Lecture 15: Actuators 1

ME/AE 6705

Introduction to Mechatronics

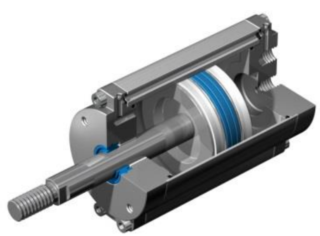
Dr. Jonathan Rogers

Lesson Objectives

- Understand construction and operation of brush DC motors
  - Be able to calculate operating speed of motor at given load
  - Be able to pick out a motor that meets desired characteristics
- Understand construction and operation of brushless DC motors
- Be able to construct a motor driver circuit for a given DC motor to interface with the MCU
  - Design a motor driver circuit with an H-Bridge and program MCU to operate it

Actuators: Introduction

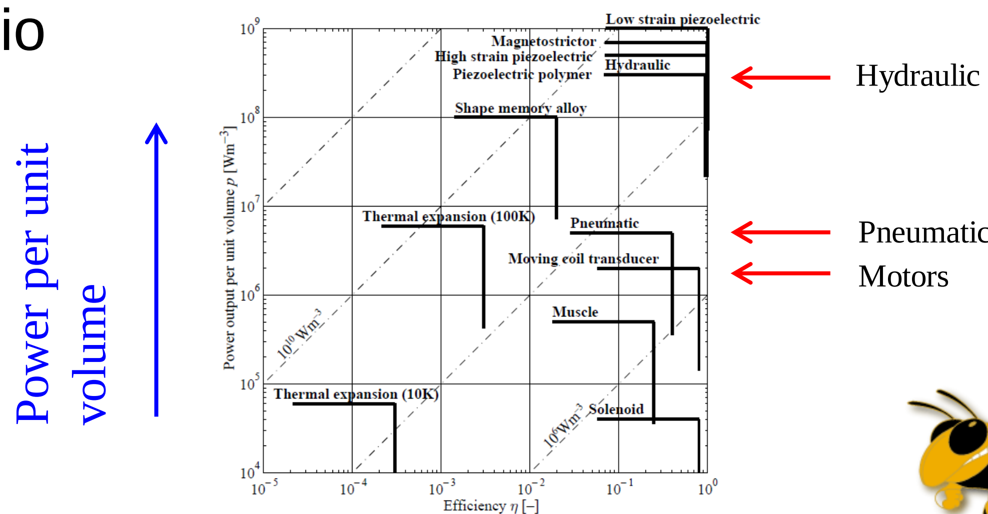
- Actuators are required to move anything
  - And that’s what we want to do since this is Mechatronics!
- Types of actuators:
  - Electric – electromagnetic effects
  - Internal combustion – burning fuel
  - Pneumatic – pressurized air
  - Hydraulic – pressurized fluid
  - Piezoelectric – piezoelectric effect



Electric Actuators (Motors)

- Advantages of electric actuators
  - Clean (do not require fluids, oil, etc.)
  - Require no extra equipment (no need for pressure tanks, etc.)
  - Can operate indoors (no emissions)
  - Can be made small economically
- Disadvantages of electric actuators
  - Low power-to-size ratio

Taken from: Huber, J., Fleck, N., Ashby, M., "The Selection of Mechanical Actuators Based on Performance Indices," Proc. R. Soc. Lond. A, Vol. 453, 1997, pp. 2185-2205.



Electric Motors

- Two major categories of electric motors: AC and DC
  - AC motors run off of alternating current
  - DC motors run off direct current

We will only discuss DC motors in this class

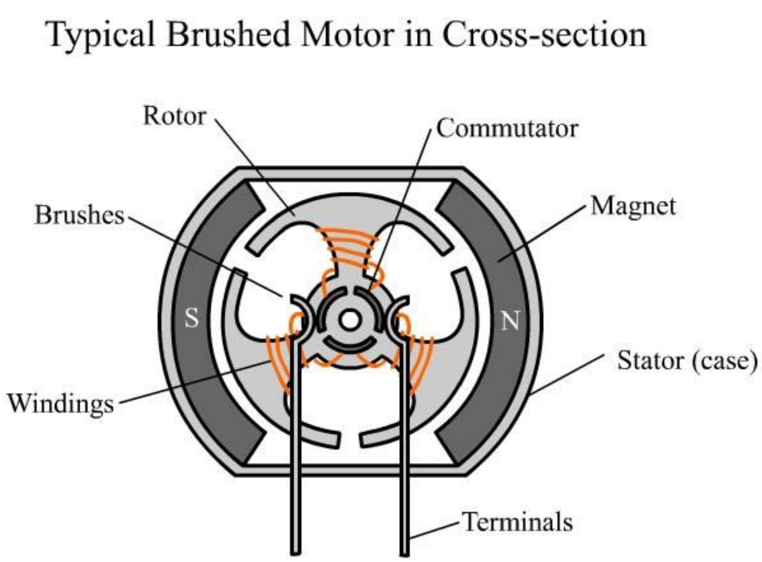
- DC motors can be further divided into two categories:
  - Brushed DC motors: Use brushes to commutate signal
  - Brushless DC motors: Use transistors and sensors to commutate signal

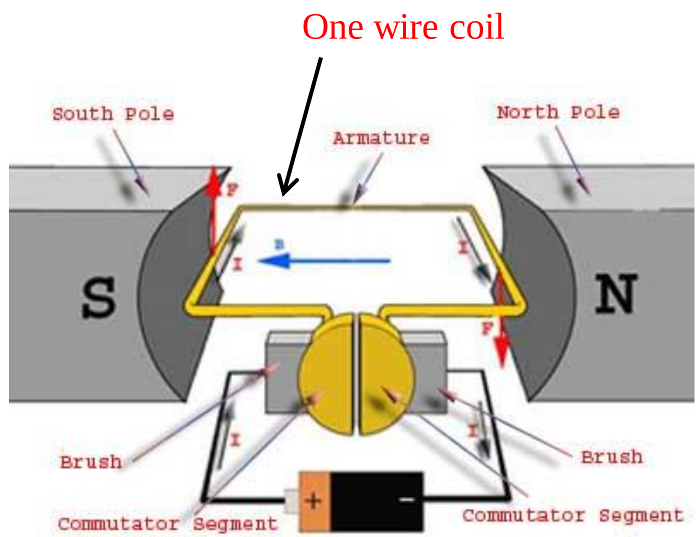
Maxon 30mm brushless motor

Pittman 30mm brushed motor

Brushed DC Motor Operation

- Brushed motors composed of two components:
  - Stator (remains stationary)
  - Rotor (turns, coupled to shaft)





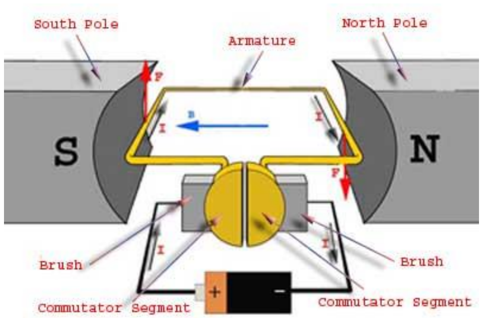
Lorentz's Law: $\vec{F} = \vec{I} \times \vec{B}$

- Wire coil runs along back end of armature to generate B field
- Commutator used to change direction of current flow as armature rotates

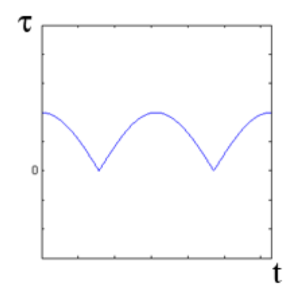
Brushed DC Motor Operation

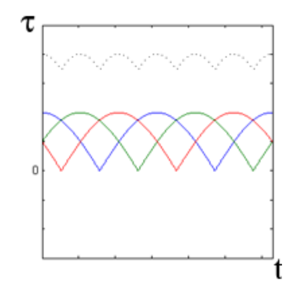
- Commutator must be composed of at least two segments
  - Motors on previous page had 3-piece commutator (left) and 2-piece commutator (right)
- As motor turns, angle of energized coil with respect to magnet changes

$\vec{F} = \vec{I} \times \vec{B}$ ⟶ Torque is function of sine of angle between B field and armature angle ⟶ Torque is not smooth using 2-piece commutator



Torque vs angle for 2-piece comm.

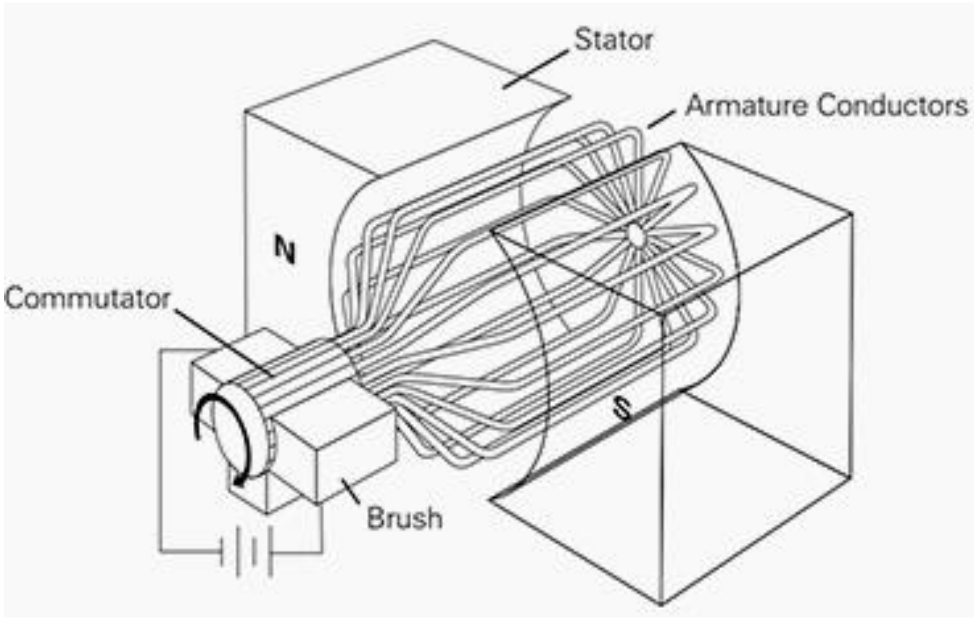




Torque vs angle for 6-piece comm.

Brushed DC Motors

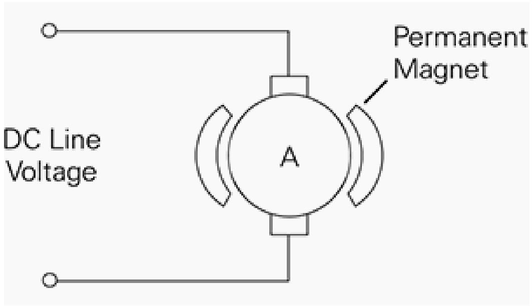
- Good drawing of a motor with multiple commutators and coils



DC Motor Types

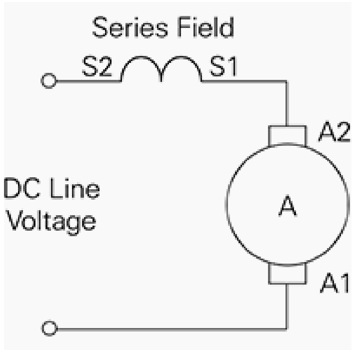
- There are 4 primary types of DC motors

PM DC Motor



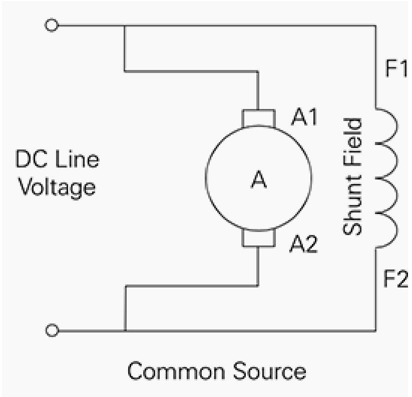
- PM supplies flux field
- Good starting torque
- Can demagnetize permanent magnets if too much current supplied

Series-Wound DC Motor



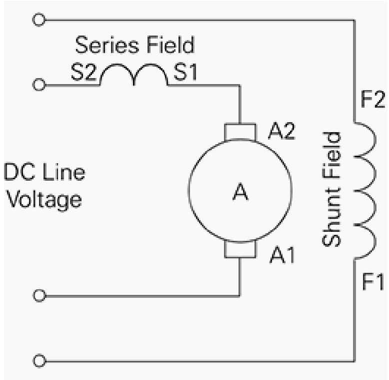
- Offers large starting torque
- Will fail if run with load disconnected

Shunt-Wound DC Motor



- Offers nearly constant speed under varying loads (good speed regulation)
- Found in machine tools

Compound-Wound DC Motor

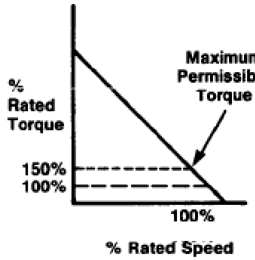


- Good starting torque and speed regulation
- Good balance of series- and shunt-wound characteristics

DC Motor Torque vs Speed Curves

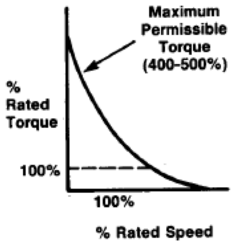
- DC motors provide a varying amount of torque depending on operating speed
  - Generally torque decreases as motor runs faster

PM DC Motor



- Torque vs speed curve is linear for a DC motor

Series-Wound DC Motor

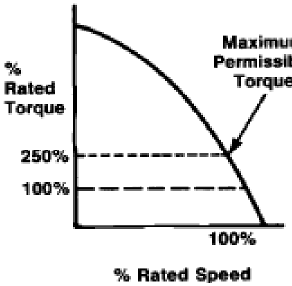


- Large starting torque
- But motor speed grows uncontrollably if zero load torque is applied

Shunt-Wound DC Motor

- Relatively flat torque-speed characteristics

Compound-Wound DC Motor

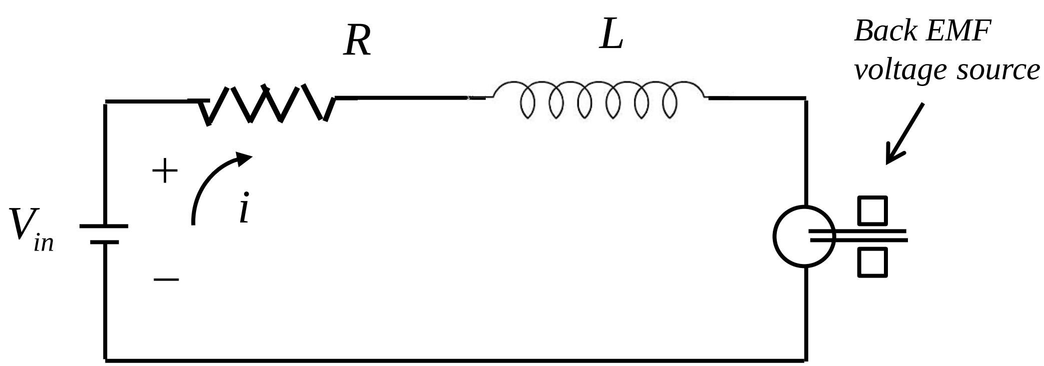


- Good starting torque and speed regulation
- Good balance of series- and shunt-wound characteristics

PM DC Motor Analysis

- Torque-speed model of permanent magnet DC motor

Electromechanical Model of PM DC Motor



- Motor modeled as resistor and inductor in series
- Back EMF voltage caused by rotation of conducting coil in stator magnetic field

Voltage-Current Relationship

$$I = V / R = \left(V_{in} - V_{bemf}\right) / R$$

(impedance of L ignored since it is << R)

Torque Proportional to Current

$$T = K_T I$$

K_T is motor torque constant

PM DC Motor Analysis

Back EMF Voltage is Proportional to Motor Speed

$$V_{bemf} = K_E \omega$$

K_E is back EMF constant (or voltage constant) and ω is speed.

Combining above equations:

$$T = \underbrace{K_T \frac{V_{in}}{R}}_{} - K_T K_E \frac{\omega}{R}$$

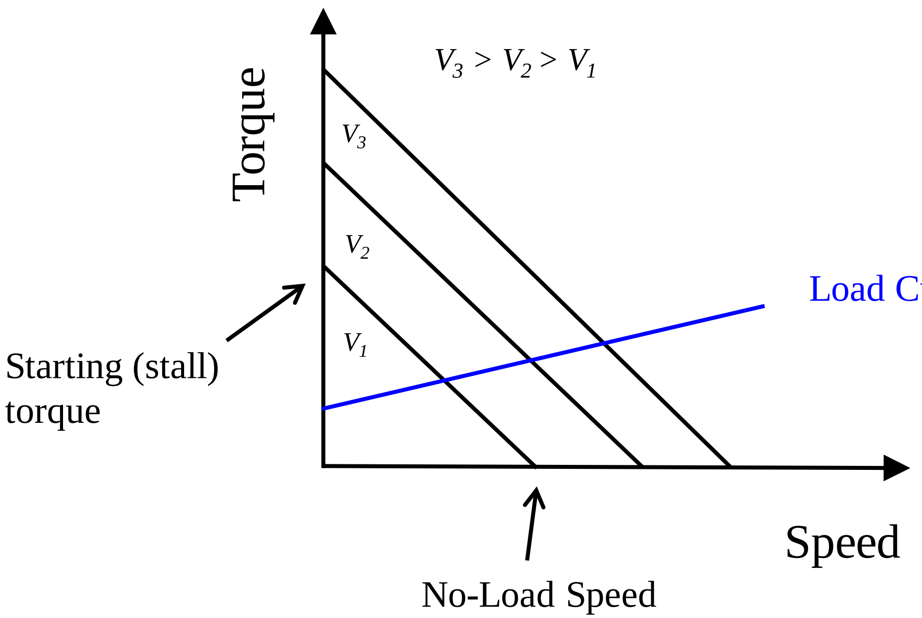
Torque when $\omega = 0$, called "starting torque" T_S

Let: $$\alpha \equiv \frac{K_T K_E}{R}$$

Linear Torque-Speed Relationship:

$$T = T_S - \alpha\omega$$

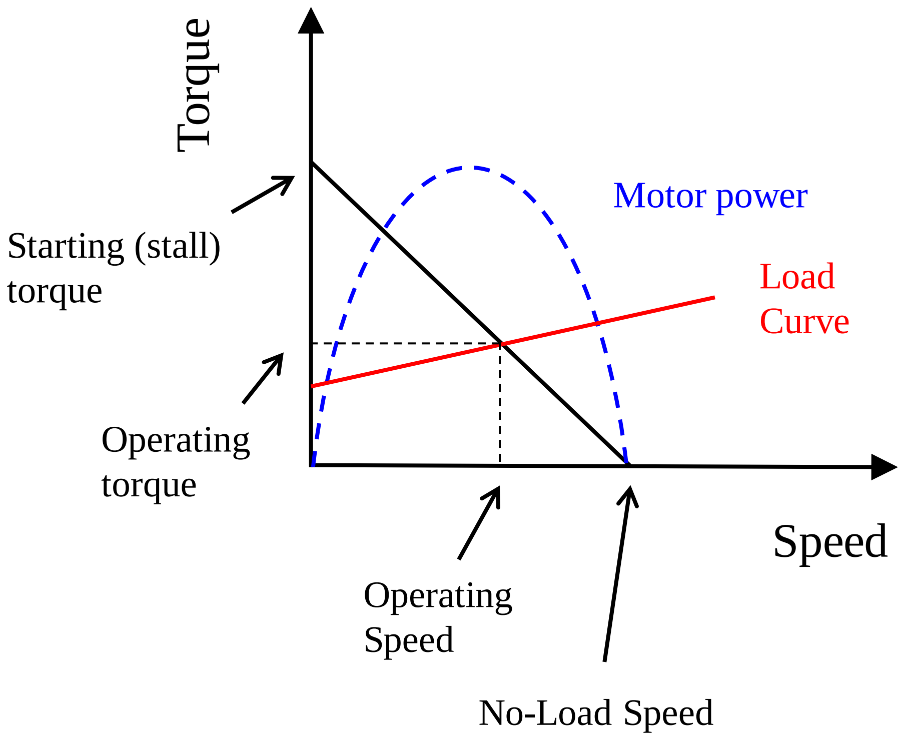
Torque-Speed Curve for DC Motor at Different Input Voltage (Vin) Values



PM DC Motor Analysis

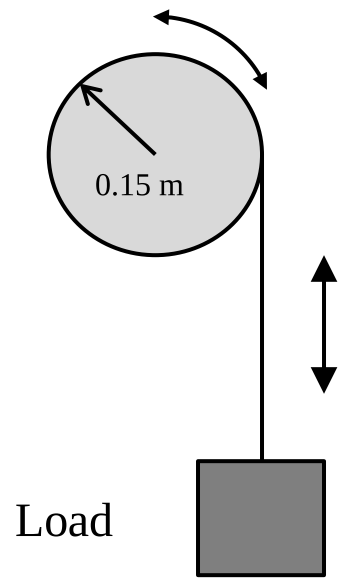
- Torque-speed curve defined by two parameters
  - Starting (stall) torque – max torque when speed is zero
  - No-load speed

- As motor rotates, back EMF generated due to rotation of coil within magnetic field reduces voltage across motor leads and thus current through motor
- This is why torque decreases with speed
- Torque continues to decrease as ω increases until torque is zero at maximum speed
- Motor delivers maximum power when it reaches half of its no load speed
- When motor drives a load, its operating speed will be where load torque equals motor torque
- If load torque increases linearly with speed, operating speed of motor will increase linearly with increase in supply voltage



Example: DC Motor Operating Conditions

- A 1/4 Hp DC motor is used to lift a 10 kg load via a pulley as shown. From the datasheet, the no-load motor speed is 300 rpm and starting torque is 23.8 N-m. Frictional resistance in pulley is 2 N-m (constant). Neglect inertia of rotor, pulley, and cable. Determine:
  - Initial acceleration of load
  - Steady-state speed of load
  - Output horsepower of motor



Example: DC Motor Operating Conditions

- Initial Acceleration

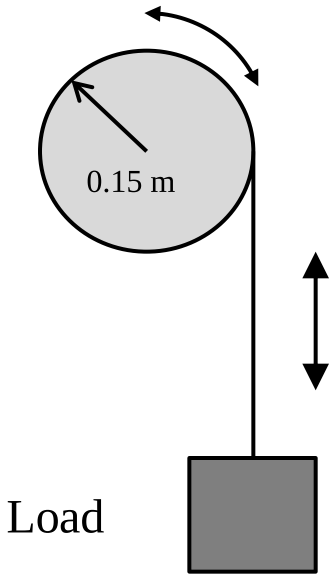
Total torque at startup:

(Total torque) = (Starting torque) – (Friction torque) – (Gravity torque)

$$T_0 = 23.8 - 2 - (10)(9.81)(0.15) \text{ N-m}$$
$$= 7.1 \text{ N-m}$$

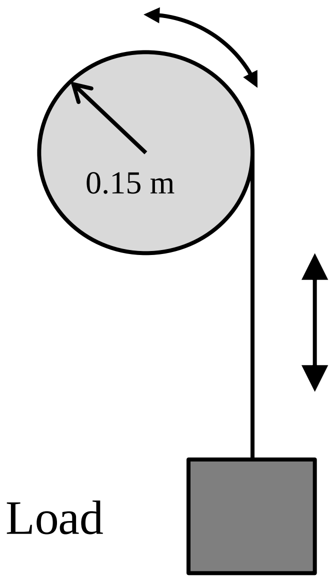
Acceleration of load due to this torque:

$$F_0 = 7.1/0.15 = 47.3 \text{ N} \Rightarrow a_0 = 47.3/10 = 4.73 \text{ m/s}^2$$



Example: DC Motor Operating Conditions

- Steady-state speed of load



Torque exerted by load in steady-state:

$$T_{Load} = 2 + (10)(9.81)(0.15) = 16.7 \quad \text{N-m}$$

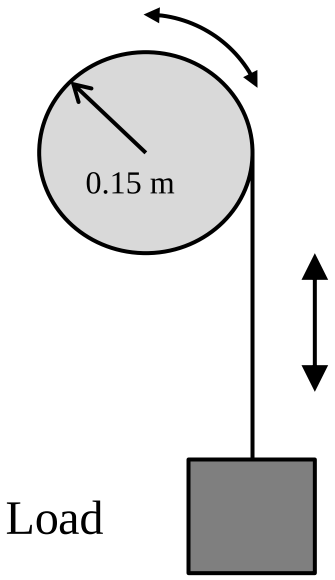
Use torque-speed equation to determine steady-state speed:

$$T_{Motor} = 23.8 - \underbrace{(23.8/300)}_{\text{Slope of torque-speed curve}}\omega = T_{Load} = 16.7 \quad \text{N-m} \xrightarrow[\text{Solve for } \omega]{} \omega = 89.5 \ \text{rpm}$$

$$\Rightarrow V_{Load} = \omega r = (89.5)(2\pi/60)(0.15) = 1.41 \ \text{m/s}$$

Example: DC Motor Operating Conditions

- Output horsepower of motor



Power given by torque times angular velocity:

$$P = (16.7)(89.5)(2\pi/60)(1/746) = 0.21 \quad \text{Hp}$$

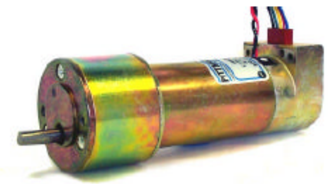
Conversion from watts to Hp

Note: Output power is less than maximum rated power for motor since steady-state speed is less than 1/2 no load speed.

Example Datasheet

GM9236S025

Lo-Cog® DC Servo Gearmotor



No-load speed →

Stall torque →

K_T, K_E →

R →

← Max continuous (nominal) torque

Assembly Data	Symbol	Units	Value	
Reference Voltage	E	V	12	
No-Load Speed	S_{NL}	rpm (rad/s)	71	(7.4)
Continuous Torque (Max.)[1]	T_C	oz-in (N-m)	480	(3.4E+00)
Peak Torque (Stall)[2]	T_{PK}	oz-in (N-m)	2585	(1.8E+01)
Weight	W_M	oz (g)	23.7	(671)
Motor Data				
Torque Constant	K_T	oz-in/A (N-m/A)	3.25	(2.29E-02)
Back-EMF Constant	K_E	V/krpm (V/rad/s)	2.40	(2.29E-02)
Resistance	R_T	Ω	0.71	
Inductance	L	mH	0.66	
No-Load Current	I_{NL}	A	0.33	
Peak Current (Stall)[2]	I_P	A	16.9	
Motor Constant	K_M	oz-in/√W (N-m/√W)	4.11	(2.90E-02)
Friction Torque	T_F	oz-in (N-m)	0.80	(5.6E-03)
Rotor Inertia	J_M	oz-in-s^2 (kg-m^2)	1.0E-03	(7.1E-06)
Electrical Time Constant	τ_E	ms	1.06	
Mechanical Time Constant	τ_M	ms	8.5	
Viscous Damping	D	oz-in/krpm (N-m-s)	0.053	(3.5E-06)
Damping Constant	K_D	oz-in/krpm (N-m-s)	12.5	(8.5E-04)
Maximum Winding Temperature	θ_{MAX}	°F (°C)	311	(155)
Thermal Impedance	R_{TH}	°F/watt (°C/watt)	56.3	(13.5)
Thermal Time Constant	τ_{TH}	min	13.5	
Gearbox Data				
Reduction Ratio			65.5	
Efficiency[3]			0.80	
Maximum Allowable Torque		oz-in (N-m)	500	(3.53)
Encoder Data				
Channels			3	
Resolution		CPR	500	

1 - Specified at max. winding temperature at 25°C ambient without heat sink. 2 - Theoretical values supplied for reference only.
3 - Effective gearbox efficiency for this unit improved by use of ball bearings.

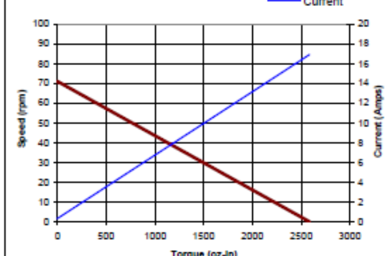
Included Features

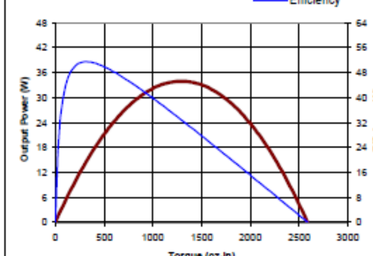
2-Pole Stator
Ceramic Magnets
Heavy-Guage Steel Housing
7-Slot Armature
Silicon Steel Laminations
Stainless Steel Shaft
Copper-Graphite Brushes
Diamond Turned Commutator
Motor Ball Bearings
Output Ball Bearing
Wide Face Gears

Customization Options

Alternate Winding
Sleeve or Ball Bearings
Modified Output Shaft
Custom Cable Assembly
Special Brushes
EMI/RFI Suppression
Alternate Gear Material
Special Lubricant
Optional Encoder
Fail-Safe Brake

Motor speed vs torque curve →





← Motor power vs torque curve

All values are nominal. Specifications subject to change without notice. Graphs are shown for reference only.

Example: Verify Datasheet Values

- Given datasheet for Pittman 9237 motor, verify listed peak torque and no-load speed values.

Specification	Units	9237 12.0 V
Supply Voltage	VDC	12.0
Continuous Torque	oz-in	11.5
	Nm	0.0812
Speed @ Cont. Torque	RPM	4050
Current @ Cont. Torque	Amps (A)	4.73
Continuous Output Power	Watts (W)	34
Motor Constant	oz-in/sqrt W	4.0
	Nm/sqrt W	0.028
Torque Constant	oz-in/A	3.00
	Nm/A	0.021
Voltage Constant	V/krpm	2.22
	V/rad/s	0.021
Terminal Resistance	Ohms	0.55
Inductance	mH	0.49
No-Load Current	Amps (A)	0.37
No-Load Speed	RPM	5210
Peak Current	Amps (A)	21.8
Peak Torque	oz-in	64.3
	Nm	0.454
Coulomb Friction Torque	oz-in	0.80
	Nm	0.0056
Viscous Damping Factor	oz-in/krpm	0.055
	Nm s/rad	3.69E-6
Electrical Time Constant	ms	0.89
Mechanical Time Constant	ms	10
Thermal Time Constant	min	14
Thermal Resistance	Celsius/W	11
Max. Winding Temperature	Celsius	155
Rotor Inertia	oz-in-sec2	0.0012
	kg-m2	8.47E-6
Weight (Mass)	oz	15.5
	g	439.4

Example: Verify Datasheet Values

- Given datasheet for Pittman GM9236S025 motor, verify listed peak torque and no-load speed values.
- Solution:

Recall motor torque equation:

$$T = K_T \frac{V_{in}}{R} - K_T K_E \frac{\omega}{R}$$

$$K_T = 0.021 \text{ N-m/A}$$
$$K_R = 0.021 \text{ V/rad/s}$$
$$R = 0.55\ \Omega$$
$$V_{in} = 12 \text{ V}$$

$$T_S = K_T \frac{V_{in}}{R} = 0.021 \frac{12}{0.55} = 0.458 \text{ N-m}$$

≈ 0.454 N-m from spec sheet

Set $\omega = 0$ for stall torque

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Weight (Mass)	oz	15.5
	g	439.4

Example: Verify Datasheet Values

- Given datasheet for Pittman GM9236S025 motor, verify listed peak torque and no-load speed values.
- Solution:

Set $T = 0$ and solve for ω:

$$0 = K_T \frac{V_{in}}{R} - K_T K_E \frac{\omega}{R}$$

$$\omega = \frac{V_{in}}{K_E}$$

$$K_T = 0.021 \text{ N-m/A}$$
$$K_R = 0.021 \text{ V/rad/s}$$
$$R = 0.55\ \Omega$$
$$V_{in} = 12 \text{ V}$$

$$\omega = 571 \text{ rad/s} = 5459 \text{ RPM}$$
$$\approx 5210 \text{ RPM from spec sheet}$$

Specification	Units	9237 12.0 V
Supply Voltage	VDC	12.0
Continuous Torque	oz-in	11.5
	Nm	0.0812
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Current @ Cont. Torque	Amps (A)	4.73
Continuous Output Power	Watts (W)	34
Motor Constant	oz-in/sqrt W	4.0
	Nm/sqrt W	0.028
Torque Constant	oz-in/A	3.00
	Nm/A	0.021
Voltage Constant	V/krpm	2.22
	V/rad/s	0.021
Terminal Resistance	Ohms	0.55
Inductance	mH	0.49
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Rotor Inertia	oz-in-sec2	0.0012
	kg-m2	8.47E-6
Weight (Mass)	oz	15.5
	g	439.4

Georgia Tech

Nominal Torque and Nominal Speed

- If PM DC motor is used in continuous operations (always on), must be operating at or below nominal speed / nominal torque
  - Otherwise brushes get too hot and burn out
  - Nominal speed ~ 75-90% of no-load speed
  - Nominal torque ~ 10-25% of stall torque
  - Values are listed on datasheet (sometimes called “max continuous”)

PittmanExpress™

GM9236S025

Lo-Cog® DC Servo Gearmotor

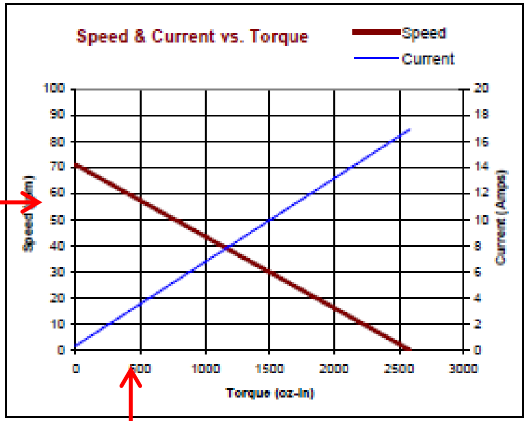
Assembly Data	Symbol	Units	Value	
Reference Voltage	E	V	12	
No-Load Speed	S_{NL}	rpm (rad/s)	71	(7.4)
Continuous Torque (Max.)[1]	T_C	oz-in (N-m)	480	(3.4E+00)
Peak Torque (Stall)[2]	T_{PK}	oz-in (N-m)	2585	(1.8E+01)
Weight	W_M	oz (g)	23.7	(671)
Motor Data				

Included Features

2-Pole Stator

Ceramic Magnets

Heavy-Guage Steel Housing

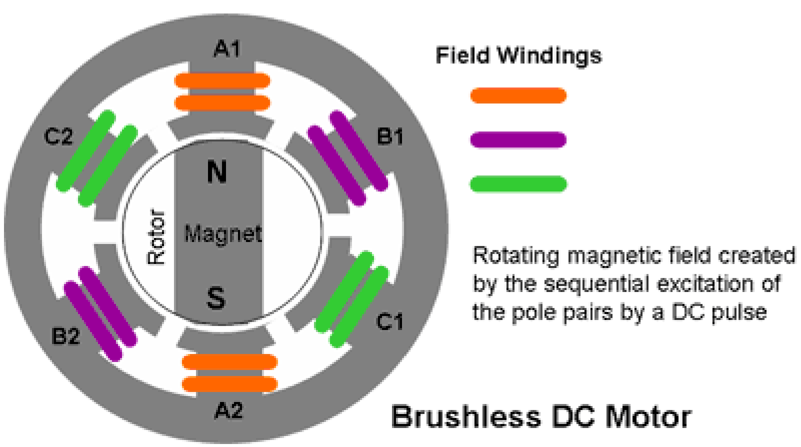


Brushless DC Motors

- In brushed DC motors, brushes create mechanical point of contact between stator and rotor
  - Necessary in order to power wire coils on rotor
  - Generate heat and acoustic noise, must be replaced periodically
- Brushless DC motors do not use brushes
  - Only points of contact between rotor and stator are bearings
  - No direct wiring to rotor

Brushless DC Motor

- In brushless DC motor, rotor is made of permanent magnet and stator is made of coils
  - This is opposite of brushed motors



Concept of operation:

- Hall effect sensor used to detect position of magnet
- Coil pairs are activated sequentially so that magnetic field is always perpendicular (as much as possible) to rotor magnet
- Causes rotor to spin
- Thus commutation is done electrically and not mechanically

Georgia Tech

Brushless DC Motor Advantages

- BLDC Rotor is lighter than on brushed motors

  → BLDC's can operate at much higher speeds than DC motors

- BLDC does not use mechanical brushes for commutation

  → BLDC's are more reliable since they do not generate much heat due to friction

  → BLDC's are quieter

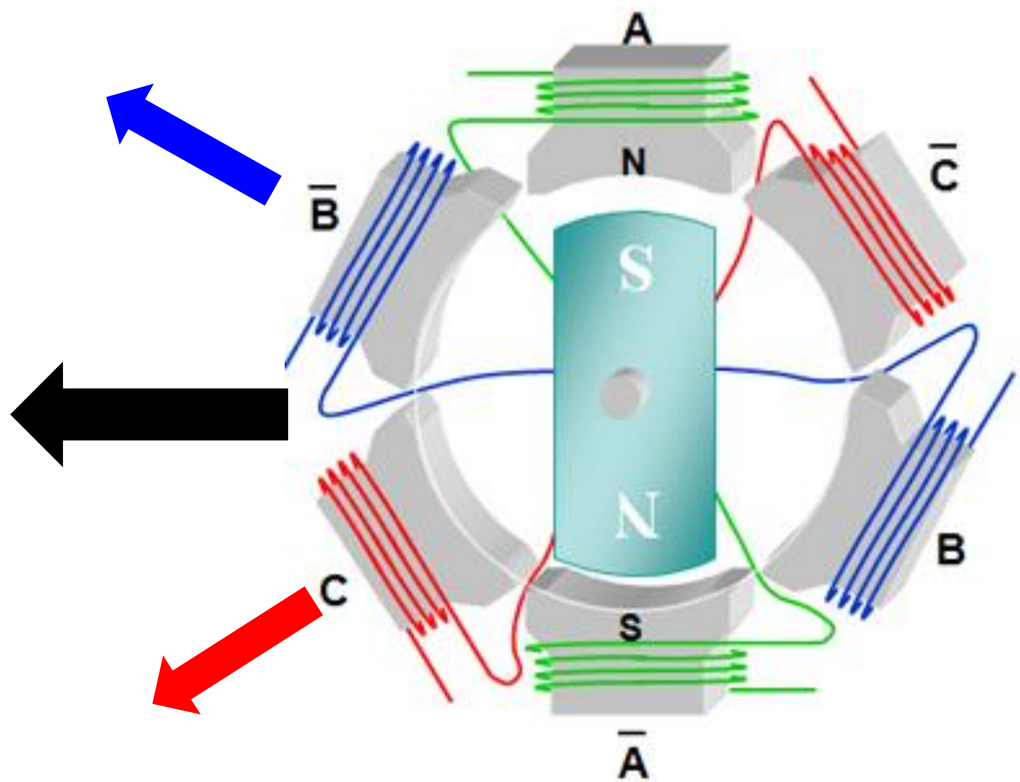
  → BLDC's are more efficient since there are less frictional losses

Disadvantages: BLDC's require more complex circuitry to operate. They are also more expensive.

Brushless DC Motor Operation

3-Pole Brushless DC Motor

- A sensor is attached to each pair of coils which detects position of PM (rotor)
- Coils are activated so that resulting magnetic field across permanent magnet is as close to perpendicular to poles as possible
- In current configuration, coils B and C would be activated (A is off)

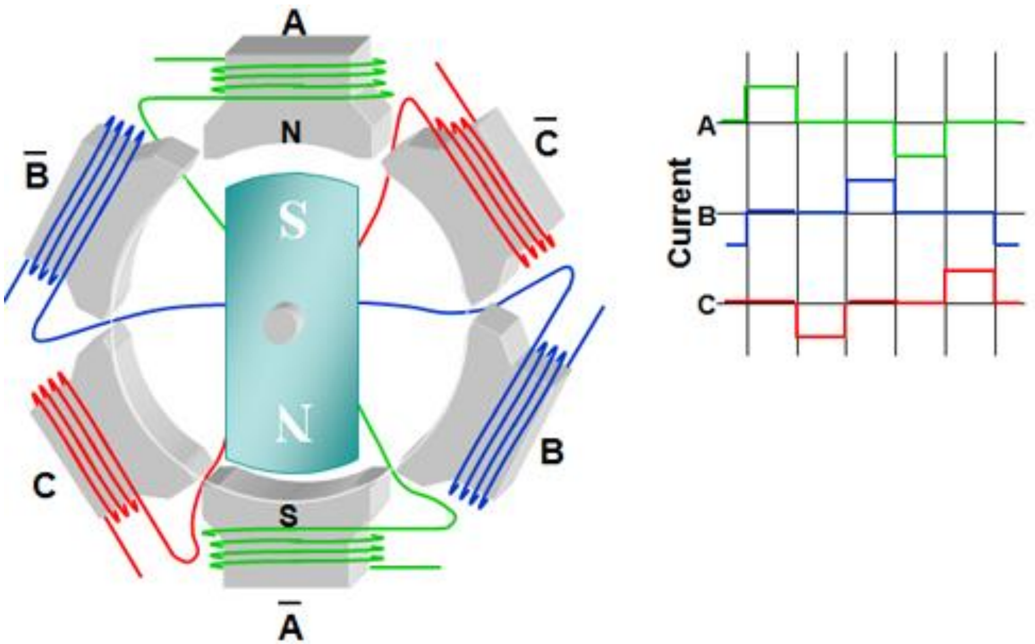


If the arrows point S to N, which direction is the motor rotating in at the current time?

Brushless DC Motor Operation

3-Pole Brushless DC Motor

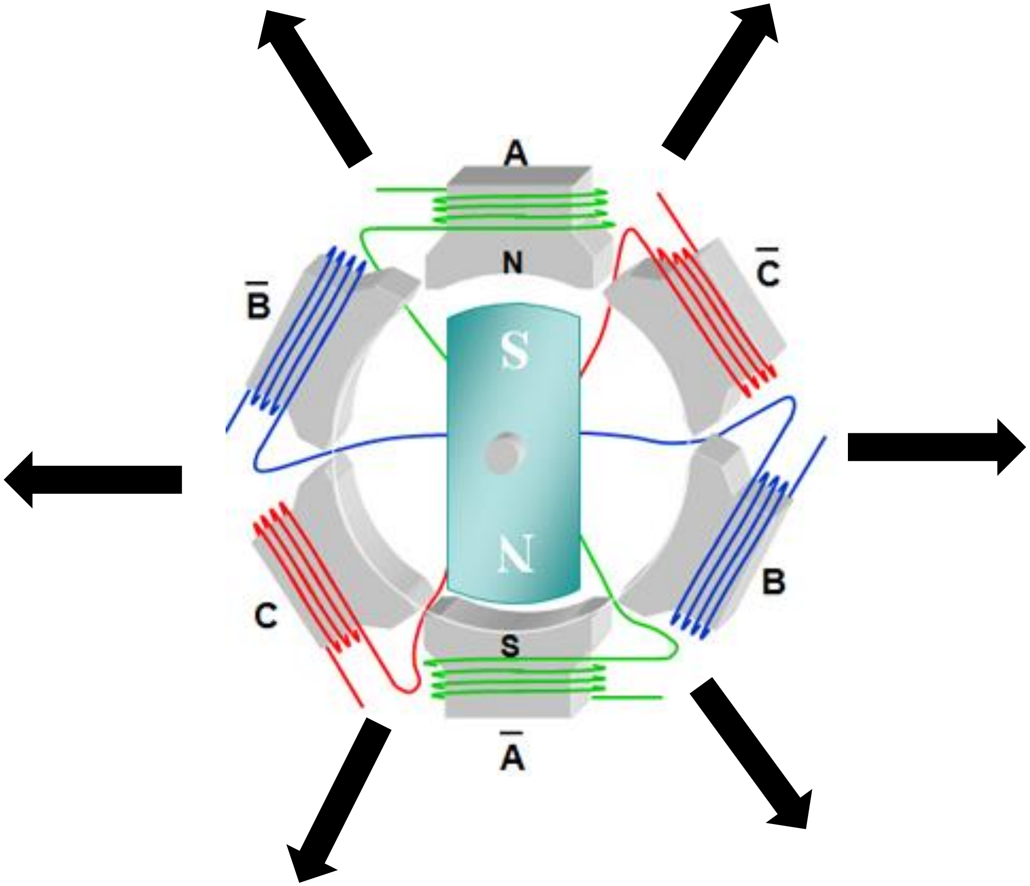
- As rotor spins, current in coils must be switched on and off rapidly
- This is <u>commutation</u>
- Commutation is performed by a high-speed integrated circuit using feedback from Hall effect sensors



Brushless DC Motor Operation

3-Pole Brushless DC Motor

- For a 3-pole BLDC in this configuration, there are <u>6 possible magnetic field vectors</u> that can be produced by the coil
- How often does the commutator sequence through them (in terms of deg rotation of rotor)?

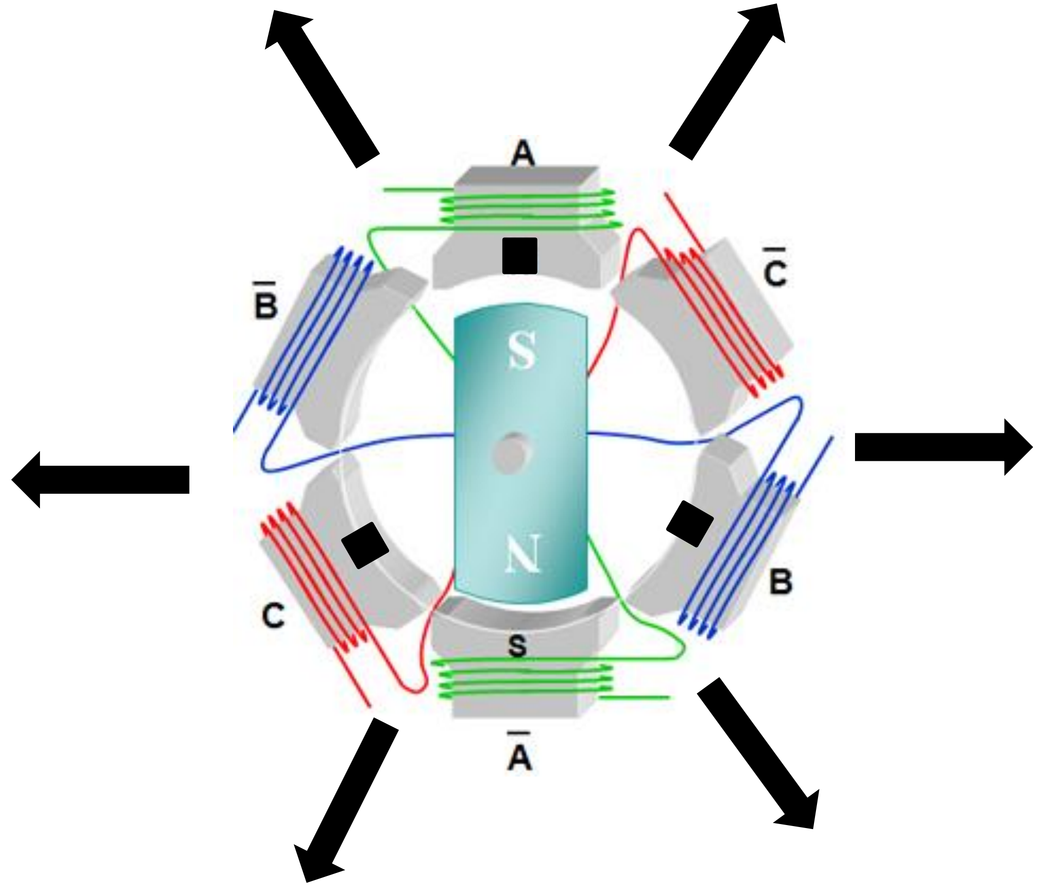


Brushless DC Motor Operation

3-Pole Brushless DC Motor

Sensor Output			CW Rotation		
C	***B***	***A***	***A***	***B***	***C***
1	0	0	NC	Hi	Low
1	0	1	Low	Hi	NC
0	0	1	Low	NC	Hi
0	1	1	NC	Low	Hi
0	1	0	Hi	Low	NC
1	1	0	Hi	NC	Low

Commutation Sequence

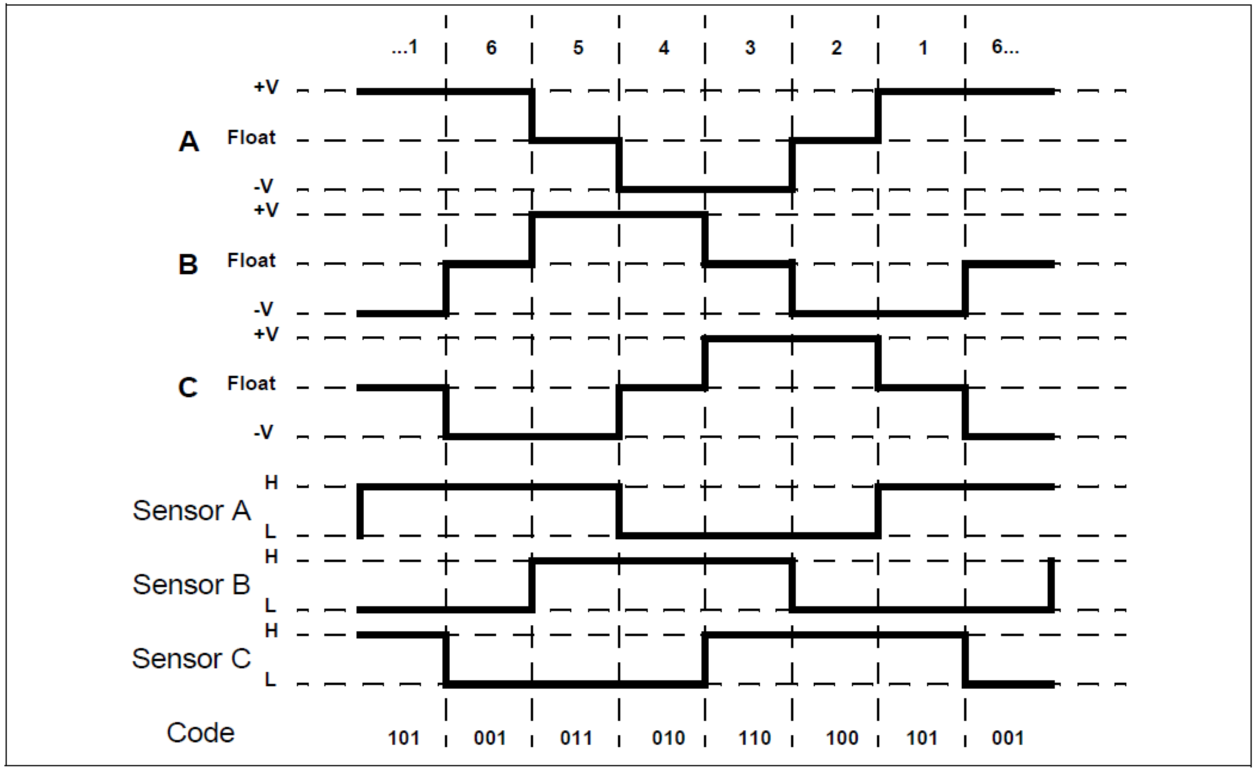


NC = No Current
Hi = +Voltage
Low = -Voltage

Black boxes indicate sensors. They output high when N pole of magnet is within 180 deg.

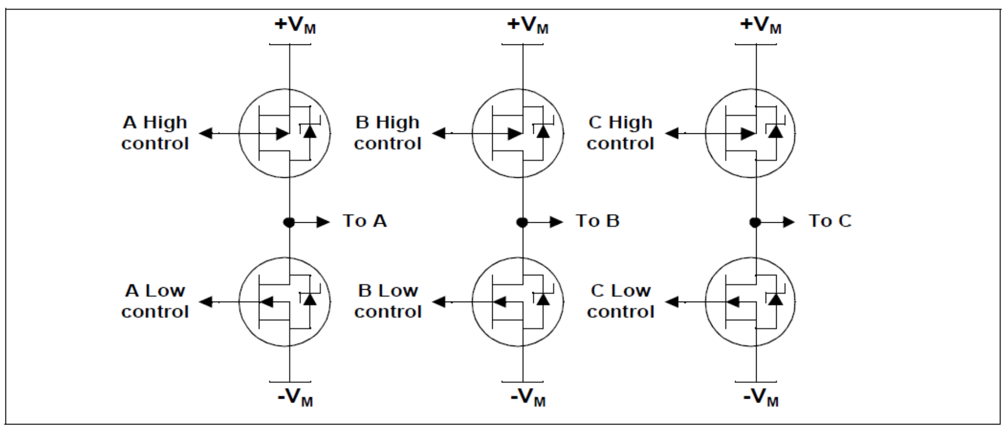
Drive Timing Diagram

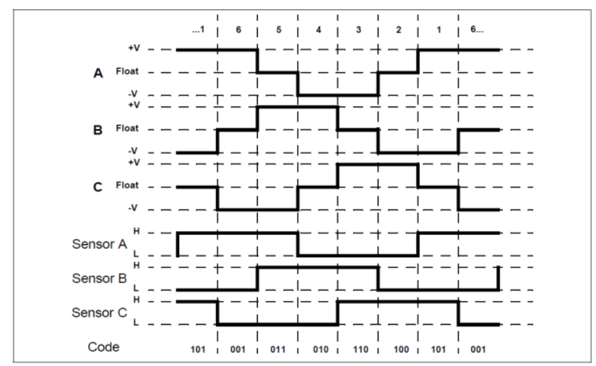
- Example drive timing diagram for a 3-phase BLDC



BLDC Motor Control

- The above timing diagram is implemented on a specific BLDC motor driver called a **three-phase bridge driver**
  - Composed of 3 half H-bridges

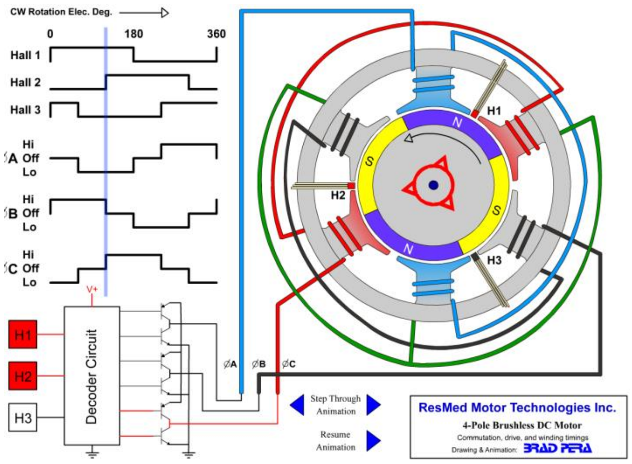




IR2130PBF 3-Phase Bridge Driver

Brushless DC Motor Operation

- Link 1: [2-pole BLDC Motor Animation]
- Link 2: [4-pole BLDC Motor Animation]



Brushless vs Brushed Motors

- How many wires does a brushed DC motor have?

- How many wires does a 3-phase brushless DC motor have, if it uses Hall Effect sensors?

Brushless vs Brushed Motors

- How many wires does a brushed DC motor have?
  - Power
  - Ground

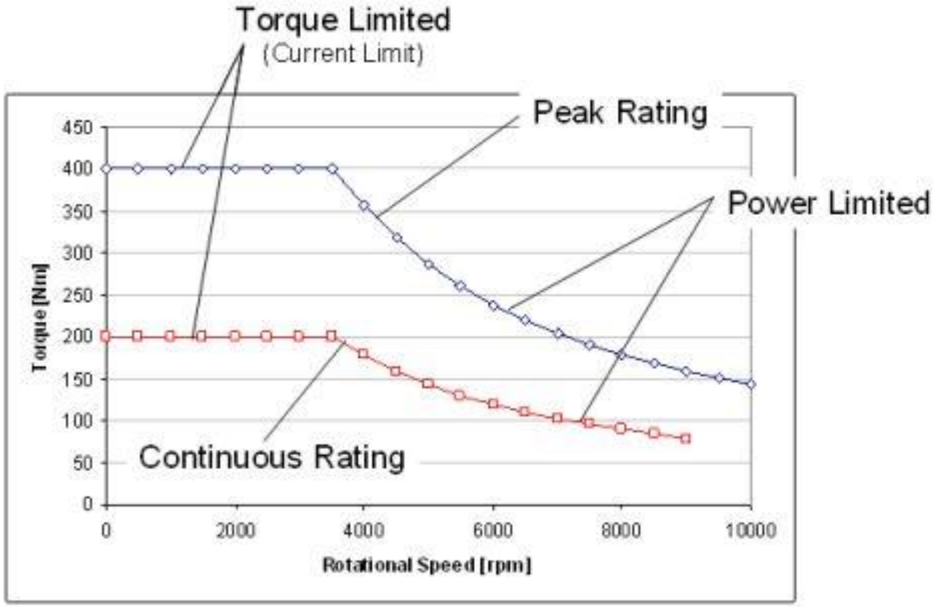
2 total

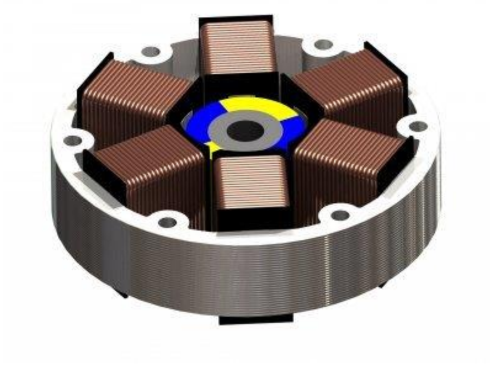
- How many wires does a 3-phase brushless DC motor have, if it uses Hall Effect sensors?
  - Ground
  - 3 sensor wires
  - 3 wires, one for each motor phase

7 total (at least)

Brushless DC Motors

- BLDC torque vs speed curve is not linear
  - Torque is usually flat over a large speed region
  - Maximum speed is usually much higher than from brushed DC motors





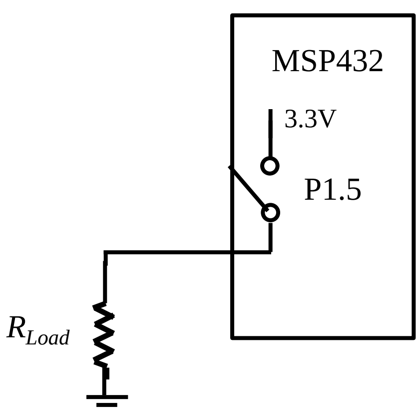
Brushless DC Motors

- Cool fact: With both brushed and brushless DC motors, you can actually brake them (as well as drive them). Knowing what you do about commutation, how is this done?

Powering DC Motors

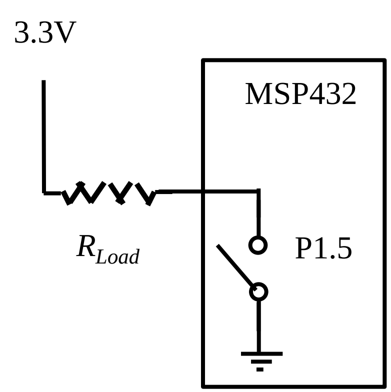
- In Lecture 9 it was noted that maximum current an output pin can provide or sink on MSP432 is 6 mA
  - And 20 mA at high drive strength
- DC motors, lights, solenoids, etc. can draw in excess of 50 A
  - These loads cannot be directly driven by a pin!

Using MCU as a Source



Don't do either of these!

Using MCU as a Sink

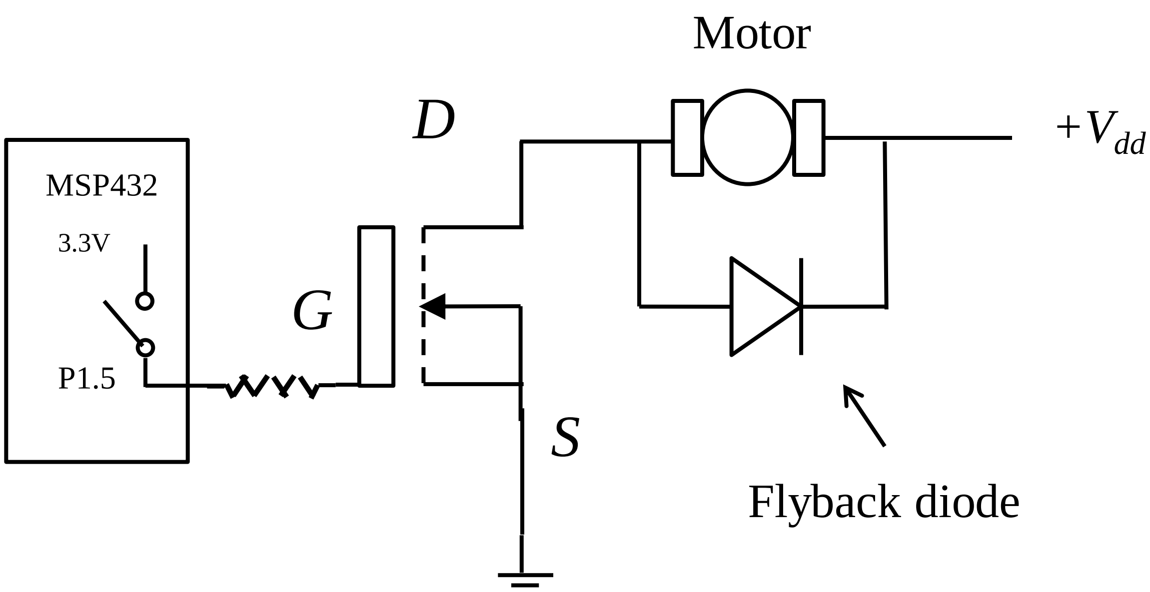


Powering DC Motors

- Power MOSFET is commonly used switch to power DC motors

Power MOSFET Circuit for Driving DC Motor

- 3.3V (high) signal to gate puts MOSFET in saturation mode
- Drain-source resistance of MOSFET in saturation mode is < 1 Ω
- 0V (low) signal to gate places MOSFET in cutoff, acts as open switch

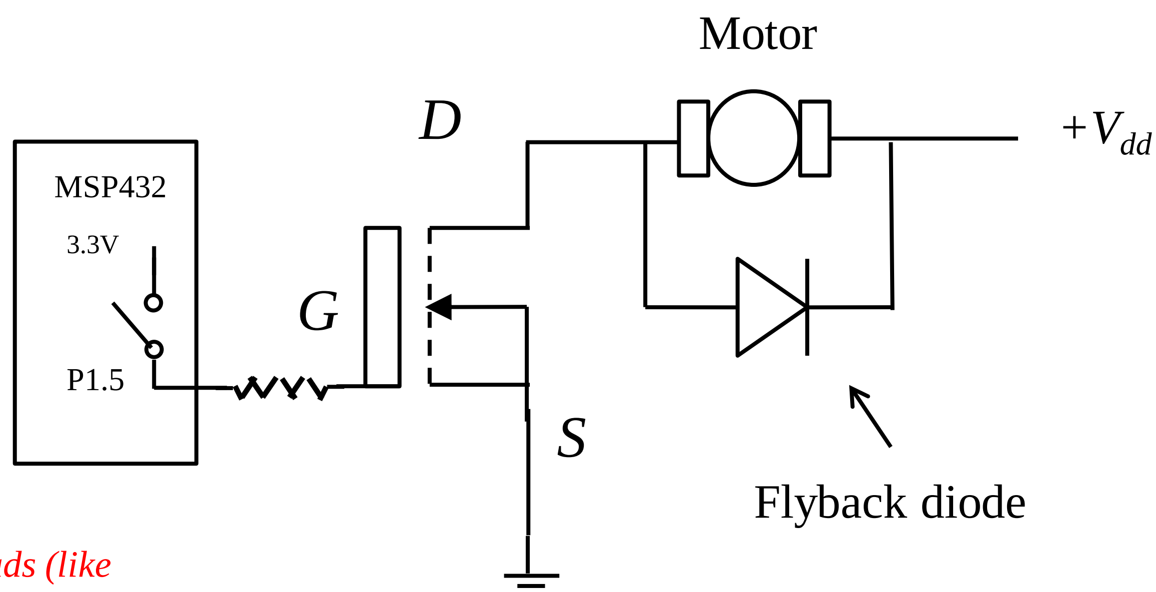


Powering DC Motors

- Power MOSFET is commonly used switch to power DC motors

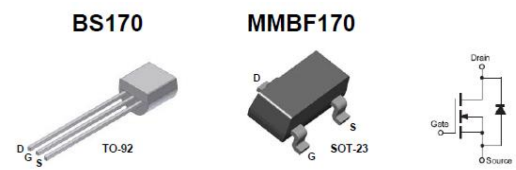
Power MOSFET Circuit for Driving DC Motor

- MOSFET is very useful as a switch because gate draws almost no current when in saturation state
- Can handle very large current loads (drain to source)
- Must use proper heatsinking!



Switching high-inductance loads (like motors) can produce reverse voltage transient that can damage MOSFET. Using flyback diode protects against this.

BS170 Power MOSFET



Absolute Maximum Ratings T_A = 25°C unless otherwise noted

Symbol	Parameter	BS170	MMBF170	Units
V_{DSS}	Drain-Source Voltage	60		V
V_{DGR}	Drain-Gate Voltage ($R_{GS} \leq 1M\Omega$)	60		V
V_{GSS}	Gate-Source Voltage	± 20		V
I_D	Drain Current - Continuous	500	500	mA
	- Pulsed	1200	800	
T_J, T_{STG}	Operating and Storage Temperature Range	- 55 to 150		°C
T_L	Maximum Lead Temperature for Soldering Purposes, 1/16" from Case for 10 Seconds	300		°C

Maximum load current 0.5 A

Electrical Characteristics T_A=25°C unless otherwise noted

Symbol	Parameter	Conditions	Type	Min.	Typ.	Max.	Units
OFF CHARACTERISTICS							
BV_{DSS}	Drain-Source Breakdown Voltage	V_{GS} = 0V, I_D = 100μA	All	60			V
I_{DSS}	Zero Gate Voltage Drain Current	V_{DS} = 25V, V_{GS} = 0V	All			0.5	μA
I_{GSSF}	Gate - Body Leakage, Forward	V_{GS} = 15V, V_{DS} = 0V	All			10	nA
ON CHARACTERISTICS (Notes 1)							
$V_{GS(th)}$	Gate Threshold Voltage	V_{DS} = V_{GS}, I_D = 1mA	All	0.8	2.1	3	V
$R_{DS(ON)}$	Static Drain-Source On-Resistance	V_{GS} = 10V, I_D = 200mA	All		1.2	5	Ω
g_{FS}	Forward Transconductance	V_{DS} = 10V, I_D = 200mA	BS170		320		mS
		$V_{DS} \geq 2\,V_{DS(on)}$, I_D = 200mA	MMBF170		320		

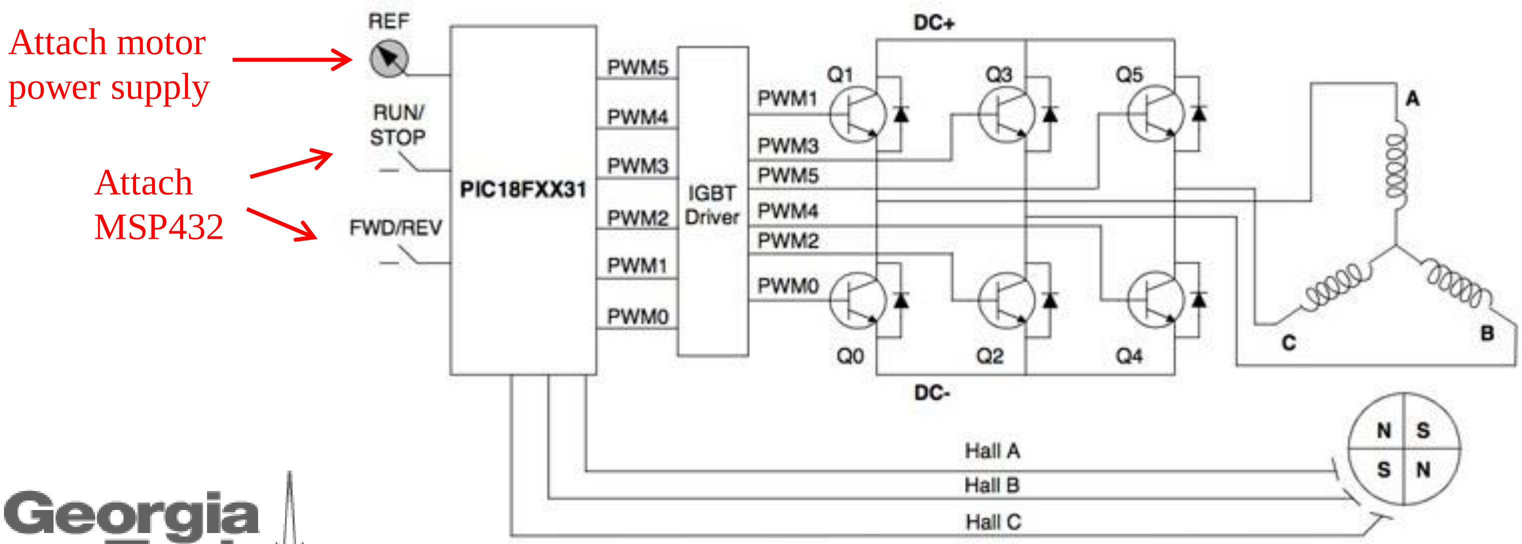
Small turn on current

Low turn on voltage

Small resistance

Driving BLDC Motors

- Driving BLDC motors is more complicated because we have to incorporate commutation circuit
  - Most motor manufacturers sell BLDC drivers for their motors
  - Usually integrate microcontroller with three-phase (or N-phase) bridge driver. Sometimes integrated into motor itself.



Driving BLDC Motors

- ON Semiconductor MC33035 BLDC motor controller IC

  - 10-30V operation
  - Can be interfaced directly to an MCU (like MSP432) at pins 3, 7, 22, 23
  - Designed for 3-phase BLDC
  - Sensor outputs of BLDC go to pins 4-6
  - Drive (coil) outputs go to pins 1, 2, 24, 19-21
  - Price: $4.29