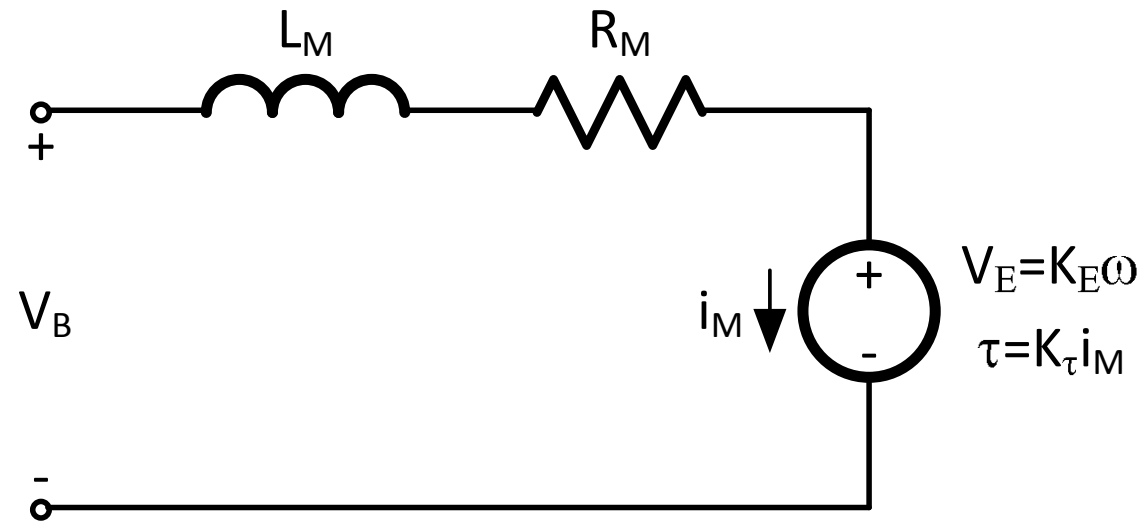
$$P = (K_M \omega)(\tau / K_M)$$

$$P = \omega \tau$$

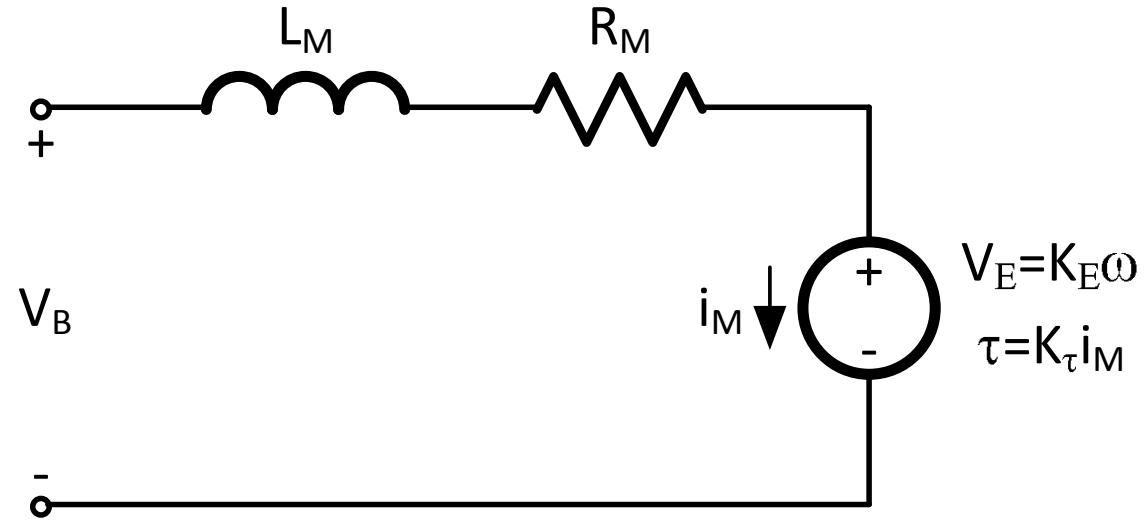
Models

- Develop mathematical expressions that predict behavior of physical (electrical and mechanical systems)
- Discard unnecessary detail to focus on the problem at hand

Motor Model



Motor Model



Motor is characterized by four parameters

Electrical: L_M , R_M

Mechanical: J_M

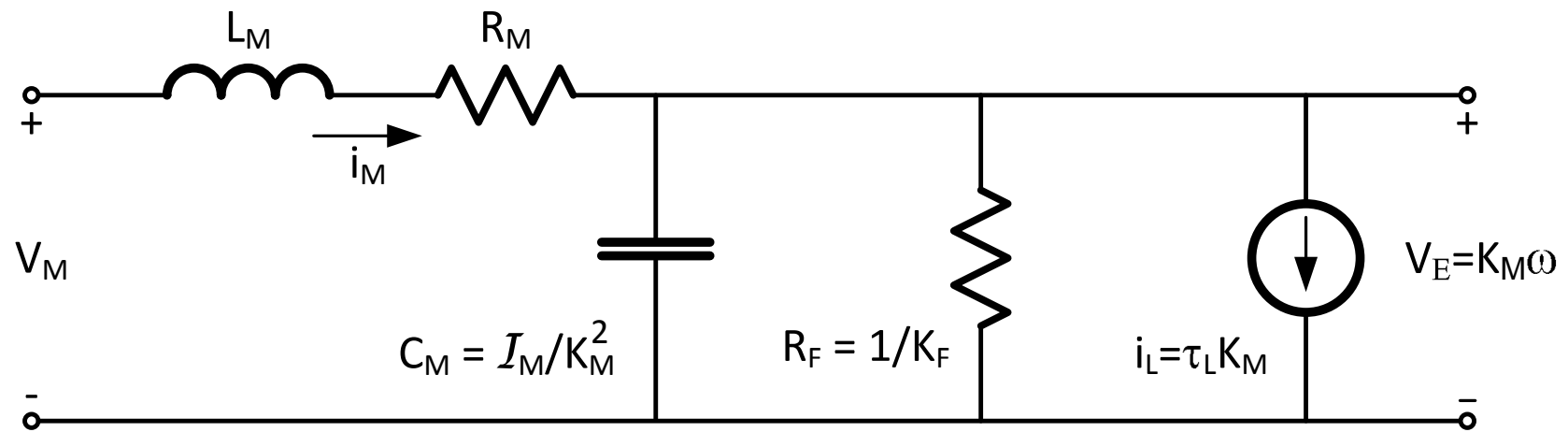
Electro-mechanical: K_M

Two key time constants

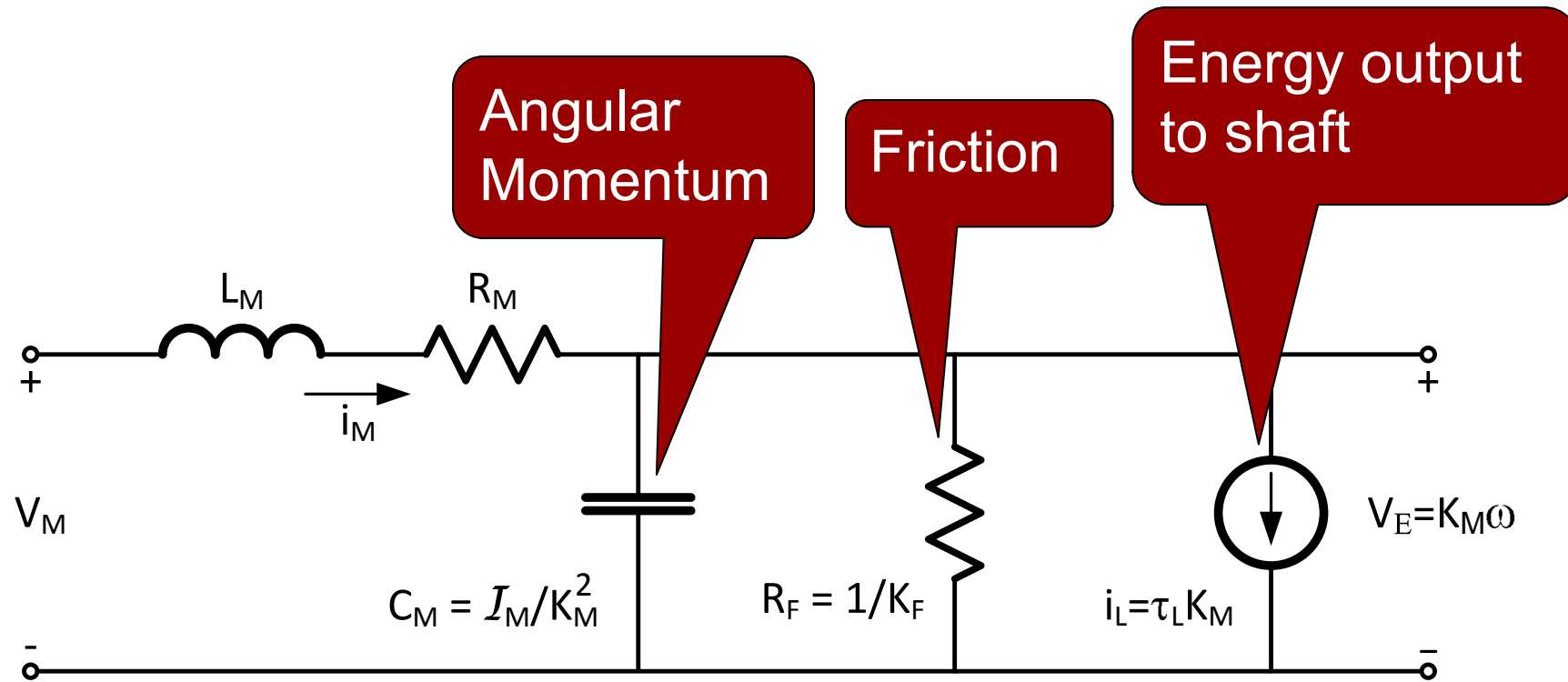
- Electrical: $\tau_E = L_M/R_M$

- Mechanical: $\tau_M = R_M J_M / K_M$ ²

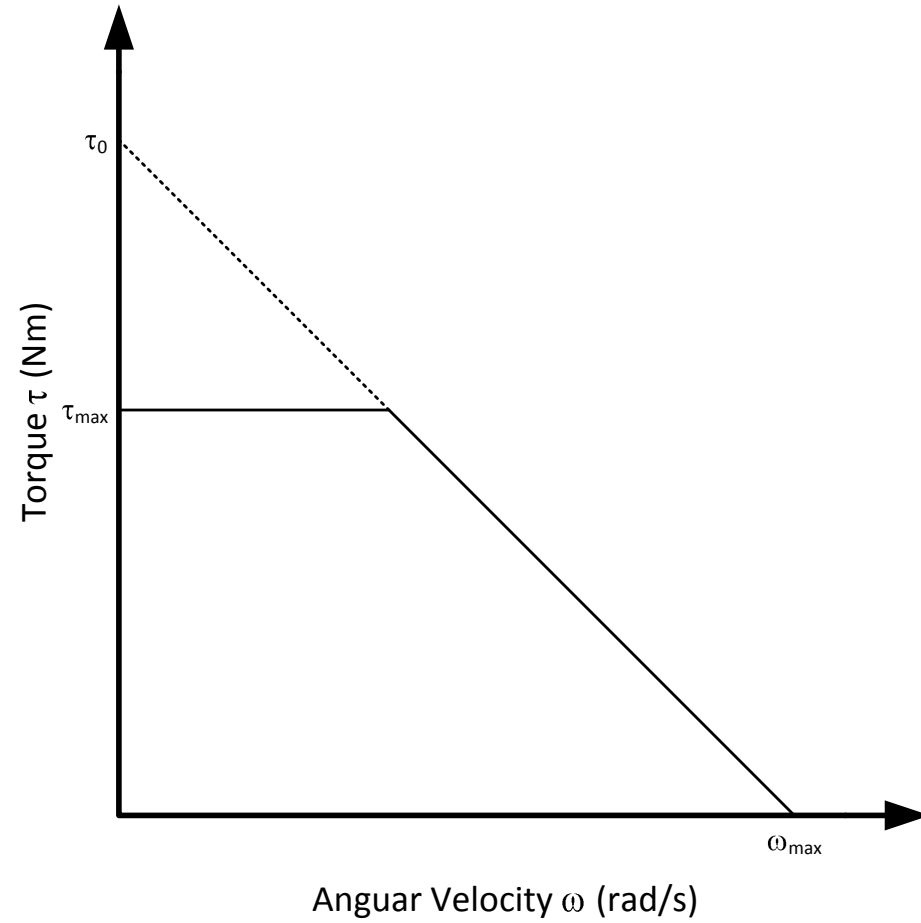
Composite Model



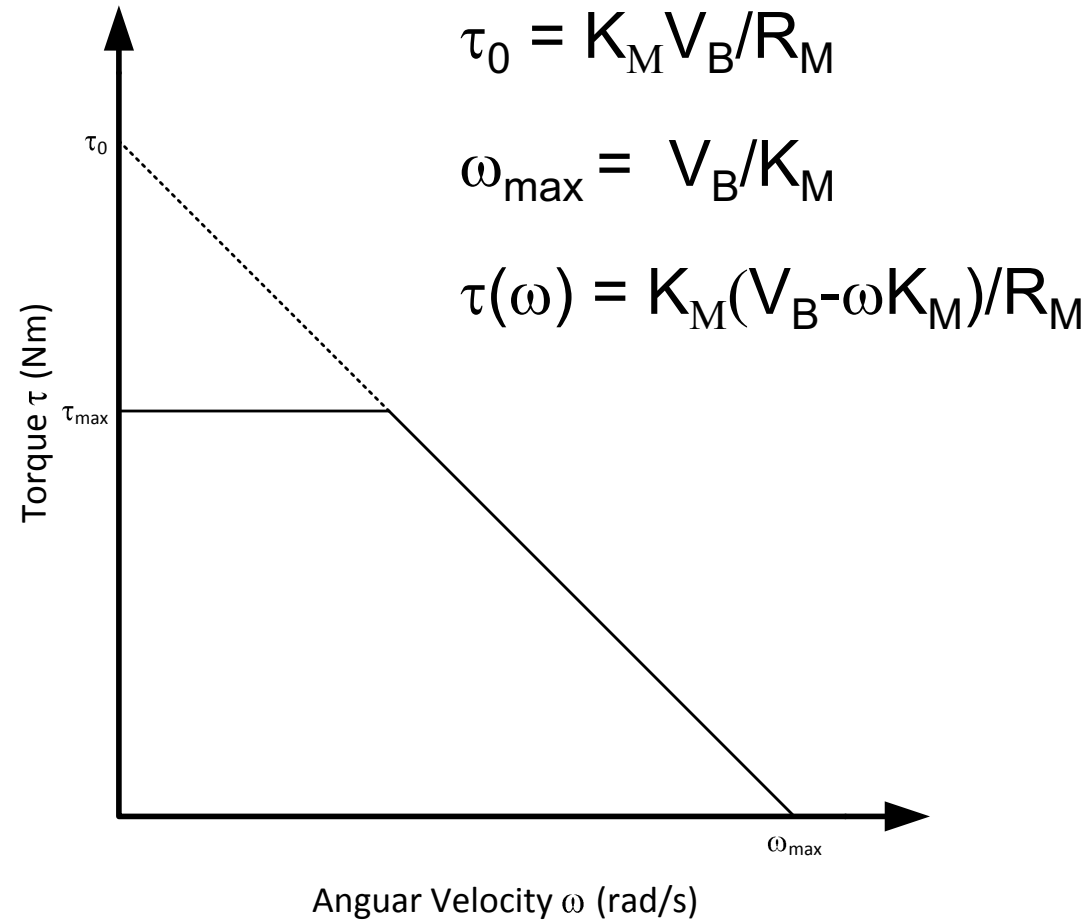
Composite Model



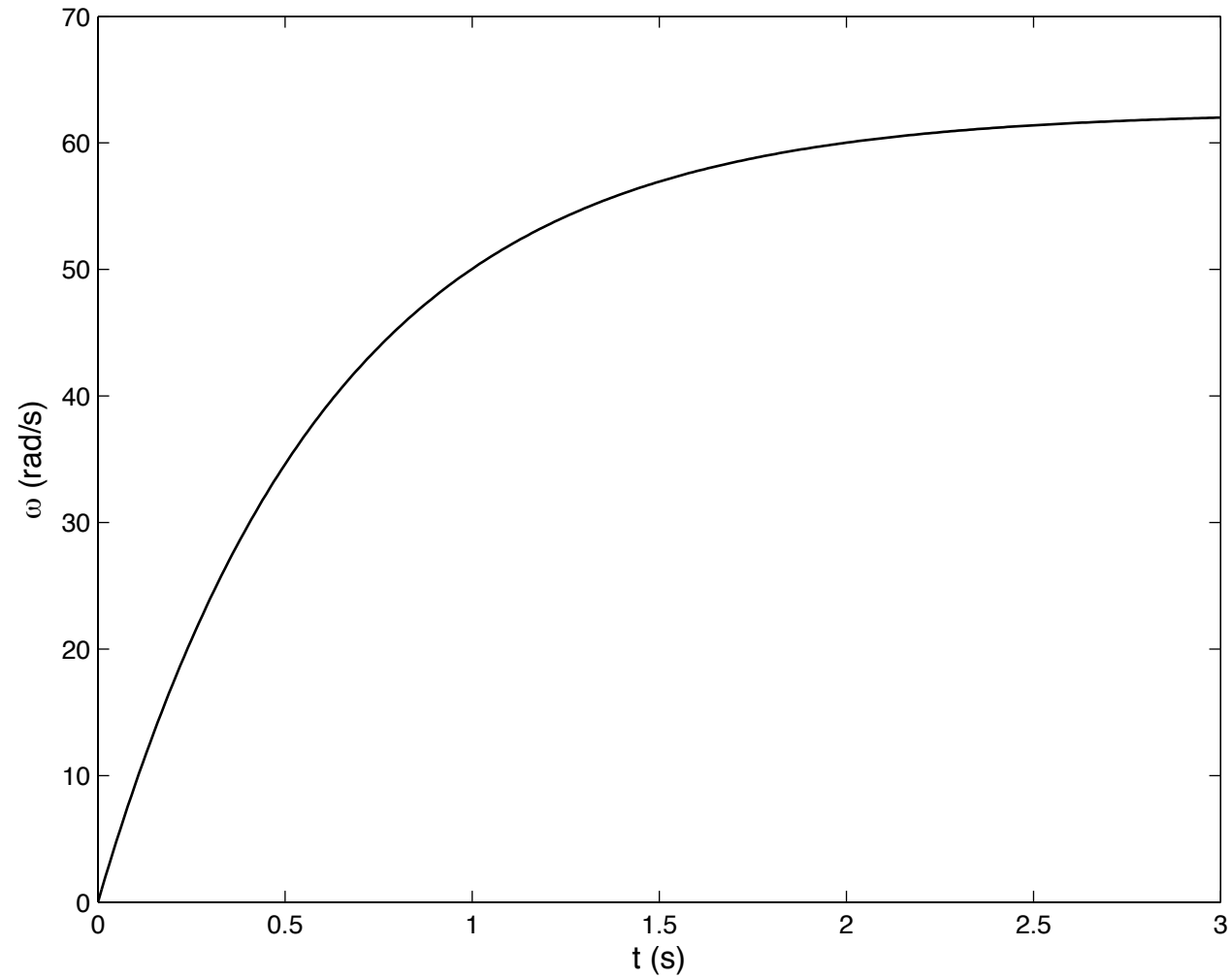
Steady-State Response



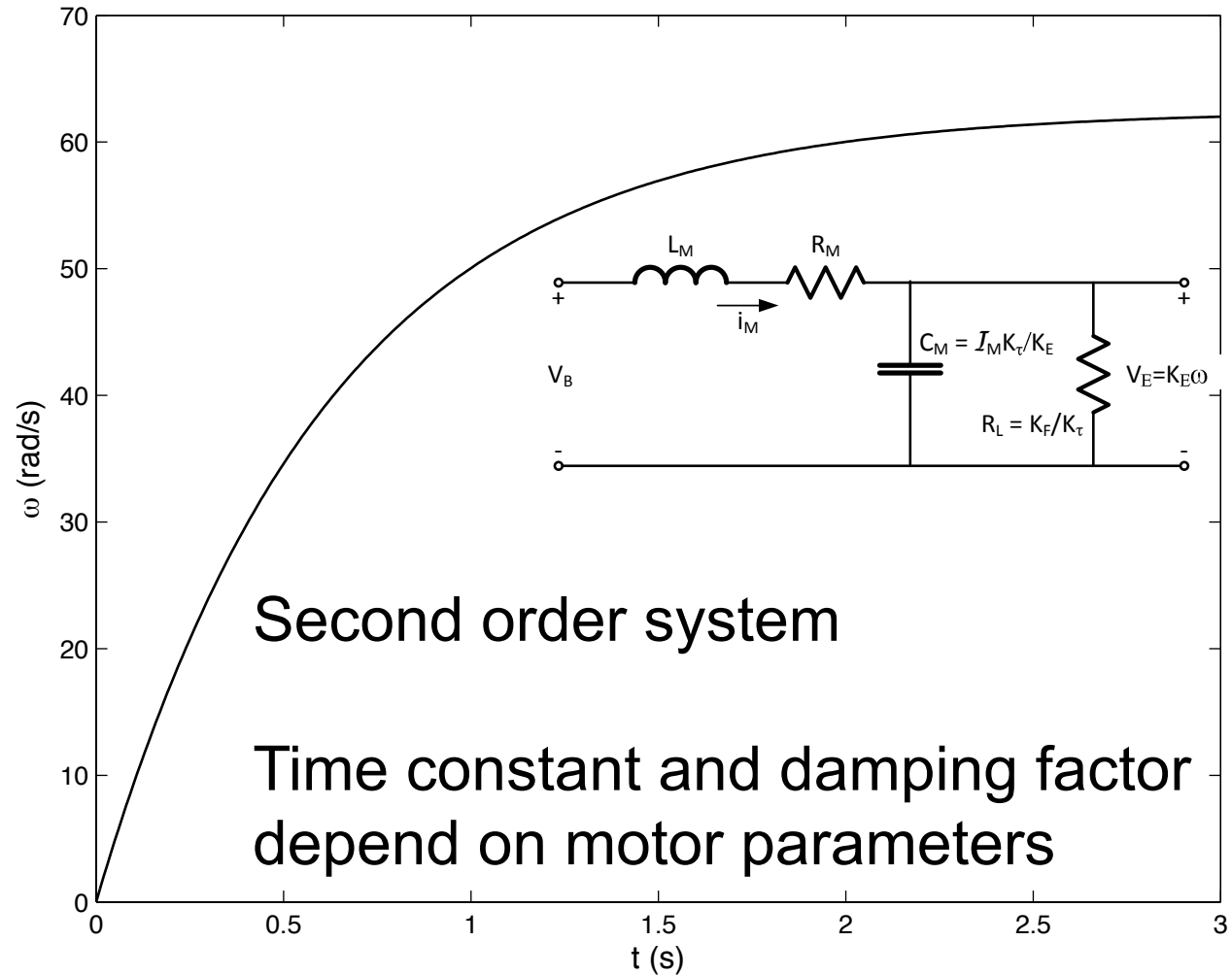
Steady-State Response



Transient Response

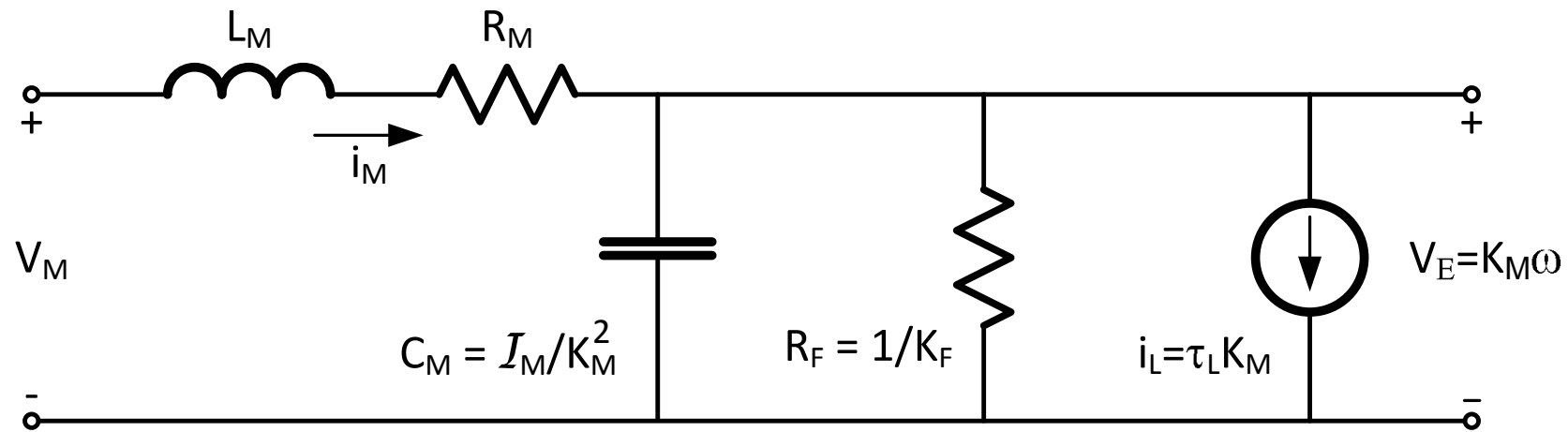


Transient Response



Composite Model

Motor is second order, but typically electrical time constant $L/R \ll$ mechanical time constant $(I_M K_F / K_E)$, so we can approximate it as a first-order system.



Need to *Control* the Motor

- Applying full battery voltage to a motor system with significant inertia will generally result in destructive currents
 - R_M is small – milliohms
 - “Locked rotor” current $I_{LR} = V_B/R_M$ is large 10^3 - 10^5 A
 - Unless inertia is very low, sustained current will
 - Destroy switching element (MOSFET or IGBT)
 - Burn insulation off of windings
 - Disconnect windings from brushes
 - Fuse windings and wiring
 - All of the above

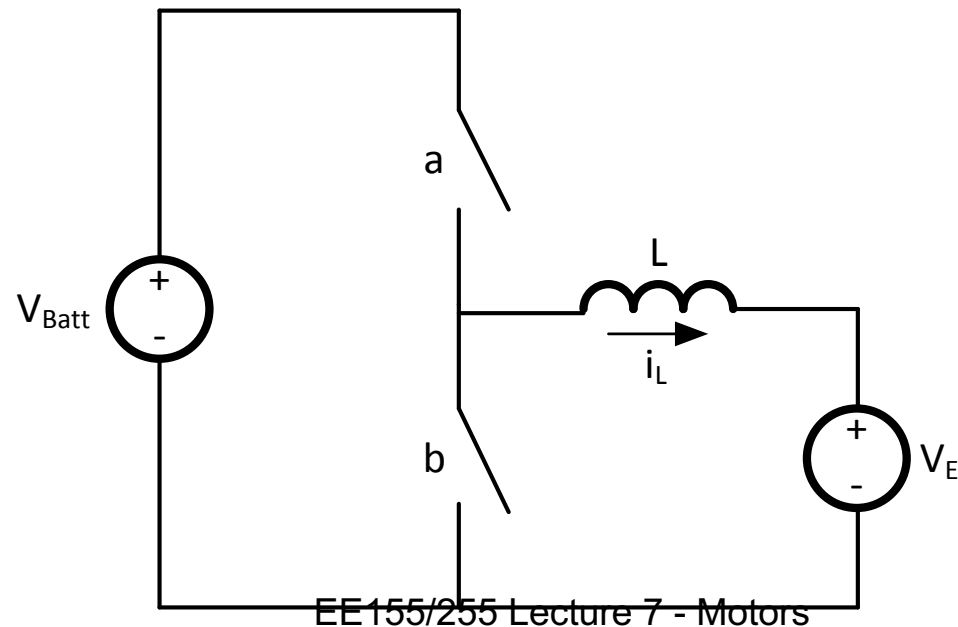
Suppose I want to Apply 16V to the motor
but all I have is a 48V battery?

Buck Converter

Motor controller is just a buck converter

Rotor winding is the inductor L

Back-EMF sets the output voltage V_E

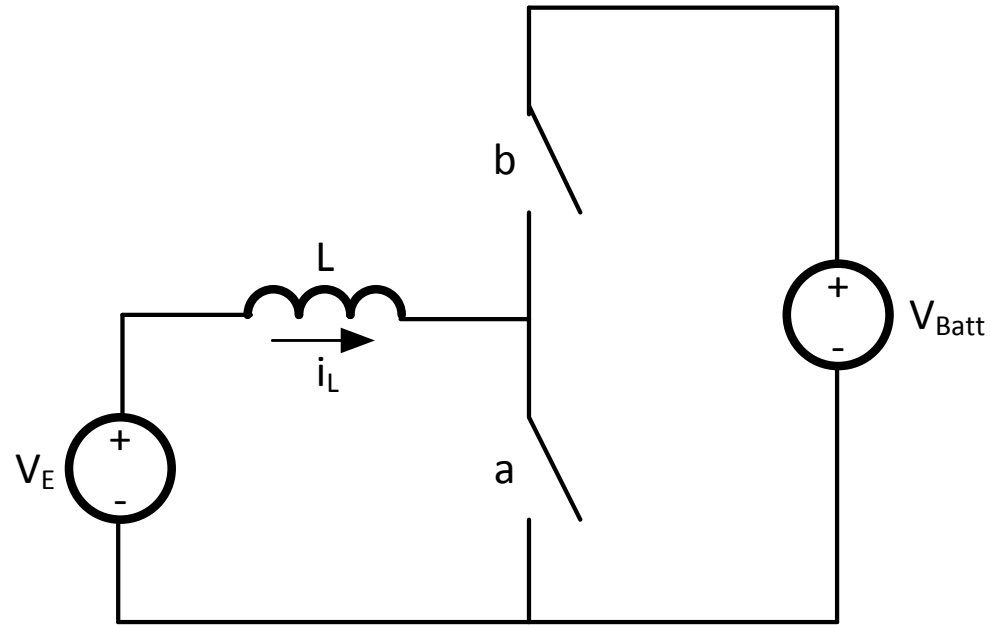


What PWM Frequency?

- Suppose $L_m = 1\text{mH}$
- $V = 48\text{V}$
- What frequency is needed to keep ripple current $< 1\text{A}$?

Regenerative Braking

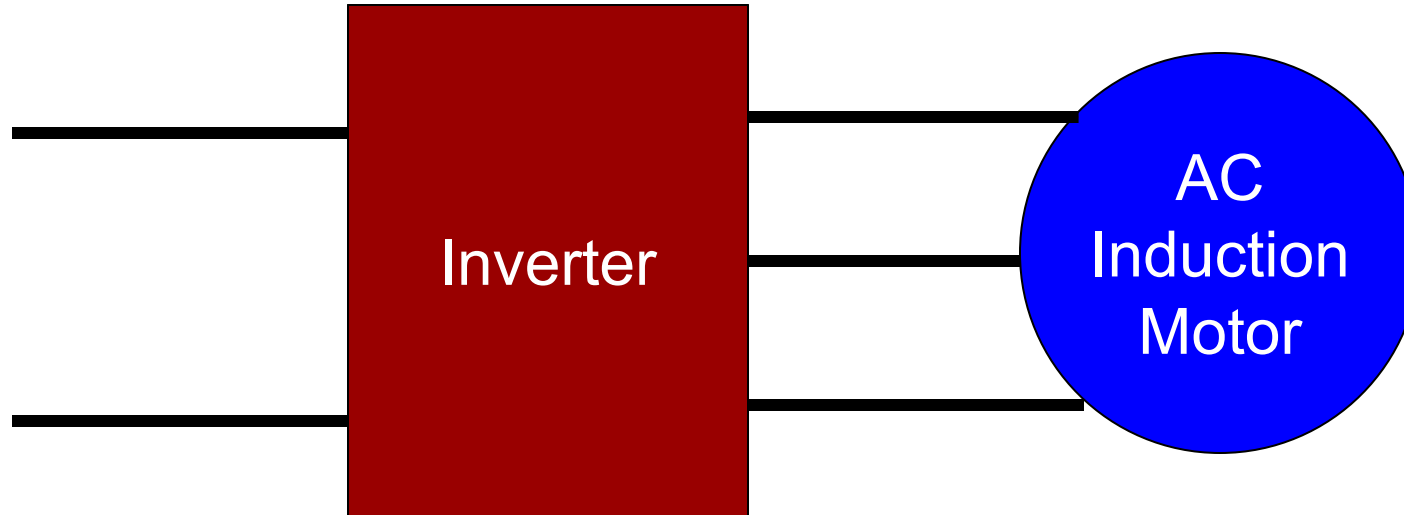
Boost Converter



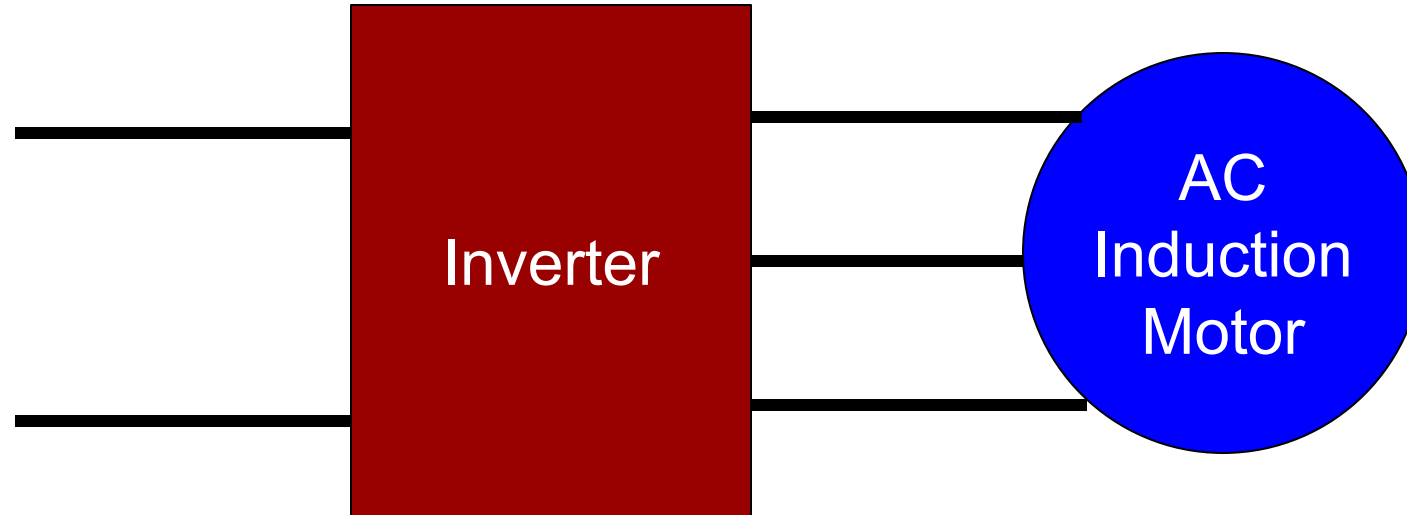
Types of Motors

- Brushed permanent magnet motors (PM)
 - What we have been talking about so far
 - PM on stator, windings on rotor switched by commutator
- Brushless permanent magnet motors (BLPM)
 - Like PM but no brushes – PM on rotor
 - Use controller to “commutate” stator current
 - AC voltage required on windings
- AC induction motors
 - Rotor is “shorted winding” acts like a transformer
 - Stator excites rotor and generates field
- Series and shunt wound DC motors
 - Separate stator and rotor windings
- Radial and axial flux versions of all of the above

All Motors Look Like a Brushed PM Motor



All Motors Look Like a Brushed PM Motor
Torque is proportional to current
Velocity generates back EMF



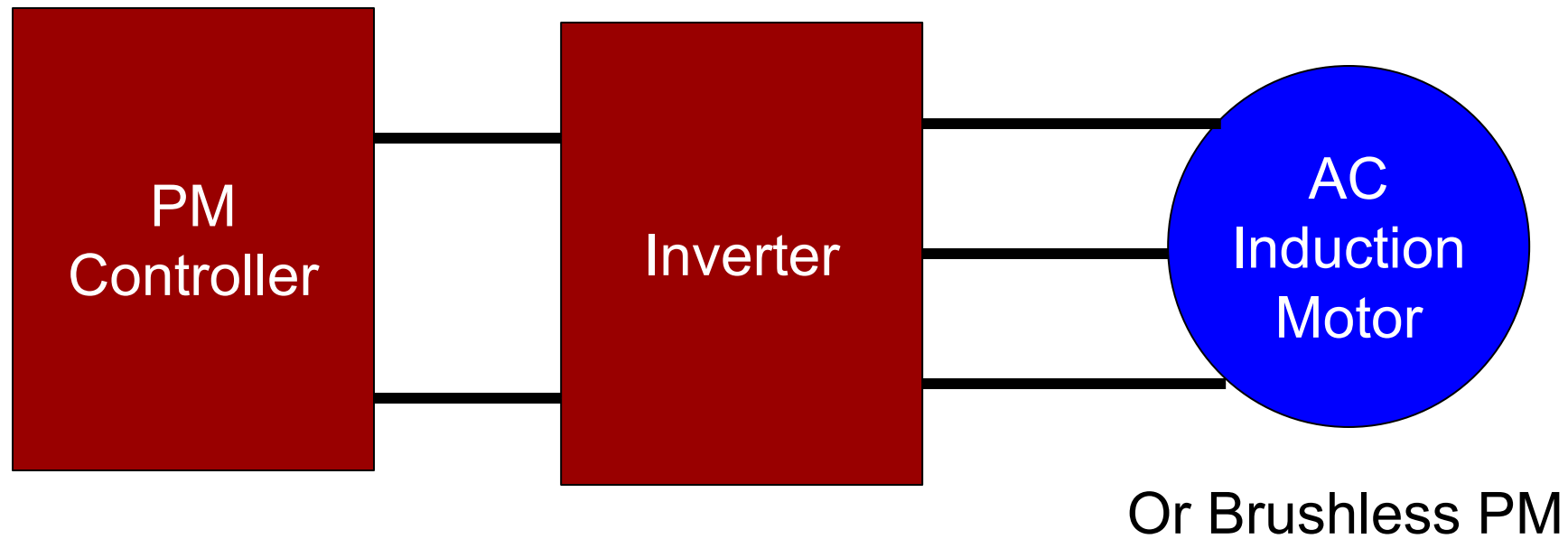
Only difference is need for “inverter”, electronic “commutator”
or other power shaping electronics

Separate Motor Controller Design

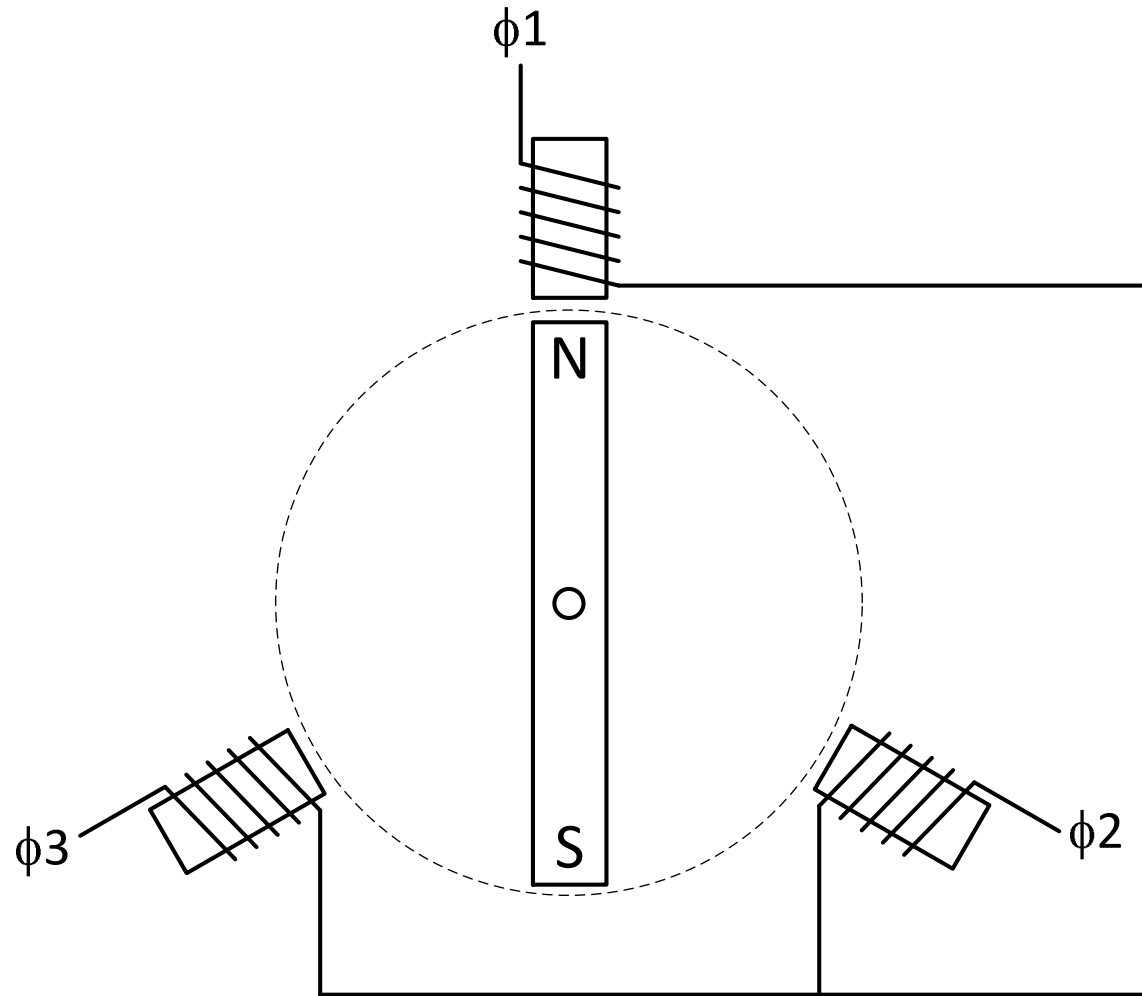
Brushed PM Controller + Inverter

Combine redundant elements

Inverter needs to estimate rotor position and/or velocity



Brushless PM Motor



Consider Brushless PM as a Generator

Angle 0 is up (0,1)

Phases at 0, 120, 240 degrees

Field produced by rotor at angle θ :

$$\mathbf{B} = (B_0 \sin \theta, B_0 \cos \theta)$$

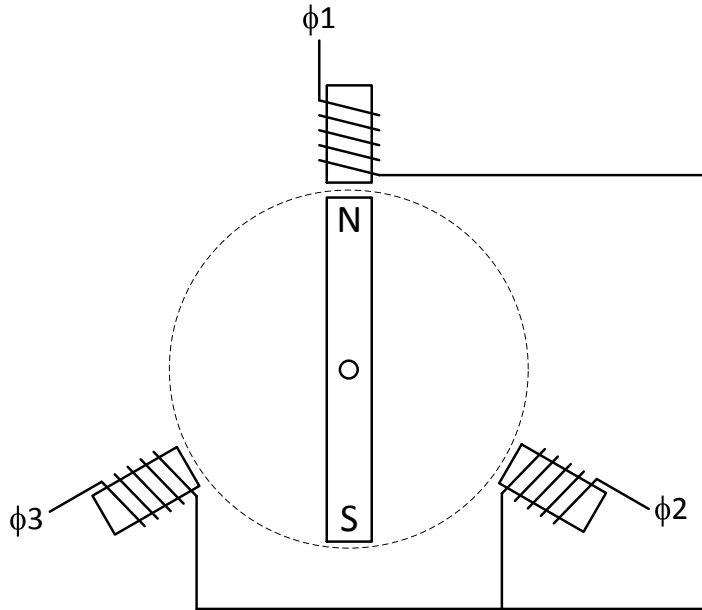
$$\phi = \mathbf{B} \mathbf{A} = (B_0 A \sin \theta, B_0 A \cos \theta)$$

Voltage in phase i is $d\phi/dt$ at α_i

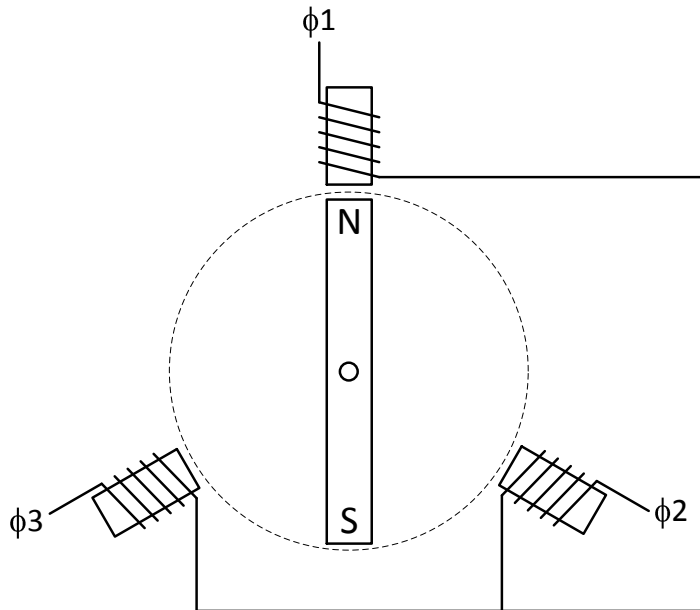
$$d\phi(\theta)/dt = (B_0 A \omega \cos \theta, -B_0 A \omega \sin \theta)$$

$$V(\alpha) = d\phi(\theta)/dt \cdot \mathbf{U}(\alpha)$$

$$V(\alpha) = -B_0 A \omega \sin(\theta - \alpha)$$



Back EMF



$$V(\alpha) = -K\omega \sin(\theta - \alpha)$$

Open-circuit voltage (back EMF) of each phase is a sinusoid that

Is proportional to ω

Reaches peak value when rotor is 90 degrees from phase.

Torque

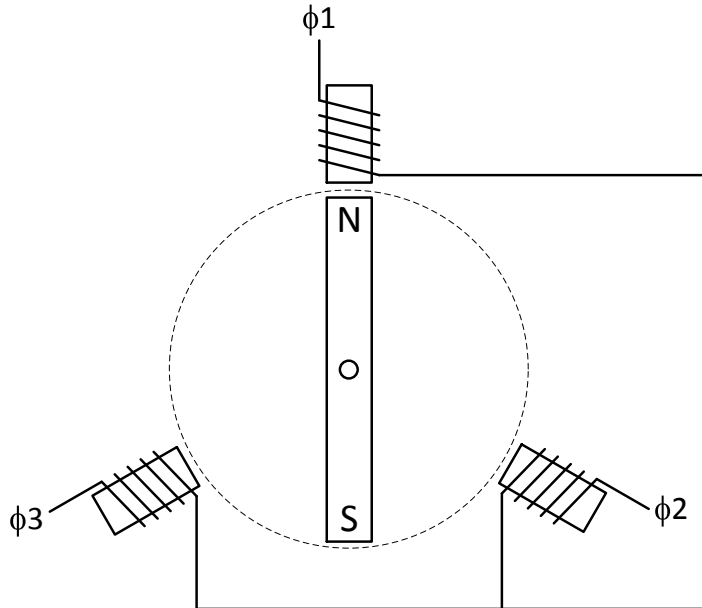
Current in winding i produces a field at angle α_i

Torque is effect of this field on the rotor at angle θ

$$\tau = -(Ki)\sin(\theta - \alpha_i)$$

Power is conserved

$$\begin{aligned}\tau\omega &= -\omega(Ki)\sin(\theta - \alpha_i) \\ &= -(i)K\omega\sin(\theta - \alpha_i) \\ &= iV\end{aligned}$$



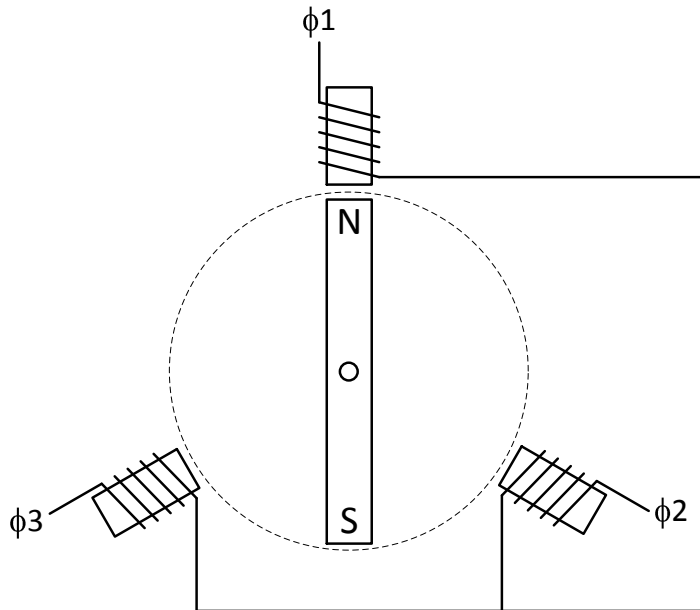
Torque

$$\tau = -(Ki)\sin(\theta - \alpha_i)$$

Torque is proportional to current

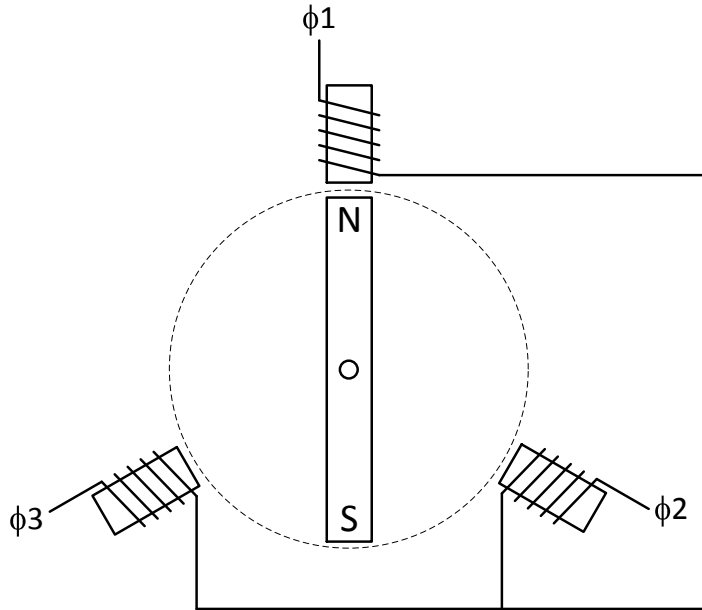
Torque is maximum when rotor is 90 degrees behind phase

Torque from each phase is sinusoidal



Rotating Stator Field

Stator field is superposition of fields from each phase



To generate a field at angle ψ apply current

$$I_i = \cos(\psi - \alpha_i)$$

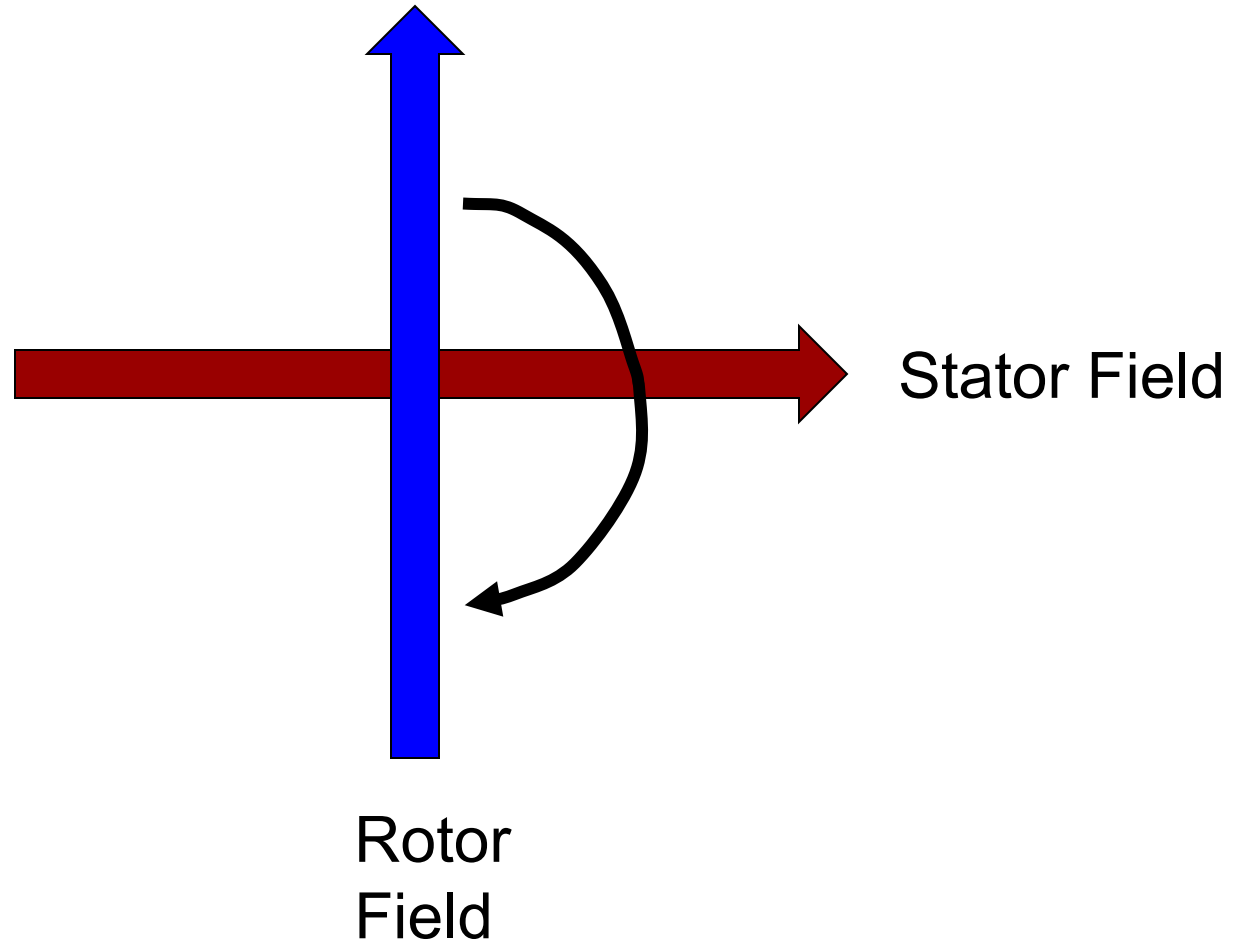
To phase i

Note currents sum to zero with evenly spaced phases

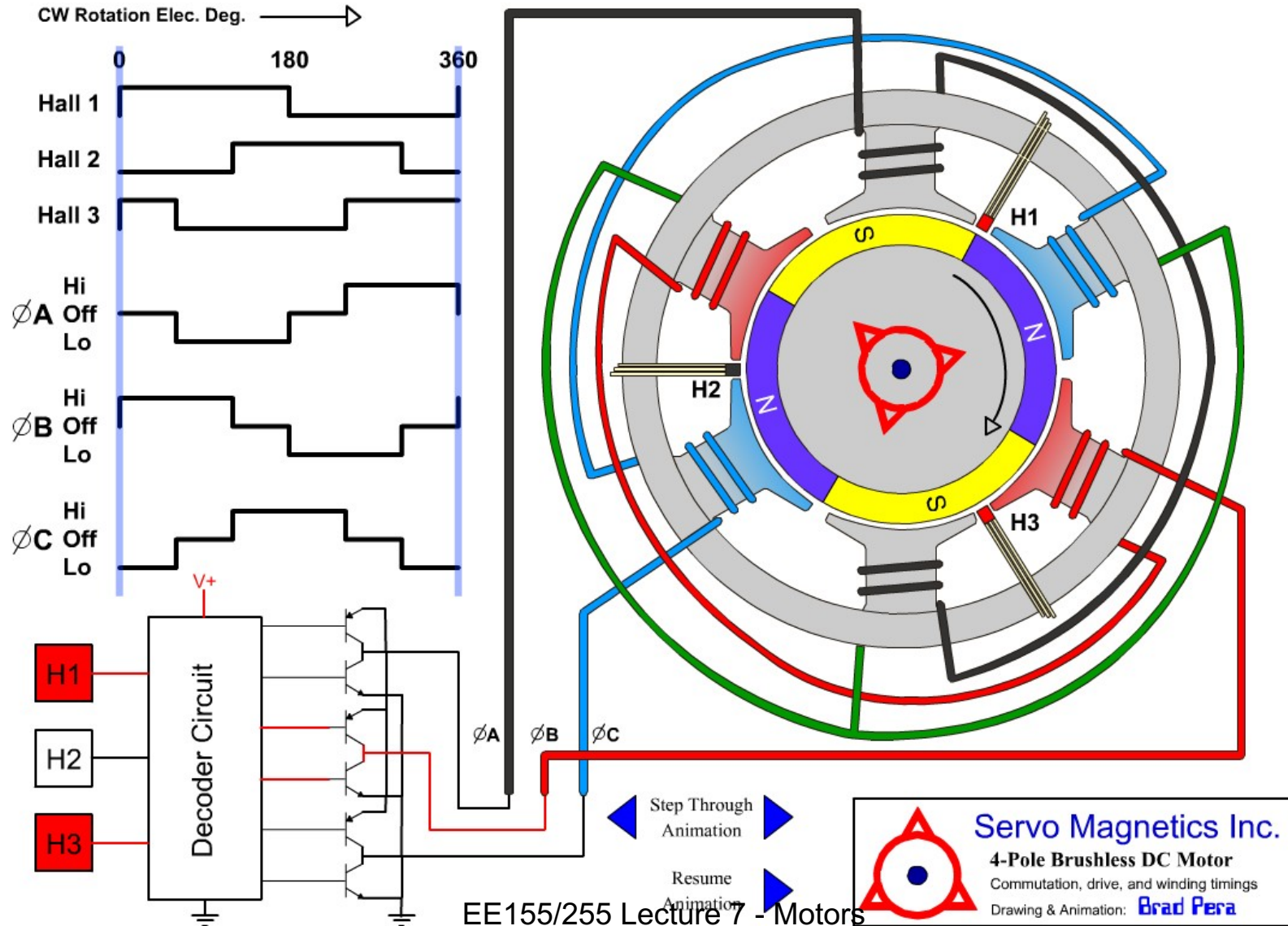
Brushless PM Motors

- Sense rotor position
 - Hall effect sensors
 - Measure phase current and voltage
 - Estimate position by fitting model
- Stator creates rotating magnetic field
 - Set angle at 90-degrees ahead of rotor to maximize torque
 - May be “effective” 90 degrees in multi-pole arrangements
- Stator field rotates at same rate as rotor
 - $\omega_s = \omega_r$
- Leads rotor by 90 degrees
 - $\Theta_s = \Theta_r + 90$

Angle of Magnetic Fields



Brushless PM Motors

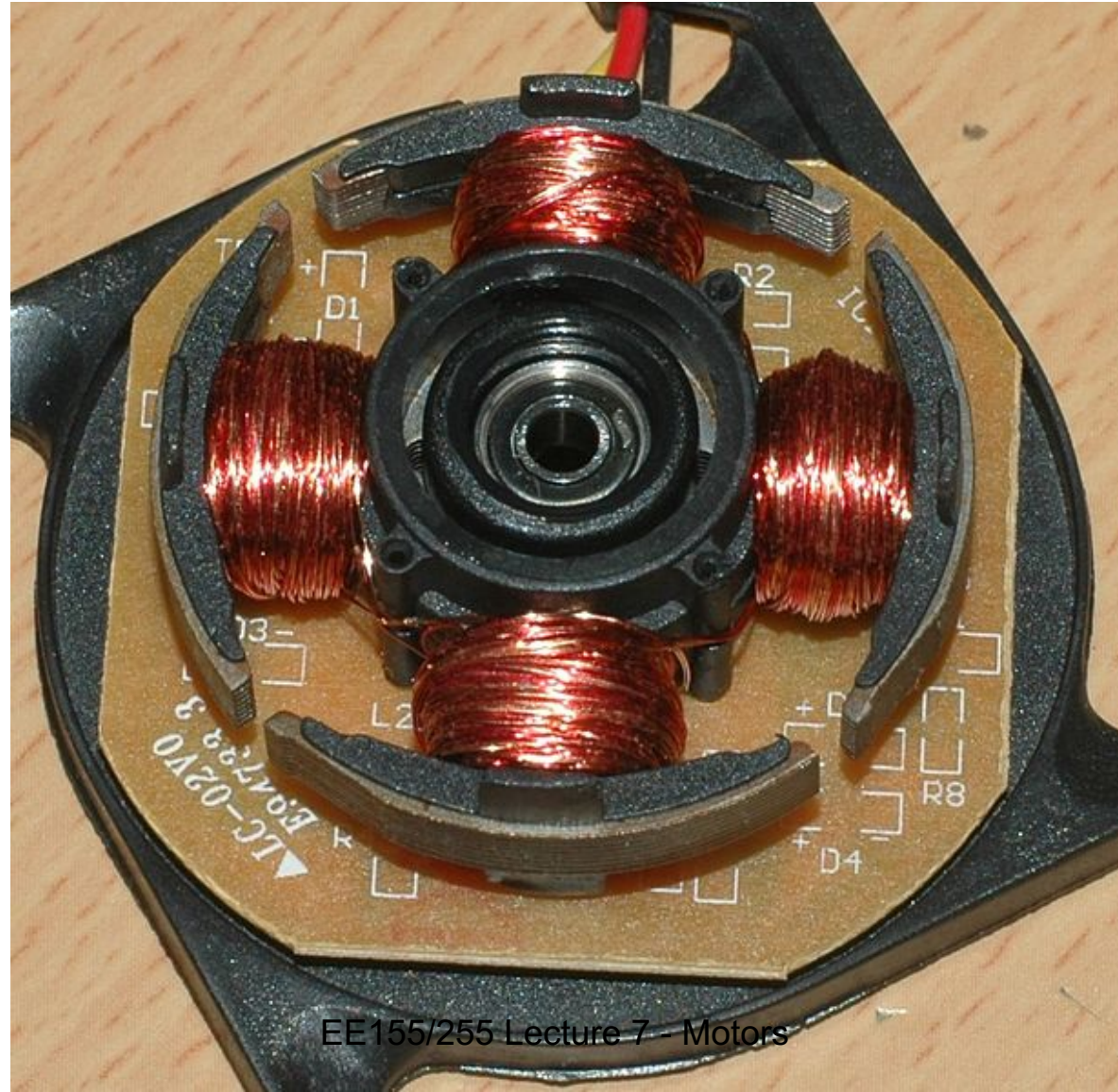


Animations of BLPM

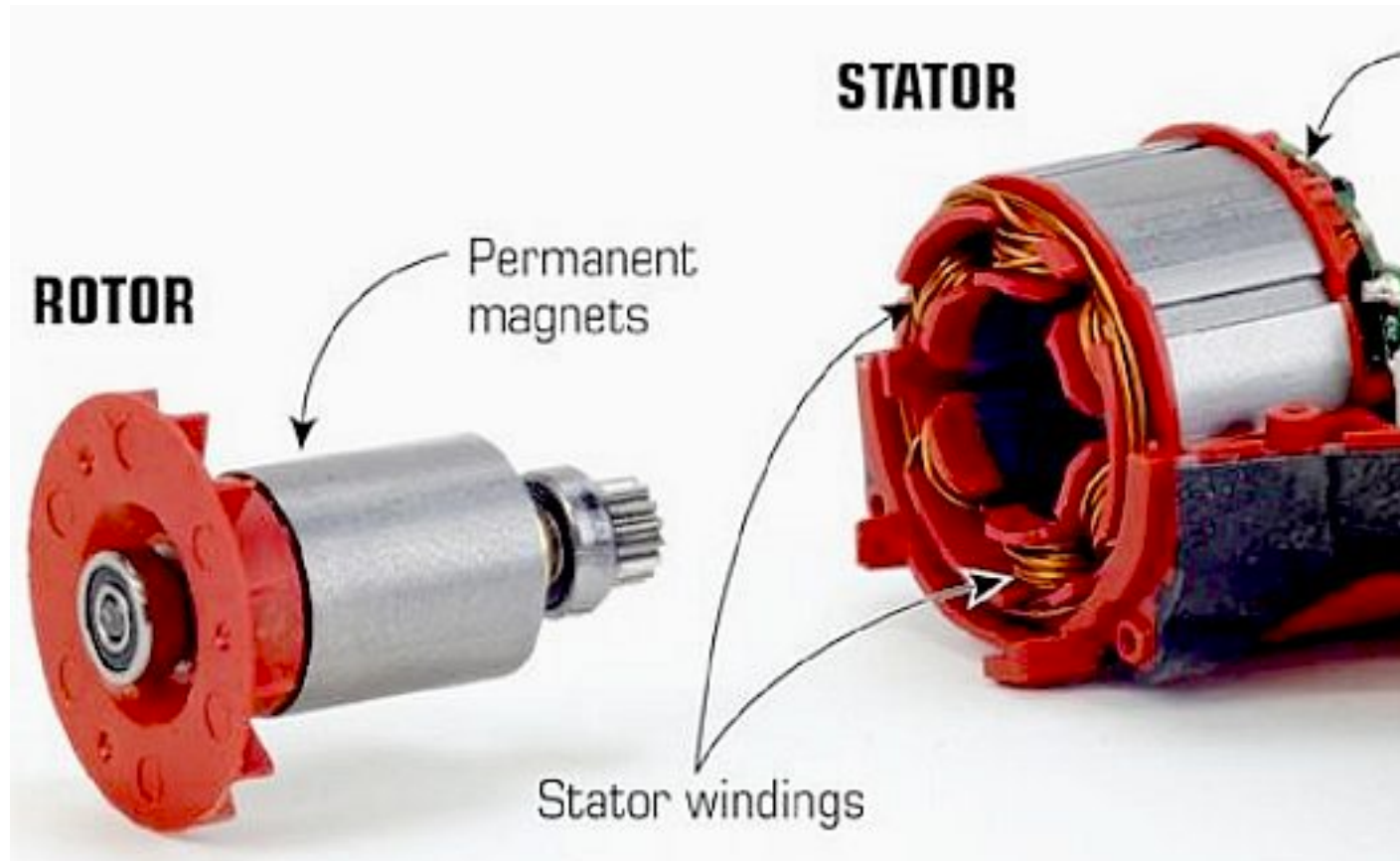
<http://www.ti.com/general/docs/video/watch.tsp?entryid=3870197889001>

<http://www.ece.umn.edu/users/riaz/animations/brushlessdc.html>

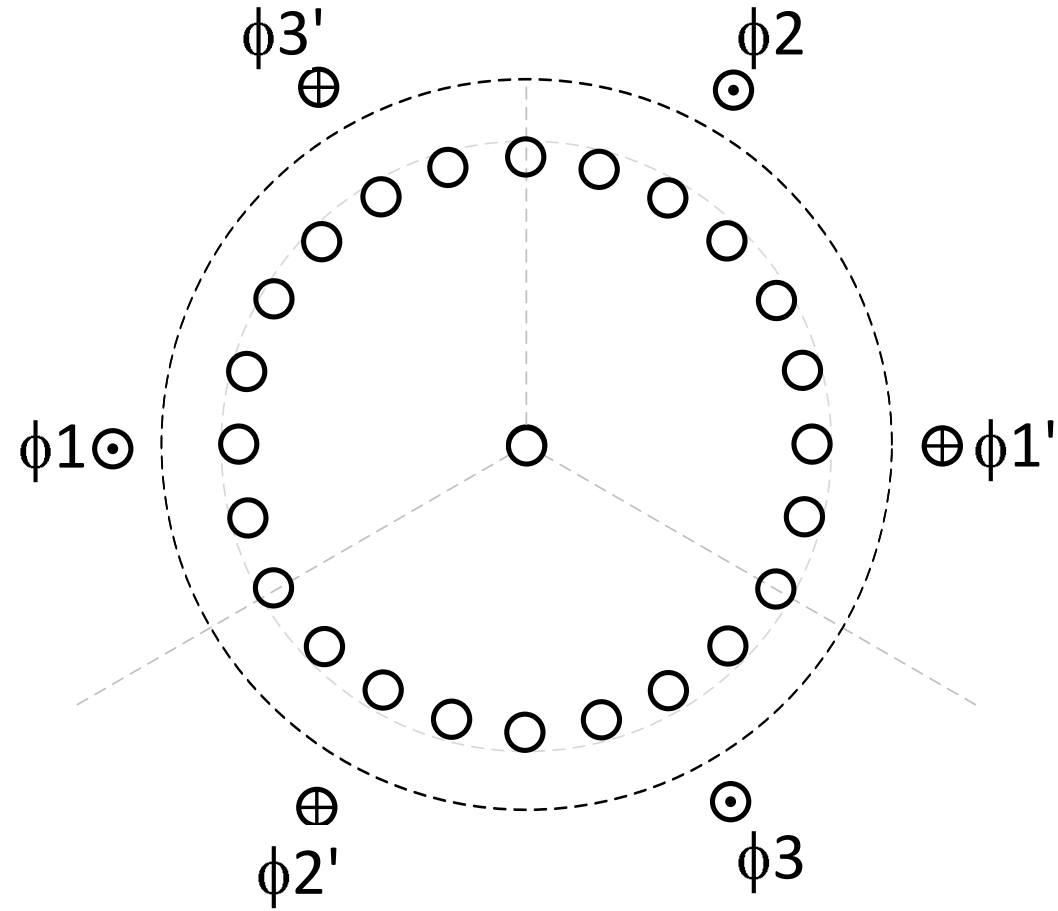
Example Stator – from fan



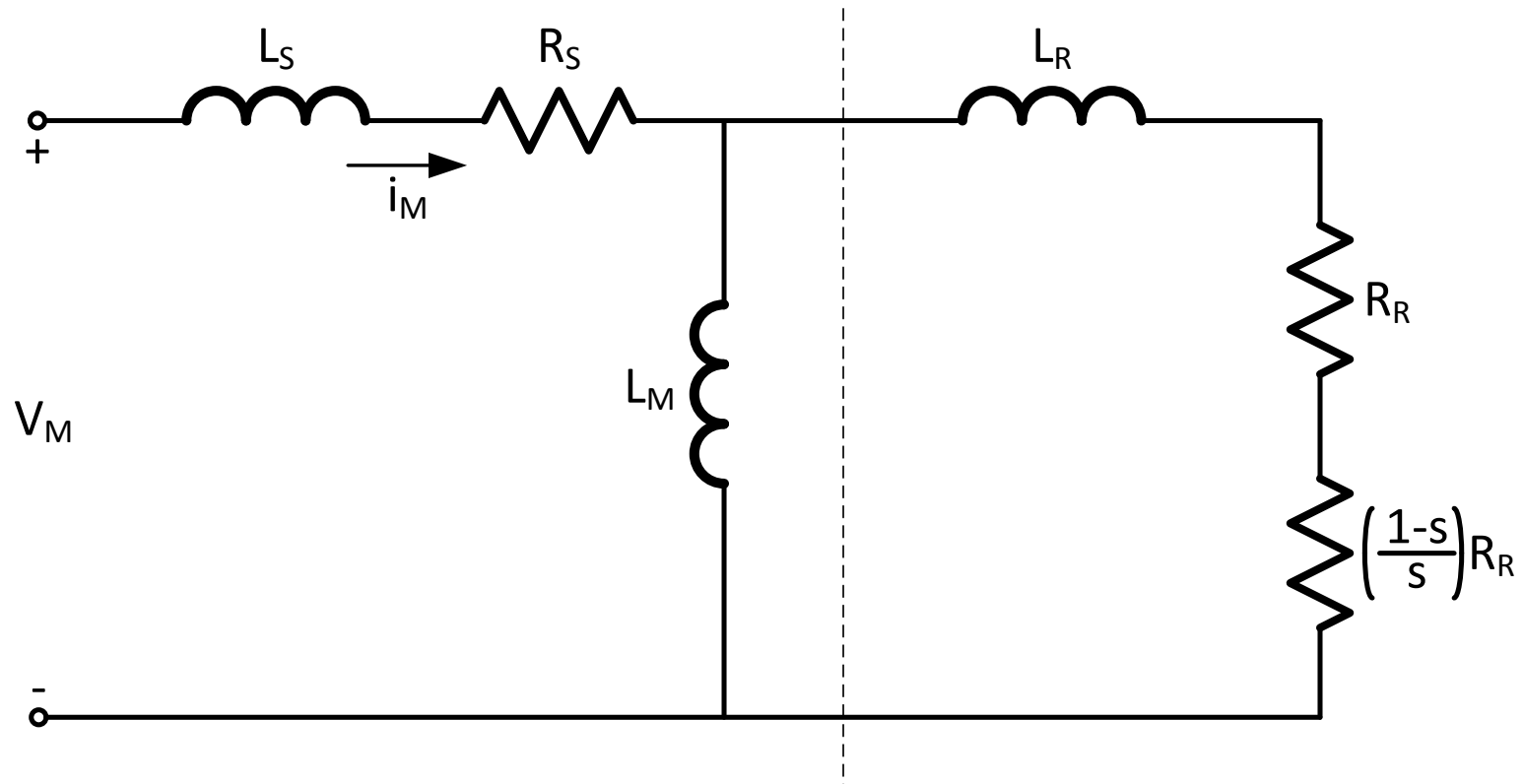
Stator Outside



AC Induction Motor

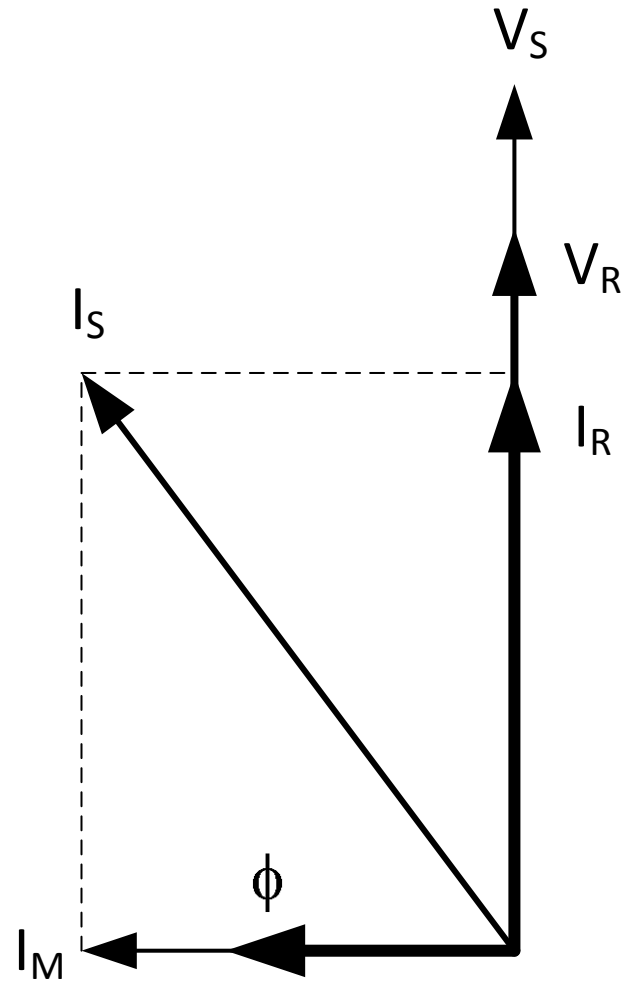


Equivalent Circuit



Rotor voltage scaled by slip
 $s = (\omega_s - \omega_r) / \omega_s$

Phase of Currents and Voltages



Torque Calculations

- Developed power

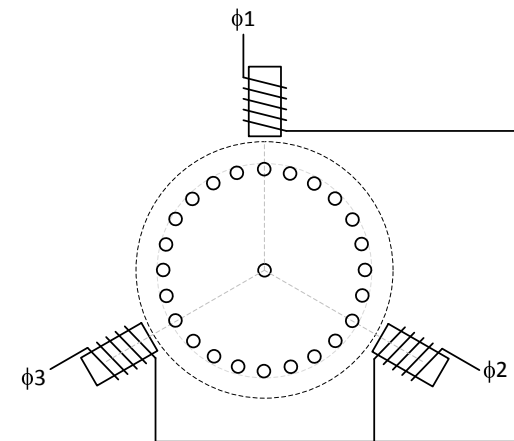
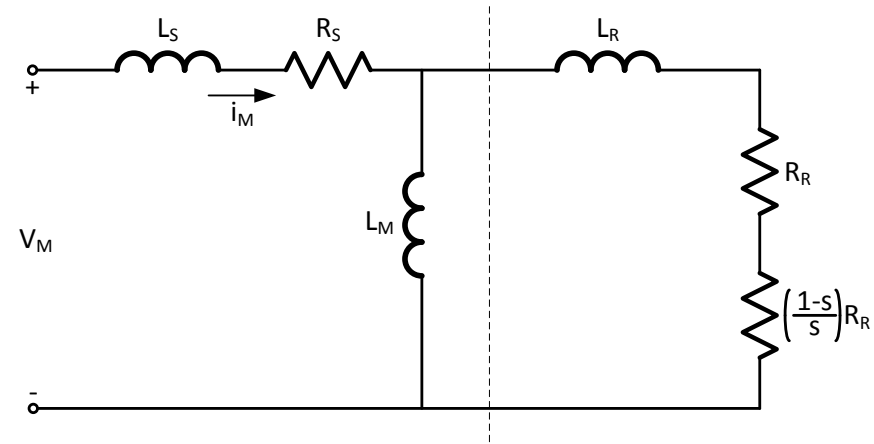
- $P = (1-s/s)I^2R_r$

- Torque

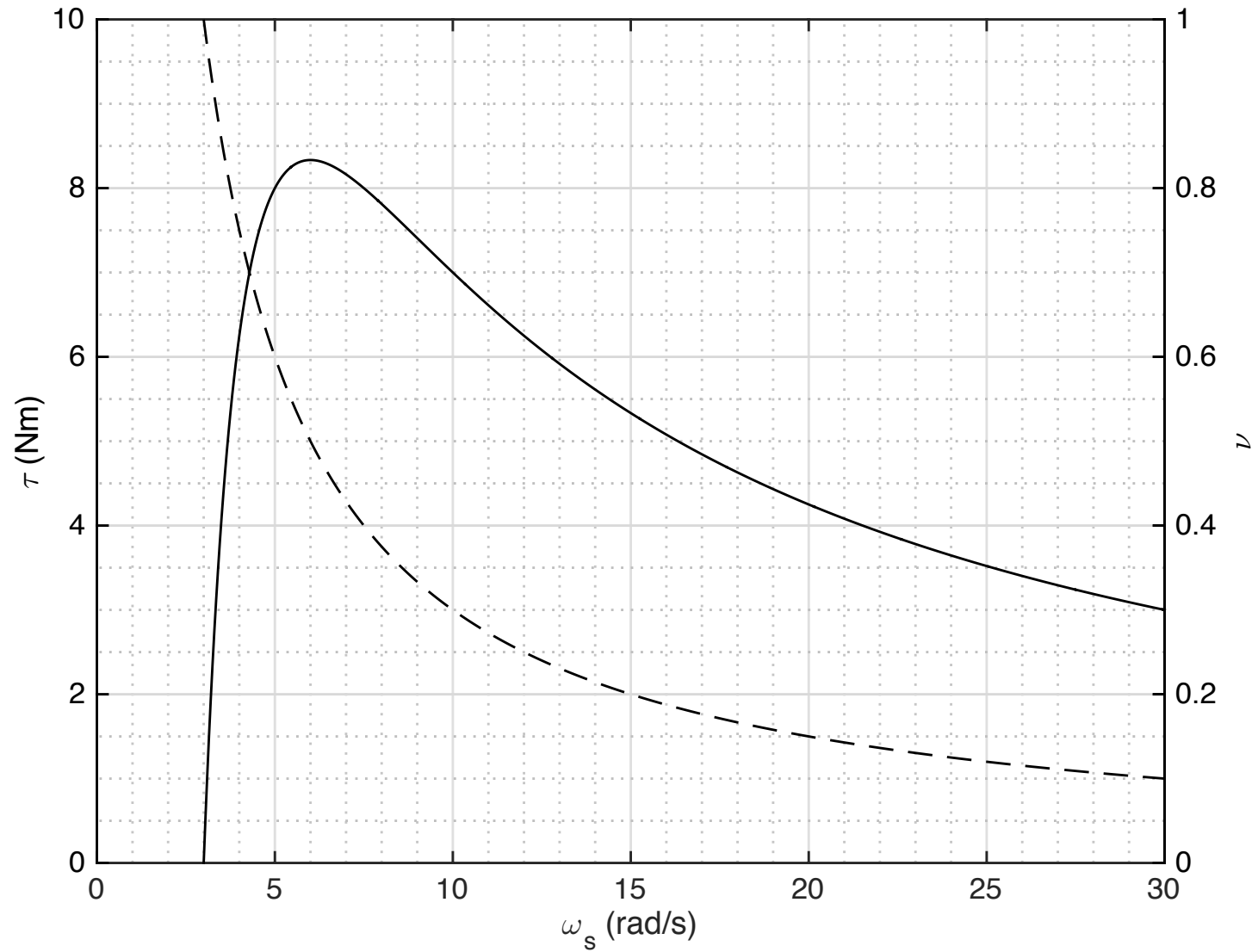
- $\tau = P/\omega = (1-s/s)I^2R_r/\omega_r$

- Starting Torque

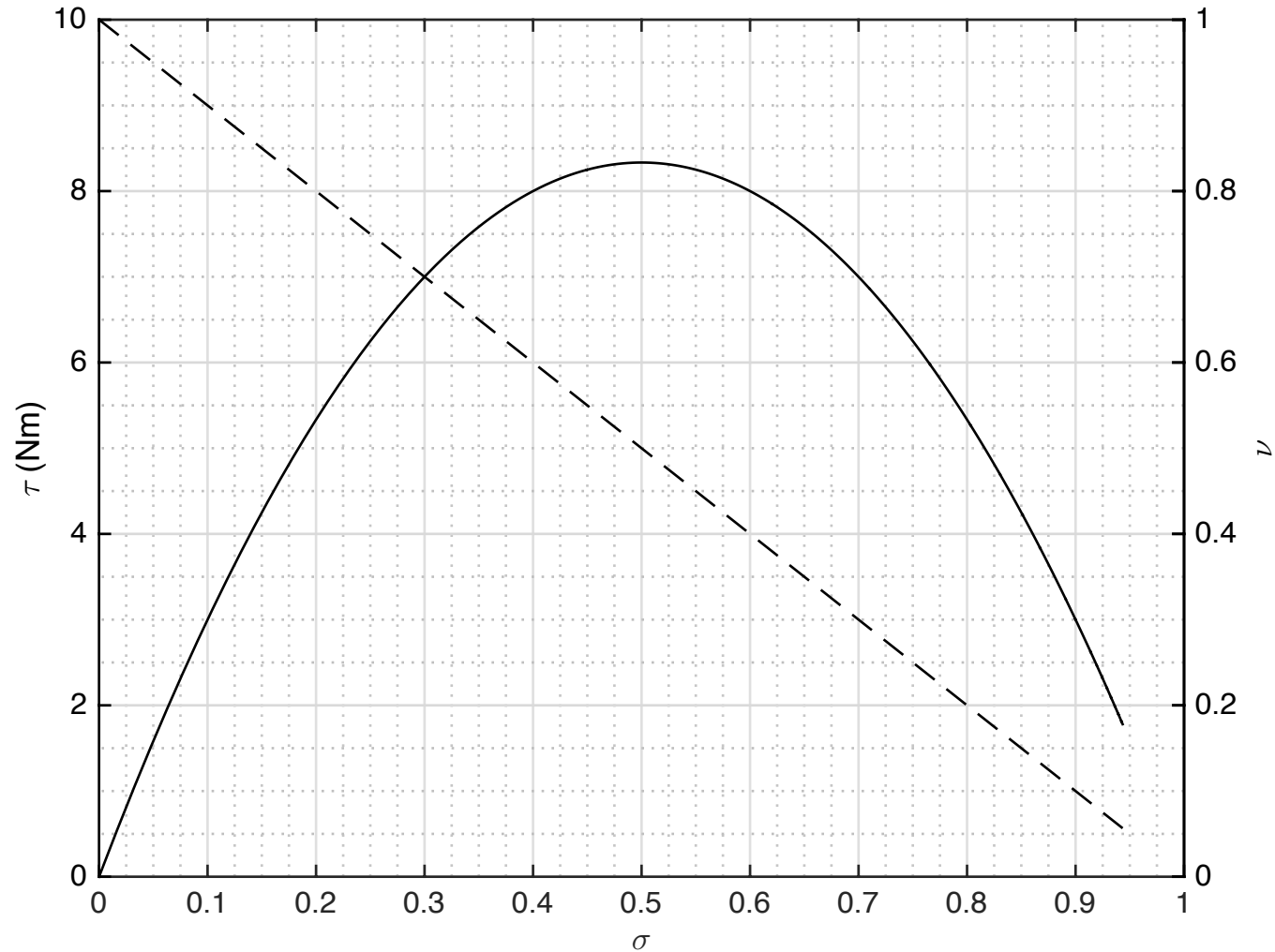
- $\tau_0 = I^2R_r/\omega_s$



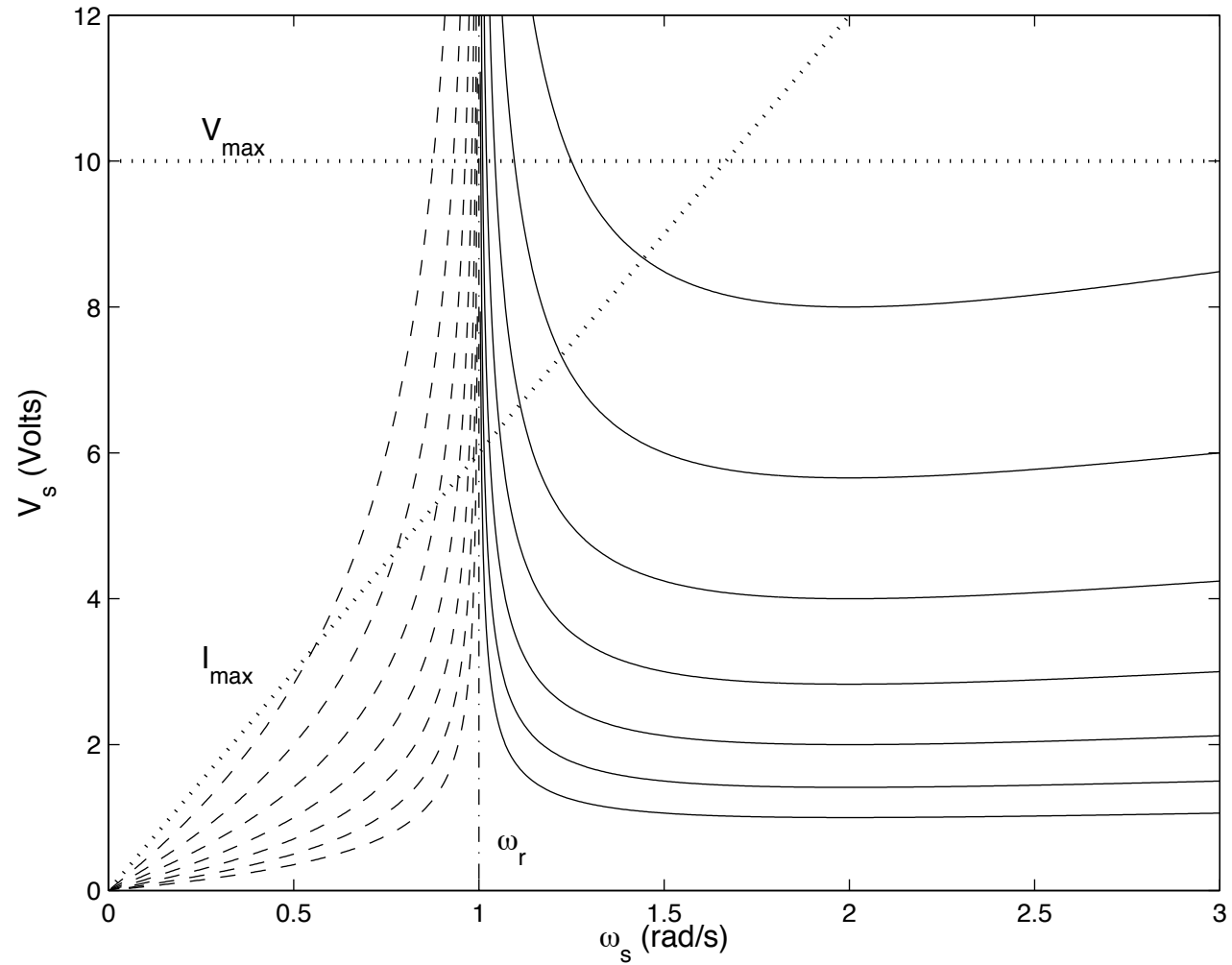
Torque and Efficiency



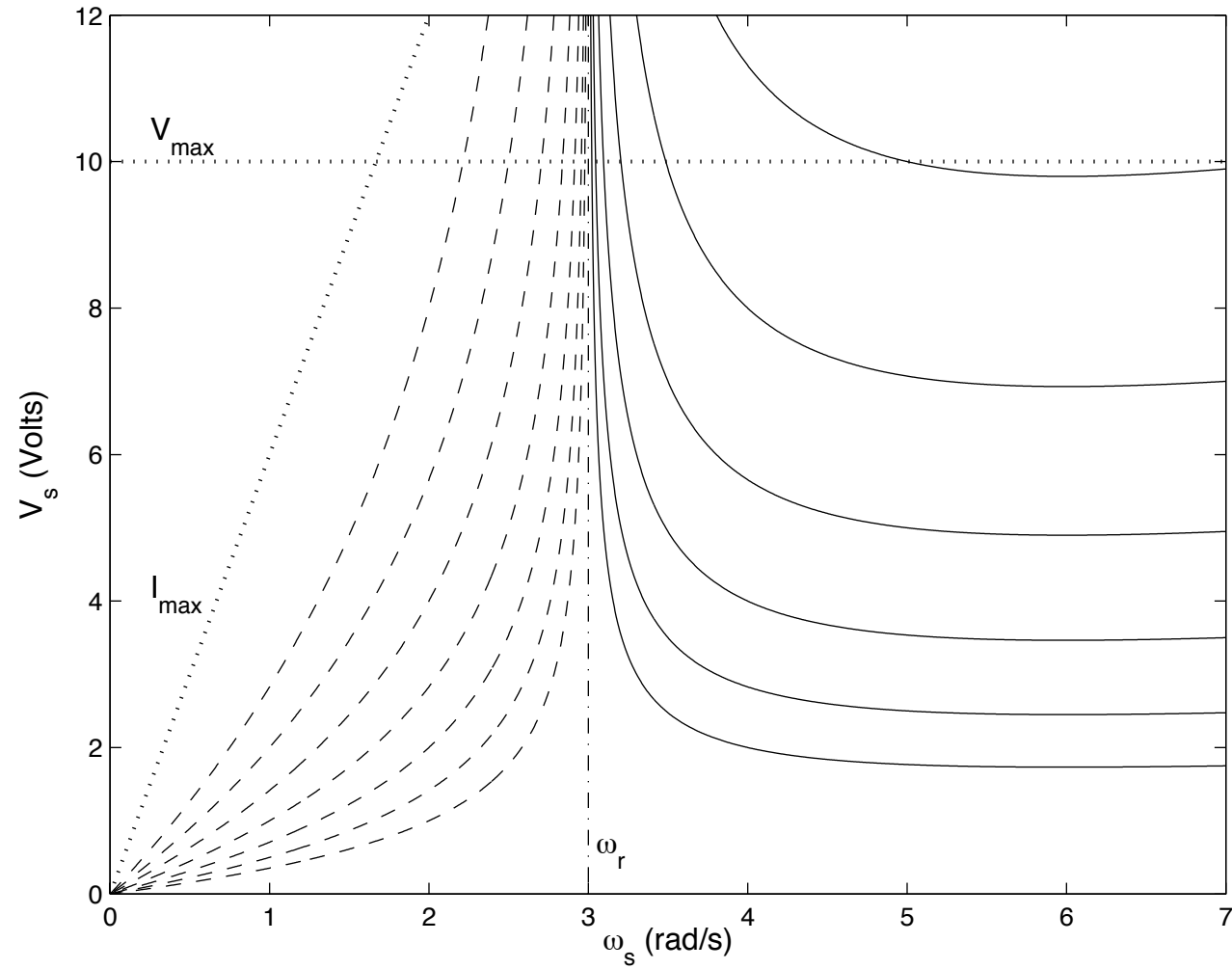
Torque and Efficiency vs Slip σ



AC Motor Control – Low Speed



AC Motor Control – High Speed



AC Induction Animation

<http://www.ece.umn.edu/users/riaz/animations/sqmovies.html>

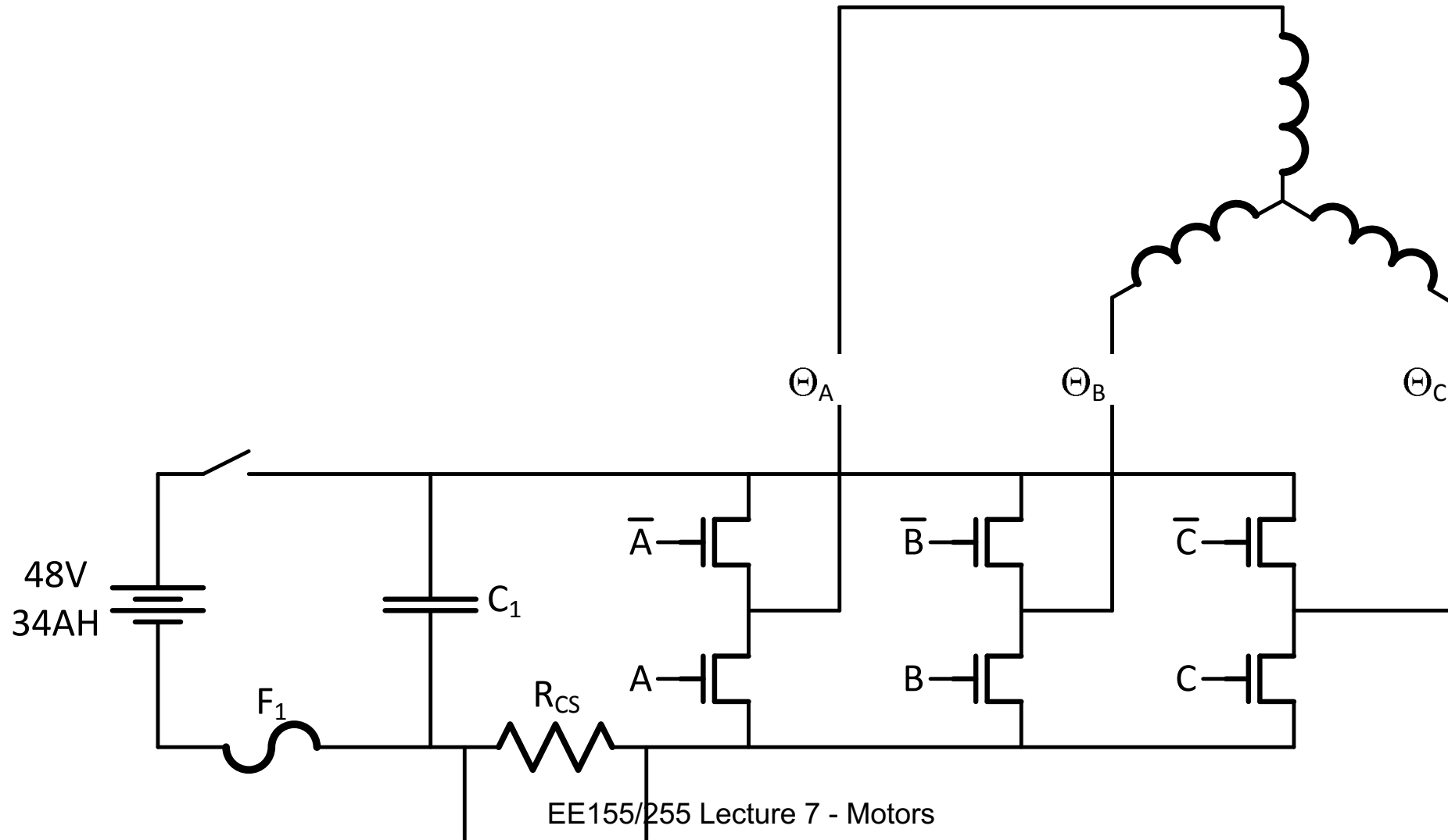
Inverters

- BLPM and Induction motors both need 3-phase inverters
- 3-channel PWM half-bridge
- Control to synthesize desired phase angle

- BLPM – sense (and estimate) rotor position – set field to equal this position

- AC – sense rotor velocity – generate rotating field with desired slip

3- Φ Inverter Power Path



3- Φ Inverter Power Path

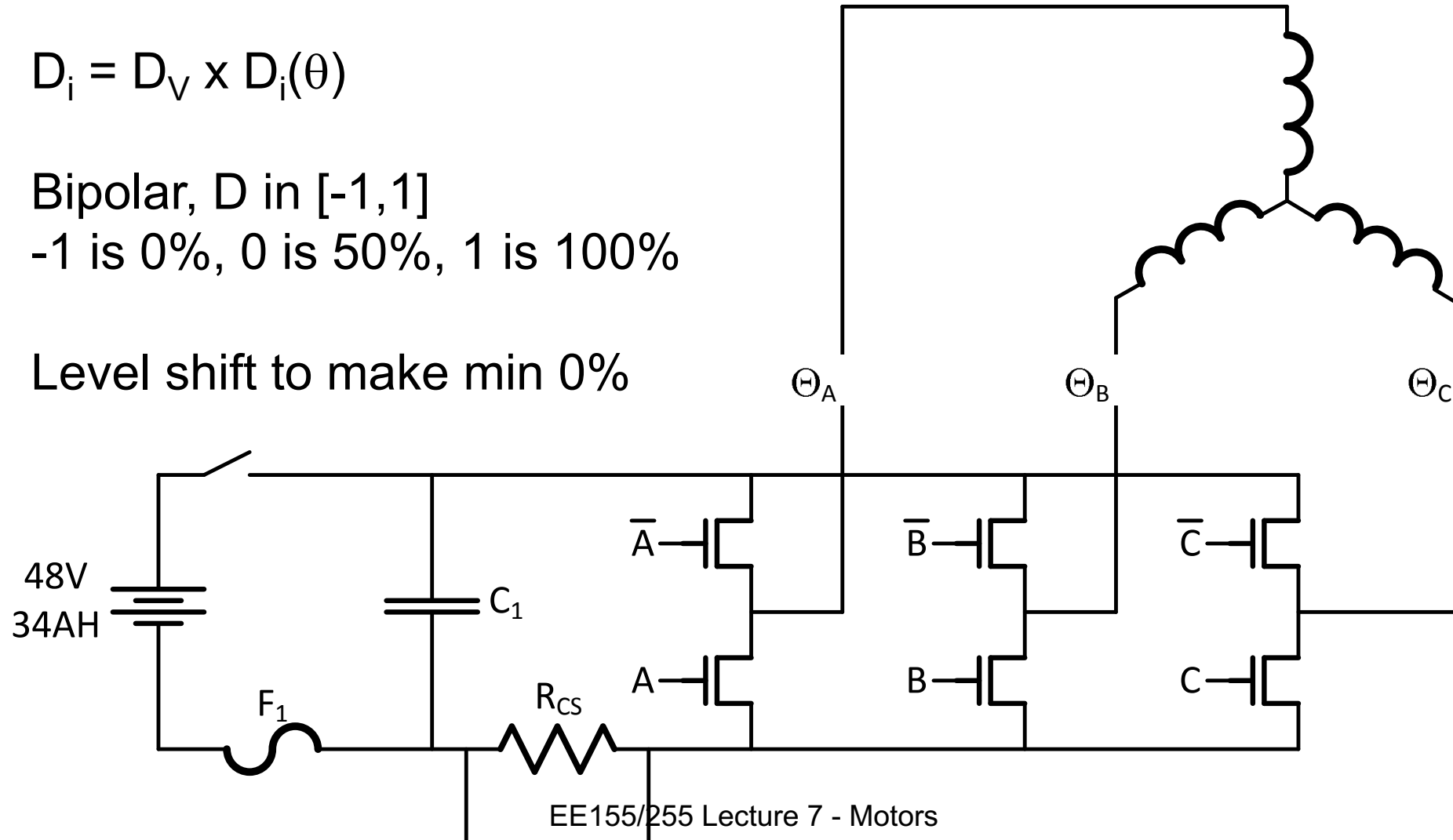
Duty factor applied to phase i

$$D_i = D_V \times D_i(\theta)$$

Bipolar, D in [-1,1]

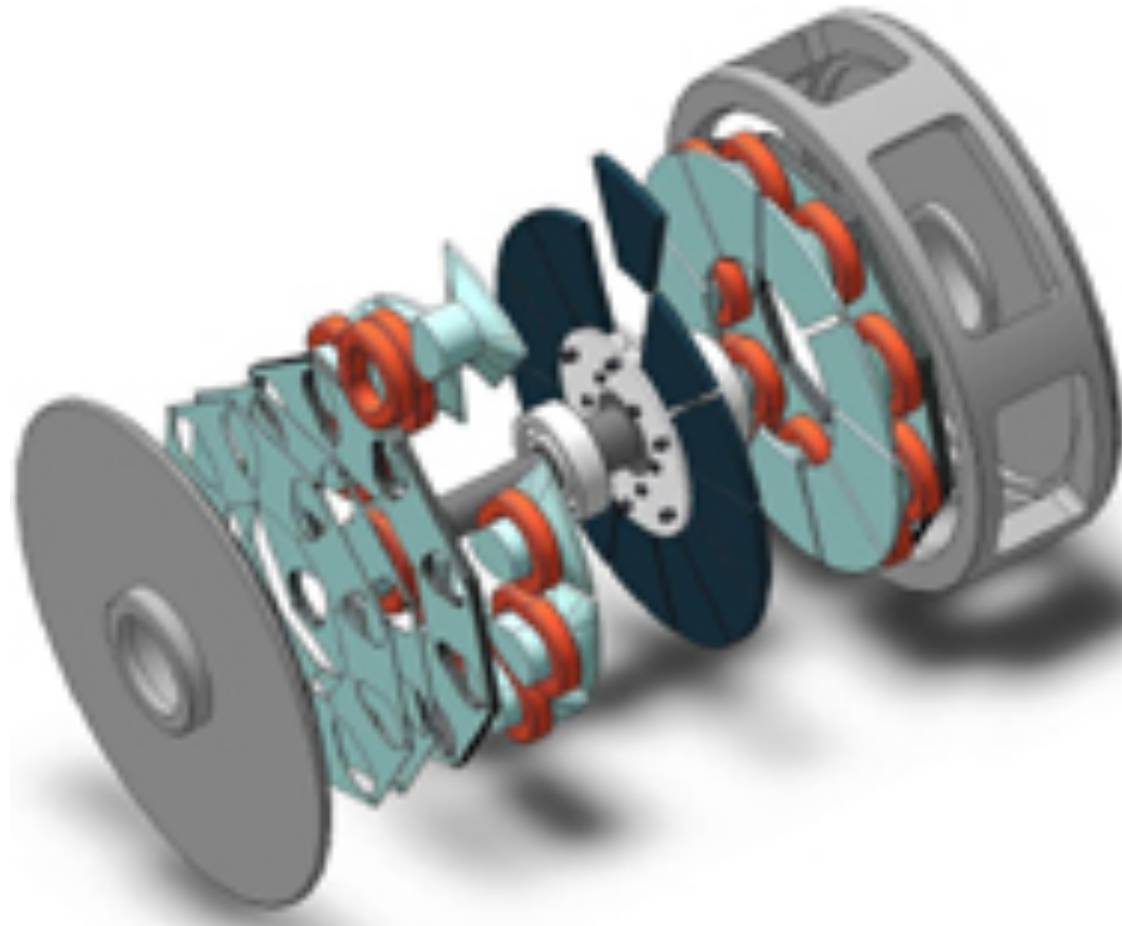
-1 is 0%, 0 is 50%, 1 is 100%

Level shift to make min 0%



Motor Geometry

- Axial Flux and Radial Flux



Poles and Phases

- A stator can be described as having P phases and $N=kP$ poles.
- Rotating phases Θ degrees rotates field Θ/k degrees
- $\omega_s = k\omega_m$
- Number or rotor poles may differ to reduce “camming”

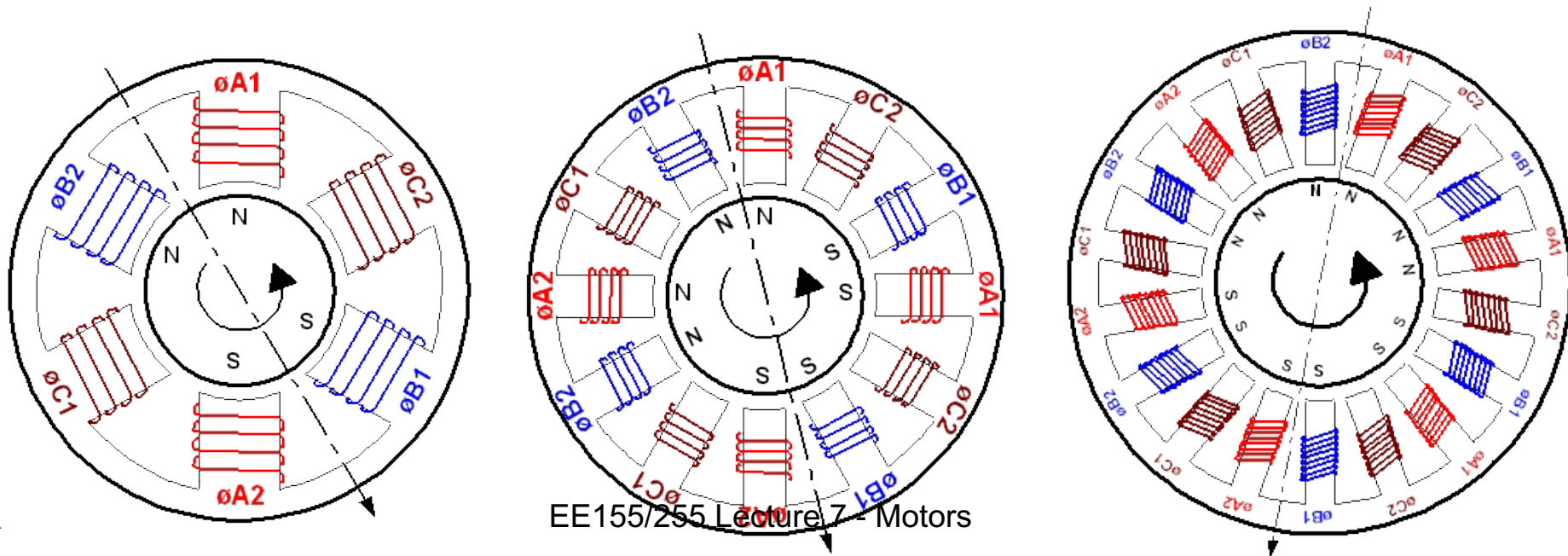
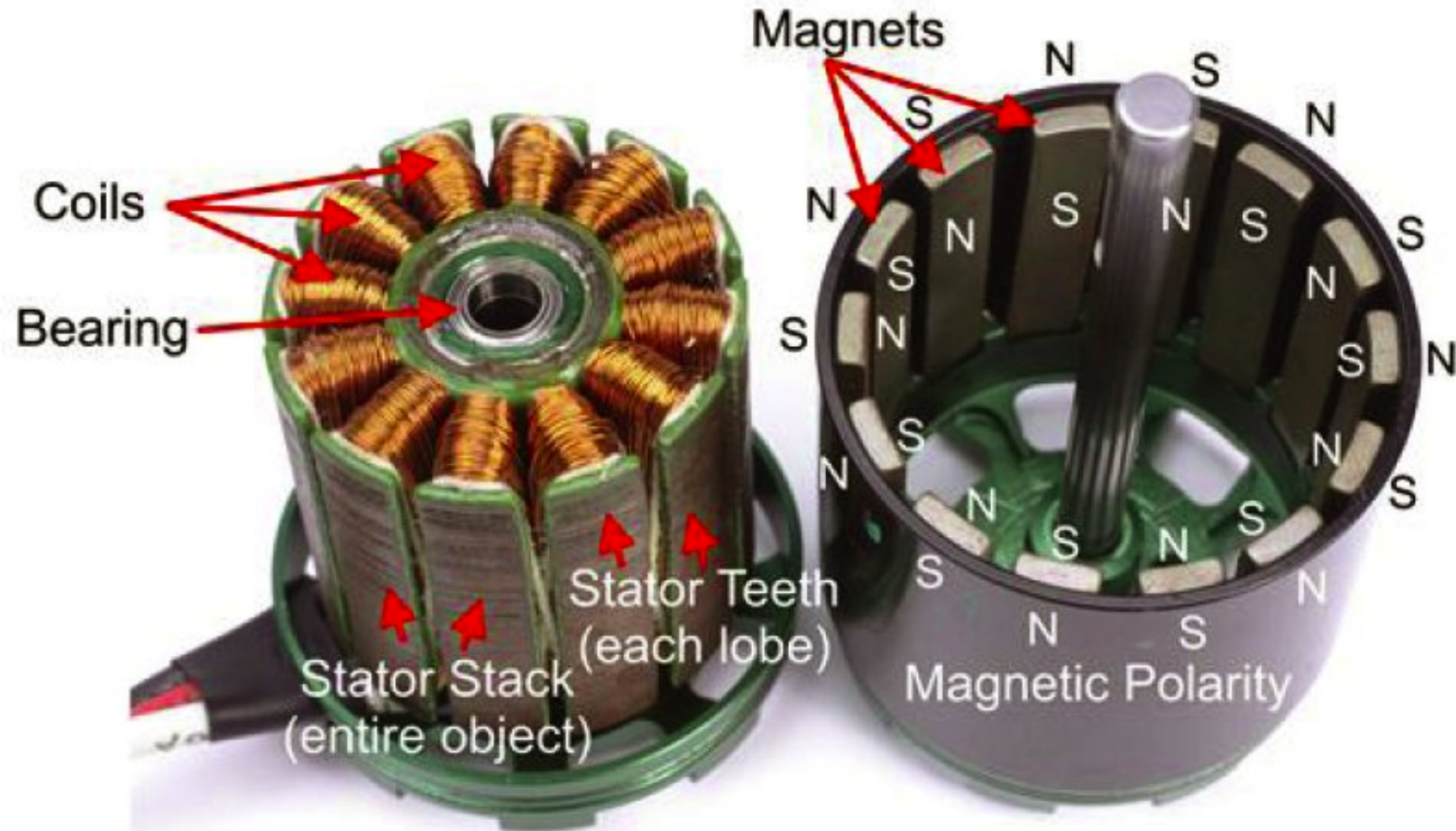
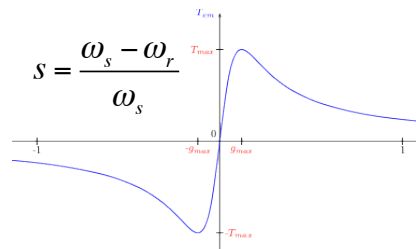
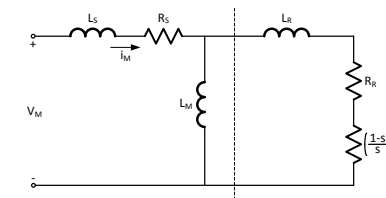
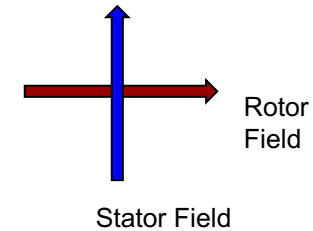
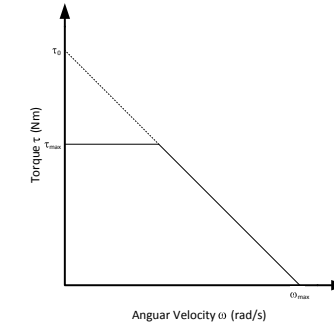
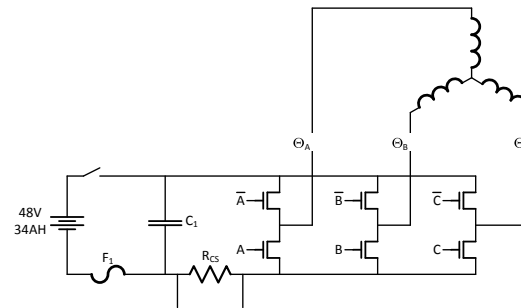
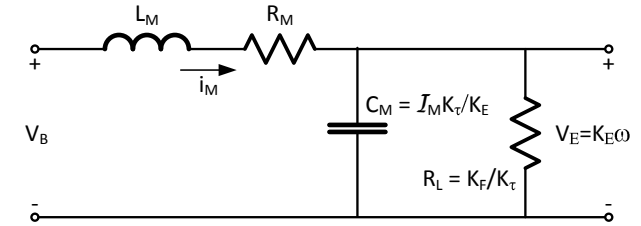
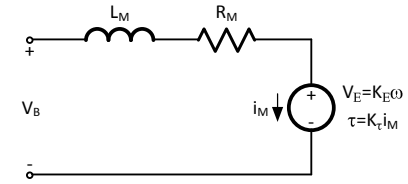




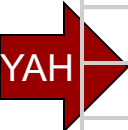
Figure 3: 4 pole and 8 pole – Permanent magnet rotor



Summary



- Motors and generators ubiquitous
- Voltage is velocity, current is torque
 - $V = K_M \omega$, $\tau = K_M i = J_M (d\omega/dt)$
- Load curve and transient response
- Control motor with PWM
 - Buck converter during drive
 - Boost during braking (gen)
- BLPM requires rotating field
 - Determine rotor angle
 - Apply stator current for perpendicular fields
 - In rotor reference field looks just like a brushed motor
- AC Induction motors
 - Torque is function of slip
 - Equivalent circuit
- Multiple poles
 - $\omega_s = k\omega_m$



No	Date	Topic	HW out	HW in	Lab out	Lab ck	Lab	HW
1	9/25/17	Intro (basic converters)	1		1		Intro to ST32F3	Periodic Steady State
2	9/27/17	Embedded Prog/Power Elect.						
3	10/2/17	Power Electronics - 1 (switches)	2	1	2	1	AC Energy Meter	Power Devices
4	10/4/17	Power Electronics - 2 (circuits)						
5	10/9/17	Photovoltaics	3	2	3	2	PV MPPT	Motor control Matlab
6	10/11/17	Feedback Control						
7	10/16/17	Electric Motors	4	3	4	3	Motor control - Lab/	Feedback
8	10/18/17	Isolated Converters						
9	10/23/17	Solar Day	5/PP	4	5	4	PS	Isolated Converters
10	10/25/17	Magnetics						
11	10/30/17	Soft Switching	6	5/PP	6	5	Magnetics	Magnetics and Inverters
12	11/1/17	Project Discussions						
13	11/6/17	Inverters, Grid, PF, and Batteries		6	P	6	Project	
14	11/8/17	Thermal & EMI						
15	11/13/17	Quiz Review				C1		
16	11/15/17	Grounding, and Debugging						
Q	11/15/17	Quiz - in the evening						
	11/20/17	Thanksgiving Break				C2		
	11/22/17	Thanksgiving Break						
17	11/27/17	Guest Lecture						
18	11/29/17	Martin Fornage - Enphase				C3		
19	12/4/17	Colin Campbell - Tesla						
20	12/6/17	No Class						
	TBD	Project presentations			P			
	12/15/17	Project webpage due						