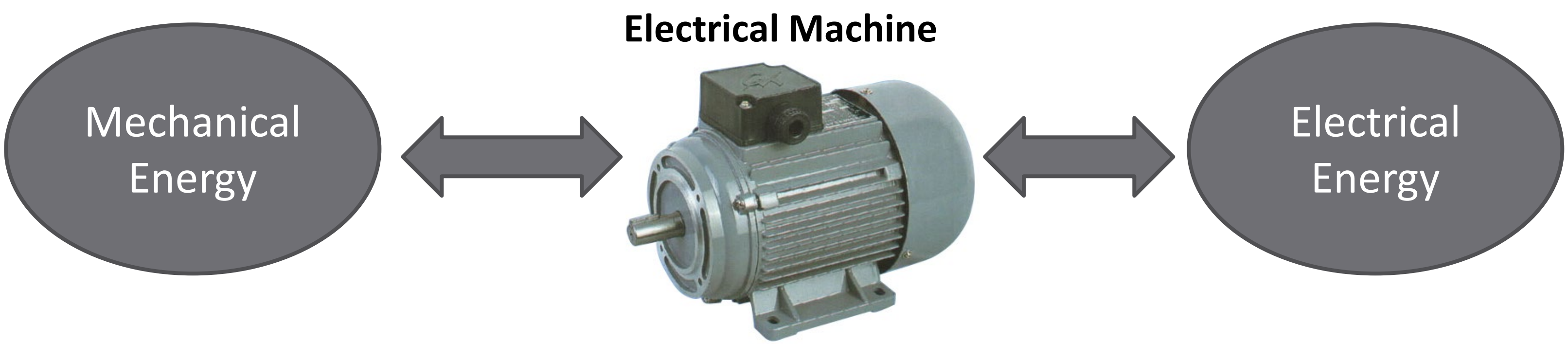
CLASS 19:
MOTORS & GENERATORS

ENGR 102 – Introduction to Engineering

Electrical Machines

- ***Electrical machines*** are ***energy conversion*** devices
  - Convert between ***electrical*** and ***mechanical*** energy
  - Includes ***motors*** and ***generators***

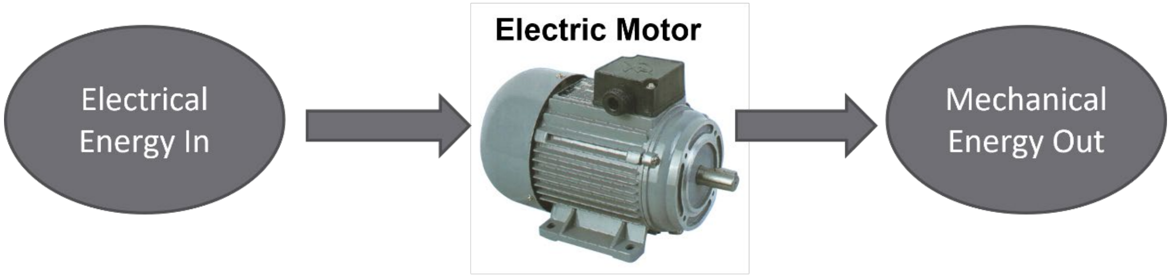


http://www.trimainternational.com/Products/de.htm

- Motors and generators are the ***same device***
  - Only difference is the ***direction of power flow***

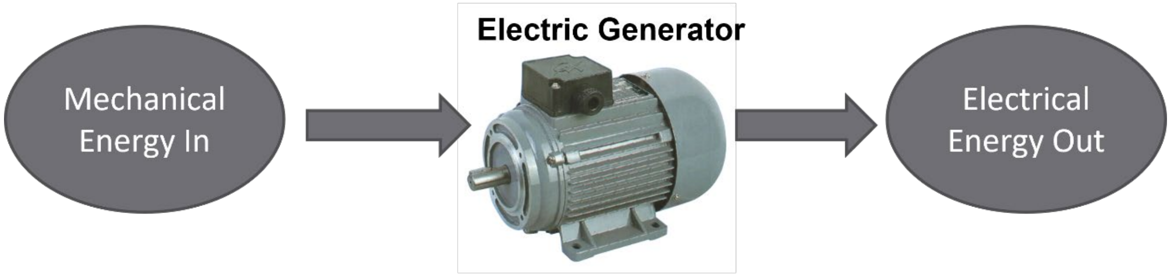
Motors & Generators

- ***Motor***
  - Electrical machine converting electrical energy to mechanical energy



http://www.trimainternational.com/Products/de.htm

- ***Generator***
  - Electrical machine converting mechanical energy to electrical energy



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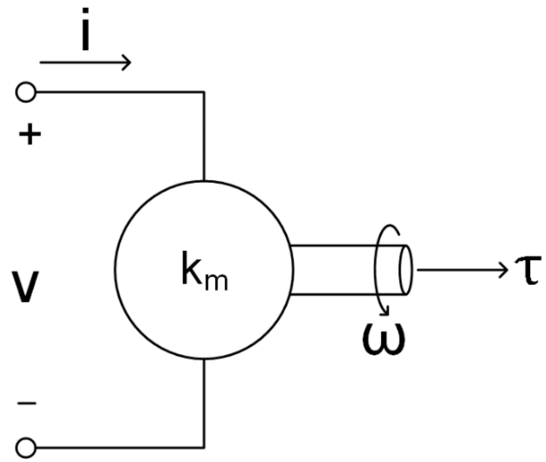
Motor/Generator Quantities



- **Electrical domain**
  - Voltage, v [V]
  - Current, i [A]
  - Power, $P = v \cdot i$ [W]
- **Mechanical domain**
  - Torque, τ [Nm]
  - Velocity, ω [rad/s]
  - Power, $P = \tau \cdot \omega$ [W]

Motor Constant

- Motor converts:
  - Current to torque
  - Voltage to angular velocity
- Generator converts:
  - Torque to current
  - Angular velocity to voltage
- Motor properties determine constant of proportionality
  - ***Motor constant***, k_m

$$\tau = k_m \cdot i$$

$$v = k_m \cdot \omega$$

- k_m has equivalent units of: [Nm/A] or [V/rad/s]

Motor Physics – Lorentz Force

- ***Lorentz force***:
  - Basis for electrical/mechanical energy conversion
  - A current-carrying wire in a magnetic field experiences a force

$$\vec{F} = \vec{I}\ell \times \vec{B}$$

where

$\vec{I}$: current vector
ℓ: length of wire
$\vec{B}$: magnetic field
$\vec{F}$: force exerted on wire

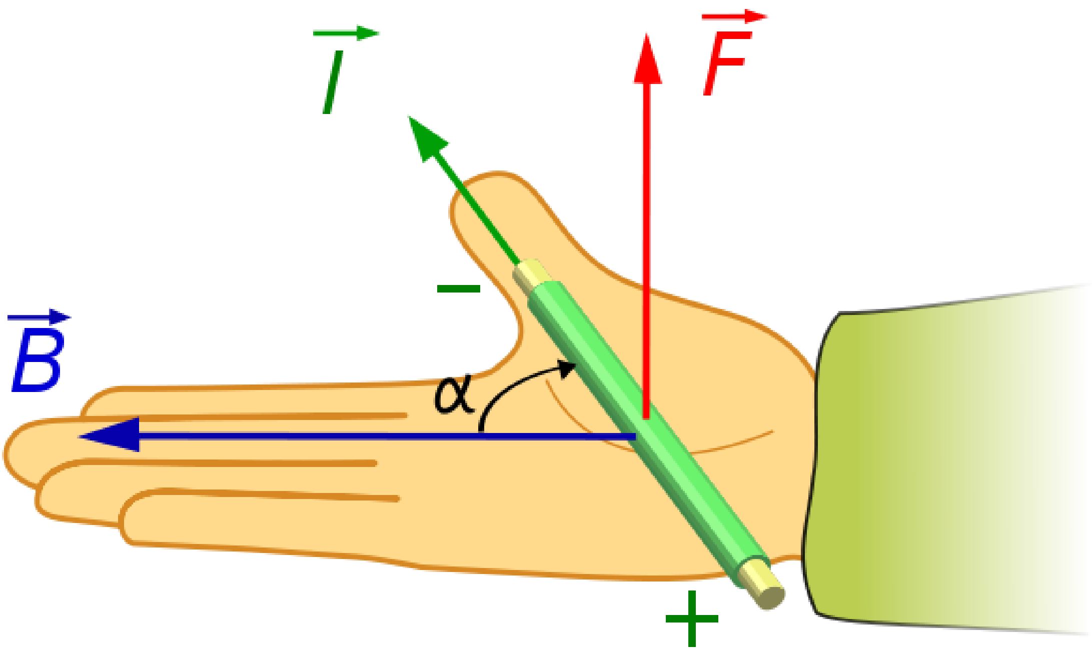
  - $\times$ is the cross product

$$F = \left|\vec{F}\right| = \mathrm{I}\ell B \sin(\theta)$$

where θ is the angle between $\vec{I}$ and $\vec{B}$

Lorentz Force – Right-Hand Rule

- Right-hand rule gives the direction of the force:
  - Fingers point in the direction of the magnetic field
  - Thumb points in the direction of the current
  - Force is out of the palm



DC Motor Operation

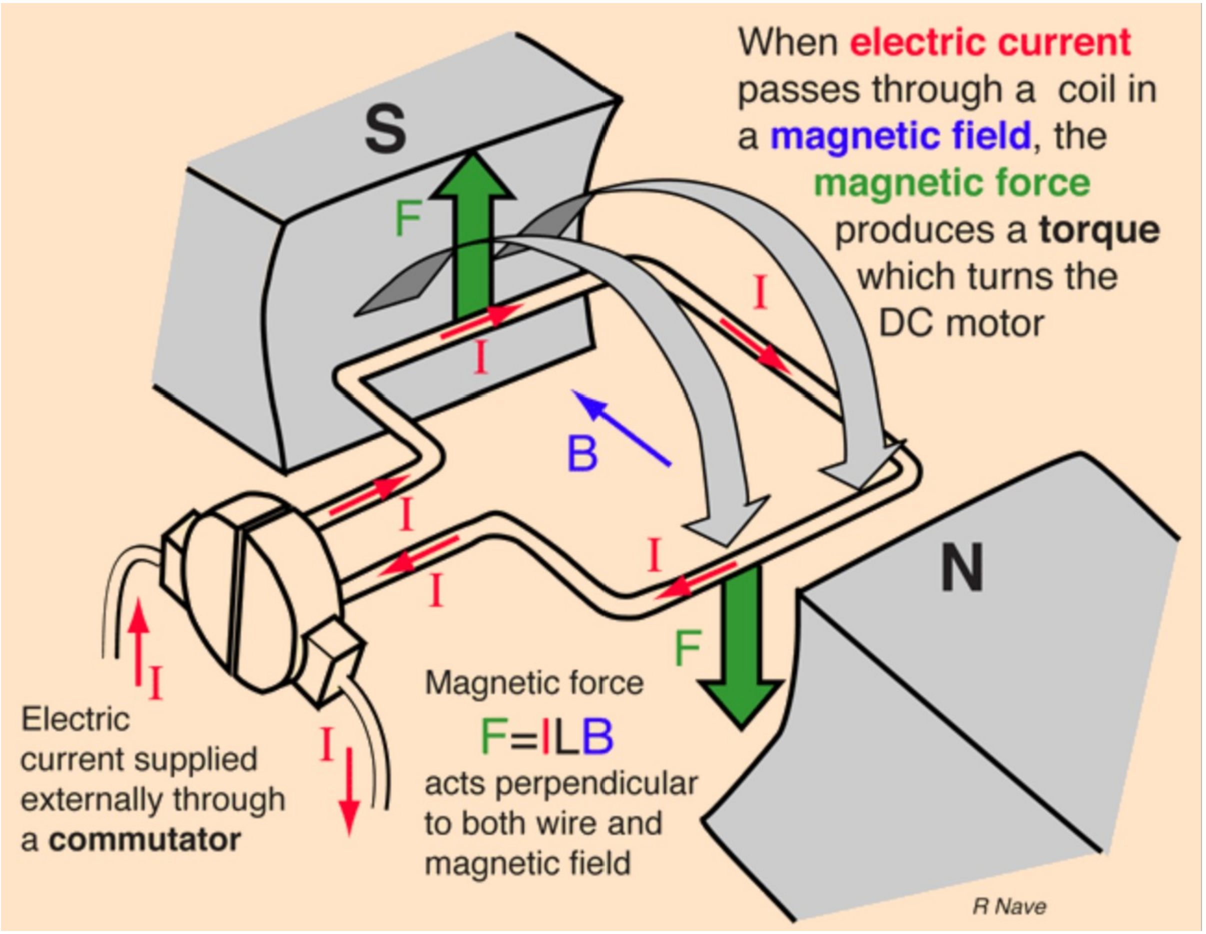


Image source: Dr. Rod Nave, http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/motdc.html#c1

DC Motor Components

- **Stator**
  - Stationary part of motor
- **Rotor**
  - Rotating part of motor
- **Armature**
  - Current-carrying coils on rotor
- **Commutator**
  - Mechanism for reversing armature current
- **Brushes**
  - Contacts to the commutator

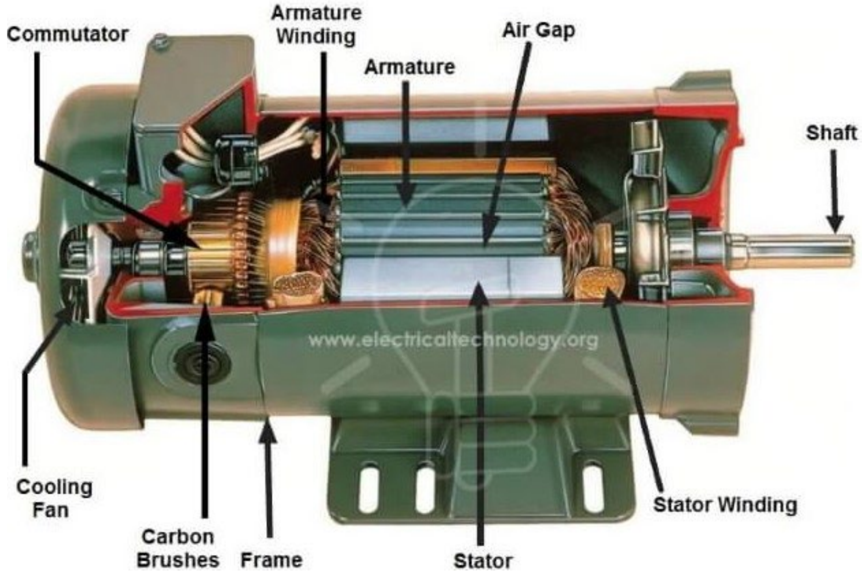


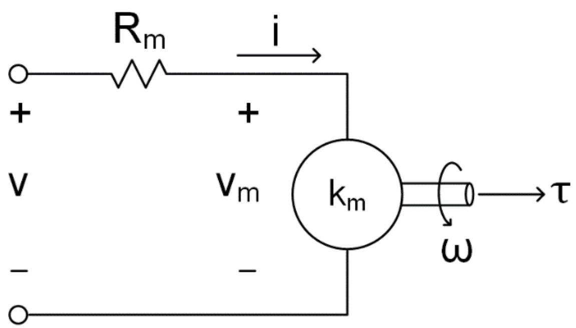
Image source: https://www.electricaltechnology.org

Types of Motors

- ***DC motors***
  - Brushed
  - Brushless (electronically-commutated motor)
- ***AC motors***
  - Synchronous (PMAC, PMSM)
  - Asynchronous (induction motors – most common)
- ***Universal motors***
  - AC or DC
  - Tools, appliances, etc.

Equivalent Circuit Model

- Simple DC motor model accounts for:
  - Energy conversion
  - Armature resistance



$v_m = k_m \cdot \omega$

$\tau = k_m \cdot i$

- ***Scenario 1: no load***
  - No external load: $\tau = 0$
  - Small internal load due to friction: τ_{int}
  - Small no-load current required to overcome τ_{int}

$$i_{nl} = \frac{1}{k_m}\tau_{int}$$

  - No-load back emf voltage:

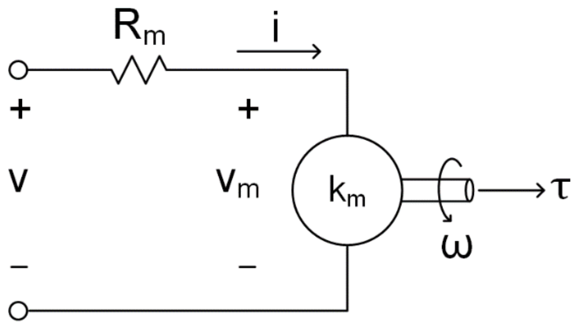
$$v_m = v - i_{nl}R_m = v - \frac{R_m}{k_m}\tau_{int}$$

  - No-load speed:

$$\omega_{nl} = \frac{1}{k_m}v_m = \frac{1}{k_m}\left(v - \frac{R_m}{k_m}\tau_{int}\right)$$

Equivalent Circuit Model

- ***Scenario 2: applied load***
  - Now, $\tau > \tau_{int}$
  - More current required to supply required torque



$$i = \frac{1}{k_m}\tau$$

  - Back emf voltage decreases with increasing load:

$$v_m = v - iR_m = v - \frac{R_m}{k_m}\tau$$

  - Speed decreases with increasing load:

$$\omega = \frac{1}{k_m}v_m = \frac{1}{k_m}\left(v - \frac{R_m}{k_m}\tau\right)$$

Equivalent Circuit Model

- ***Scenario 3: stall torque***
  - Applied load causes motor to stall
  - Speed goes to zero, $\omega = 0$
  - Back emf goes to zero:

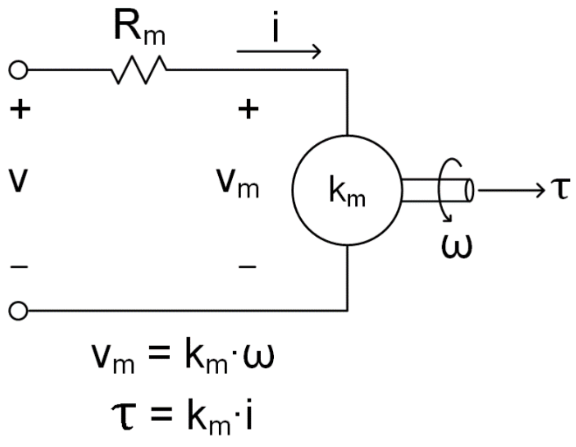
$$v_m = k_m \omega = 0$$

  - Ohm's law gives the stall current:

$$i_{stall} = \frac{v}{R_m}$$

  - The stall torque is:

$$\tau_{stall} = k_m i_{stall} = \frac{k_m}{R_m} v$$



Operating Quadrants

- ***Motoring***
  - Torque and velocity in the same direction
- ***Generating***
  - Torque and velocity in opposing directions