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College of Engineering and Petroleum

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ME319 MECHATRONICS

Part IV: The Muscles – Actuators

Lecture 1: DC Motors

Spring 2021

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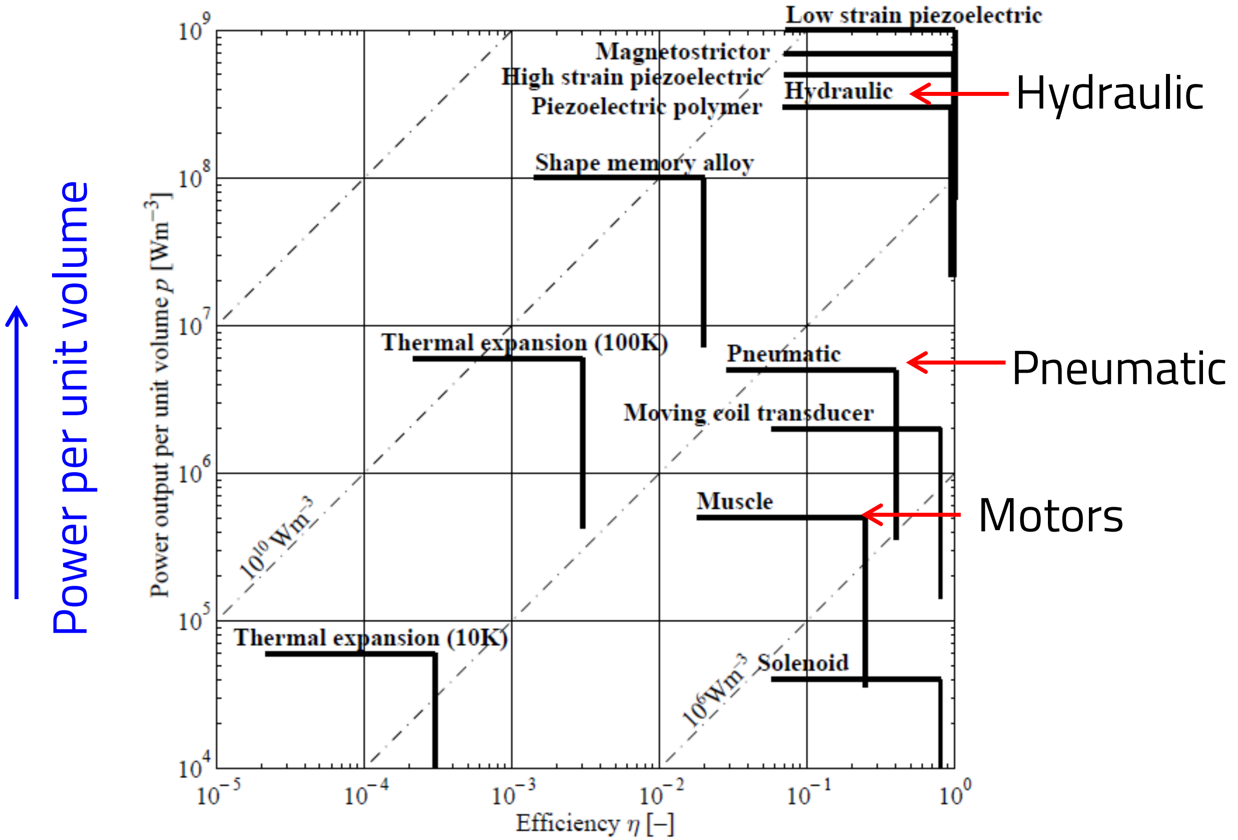
- Advantages of electric actuators
- Clean (do not require fluids, oil, etc.)
- Require no extra equipment
  (no need for pressure tanks, etc.)
- Can operate indoors (no emissions)
- Can be made small economically
- Disadvantages of electric actuators
- Low power-to-size ratio



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 Actuators

- Most commonly: Motors
  - Electric solenoids can be classified as electric actuators too
- Motors
  - Many different types, names, technologies
  - No uniform way to classify them
  - More logical classify by group rather than type (Operating principle)

- Motor *Groups* (Hughes' Electric Motors and Drives, 2013):
  1. Conventional DC Motors
  2. Induction Motors
  3. Synchronous and Brushless Permanent Magnet Motors
  4. Stepping and Switched-Reluctance

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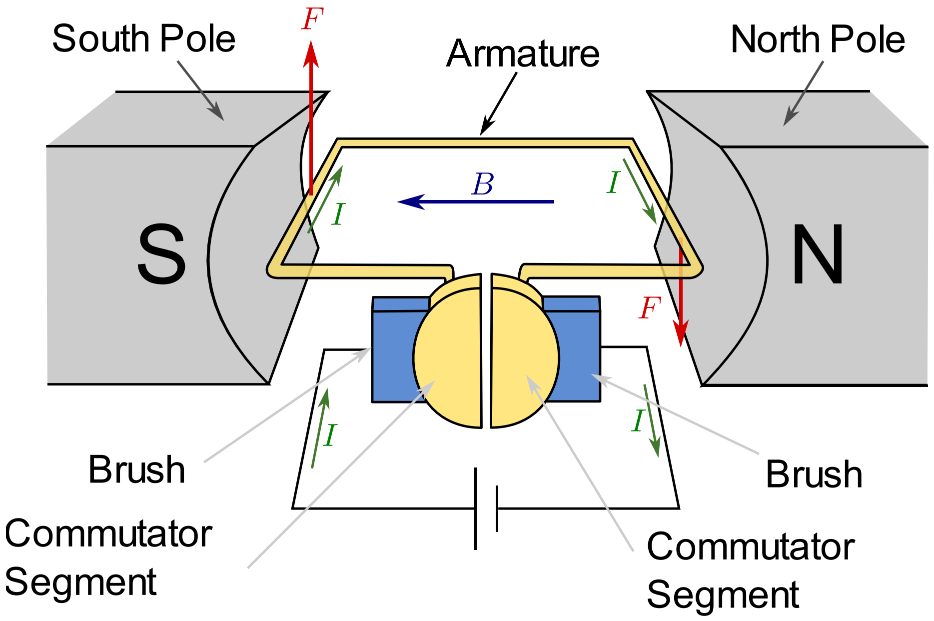
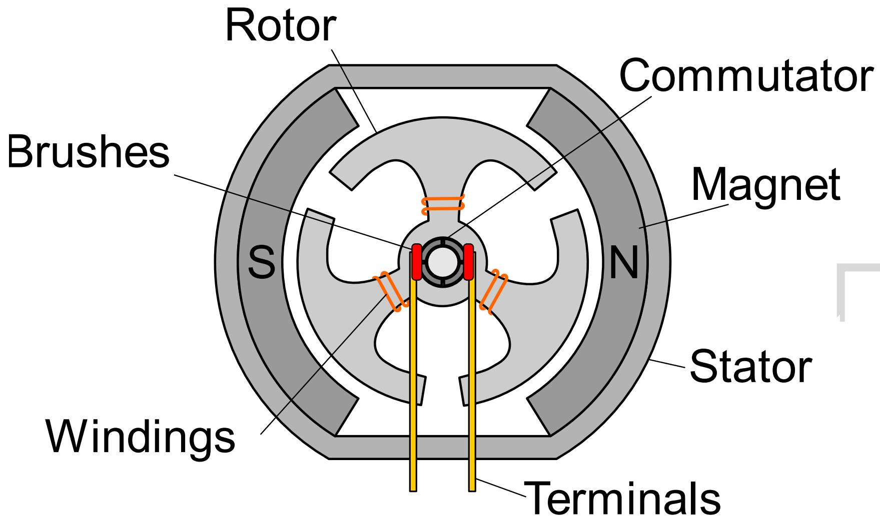
- a.k.a Brushed DC Motors
  - The ones you find in most toys
  - Simple Operation
    - Supply voltage across them, they move.
- Brushed motors composed of two components:
  - Stator (remains stationary)
  - Rotor (turns, coupled to shaft)
- Lorentz's Law $\vec{F} = \vec{I} \times \vec{B}$

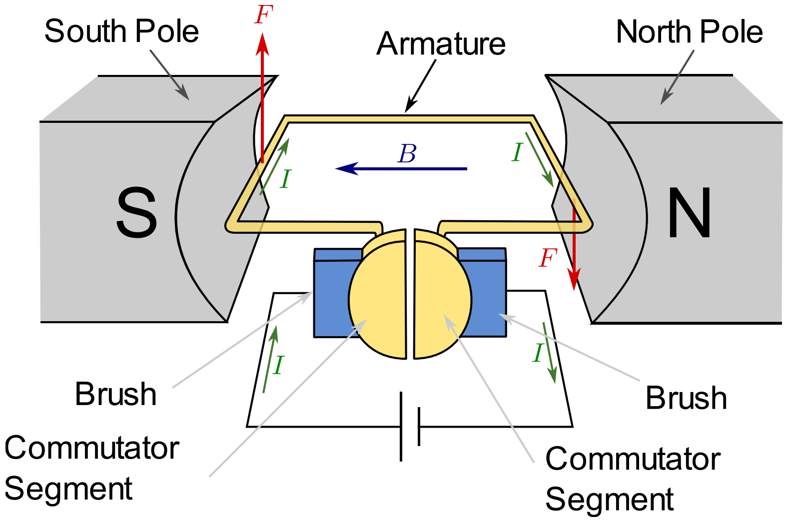


- Wire coil runs along back end of armature to generate B field
- Commutator used to change direction of current flow as armature rotates

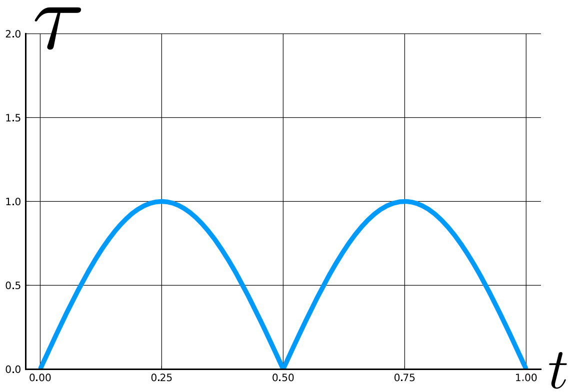


- Commutator must be composed of at least two segments
  - Motors on previous page had 3-piece commutator (left) and 2-piece commutator (right)
- As motor turns, angle of energized coil with respect to magnet changes

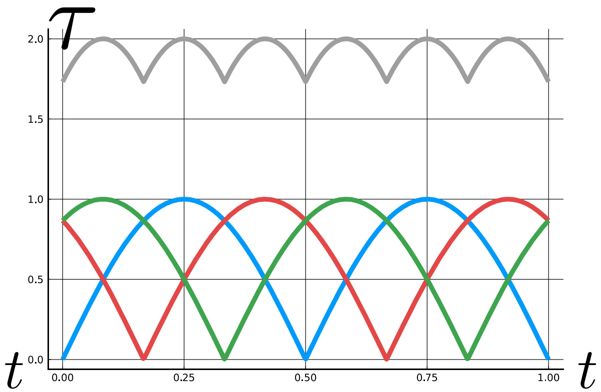
$$\vec{F} = \vec{I} \times \vec{B}$$ → Torque is function of sine of angle between B field and armature angle → Torque is not smooth using 2-piece commutator



Torque vs angle for 2-piece comm.



Torque vs angle for 6-piece comm.

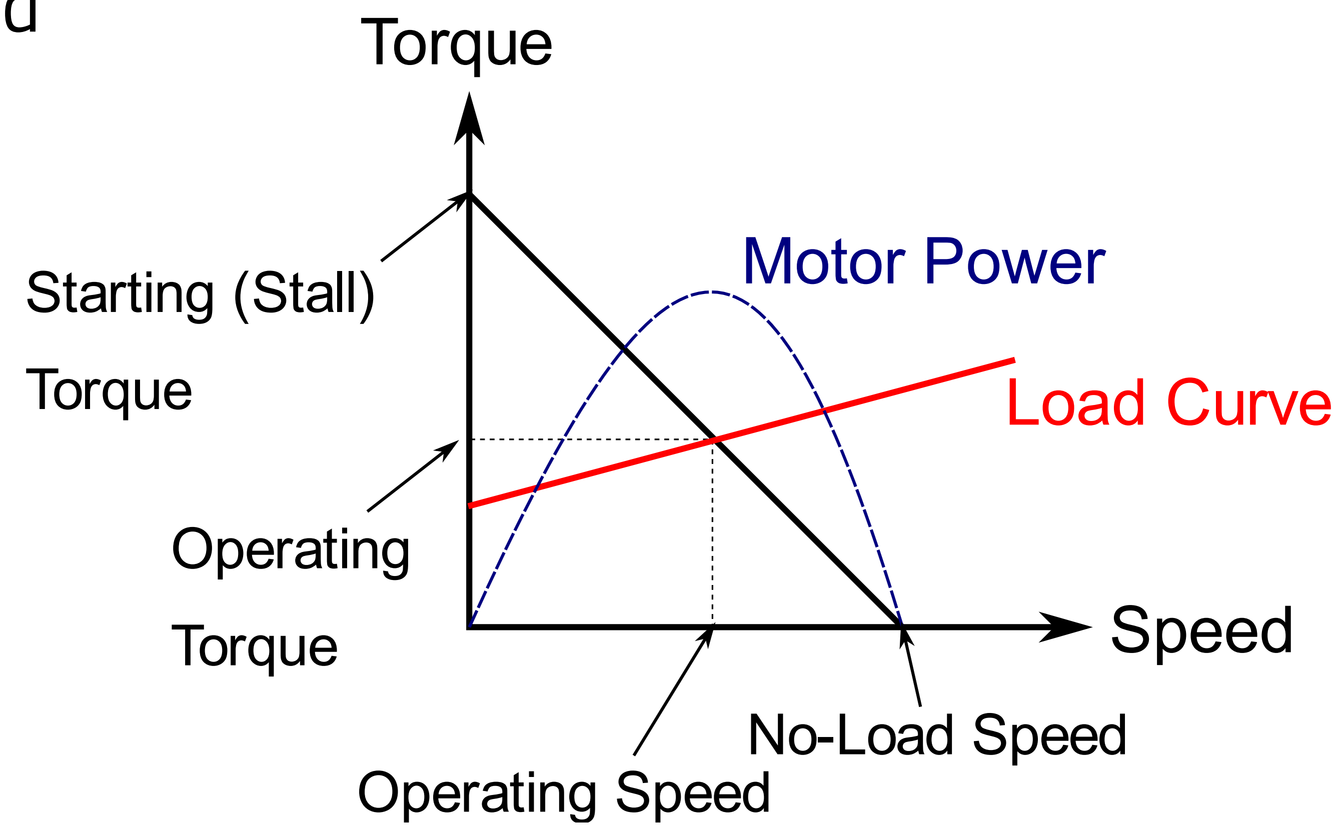


Brushed DC Motor

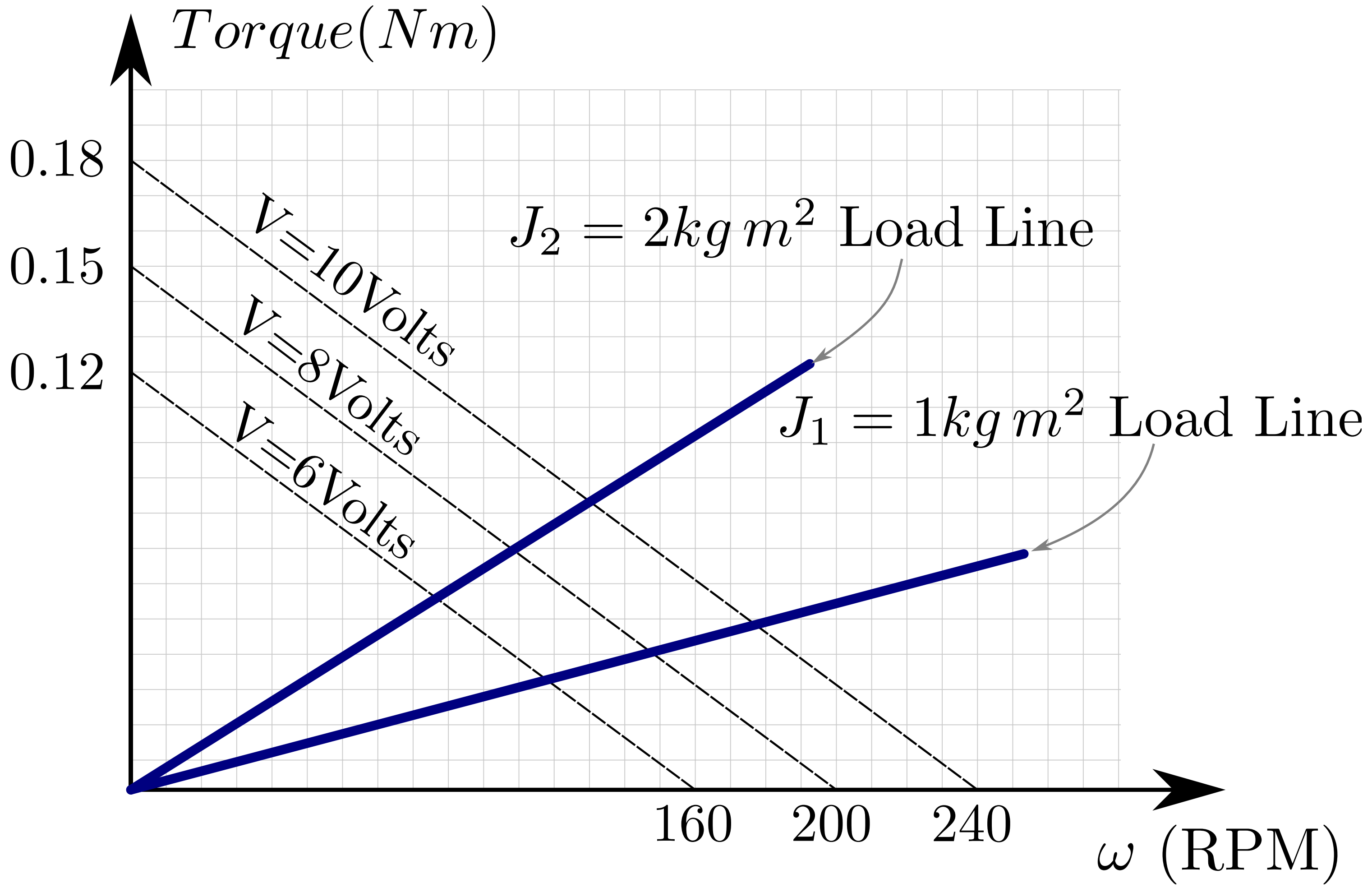
- Video

Conventional PM DC Motor Analysis

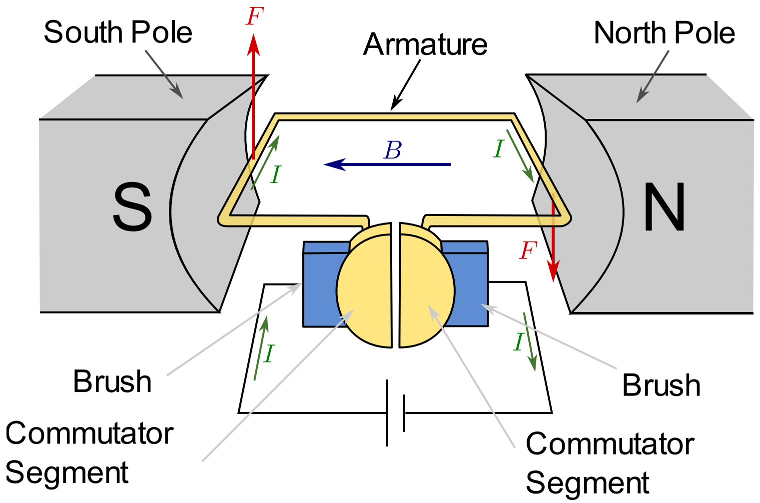
- Torque-speed curve defined by two parameters (Assuming linear torque-speed curve)
  - Starting (stall) torque – max torque when speed is zero
  - No-load speed

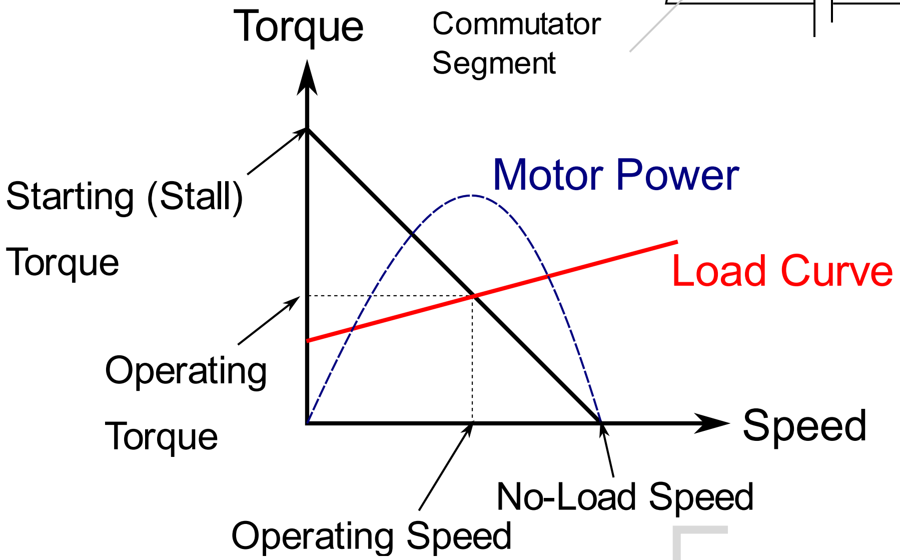


- Note that for a given load, we get the load line, which relates the output torque to various voltage values, and the corresponding speed

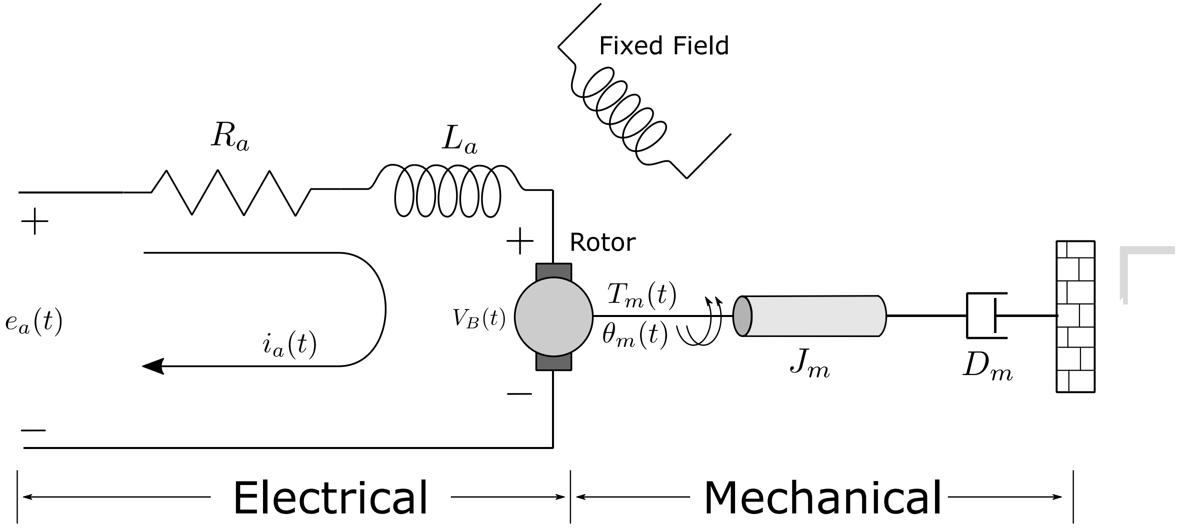


- As motor rotates, back EMF generated due to rotation of coil within magnetic field reduces voltage across motor leads and thus current through motor
- This is why torque decreases with speed
- Torque continues to decrease as ω increases until torque is zero at maximum speed
- Motor delivers maximum power when it reaches half of its no load speed: $P = T\omega$ ($T = Torque$)
- 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

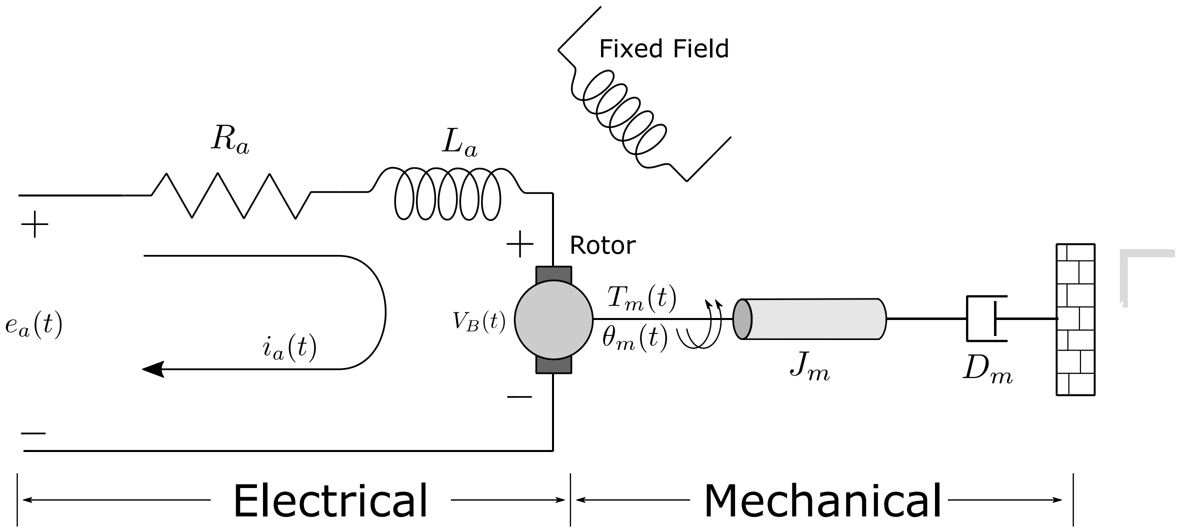




- The DC Motor is modeled as a circuit + rotational mechanical system
- On the electrical side, we apply voltage across the coils which have resistance and inductance, modeled as R_a and L_a.
  - $R_a I_a(s) + L_a s I_a(s) + V_B(s) = E_a(s) \quad (eq. 1)$
- The motor is represented as a back-emf voltage in the circuit, $V_B(t)$.
  - $V_B = K_B \dot{\theta}_m \Leftrightarrow V_B(s) = K_B s \Theta_m(s) \quad (eq. 2)$
  - K_B: back-emf constant



- The Fixed Field represents the permanent magnets' field.
- The torque developed by the motor is proportional to the field current.
  - $T_m(s) = K_t I_a(s) \quad (eq.3)$, K_t: motor torque constant
- Combining equations 1 to 3
  - $\frac{(R_a+L_a s)T_m(s)}{K_t} + K_B s\Theta_m(s) = E_a(s) \quad (eq.4)$

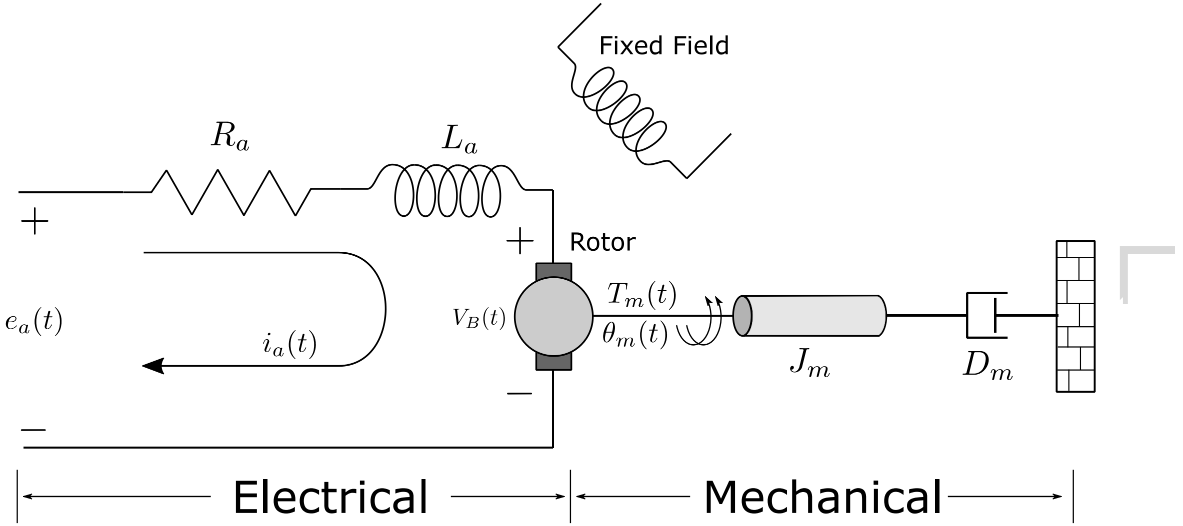


- On the mechanical side, the motor itself has an inertia J_m , that rotates with angular velocity $\dot{\theta}_m$, in addition to mechanical bearing friction (viscous damping) D_m
  - $T_m(s) = (J_m s^2 + D_m s)\Theta_m(s) \quad (eq. 5)$

- Combining equations 4 & 5, and rearranging to express $\frac{\Theta_m(s)}{E_m(s)}$, ignoring L_a as $R_a/L_a \gg 1$

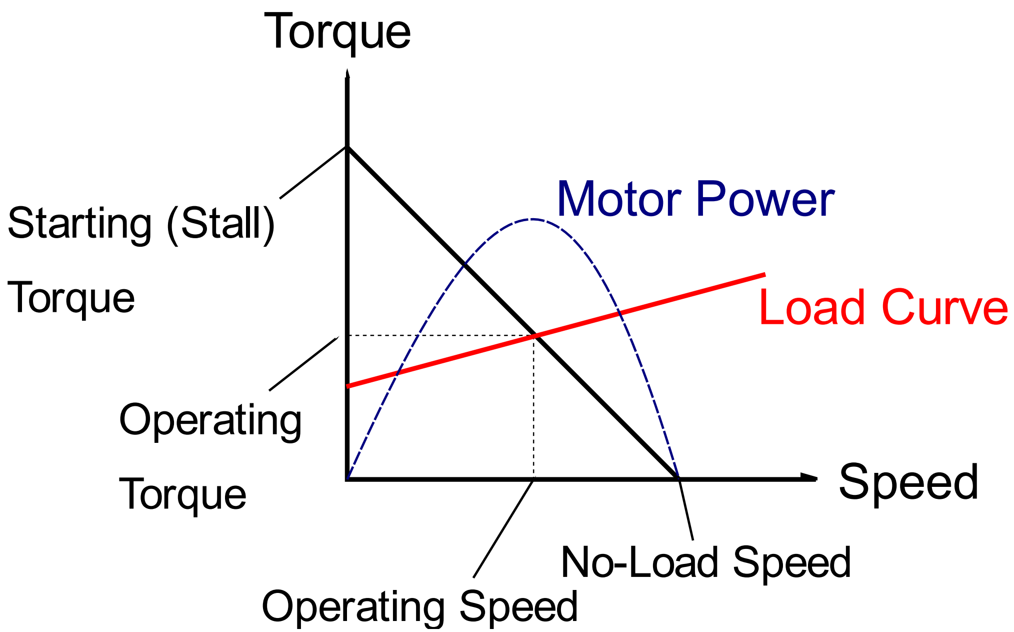
  - $\frac{\Theta_m(s)}{E_m(s)} = \frac{K_t/(R_a J_m)}{s[s+\frac{1}{J_m}(D_m+\frac{K_t K_B}{R_a})]} \quad (eq. 6) = \frac{K}{s(s+\alpha)}$

- The constants K, α
  - $K = K_t/(R_a J_m)$
  - $\alpha = \frac{1}{J_m}(D_m + \frac{K_t K_B}{R_a})$



- How do we find the constants' values?
- A dynamometer can be used to generate a profile of the motor
- A dynamometer is a test bench for motors, allows for changing mechanical load, changing supplied voltage and measuring generated torque and current consumed. The generated profile is a torque-speed curve.

<u>Ideal</u> Steady-State Torque-Speed Curve for a Brushed DC Motor



Note: If you search for Torque-Speed curves you will get different shaped curves, those are for different types of motors
or different assumptions made or different operating conditions, but the key characteristics above apply.

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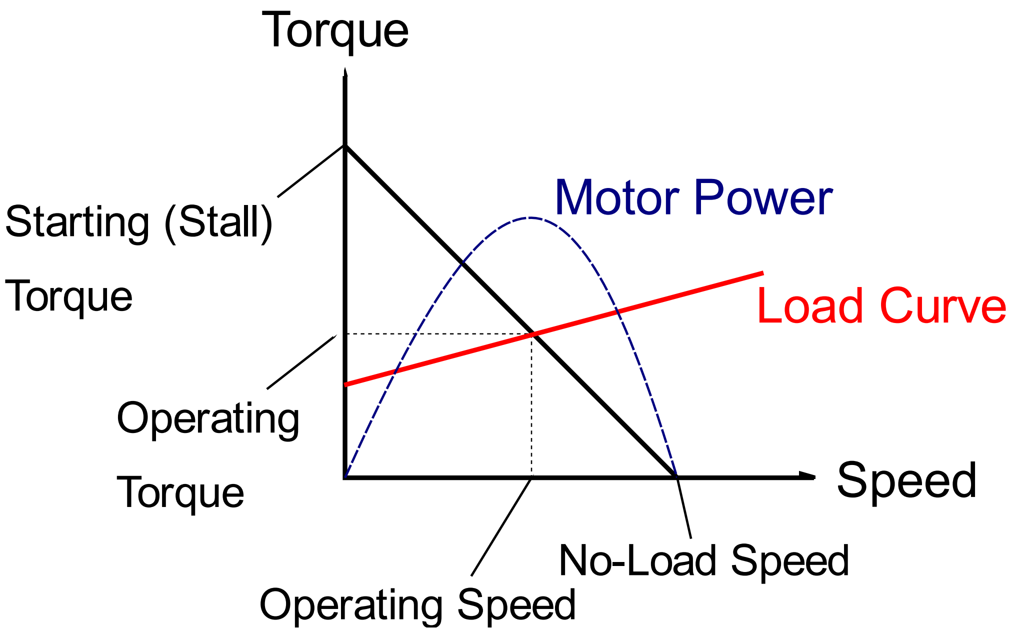
- From equation 4, if we consider the steady-state response of the motor, we can simplify by setting inductance $L_a = 0$, we get
  - $\frac{R_a}{K_t} T_m(s) + K_B s \Theta_m(s) = E_a(s) \quad (eq.6)$

Ideal Steady-State Torque-Speed Curve for a Brushed DC Motor



- Taking $\mathcal{L}^{-1}(eq.6)$ and rearranging
  - $T_m(t) = -\frac{K_B K_t}{R_a} \omega_m(t) + \frac{K_t}{R_a} e_a(t) \quad (eq.7)$
  - Equation 7 matches the Torque-Speed Curve

- Stall is when $\omega_m = 0$
  - $T_m(t) = \frac{K_t}{R_a} e_a(t)$: **Stall Torque**

- No Load Speed is when $T_m(t) = 0$,
  - $\omega_{no\ load} = \frac{e_a}{K_B}$: **No Load Speed**

- The constants can then be computed from the dyno generated curves.

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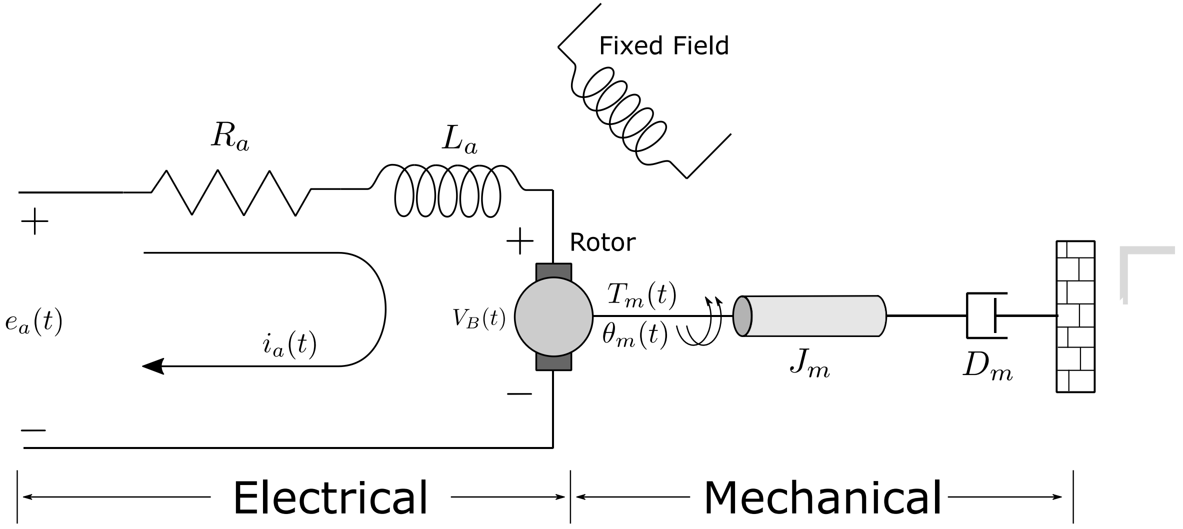
- DC Motor Model, Combining:
  - Electrical Part Gives: $R_a I_a(s) + L_a s I_a(s) + V_B(s) = E_a(s)$
  - Mechanical Part Gives: $T_m(s) = (J_m s^2 + D_m s)\Theta_m(s)$
  - Additional relationship 1: $V_B(s) = K_B s \Theta_m(s)$
  - Additional relationship 2: $T_m(s) = K_t I_a(s)$
- We get:

$$\frac{\Theta_m(s)}{E_m(s)} = \frac{K_t/(R_a J_m)}{s[s+\frac{1}{J_m}(D_m+\frac{K_t K_B}{R_a})]}$$

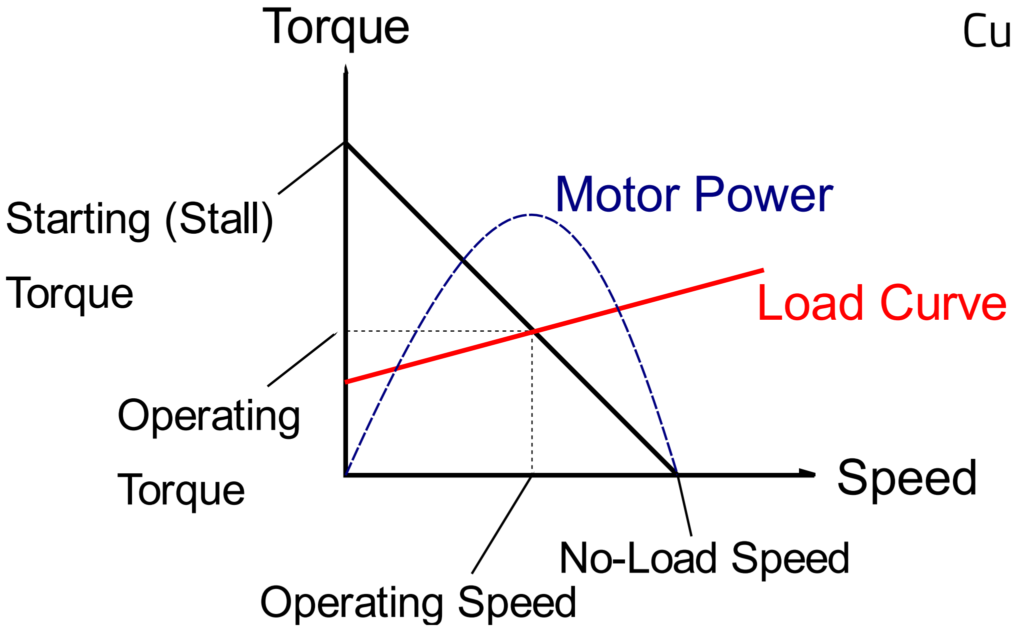


- Torque-Speed Curve

$$T_m(t) = \underbrace{\frac{K_t}{R_a} e_a(t)}_{Stall\ Torque} \underbrace{- \frac{K_B K_t}{R_a}}_{Slope\ of\ Torque\ Speed\ Curve}$$

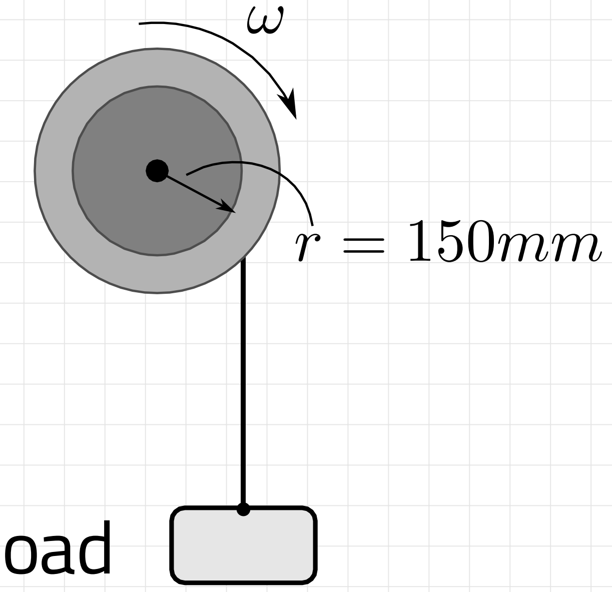
$$\omega_m(t) = \tau_{stall} - Slope_{\tau-\omega}\,\omega(t)$$

Ideal Steady-State Torque-Speed Curve for a Brushed DC Motor



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:

a. Initial acceleration of load
b. Steady-state speed of load
c. Output horsepower of motor



a. Initial Acceleration:

Total Torque at Startup $\tau_{Total} = \tau_{starting} - \tau_{friction} - \tau_{gravity}$

$\tau_{total} = 23.8 - 2 - 10 \cdot 9.81 \cdot 0.15\ N-m = 7.1\ N-m$

Acceleration of load due to this torque

$$F_{total} = \frac{\tau_{total}}{r} = \frac{7.1N-m}{0.15m} = 47.3N \rightarrow a = \frac{F}{m} = \frac{47.3N}{10kg} = 4.731 m/s^2$$

b. Steady-State Speed

At steady state, the load is not accelerating, and the net torque exerted is

$$\tau_{ss} = \tau_{frictional} + \tau_{gravity} = 2 + 10 \cdot 9.81 \cdot 0.15 = 16.7\ N-m$$

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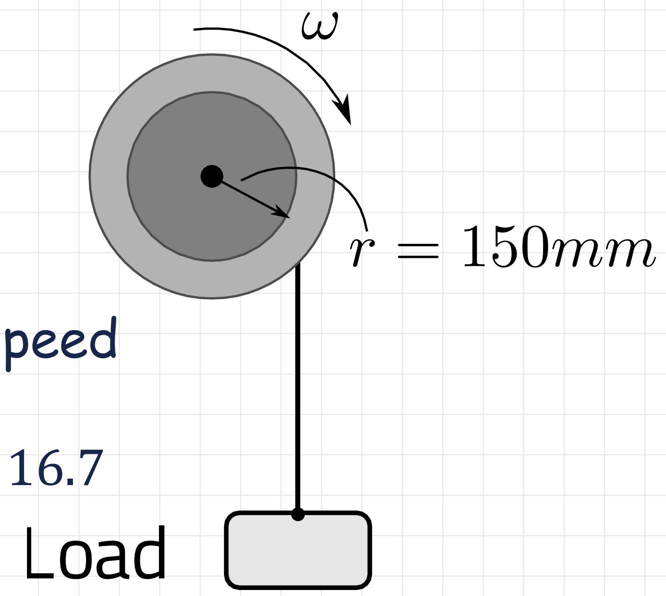


Using the torque-speed equation, we can determine the steady-state speed

$$\tau_{motor} = \tau_{stall} - Slope_{\tau-\omega}\omega(t) = 23.8 - \underbrace{(23.8/300)}_{Slope\ of\ torque-speed\ curve} \quad \omega = \tau_{ss} = 16.7$$

$$\omega = 89.5RPM \rightarrow v = \omega r = 89.5RPM \cdot \frac{2\pi}{60} \cdot 0.15m = 1.41m/s$$

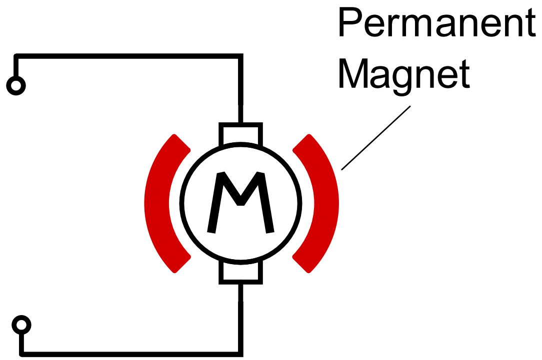
c. Output Horsepower of Motor

$$P = \tau\omega = 16.7N - m \cdot 89.5RPM \cdot \frac{2\pi}{60}\frac{1Hp}{746Watts} = 0.21Hp < P_{rated} = 0.25Hp$$

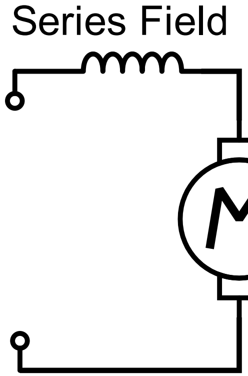
- There are 4 primary types of DC motors

PM DC Motor

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



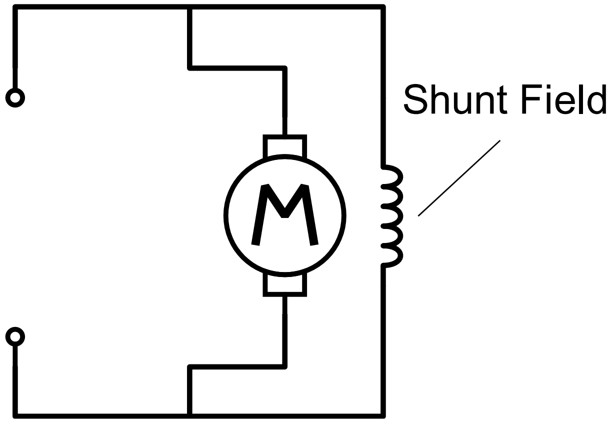
Series-Wound DC Motor



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

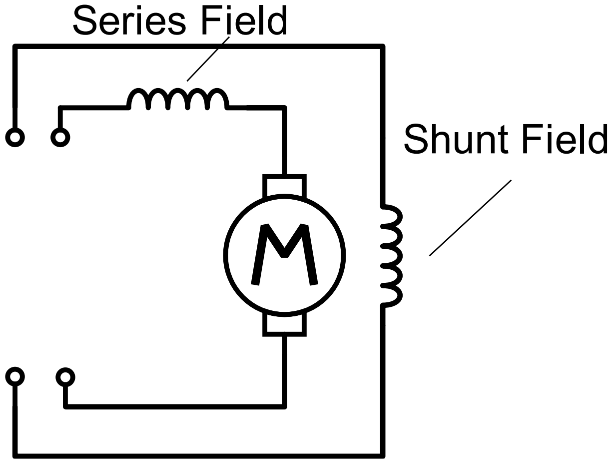
Shunt-Wound DC Motor

- 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

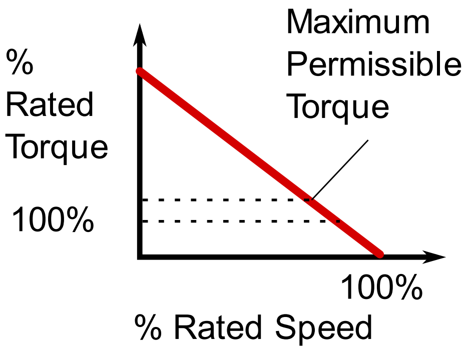


Conventional DC Motor Torque vs Speed Curves

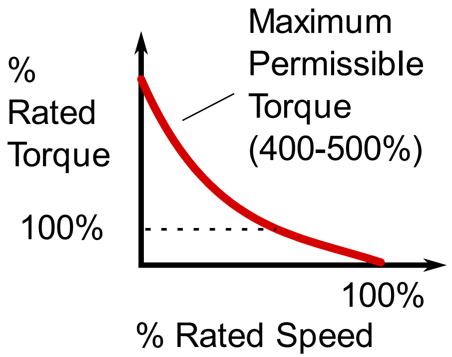
- DC motors provide a varying amount of torque depending on operating speed
  - Generally torque decreases as motor runs faster

PM DC Motor

- Torque vs speed curve is linear for a DC motor



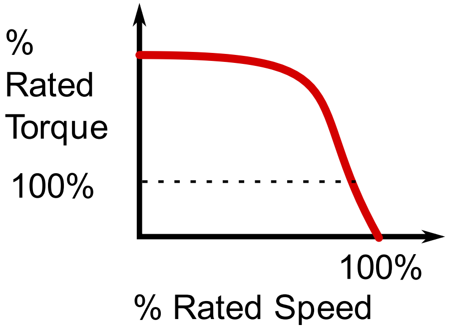
Series-Wound DC Motor



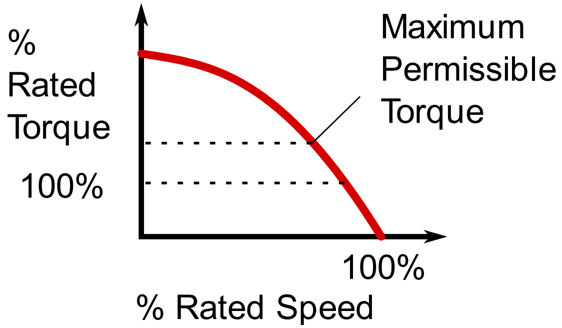
- Large starting torque
- But motor speed grows uncontrollably if zero torque is applied

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

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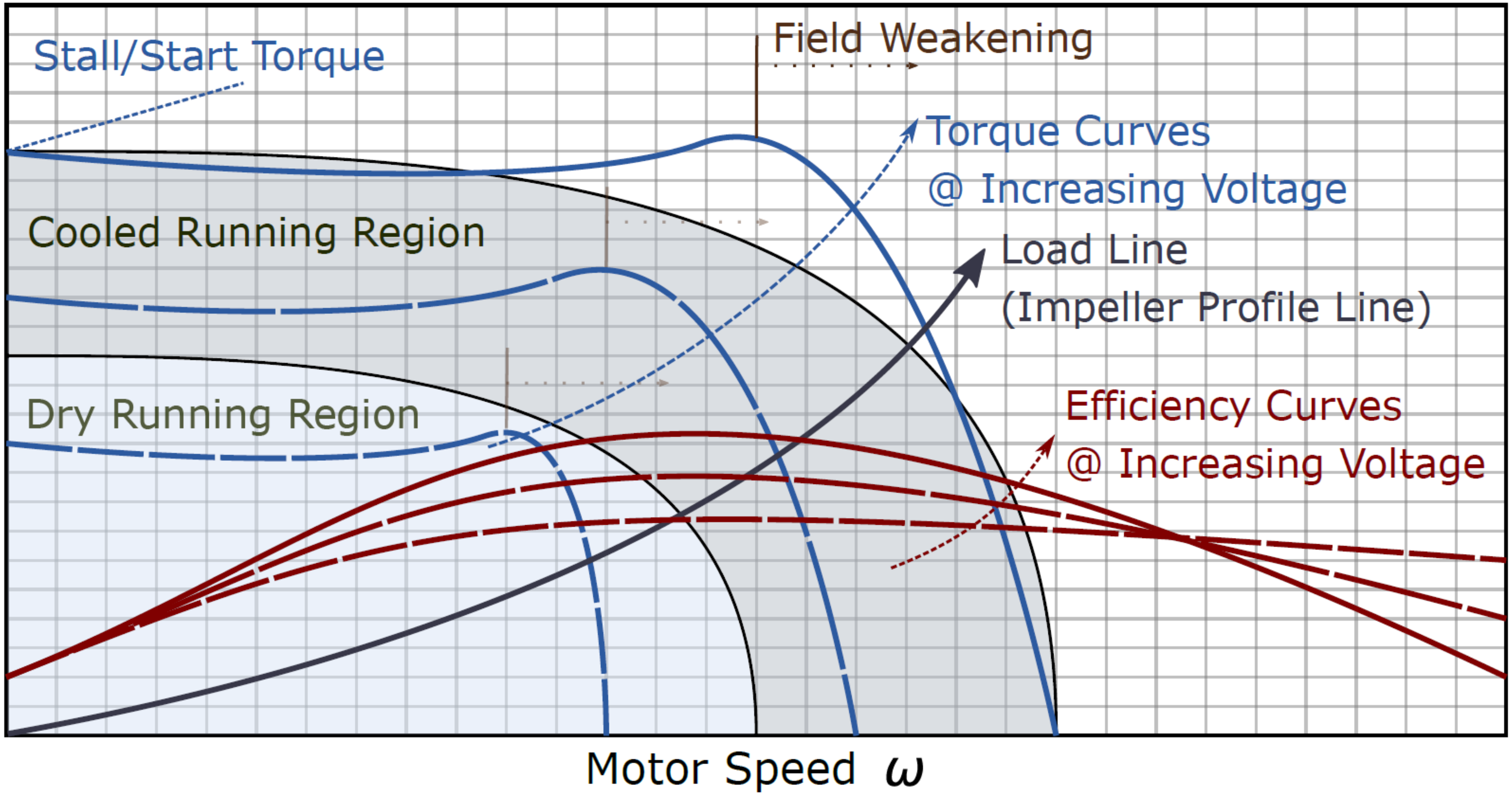

Mechatronic design of autonomous underwater vehicles for confined spaces, AlSaibie, PhD Thesis, 2018

Brushless PM 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

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Brushless Motor Names

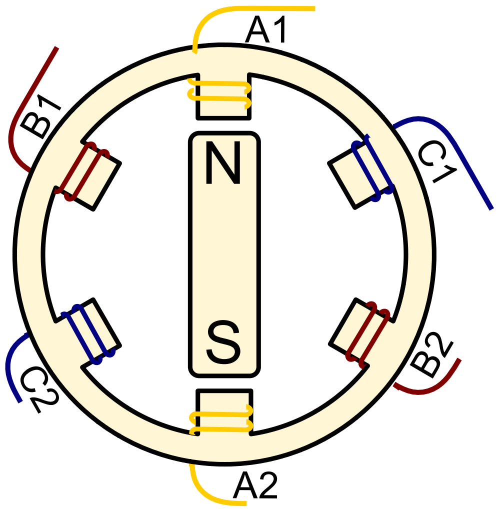
- These are essentially the same type of motor:
  - Synchronous Machine
  - Permanent Magnet Synchronous Machine
  - Brushless Permanent Magnet Synchronous Motor
  - Brushless A.C. Motor
  - Brushless D.C. Motor
  - Permanent Magnet Servo Motor

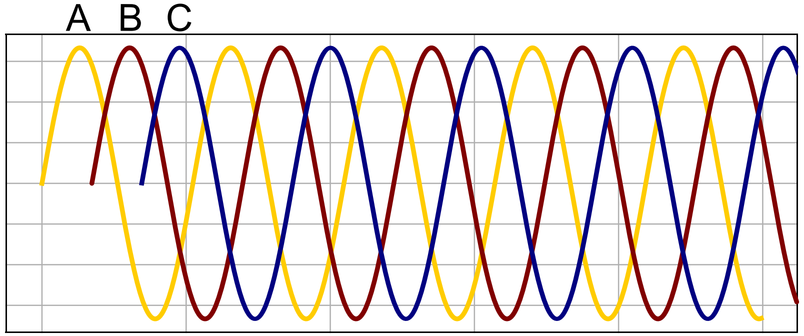
- The different names serve to confuse us.
  - They may vary a bit, but principle of operation is the same.

- Just use the term: Brushless Motor (most common in mechatronics/robotics)

Brushless Motor Operation

- 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:
  - Position of magnet is detected
    - Through hall-effect sensor
    - Or by measuring current (sensor-less operation)
  - 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
    - In a conventional DC motor, the current switches direction when the shaft commutator rotates flips current direction





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Brushless Motor

- Is it AC or DC?
  - It’s a multi-phase (3-phase most commonly), that operates via principle of switching current direction (ac).
  - Why do they call it a Brushless DC motor sometimes?
    - Because the “controller” can be supplied a DC current, and the “controller” produces the ac like currents to the motor.
    - So to be specific the “controller” is dc. The motor itself is not.

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Brushless DC Motor Advantages

- BLDC Rotor is lighter than on brushed motors
  - (+) BLDC's can operate at much higher speeds than DC motors

- BLCD 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
  - (-) BLDC's require more complex circuitry to operate. They are also more expensive.

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