Machines

POWERUNIT

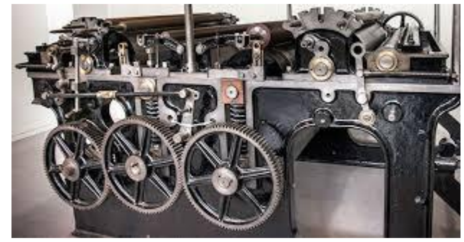
Introduction to Machinery Principles

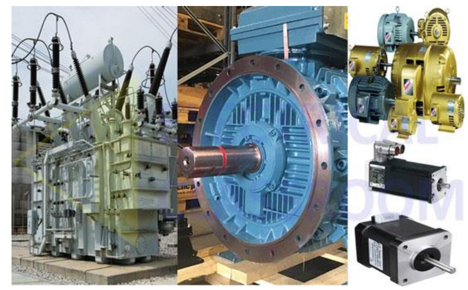
Chapter 1

Table of Content

Introduction

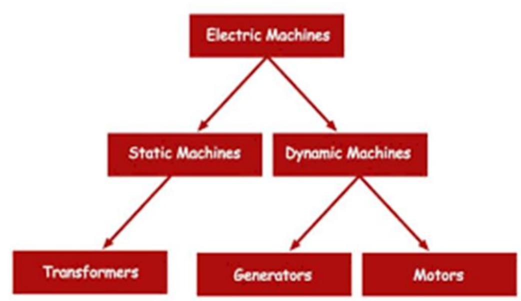
- Machine: a piece of equipment with several moving parts that uses power to do a particular type of work.
- Machine: is a device, having a unique purpose, that replaces human effort for the accomplishment of physical tasks. The operation of a machine may involve the transformation of chemical, thermal, electrical, or nuclear energy into mechanical energy, or vice versa, or its function may simply be to modify and transmit forces and motions.
- An electrical machine is a device which converts mechanical energy into electrical energy or vice versa. Electrical machines also include transformers, which do not actually make conversion between mechanical and electrical form but they convert AC current from one voltage level to another voltage level.





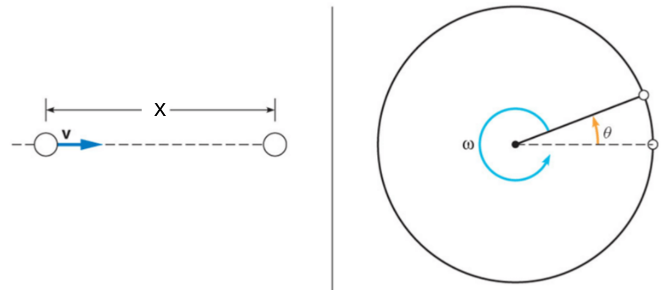
Electrical Machine Everywhere

- The washer
- The electric screwdriver
- The vacuum cleaner
- The electric toothbrush
- The hair dryer
- Power windows
- Power seats (up to seven motors per seat)
- Fans for the heater and the radiator
- Most toys that move have at least one motor
- Electric clocks
- The garage door opener
- Aquarium pumps

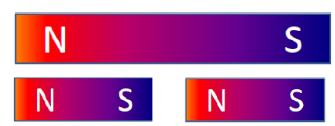


Linear Vs Rotational Motion

	Linear Motion	Rotational Motion	
Position	x	θ	Angular position
Velocity	v	ω	Angular velocity
Acceleration	a	α	Angular acceleration
Mass (linear inertia)	m	I	Moment of inertia
Newton's second law	$F = ma$	$\tau = I\alpha$	Newton's second law
Work	Fd	$\tau\theta$	Work
Kinetic energy	$\frac{1}{2}mv^2$	$\frac{1}{2}I\omega^2$	Kinetic energy
Power	Fv	$\tau\omega$	Power

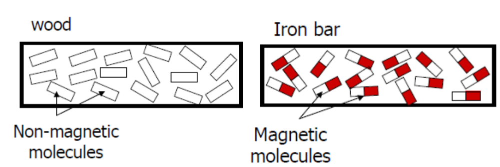


Magnetic Field Basics



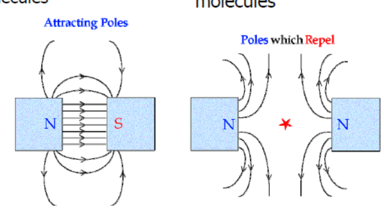
Magnetic Materials

- Points in the direction of geometric north and south pole when suspended freely and attracts iron fillings.
- Magnets do not come in separate charges, any magnetic/magnetized object has a North and South pole
- If you break a magnet in half, each piece will have a North and a South end



Classification :

- Natural Magnets: magnetite or iron oxide ($Fe2O3$).
- Temporary magnets (ferromagnetic): iron, steel, cobalt, nickel and some of their alloys.
- Non-magnetic materials: water, wood, air, quartz

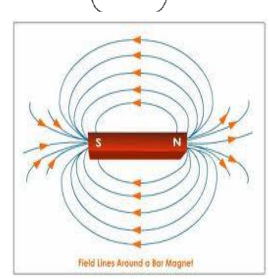


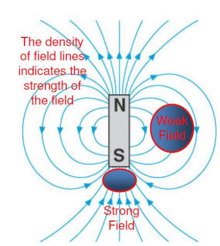
Magnetic lines of force:

Closed 3 D path radiating from north pole, passes through the surrounding, terminates at south pole and is from south to north pole within the body of the magnet.

Properties:

- Each line forms a closed loop and never intersect each other.
- Strong near the magnet and weakens at points away from the magnet.





Magnetic Field

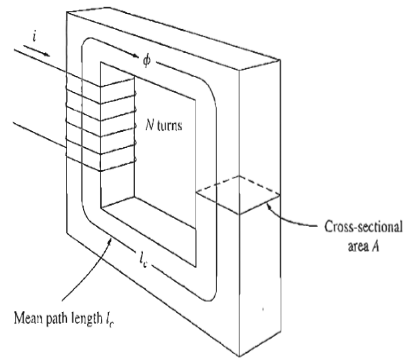
Four basic principles describe how magnetic fields are used in these devices:

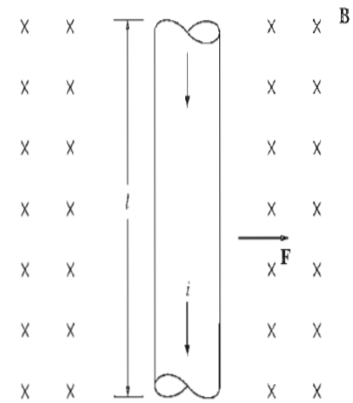
1. A current-carrying wire produces a magnetic field in the area around it.(Ampere's law)

2. A time-changing magnetic field induces a voltage in a coil of wire if it passes through that coil. (This is the basis of *transformer action.)*

3. A current-carrying wire in the presence of a magnetic field has a force induced on it. (This is the basis of *motor action.)*

4. A moving wire in the presence of a magnetic field has a voltage induced in it. (This is the basis of *generator action.)*





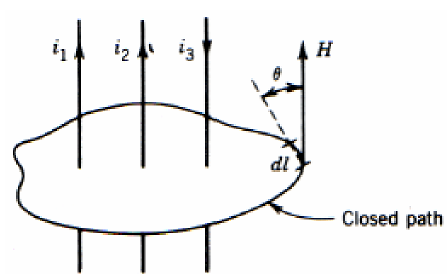
Ampere's Law

- The relationship between current and magnetic field intensity can be obtained by using Ampere's Law.
- Ampere's Law states that the line integral of the magnetic field intensity, H around a closed path is equal to the total current linked by the contour.

$$\oint H.dl = \sum i$$

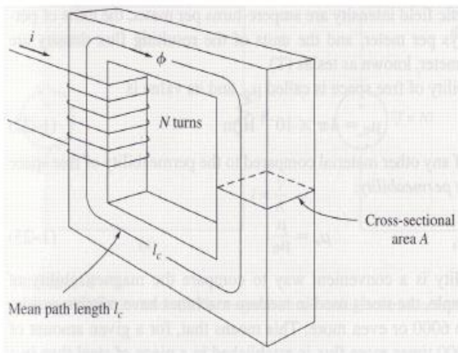
  - H: the magnetic field intensity at a point on the contour
  - dl: the incremental length at that point
- If : the angle between vectors H and dl then:

$$\oint Hdl\cos\theta = \sum i$$



Ampere's Law

Consider a rectangular core with N winding



$$\sum i = Ni$$

$$dl = l_c$$

$$\therefore Hl_c = Ni$$

Therefore

$$H = \frac{Ni}{l_c}$$

H - magnetic field intensity

Assumption:

- All fluxes are confined to the core
- The fluxes are uniformly distributed in the core

The flux outside the toroid (called leakage flux), is so small (can be neglected)

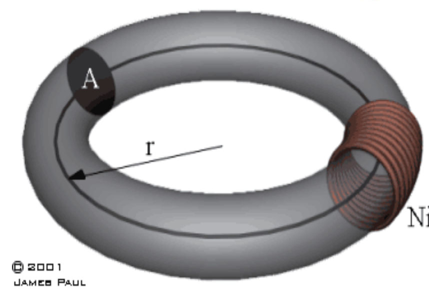
Use Ampere's Law,

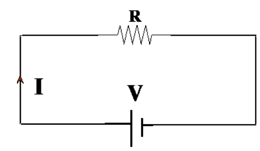
$$\oint H.dl = Ni$$

$$Hl = Ni \qquad Hl = Ni = F$$

$$H.2\pi r = Ni$$

F = Magnetomotive force (mmf)





Magnetic Circuit

Magnetic Field Strength (H)

- The magneto motive force per meter length of the magnetic circuit
- $H = (N\,I) / lc$
- Unit : *AT / meter*

Analogy: Electric field strength

Magnetic Flux Density (B):

- No. of magnetic lines of force created in a magnetic circuit per unit area normal to the direction of flux lines
- $B = \Phi/A$
- Unit : *Weber/m^2 (Tesla)*

Analogy: Current Density

Magnetic Circuit

Permeability (μ)

- A property of a magnetic material which indicates the ability of magnetic circuit to carry magnetic flux.
- $\mu = B / H$
- Unit: ***Henry / meter***
- Permeability of free space or air or non magnetic material $\mu_0 = 4 * \Pi * 10^{-7}$ *Henry/m*
- Relative permeability, $\mu_r : \mu/\mu_0$

$$\Re = \frac{l_c}{\mu A}$$

Analogy: Conductivity

Magnetic Circuit

Magneto Motive Force, MMF (*F*)

- Force which drives the magnetic lines of force through a magnetic circuit
- *MMF,* $F = \Phi \Re$, where 'Φ' is the magnetic flux and '$\Re$' is the Reluctance of the magnetic path.
- Also, For Electromagnets:

  MMF= *N I* (No. of turns*Current),

  where N is the number of turns of the coil and I is the current flowing in the coil
- Unit: *AT* (Ampere Turns)

Analogy: EMF, $V=IR$

Magnetic flux (Φ):

- Number of magnetic lines of force created in a magnetic circuit.
- Unit : *Weber (Wb)*

Analogy: Electric Current, I

Reluctance ($\Re$):

- Opposition of a magnetic circuit to the setting up of magnetic flux in it.
- Unit : *AT / Wb*

Analogy: Resistance, R

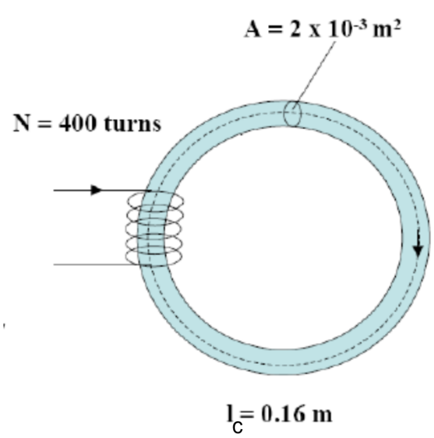
Analogy with Electric circuits

Similarities:			
Electric circuit		**Magnetic circuit**	
Quantity	**Unit**	**Quantity**	**Unit**
EMF (E=IR)	**Volt (V)**	**MMF (F=ϕℜ)**	**Ampere-turns**
Current (I)	**Ampere (A)**	**Flux (ϕ)**	**Weber (Wb)**
Current density (J)	**A/ m^2**	**Flux density (B)**	**Wb / m^2** or **Tesla**
Resistance (R)	**Ohm (Ω)**	**Reluctance (ℜ)**	**Ampere-turns/Wb**
Electric field strength (E)	**Volts/m**	**Magnetic field strength (H)**	**Ampere-turns/m**
Conductivity (σ) σ=l/RA	**Siemen/m**	**Permeability, μ μ=lc/ℜA**	**Henry/m**

In electrical circuit current actually flows but in magnetic circuit flux is created, and it is not a flow.

Example 1

- Find the value of *I* needed to develop a magnetic flux of 4 x 10^{-4} Wb
- The permeability of the material is 1.818 x 10^{-3} Wb/Am



$$B = \frac{\Phi}{A} = \frac{4\times10^{-4}}{2\times10^{-3}} = 0.2\ T$$

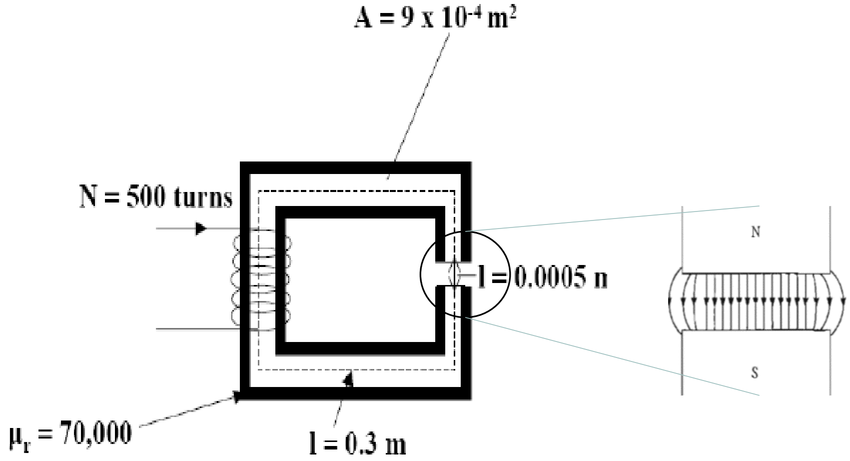
$$H = \frac{B}{\mu} = \frac{0.2}{1.818\times10^{-3}} = 110\ At/m$$

$$\mathbf{F} = NI = Hl_c$$

$$I = \frac{Hl_c}{N} = \frac{110\times0.16}{400} = 44\ mA$$

Example 2

- Find the flux if the flux density is 1.0 T
- The current in the coil
- The magnetic field strength in the air gap and in the magnetic core (μ_r = 70,000)

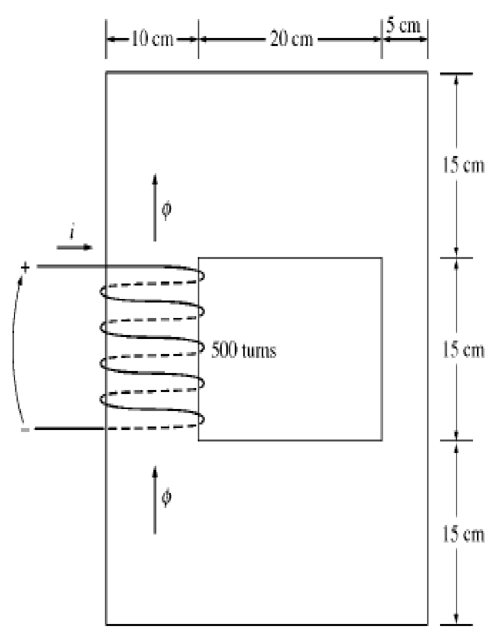


The fringing effect of a magnetic field at an air gap. Note the increased cross-sectional area of the air gap compared with the cross-sectional area of the metal.

Example 3

A ferromagnetic core shown in the figure. The depth of the core is 5 cm. The other dimensions of the core are as shown in the figure. Find the value of the current that will produce a flux of 0.003 Wb.

- With this current, what is the flux density at the top of the core? What is the flux density at the right side of the core? Assume that the relative permeability of the core is 1000.



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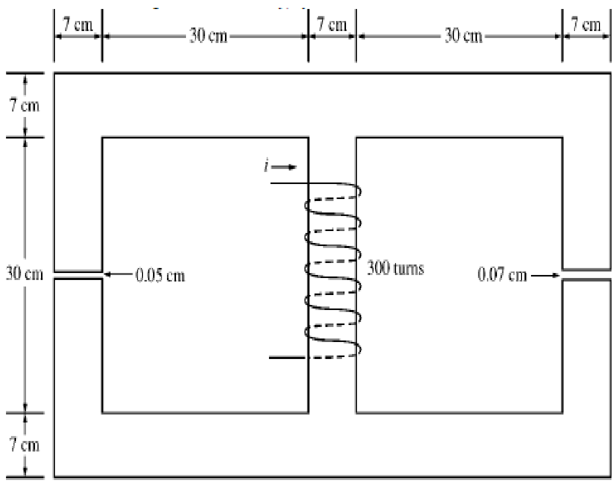
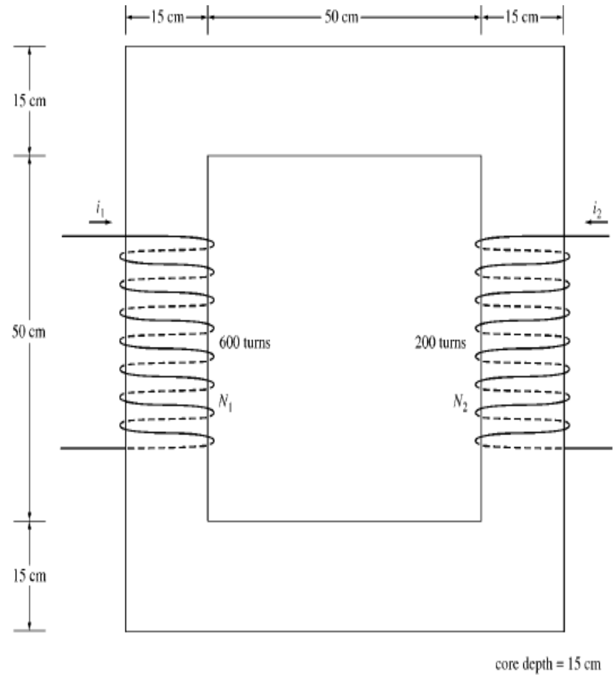
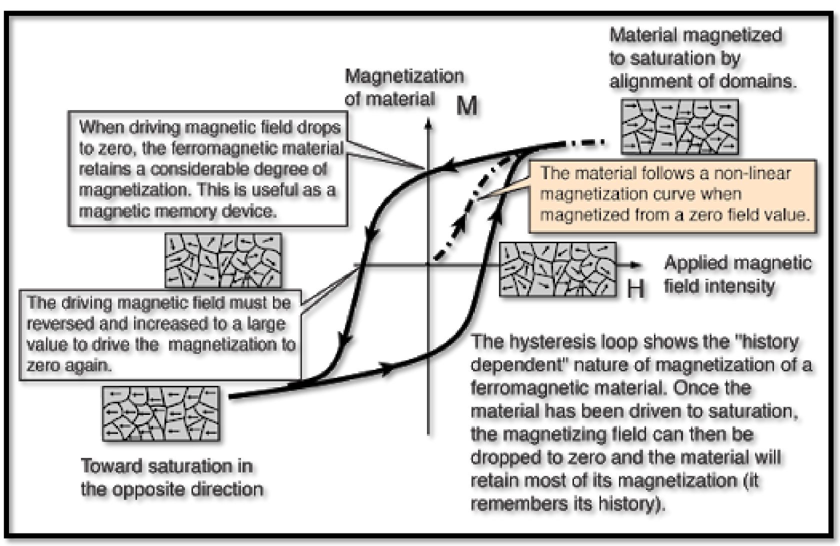
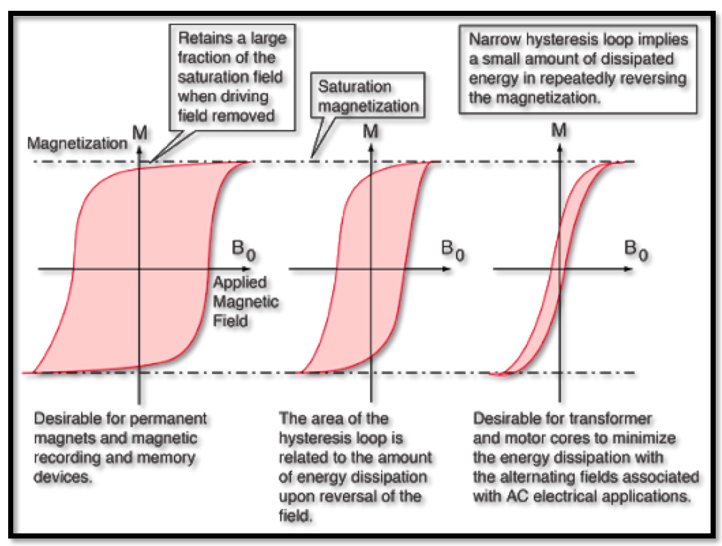




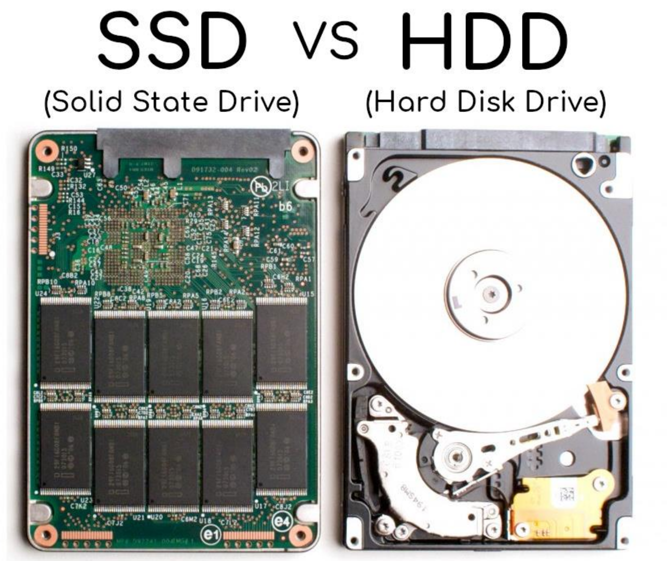
Hysteresis

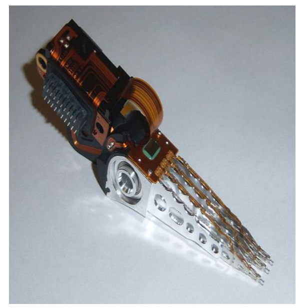




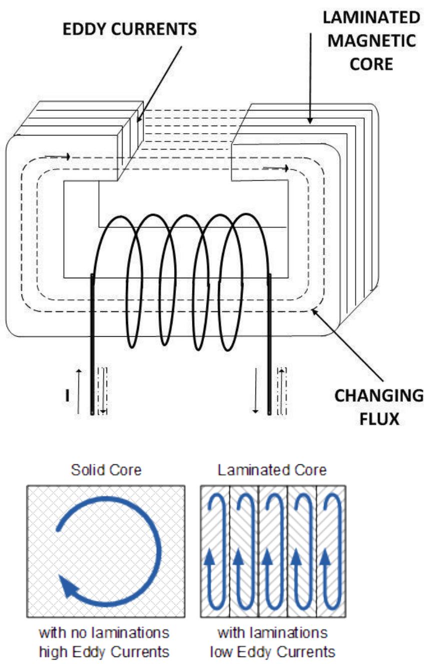
Retentivity: It is defined as the degree to which a magnetic material gains its magnetism after magnetizing force (H) is reduced to zero, it is also called the residual flux in the core.

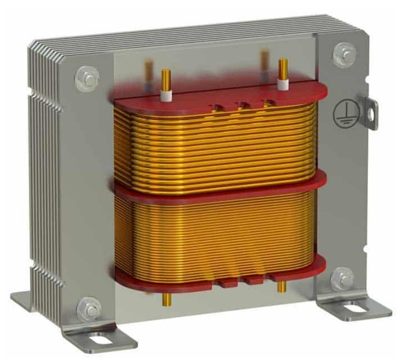
Hard Disk





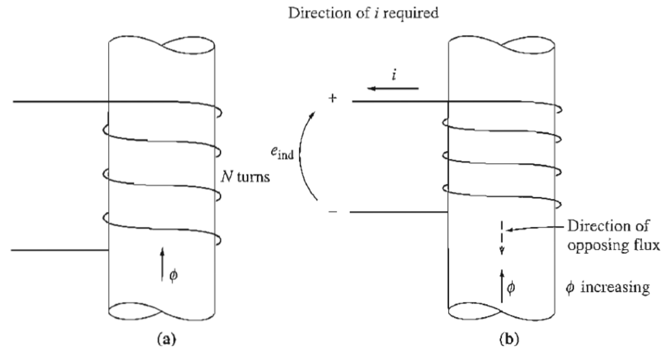
Eddy Current





Faraday's Law

- Any change in the magnetic environment of a coil of wire will cause a voltage (emf) to be "induced" in the coil. No matter how the change is produced, the voltage will be generated. The change could be produced by changing the magnetic field strength, moving a magnet toward or away from the coil, moving the coil into or out of the magnetic field, rotating the coil relative to the magnet, etc.
- Lenz's law states that the polarity of the induced voltage is such that the voltage would produce a current that opposes the change in flux linkages responsible for inducing that emf.

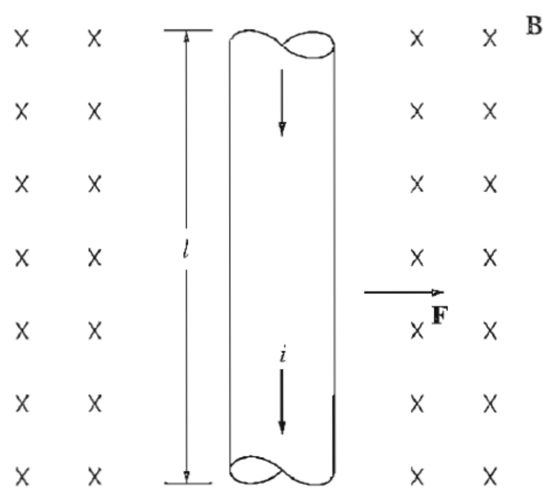


$$Emf = -N\frac{\Delta\phi}{\Delta t}$$

Where N= number of turns
ϕ = magnetic flux
The minus sign denotes Lenz's Law.

Motor Action

One of the major effects of a magnetic field on its surroundings is that it induces a force on a current-carrying wire within the field. The figure shows a conductor present in a uniform magnetic field of flux density **B,** pointing into the page. The conductor itself is *l* meters long and contains a current of *i* amperes. The force induced on the conductor *is* given by



$$\mathbf{F} = i\,(\mathbf{l} \times \mathbf{B})$$

where

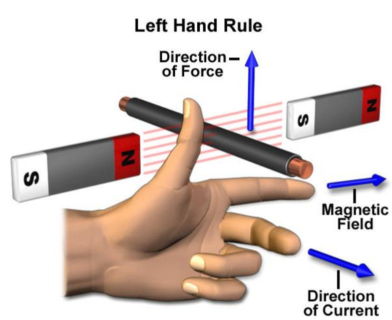
i = magnitude of current in wire

l = length of wire, with direction of l defined to be in the direction of current flow

B = magnetic flux density vector

The direction of the force is given by the left-hand rule:

- All fingers the magnetic effect (Flux-**B**)
- Thumb for the mechanical effect (Force-**F**)
- Outside hand palm for electrical effect (current-**i**)



The magnitude of the force is given by the equation

$$F = ilB \sin\theta$$

where θ is the angle between the wire and the flux density vector.

Generator Effect

One of major way in which a magnetic field interacts with its surroundings. If a wire with the proper orientation moves through a magnetic field, a voltage is induced in it. The voltage induced in the wire is given by

$$e_{ind} = (\mathbf{v} \times \mathbf{B}) \bullet \mathbf{l}$$

where

v = velocity of the wire

B = magnetic flux density vector

l = length of conductor in the magnetic field

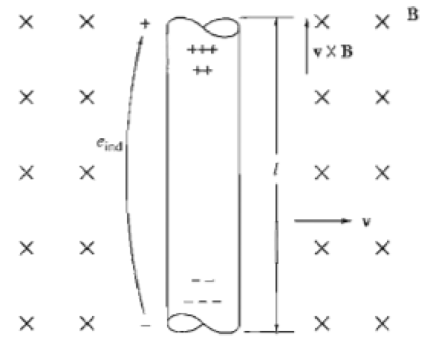
The direction of the force is given by the right-hand rule:

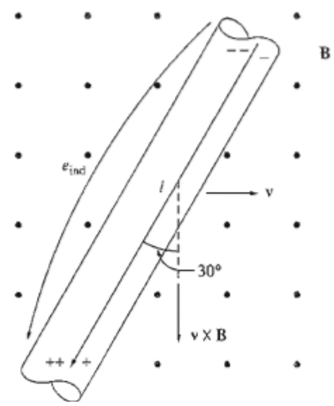
- All fingers the magnetic effect (Flux B)
- Thumb for the mechanical effect (velocity v)
- Outside hand palm for electrical effect (e_{ind})

The magnitude of the force is given by the equation

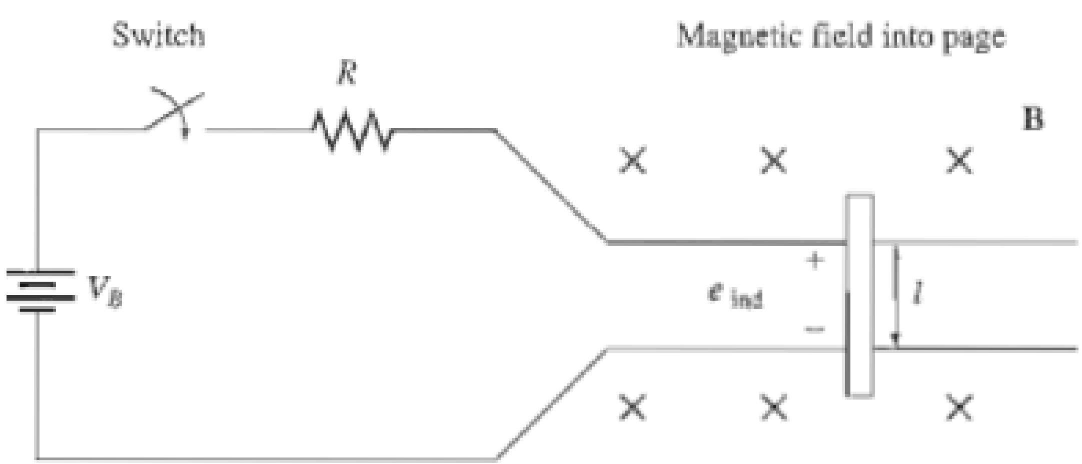
$$e_{ind} = \mathbf{vBl}\cos\theta$$

where θ is the angle between the ($\mathbf{v} \times \mathbf{B}$) result and the flux density vector.





The Linear DC Machine



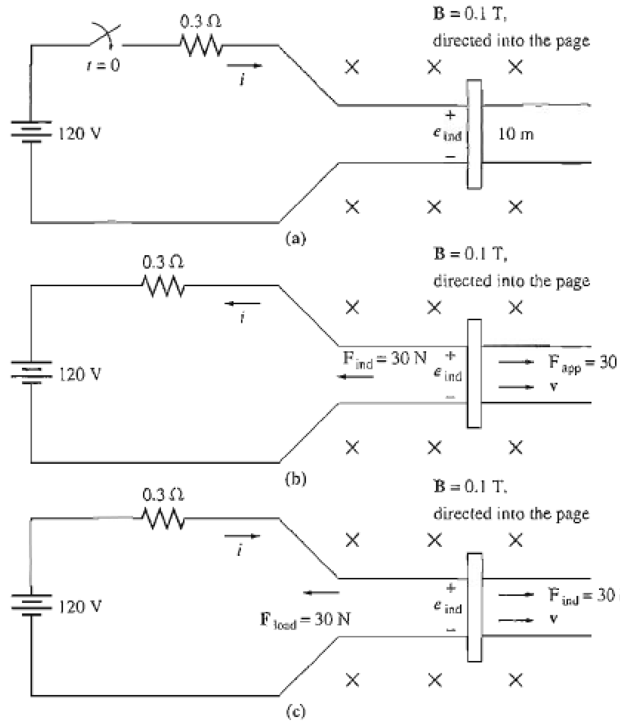
Example 4

The linear dc machine shown in the Figure has a battery voltage of 120 V, an internal resistance of 0.3 Ω, and a magnetic flux density of *0.1* T.

(a) What is this machine's maximum starting current? What is its steady-state velocity at no load?

(b) Suppose that a 30-N force pointing to the right were applied to the bar. What would the steady-state speed be? How much power would the bar be producing or consuming? How much power would the battery be producing or consuming? Is this machine acting as a motor or as a generator?

(c) Now suppose a 30-N force pointing to the left were applied to the bar. What would the new steady-state speed be? Is this machine a motor or a generator now?



Transformers

Chapter 2

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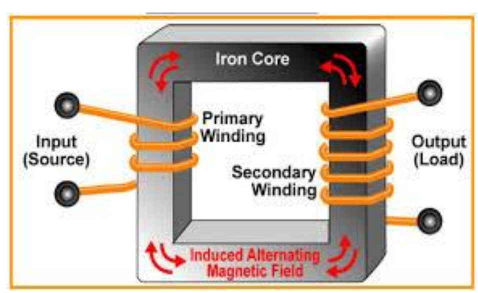
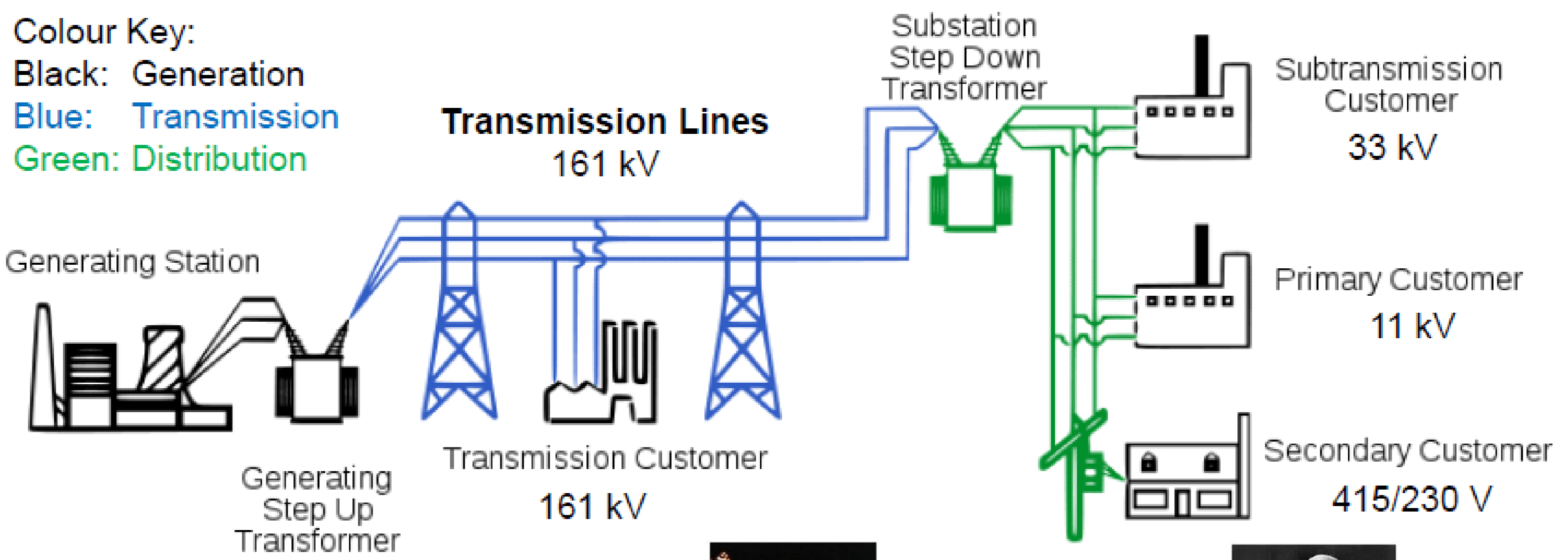
Introduction

- A *transformer* is a device that changes ac electric power at one frequency and voltage level to ac electric power at the same frequency and another voltage level through the action of a magnetic field. **It** consists of two or more coils of wire wrapped around a common ferromagnetic core. These coils are (usually) not directly connected. The only connection between the coils is the common magnetic flux present within the core.



- One of the transformer windings is connected to a source of ac electric power, and the second transformer winding supplies electric power to loads. The transformer winding connected to the power source is called the *primary winding* or *input winding,* and the winding connected to the loads is called the *secondary winding* or *output winding.*

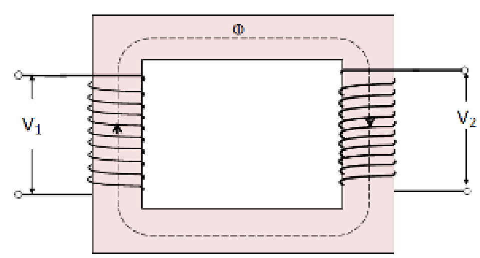
Why Transformers Are Important To Modern Life

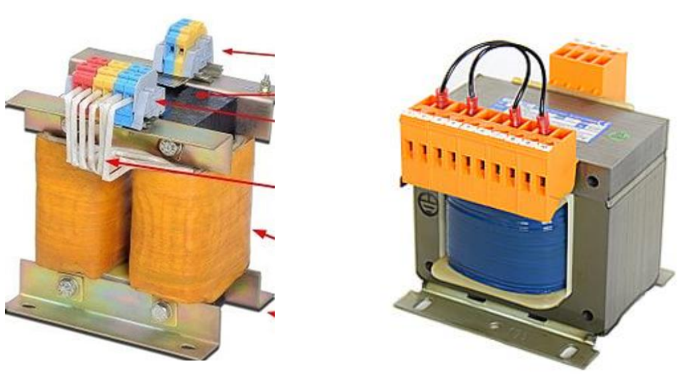


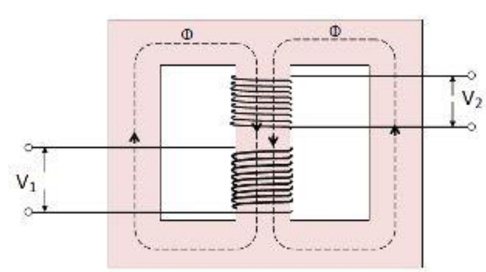
Power Transformer Types

Power transformers are constructed on one of two types of cores:

- **Core types transformer**: Simple rectangular laminated piece of steel with the transformer windings wrapped around two sides of the rectangle.
- **Shell type transformer**: three legged laminated core with the windings wrapped around the centre leg.







The Ideal Transformer

- The relationship between voltage and the number of turns.

$$\frac{v_p(t)}{v_s(t)} = \frac{N_p}{N_s} = a$$

where a is defined to be the turns ratio of the transformer.

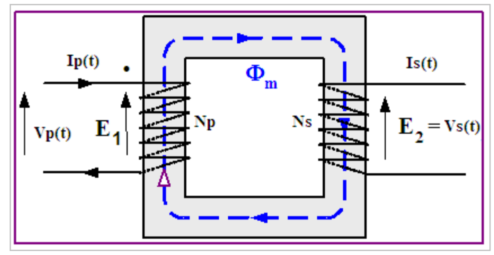
- The relationship between current into the primary side, $I_p(t)$, of transformer versus the secondary side, $I_s(t)$, of the transformer;

$$N_p I_p(t) = N_s I_s(t) \qquad \frac{I_p(t)}{I_s(t)} = \frac{1}{a}$$

- In term of phasor quantities;

$$\frac{V_p}{V_s} = a \qquad \frac{I_p}{I_s} = \frac{1}{a}$$

- **Note that Vp and Vs are in the same phase angle. Ip and Is are in the same phase angle too.**
- **the turn ratio, a, of the ideal transformer affects the magnitude only but not the their angle.**

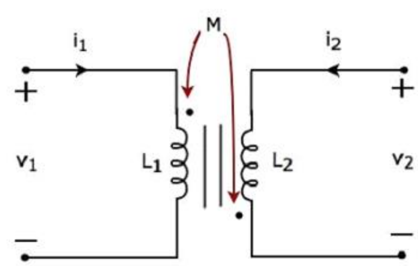


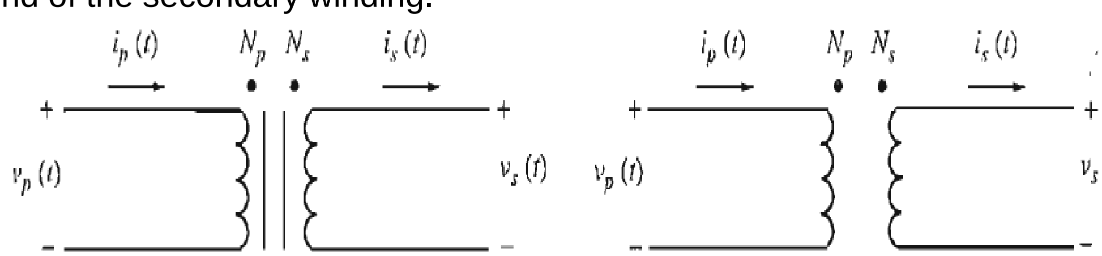
Np , number of turns of wire on its primary side.
Ns , number of turns of wire on its secondary side.
Vp(t), voltage applied to the primary side.
Vs(t), voltage applied to the secondary side.

Dot Convention For Transformers

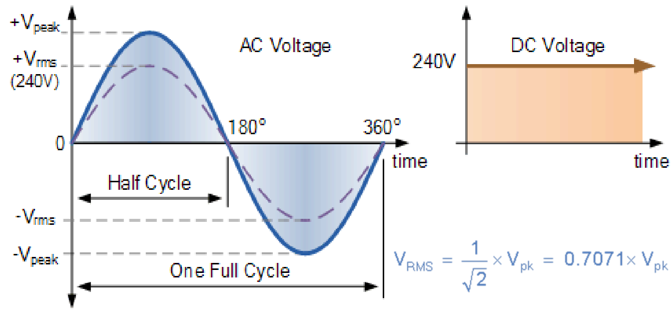
The dot convention appearing at one end of each winding tell the polarity of the voltage and current on the secondary side of the transformer.

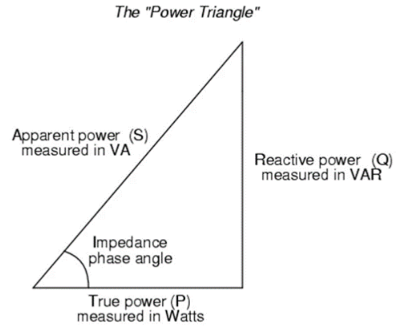
1. If the primary voltage is positive at the dotted end of the winding with respect to the un-dotted end, then the secondary voltage will be positive at the dotted end also. Voltage polarities are the same with respect to the doted on each side of the core.
2. If the primary current of the transformer flow into the dotted end of the primary winding, the secondary current will flow out of the dotted end of the secondary winding.





Real, Reactive, and Apparent Power





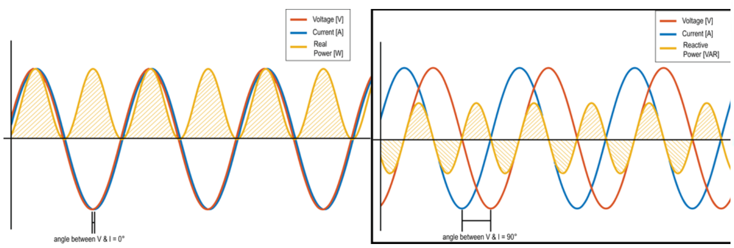
$$\text{Complex Power} = \mathbf{S} = P + jQ = \mathbf{V}_{\text{rms}}(\mathbf{I}_{\text{rms}})^* = \mathbf{V}_{\text{rms}}\mathbf{I}_{\text{rms}}\angle\theta_v - \theta_i$$

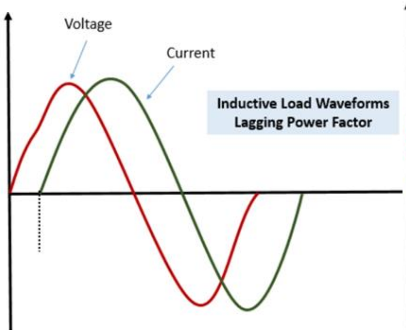
$$\text{Apparent Power} = S = |\mathbf{S}| = \mathbf{V}_{\text{rms}}\mathbf{I}_{\text{rms}} = \sqrt{P^2 + Q^2}$$

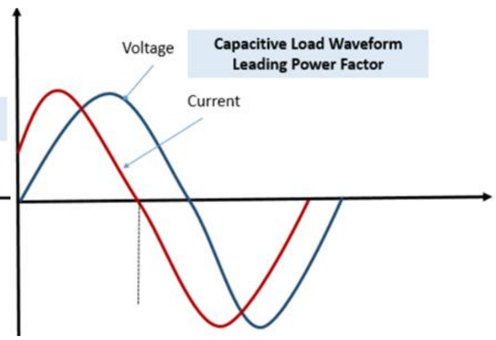
$$\text{Real Power} = P = \text{Re}(\mathbf{S}) = S\cos(\theta_v - \theta_i)$$

$$\text{Reactive Power} = Q = \text{Im}(\mathbf{S}) = S\sin(\theta_v - \theta_i)$$

$$\text{Power Factor} = \frac{P}{S} = \cos(\theta_v - \theta_i)$$







Power in an Ideal Transformer

- Power supplied to the transformer by the primary circuit is given by:

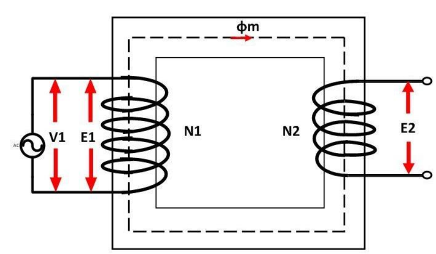
$$P_{in} = V_p I_p \cos\theta_p$$

where, θ_p is the angle between the primary voltage and the primary current.

- The power supplied by the transformer secondary circuit to its loads is given by the equation:

$$P_{out} = V_s I_s \cos\theta_s$$

where, θ_s is the angle between the secondary voltage and the secondary current.



$$P_{out} = \frac{V_p}{a}(aI_p)\cos\theta \Rightarrow P_{out} = V_p I_p \cos\theta = P_{in}$$

- The reactive power, Q, and the apparent power, S;

$$Q_{in} = V_p I_p \sin\theta = V_s I_s \sin\theta = Q_{out}$$

$$S_{in} = V_p I_p = V_s I_s = S_{out}$$

Example 1

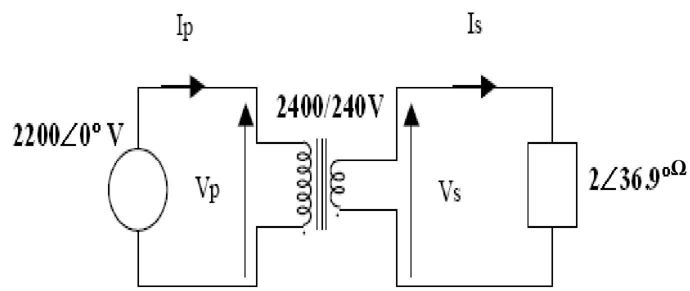
Consider an ideal, single-phase 2400V-240V transformer. The primary is connected to a 2200V source and the secondary is connected to an impedance of 2 W < 36.9^{o}, find,

a) The secondary output current and voltage.

b) The primary input current.

c) The load impedance as seen from the primary side.

d) The input and output apparent power.



Impedance Transformation through a Transformer

Impedance of the load:

$$Z_L = V_s/I_s$$

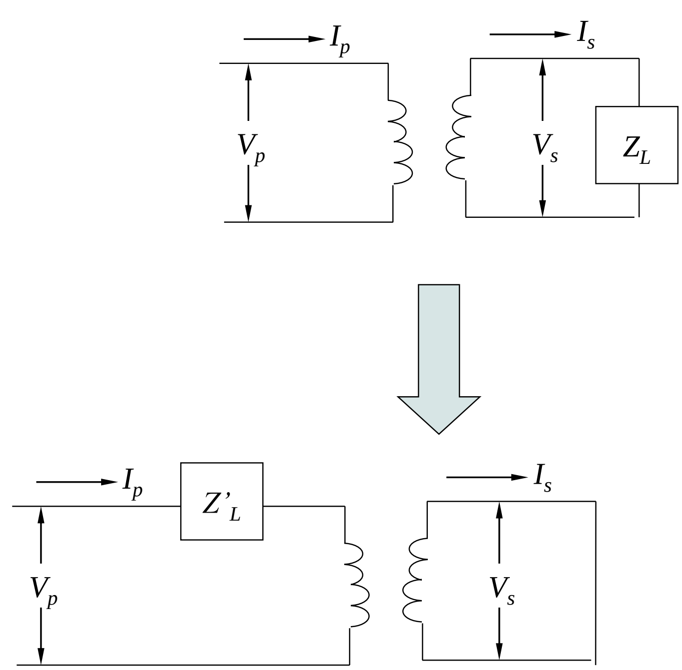
The impedance of the primary circuit:

$$Z'_L = V_p/I_p$$

$$= (aV_s)/(I_s/a)$$

$$= a^2 (V_s / I_s)$$

$$= a^2 Z_L$$



The Equivalent Circuit of a Real Transformer

The losses that occur in transformers have to be accounted for in any accurate model of transformer behaviour.

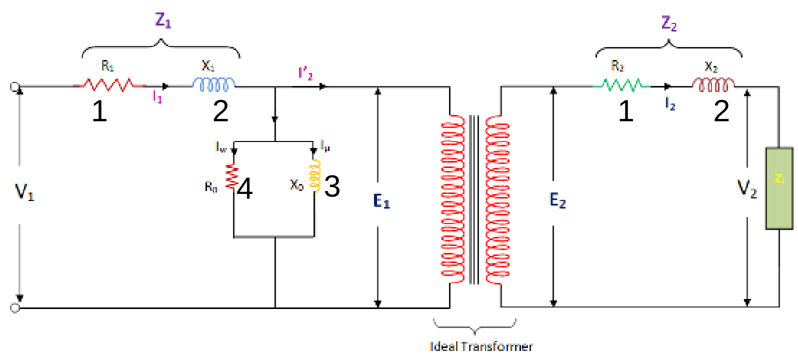
1. Copper (I^2R) losses. Copper losses are the resistive heating losses in the primary and secondary windings of the transformer. They are proportional to the square of the current in the windings.

2. Eddy current losses. Eddy current losses are resistive heating losses in the core of the transformer. They are proportional to the square of the voltage applied to the transformer.

3. Hysteresis losses. Hysteresis losses are associated with the rearrangement of the magnetic domains in the core during each half-cycle. They are a complex, nonlinear function of the voltage applied to the transformer.

4. Leakage flux. The fluxes which escape the core and pass through only one of the transformer windings are leakage fluxes. These escaped fluxes produce a self-inductance in the primary and secondary coils, and the effects of this inductance must be accounted for.

$$V_1 = I_1 \left[Z_1 + \frac{Z_m\,(Z'_m + Z'_L\,)}{Z_m + (Z'_2 + Z'_L\,)} \right]$$



Steps for Selecting the Proper Transformer

SINGLE PHASE LOADS

1. Determine electrical load

A. Voltage required by load.
B. Amperes or KVA capacity required by load.
C. Frequency in Hz (cycles per second).
D. Verify load is designed to operate on a single phase supply.

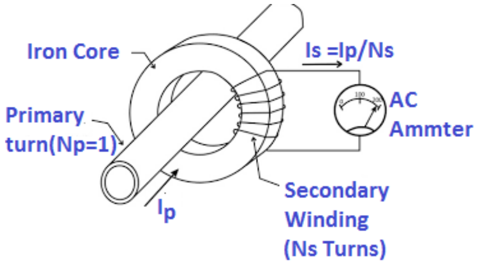
All of the above information is standard data normally obtained from equipment nameplates or instruction manuals.

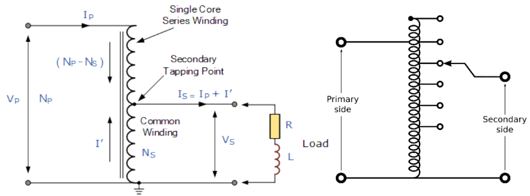
2. Determine supply voltage

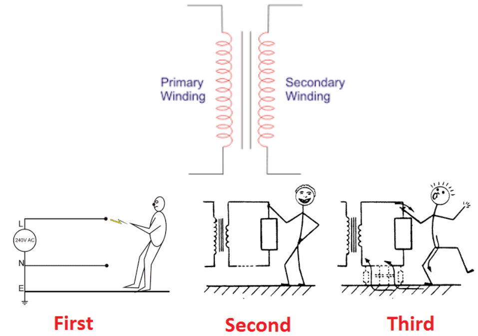
A. Voltage of supply (source).
B. Frequency in Hz (cycles per second).

The frequency of the line supply and electrical load must be the same. Select single phase transformer designed to operate at this frequency, having a primary (input) equal to the supply voltage and a secondary (output) equal to the voltage required by the load.

Other Transformers



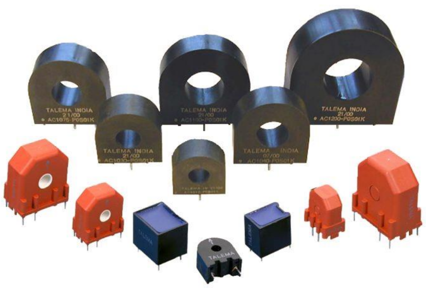




CURRENT TRANSFORMER

AUTOTRANSFORMER

ISOLATION TRANSFORMER

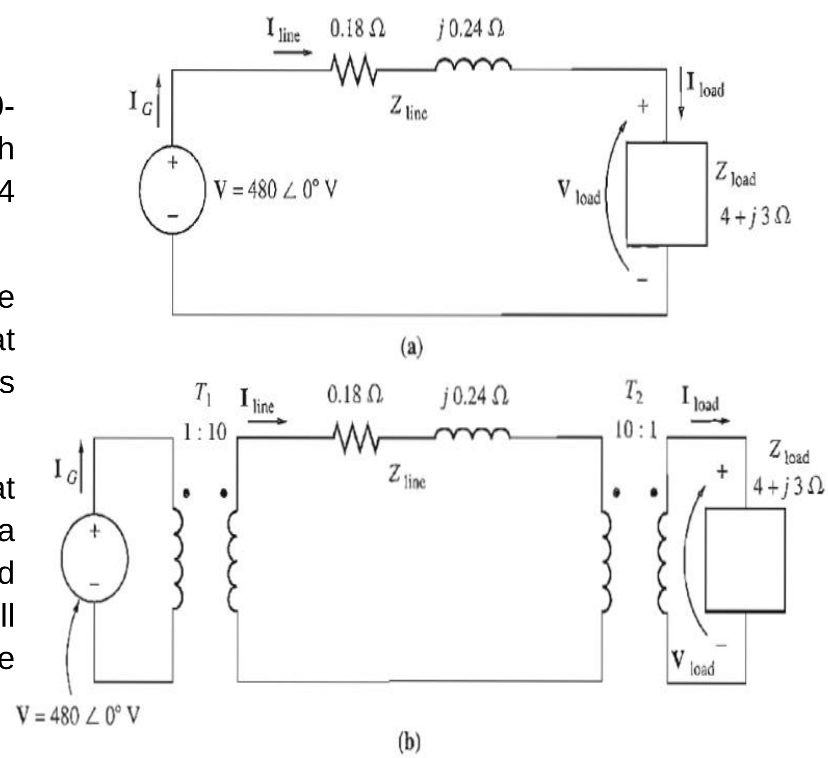


Example 2

A single-phase power system consists of a 480-V 60-Hz generator supplying a load Z_{load} = 4 + j3 Ω through a transmission line of impedance Z_{line} = 0.18 + j 0.24 Ω. Answer the following questions about this system.

a) If the power system is exactly as described above (and shown in Figure a), what will the voltage at the load be? What will the transmission line losses be?

b) Suppose a 1: 10 step-up transformer is placed at the generator end of the transmission line and a 10:1 step-down transformer is placed at the load end of the line (as shown in Figure b). What will the load voltage be now? What will the transmission line losses be now?



DC MACHINERY FUNDAMENTALS

Chapter 3

1

Table of Content

Introduction

- DC Motors are widely used in robotics because of their small size and high energy output.

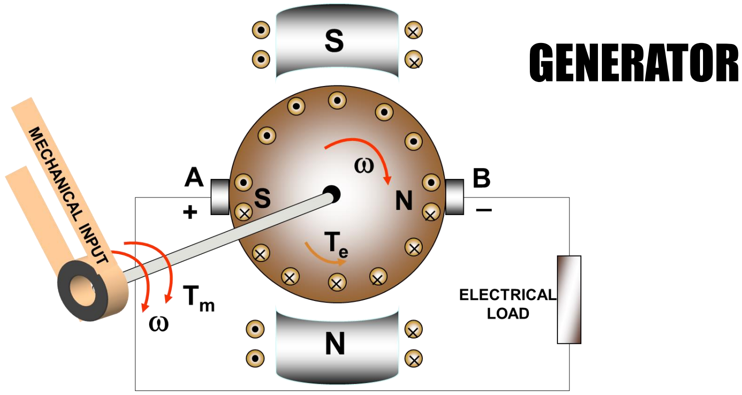
- Key characteristics of DC motors include:
  1. High Speed
  2. Low Torque
  3. Reversibility

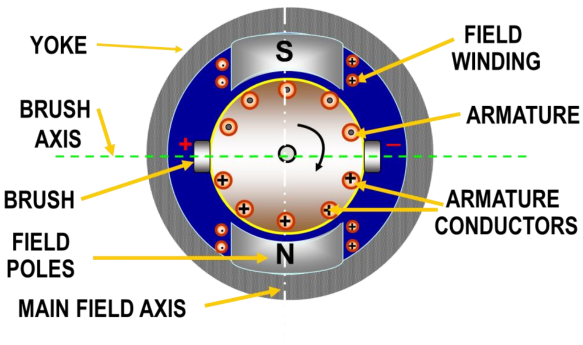
DC Motor Applications

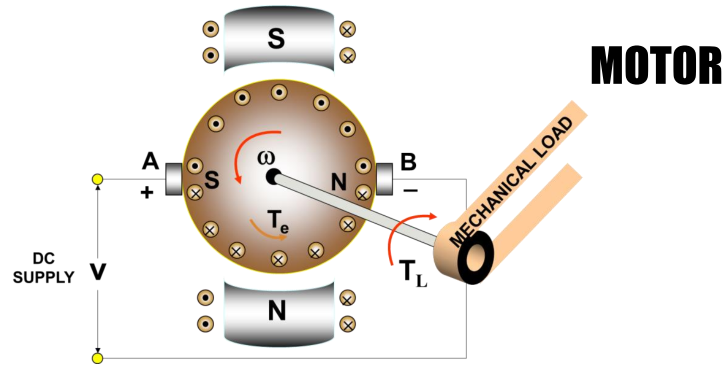
- Cordless hand drill
- Electric lawnmower
- Fans
- Toys
- Electric toothbrush
- Servo Motor
- Automobiles
  - Windshield Wipers
  - Door locks
  - Window lifts
  - Antenna retractor
  - Seat adjust
  - Mirror adjust
  - Anti-lock Braking System

DC MACHINES

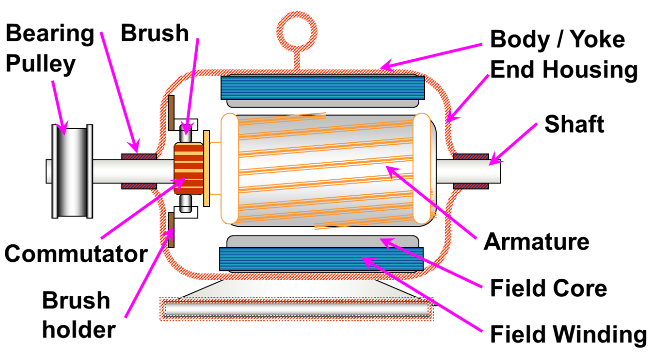
A DC machine is an electro-mechanical energy conversion device. It can convert Mechanical power into Electrical Power. When output electrical power is DC , it is called DC Generator. When it converts DC electrical power into mechanical power , it is known as DC Motor.

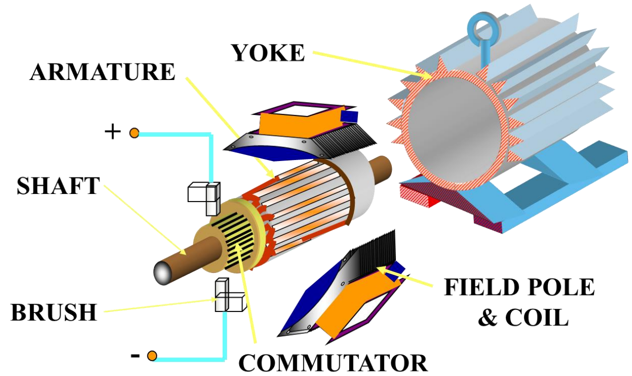


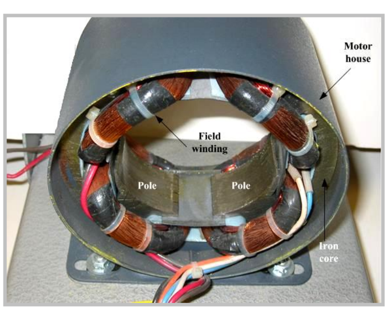


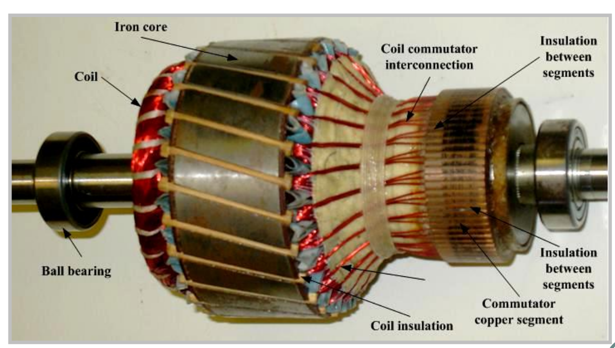


Construction of DC Machine



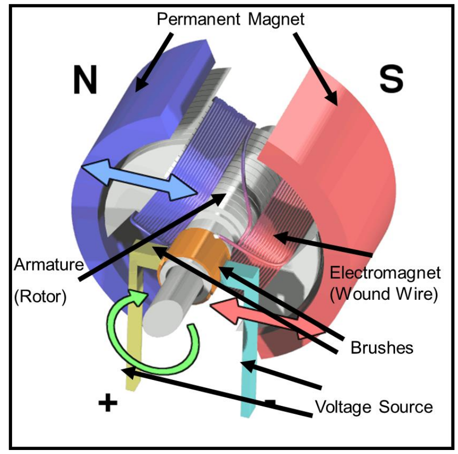


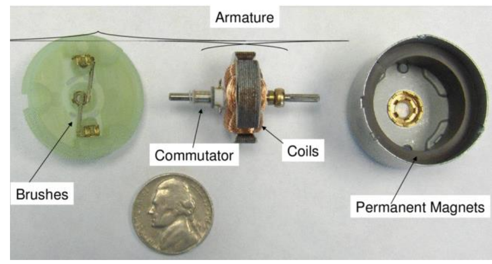




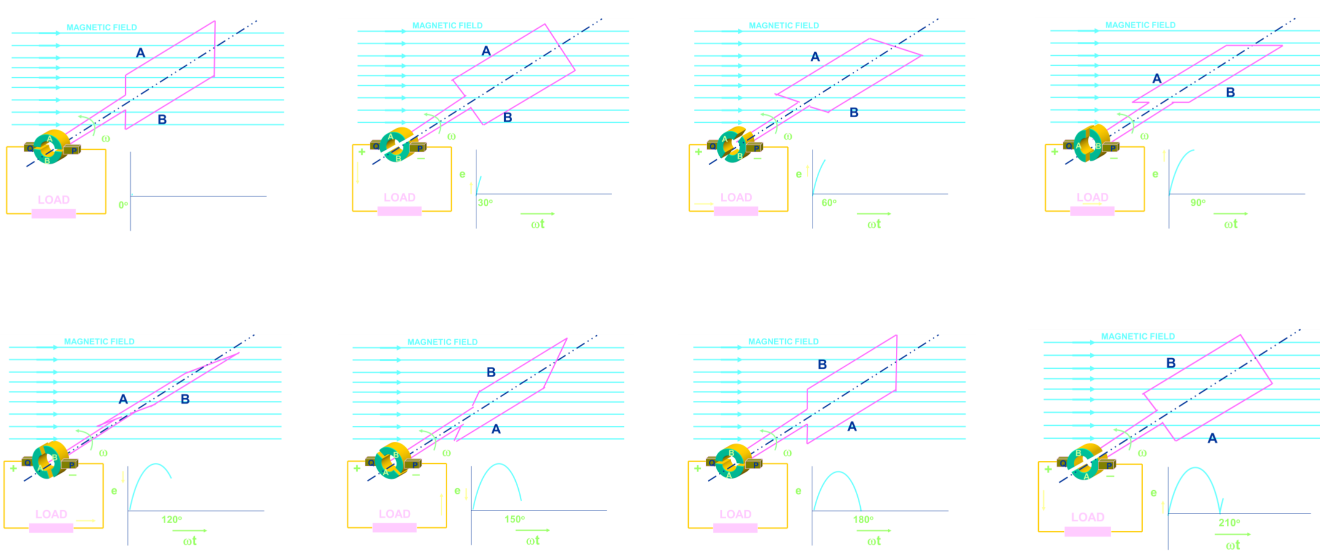
DC Motor - How it Works

- A DC Motor has 4 major components:
  - A permanent magnet that doesn’t move, called the stator.
  - An electromagnet (usually wound bare wire)
  - A frame on which the electromagnet is wound, called the armature
  - A set of brushes for transferring voltage to the armature
- If a loop of wire were placed within a magnetic field, and current were applied to it, a magnetic field would be induced in the loop and it would try to rotate until both magnetic fields lined up.
- As the loop of wire rotates, its connection with the brushes is broken, but because of momentum, the loop will continue to rotate until, after 180^0, the other sides of the loop are in contact with the brushes.
- As long as current is applied to the brushes, the loop of wire will continue to rotate again and again and the rotor will continue rotation.
- Direction of rotation depends upon the polarity of the applied voltage.
- To change the direction of a DC Motor, simply change the polarity of the applied voltage.



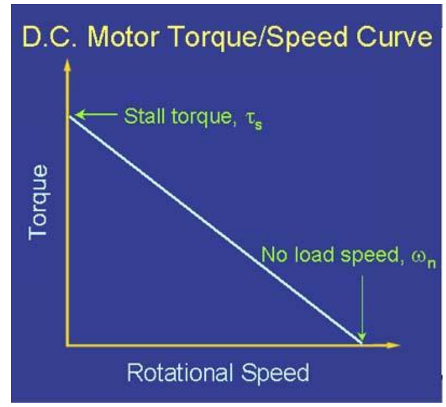


DC Motor - How it Works



Power, Torque and Speed

- The power of a DC Motor is proportional to the product of its torque and its speed.
- As the speed of the motor decreases, the torque increases proportionally until maximum torque is achieved. At this point, the motor is stalled, meaning that the motor is not turning even though power is being supplied to it. This is known, appropriately, as the "Stall Torque."
- The DC Motor has two "End States"- the Unloaded Speed (maximum speed, no torque) and Stalled Speed (zero speed, maximum torque).
- Current ratings of DC Motors are given at the stall torque, since this is the point of maximum current.
- Maximum power is achieved at a point between Stall and Unloaded Speed, where the speed and torque curves intersect.
- The speed of the DC Motor is directly proportional to the applied voltage. Increase the voltage for higher speeds and decrease the voltage for lower speeds



Important DC Machine Equations

EMF Equation

$$E = k_A \phi \omega = k'_A \phi n$$

$$n = \frac{60\omega}{2\pi}$$

E = EMF induced in armature (V)
k_A = geometry constant
ϕ= flux/pole (Wb)
ω = speed of rotation (rad/s)
n = speed of rotation of armature (rpm)

Power Equation

$$P = EI_A = T\omega$$

P=power (W) – not counting losses
E = EMF induced in armature (back EMF)
I_A = armature current (A)
T = torque of armature (N-m)
ω = speed of rotation (rad/s)
Note that $P_{in} = V_L I_L$ which will be higher than P because of loss in the field and armature windings as well as rotational (friction) losses.

Torque Equation

$$T = k_A \phi I_A$$

T = torque of armature (N-m)
k_A = geometry constant
ϕ= flux/pole (Wb)
I_A = armature current (A)

Geometry Constant

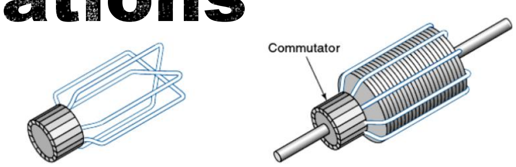
$$k_A = \frac{pN}{2\pi M}(rad/s), k'_A = \frac{pN}{60M}(rpm)$$

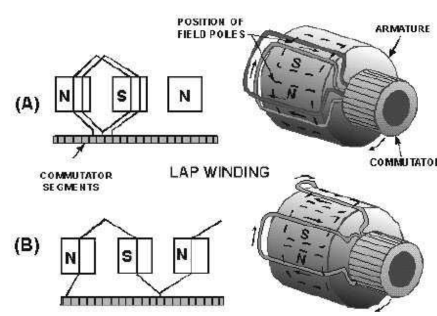
p = number of field poles
N = number of active conductors on armature
M = number of parallel paths in armature winding (=p for lap winding, =2 for wave winding)

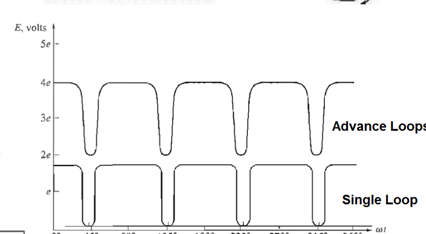
$$Z = 2CN_C$$

$$K = \frac{ZP}{2\pi a}$$

Z = number of conductors on rotor
C = number of coils on rotor
N_C = number of turns per coil



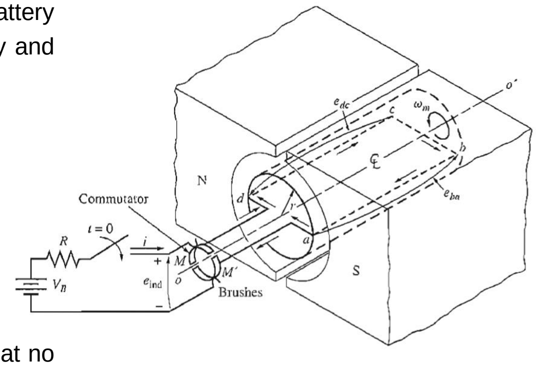


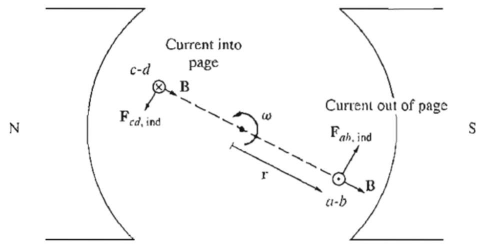


Example

The following figure shows a simple rotating loop between curved pole faces connected to a battery and a resistor through a switch. The resistor shown models the total resistance of the battery and the wire in the machine. The physical dimensions and characteristics of this machine are:

$$r = 0.5\ \text{m} \qquad l = 1.0\ \text{m}$$
$$R = 0.3\ \Omega \qquad B = 0.25\ \text{T}$$
$$V_B = 120\ \text{V}$$





(a) What happens when the switch is closed?

(b) What is the machine's maximum starling current? What is its steady-state angular velocity at no load?

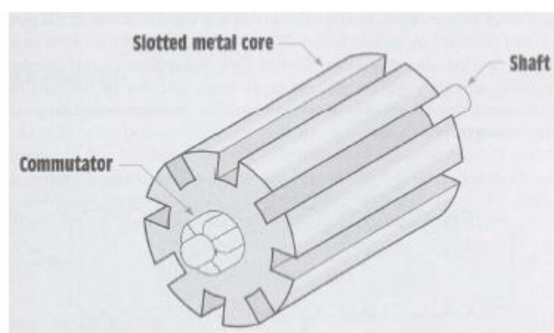
(c) Suppose a load is attached to the loop, and the resulting load torque is 10 N· m. What would the new steady-state speed be? How much power is supplied to the shaft of the machine? How much power is being supplied by the battery? Is this machine a motor or a generator?

(d) Suppose the machine is again unloaded, and a torque of 7.5 N • m is applied to the shaft in the direction of rotation. What is the new steady-state speed? Is this machine now a motor or a generator?

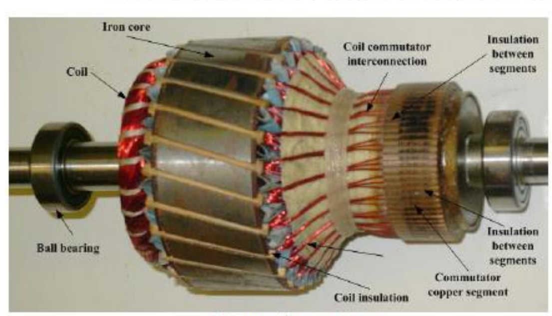
(e) Suppose the machine is running unloaded. What would the final steady-state speed of the rotor be if the flux density were reduced to 0.20 T?

Armature

- More loops of wire = higher rectified voltage
- In practical, loops are generally placed in slots of an iron core
- The iron acts as a magnetic conductor by providing a low-reluctance path for magnetic lines of flux to increase the inductance of the loops and provide a higher induced voltage.
- The commutator is connected to the slotted iron core.
- The entire assembly of iron core, commutator, and windings is called the armature.
- The windings of armatures are connected in different ways depending on the requirements of the machine.



Loops of wire are wound around slot in a metal core

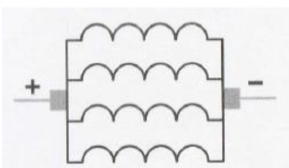


DC machine armature

Armature Windings

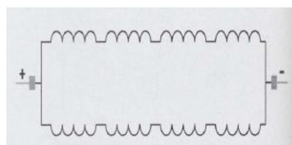
Lap Wound Armatures

- They are used in machines designed for low voltage and high current
- The windings are connected in parallel. This permits the current capacity of each winding to be added and provides a higher operating current
- They are used is in the starter motor of almost all automobiles



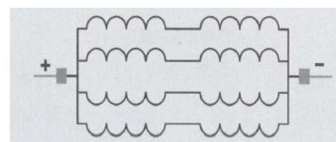
Wave Wound Armatures

- They are used in machines designed for high voltage and low current
- The windings connected in series. This permits the voltage of each winding added and provides a higher operating voltage
- They are used is in the small generator in hand-cranked megohmmeters



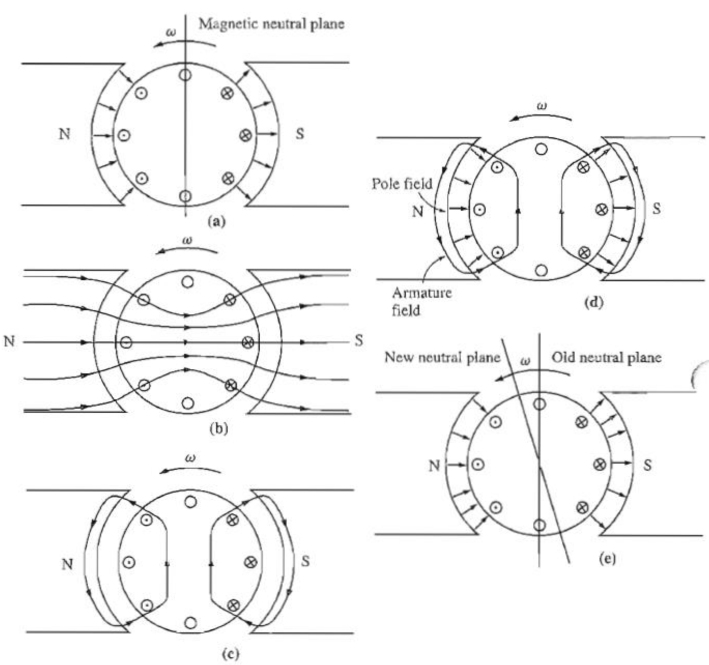
Frogleg Wound Armatures

- They are designed for use with moderate current and moderate armatures voltage and they most used in practical nowadays
- The windings are connected in series parallel.
- Most large DC machines use frogleg wound armatures.



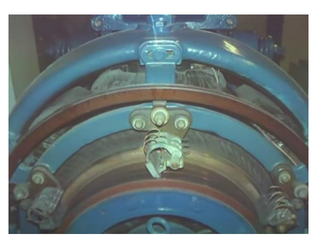
Frogleg wound armatures

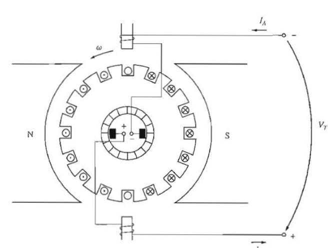
Armature Reaction

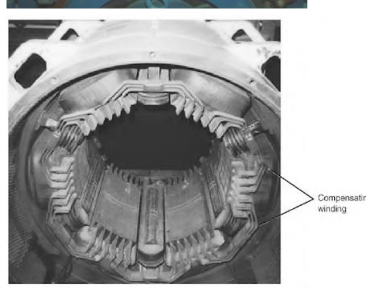


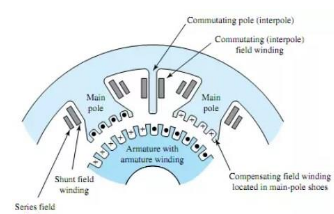
Solutions to the Problems with Commutation

1. Brush shifting
2. Commutating poles or interpoles
3. Compensating windings









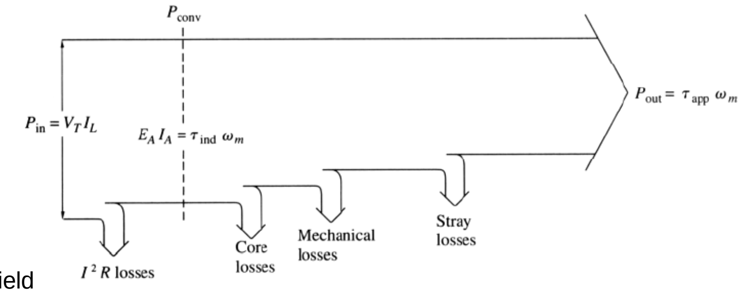
Section of a dc machine illustrating the arrangement of various field windings.

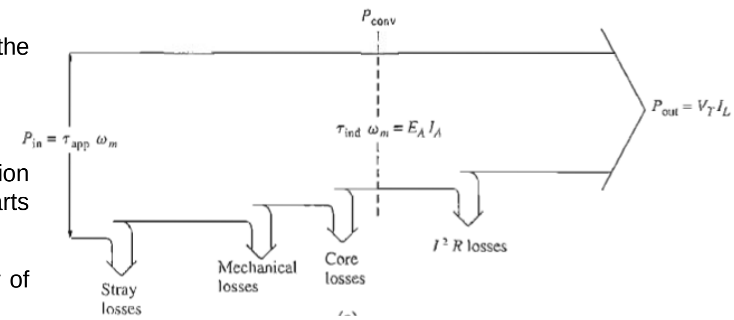
Power flow and losses in DC machines

The efficiency of a DC machine is:

$$\eta = \frac{P_{out}}{P_{in}} x100\%$$

$$\boxed{\eta = \frac{P_{in} - P_{loss}}{P_{in}} x100\%}$$





There are **five** categories of losses occurring in DC machines.

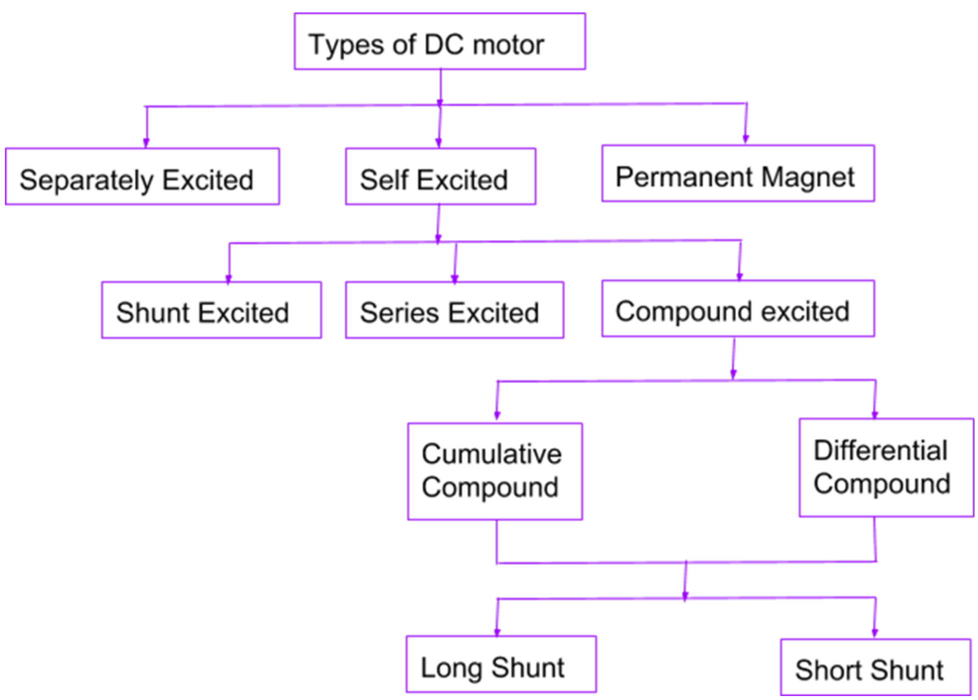
1. Electrical or copper losses – the resistive losses in the armature and field windings of the machine.
2. Brush (drop) losses – the power lost across the contact potential at the brushes of the machine.
3. Core losses – hysteresis losses and eddy current losses.
4. Mechanical losses – losses associated with mechanical effects: friction (friction of the bearings) and windage (friction between the moving parts of the machine and the air inside the casing).
5. Stray (Miscellaneous) losses – losses that cannot be classified in any of the previous categories.

DC Motors and Generators

Chapter 4

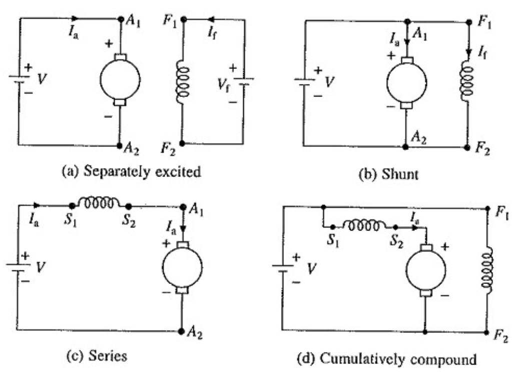
Table of Content

Introduction



DC Motor Types

- In a dc motor, the stator poles are supplied by dc excitation current, which produces a dc magnetic field.
- There are four major types of dc motor in general used;
  - (1) Separately Excited DC Motor.
  - (2) Shunt DC Motor.
  - (3) Series DC Motor.
  - (4) Compounded DC Motor.



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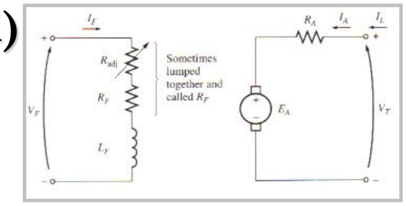

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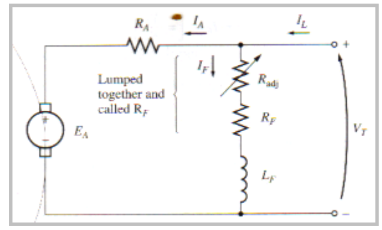

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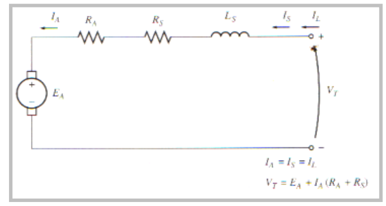

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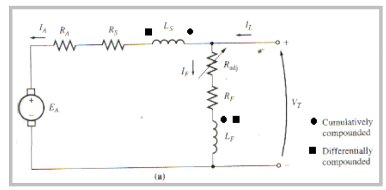
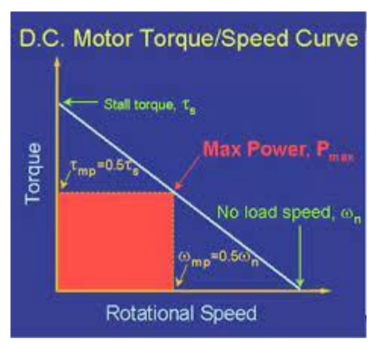


Speed Regulation (SR)

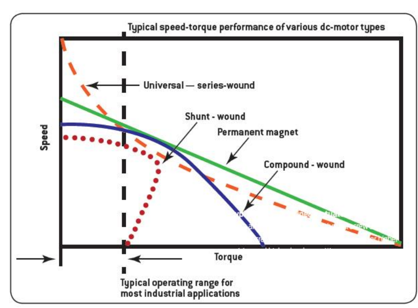
- DC motors are often compared by their speed regulation (SR) which is defined as;

$$SR = \frac{\omega_{nl} - \omega_{fl}}{\omega_{fl}} \times 100\%$$

- SR is the measure of the shape of the motor's torque-speed characteristic.
  - (a) Positive SR means that the motor's speed drops with increasing load.
  - (b) Negative SR means that the motor's speed increasing with increasing load.
  - (c) The magnitude of the SR tells approximately how steep the slope of the torque-speed curve is

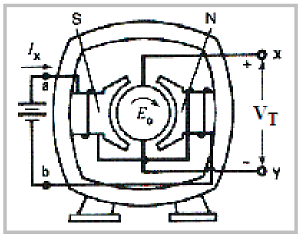


- On application of load the speed of a DC motor decreases gradually. This is not at all desirable. So the difference between no load and full load speed should be very less.
- The motor capable of maintaining a nearly constant speed for varying load is said to have good speed regulation i.e the difference between no load and full load speed is quite less.
- The speed regulation of a permanent magnet DC motor is good ranging from 10 – 15% whereas for DC shunt motor it is somewhat less than 10 %. DC series motor has poor value of regulation. In case of compound DC motor for DC cumulative compound the speed regulation is around 25 % while differential compound has its excellent value of 5 %



Separately Excited and Shunt DC Motors

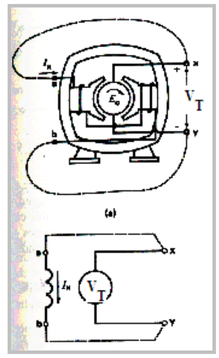
- The armature circuit is represented by the E_A and R_A.
- The field coil is represented by the L_F and R_F.



$$I_F = \frac{V_F}{R_F}$$

$$V_T = E_A + I_A R_A$$

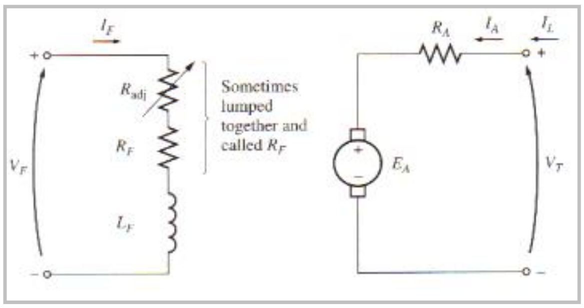
$$I_L = I_A$$

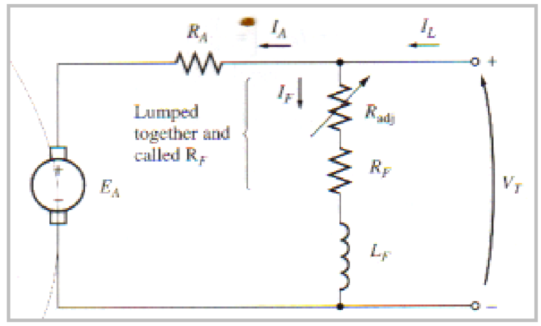


$$I_F = \frac{V_T}{R_F}$$

$$V_T = E_A + I_A R_A$$

$$I_L = I_A + I_F$$





Speed Torque Characteristics

- The internal generated voltage, E_A.

$$V_T = E_A + I_A R_A \qquad E_A = K\phi\omega$$

- Solving for the above equation yields; ω,

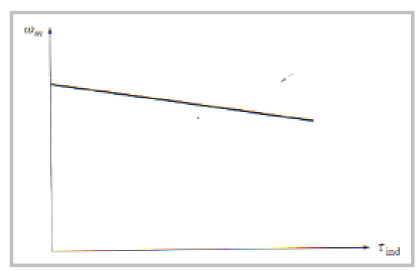
$$\omega = \frac{V_T - I_A R_A}{K\phi}$$

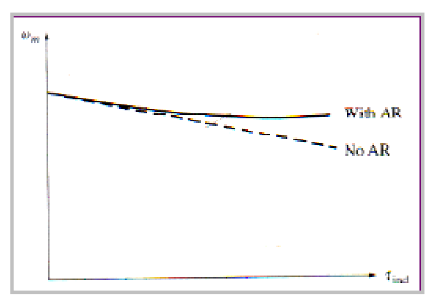
- The loss of field excitation results in over speeding for a shunt motor. Thus, care should be taken to prevent the field circuit from getting open.
- The armature current may be expressed as follows:

$$I_A = \frac{\tau_{ind}}{K\phi}$$

- The speed–torque equation of a DC shunt motor.

$$\omega_m = \frac{V_T}{K\phi} - \frac{R_A}{(K\phi)^2}\tau_{ind}$$

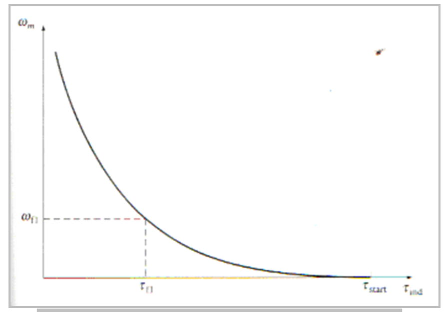




The actual machine, as the ***load increases***, the ***flux is reduced*** because of armature reaction. Since the denominator terms decrease.

Series DC Motor

- The induced or developed torque is given by: $\tau_{ind} = K\Phi I_A$
- The flux in this motor is directly proportional to its armature current. Therefore, the flux in the motor can be given by $\Phi = cI_A$
- where c is a constant of proportionality. The induced torque in this machine is thus given by $\tau_{ind} = K\Phi I_A = KcI_A^{\,2}$
- This equation shows that a series motor give more torque per ampere than any other dc motor, therefore it is used in applications requiring very high torque, example starter motors in cars, elevator motors.
- One disadvantage of series motor can be seen immediately from this equation. When the torque on this motor goes to zero, its speed goes to infinity. If no other load is connected to the motor, it can turn fast enough to seriously damage itself.
- However, if no other load is connected to the motor, it can turn fast enough to seriously damage itself.



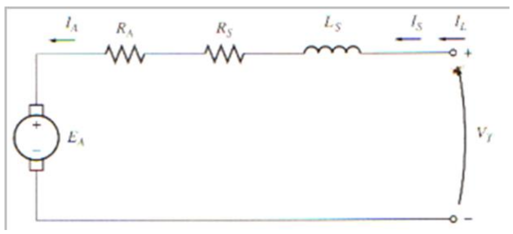
$$V_T = E_A + I_A(R_A + R_S)$$

$$I_A = \sqrt{\frac{\tau_{ind}}{Kc}} \qquad \tau_{ind} = \frac{K}{c}\Phi^2 \qquad \Phi = \sqrt{\frac{c}{K}}\sqrt{\tau_{ind}}$$

$$V_T = K\Phi\omega + \sqrt{\frac{\tau_{ind}}{Kc}}(R_A + R_S)$$

$$V_T = K\sqrt{\frac{c}{K}}\sqrt{\tau_{ind}}\,\omega + \sqrt{\frac{\tau_{ind}}{Kc}}(R_A + R_S)$$

$$\omega = \frac{V_T}{\sqrt{Kc}}\frac{1}{\sqrt{\tau_{ind}}} - \frac{R_A + R_S}{Kc}$$



Compound DC Motor

- The shunt field is always stronger than the series field in a cumulative compound motor the mmf of the two fields add in a differential compound motor the series field is connected so the mmf opposes the mmf of the shunt field

$$F_{net} = F_F \pm F_{SE} - F_{AR}$$

- Where,

  F_F = magnetmotive force (shunt field)

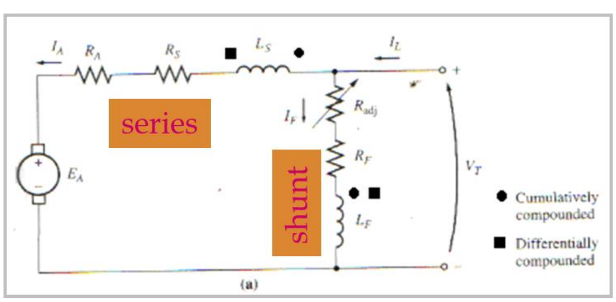
  F_{SE} = magnetomotive force (series field)

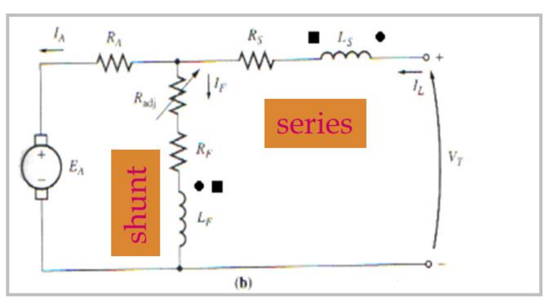
  F_{AR} = magnetomotive force (armature reaction)

- The positive (+) sign is for cumulatively compound motor
- The negative (-) sign is for differentially compound motor

$$V_T = E_A + I_A(R_A + R_S)$$

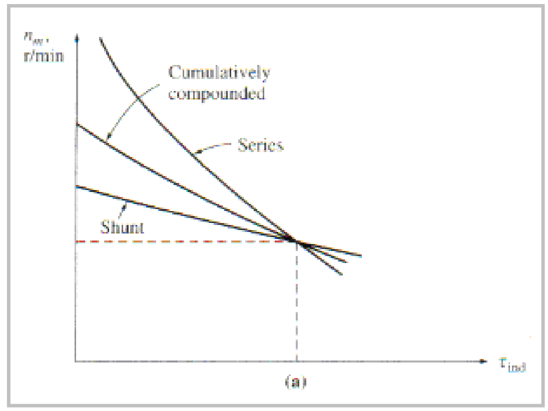
$$I_A = I_L - I_F \qquad I_F = \frac{V_T}{R_F}$$





Torque Speed Characteristic

- The cumulatively compounded motor has a higher starting torque than a shunt motor (whose flux is constant) but a lower starting torque than a series motor (whose entire flux is proportional to armature current).
- It combines the best features of both the shunt and the series motors.
- Like a series motor, it has extra torque for starting; like a shunt motor, it does not over speed at no load.
- At light loads, the series field has a very small effect, so the motor behaves approximately as a shunt dc motor.
- As the load gets very large, the series flux becomes quite important and the torque speed curve begins to look like a series motor's characteristic.



Example 1

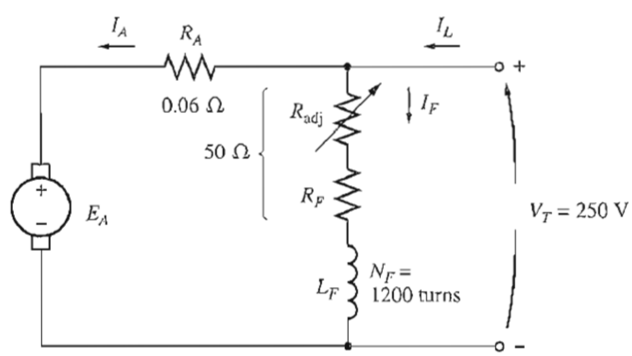
A 50-hp, *250-V,* 1200 *r/min* de shunt motor with compensating windings has an armature resistance (including the brushes, compensating windings, and interpoles) of 0.06 Ω. Its field circuit has a total resistance $R_{adj} + R_F$ of 50 Ω, which produces a *no-load* speed of 1200 *r/min.* There are 1200 turns per pole on the shunt field winding

(a) Find the speed of this motor when its input current is 100 A.

(b) Find the speed of this motor when its input current is 200 A.

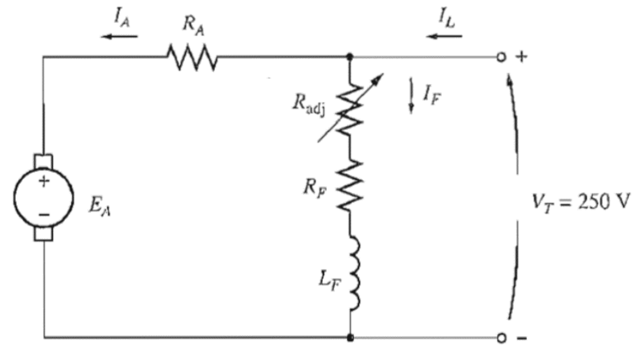
(c) Find the speed of this motor when its input current is 300 A.

(d) Plot the torque-speed characteristic of this motor.



Example 2

A 50-hp, 250-V, 1200 r/min shunt dc motor has a rated armature current of 170 A and a rated field current of 5 A. When its rotor is blocked, an armature voltage of 10.2V (exclusive of brushes) produces 170 A of current flow, and a field voltage of 250 V produces a field current flow of 5 A. The brush voltage drop is assumed to be 2 V. At no load with the terminal voltage equal to 240 V, the armature current is equal to 13.2 A, the field current is 4.8 A, and the motor 's speed is 1150 r/min.***(Assume stray losses are 1 percent of input power)***



(a) How much power is output from this motor at rated conditions?

(b) What is the motor's efficiency?

DC Generators

- DC generators are dc machines used as generator.
- There are five major types of dc generators, classified according to the manner in which their field flux is produced:

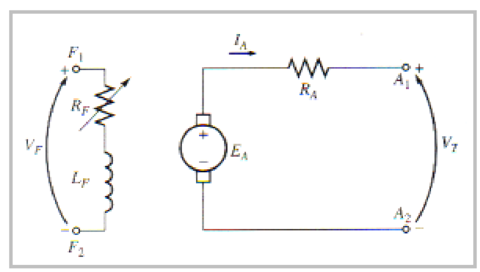
(1) Separately Excited Generator: In separately excited generator, the field flux is derived from a separately power source independent of the generator itself.

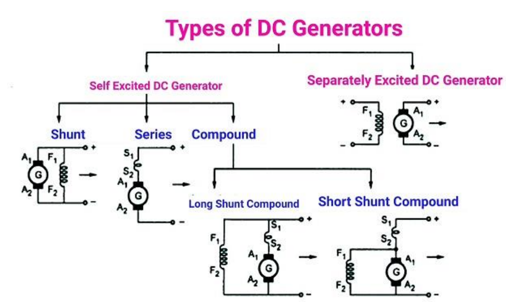
(2) Shunt Generator: In a shunt generator, the field flux is derived by connecting the field circuit directly across the terminals of the generators.

(3) Series Generator: in a series generator, the filed flux is produced by connecting the filed circuit in series with the armature of the generator.

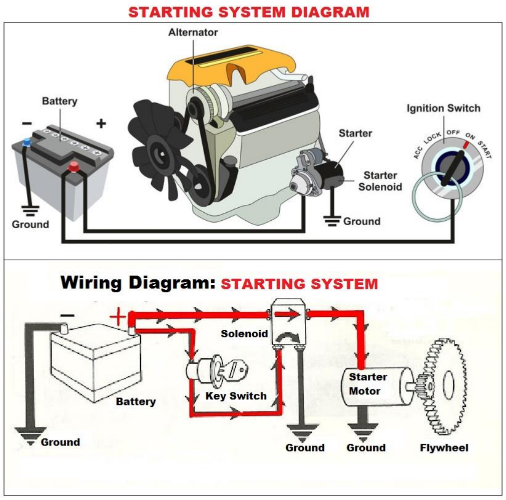
(4) Cumulatively Compounded Generator: In a cumulatively compounded generator, both a shunt and series field is present, and their effects are additive.

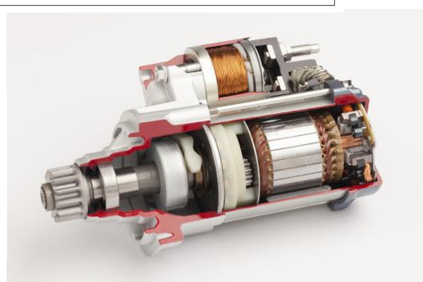
(5) Differentially Compounded Generator: In differentially compounded generator: In a differentially compounded generator, both a shunt and a series field are present, but their effects are subtractive.

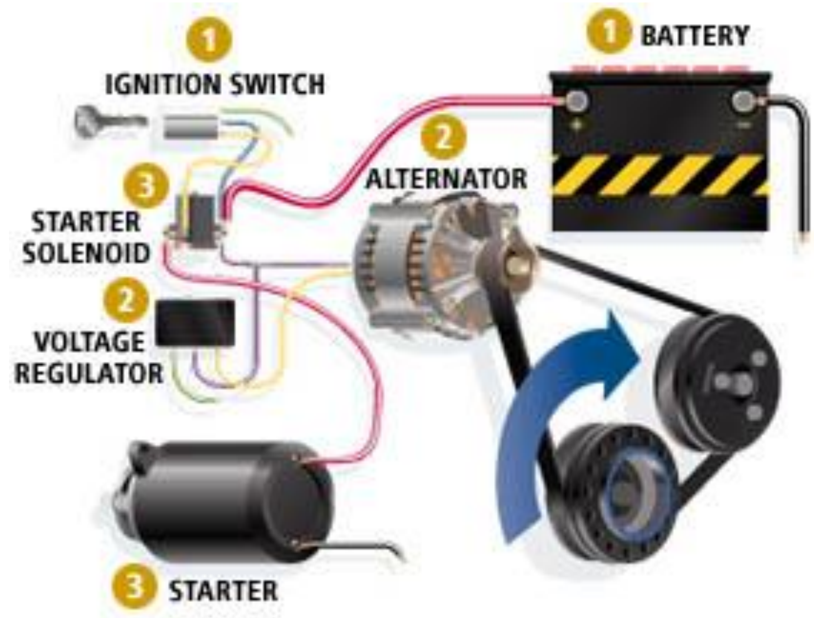




Motors and Generator in Cars

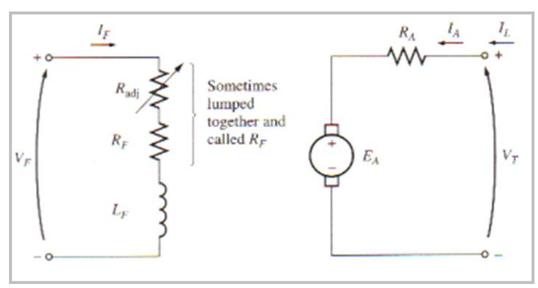






Brushed DC Motor Type Comparison

Characteristic	Permanent Magnet	Shunt	Series	Compound
COST	Low	Moderate	Moderate	High
Loss of Magnetism	Worst	None	None	None
Torque vs. Speed	Good at low speed Less at high speed	Good, consistent at low speed.	Great at low speed	Best at low speed
Safety (Motor Runaway)	No chance	High chance	High chance	Low chance
Speed Control	Excellent	Excellent	Poor	Great



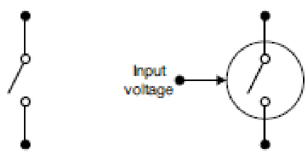
Speed control methods for dc motors are simpler and less expensive than those for ac motors. The speed of a dc motor can be changed by using the following methods:

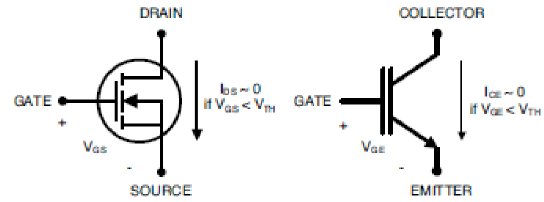
(a) Field control method

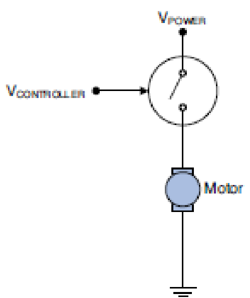
(b) Armature resistance control method

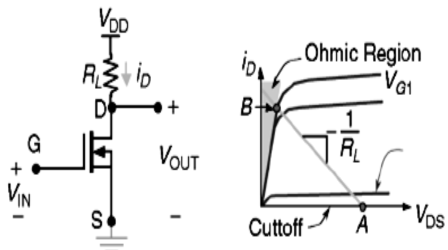
(c) Armature voltage control method

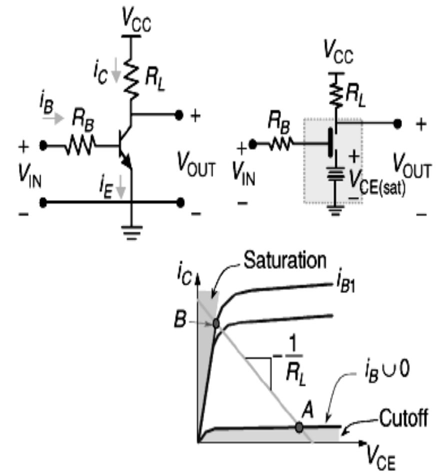
Switching Circuitry









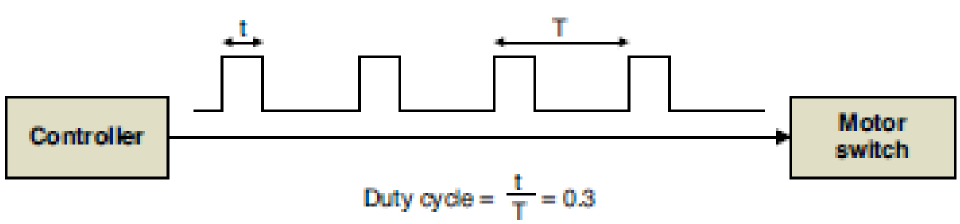


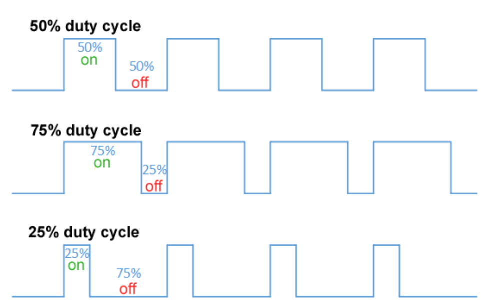
Pulse Width Modulation (PWM)

With an electrical switch, the controller can turn a motor's current fully on or fully off. But what if you want the motor to rotate at 75% of its full speed? What if you want the motor's speed to ramp up gradually?

Instead, controllers govern the motor's behaviour by delivering pulses that open and close the switch for precise amounts of time. This pulse delivery is referred to as pulse width modulation, or PWM.

Pulse Width Modulation is used when the amount of power delivered to the DC Motor is to be reduced without decreasing the input voltage.





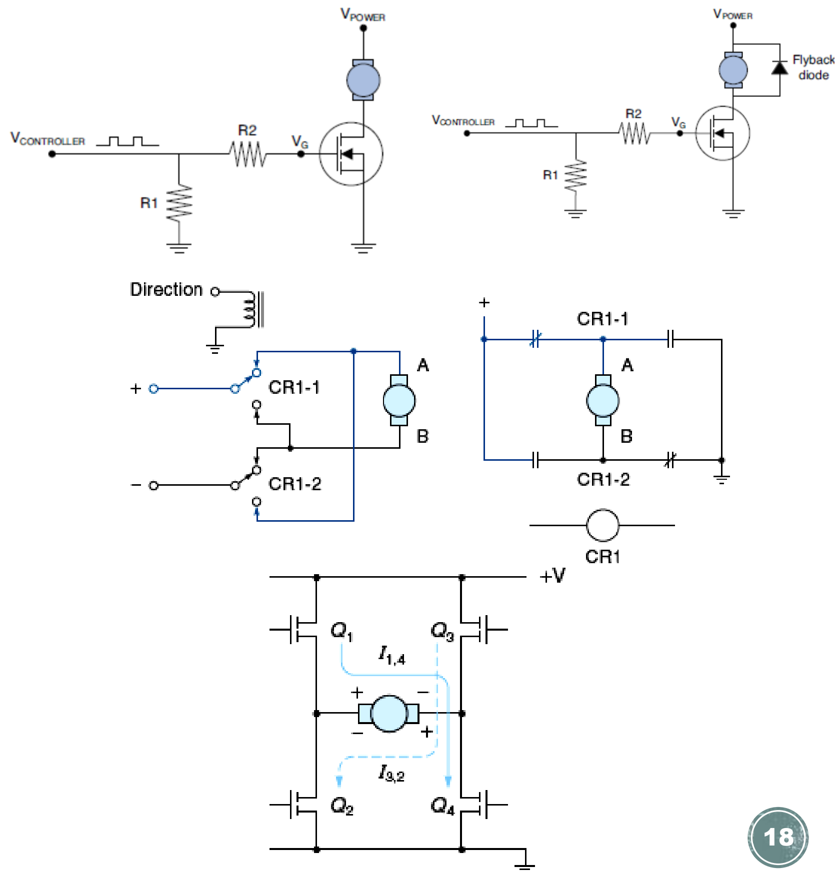
Control Circuitry

Controlling a brushed motor is straightforward because the motor's operation is so easy to understand.

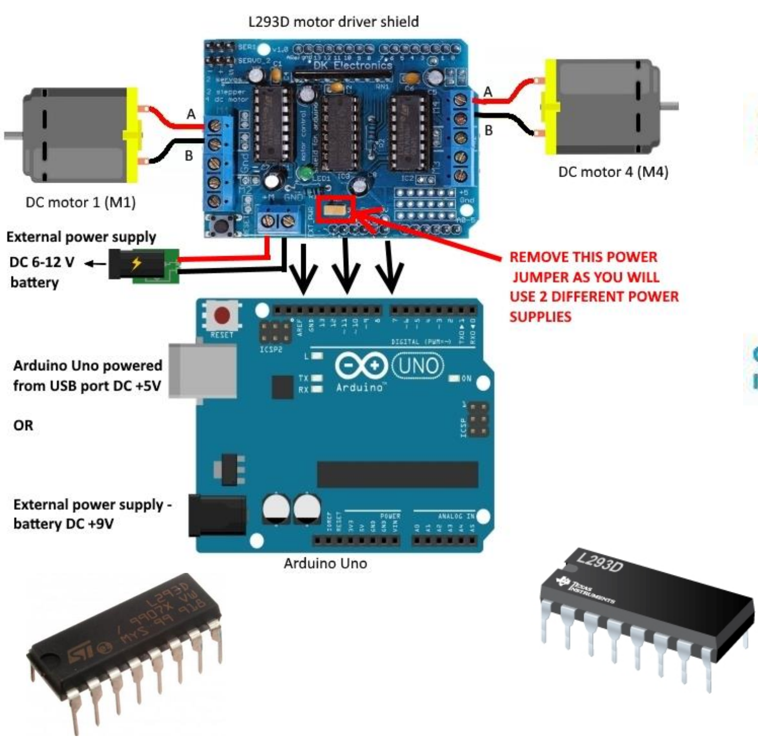
- Single-direction control— If the motor only needs to turn in one direction, the circuit can be easily constructed with a transistor.
- Dual-direction control— If the motor's direction needs to be changed, an H bridge should be added to the circuit.

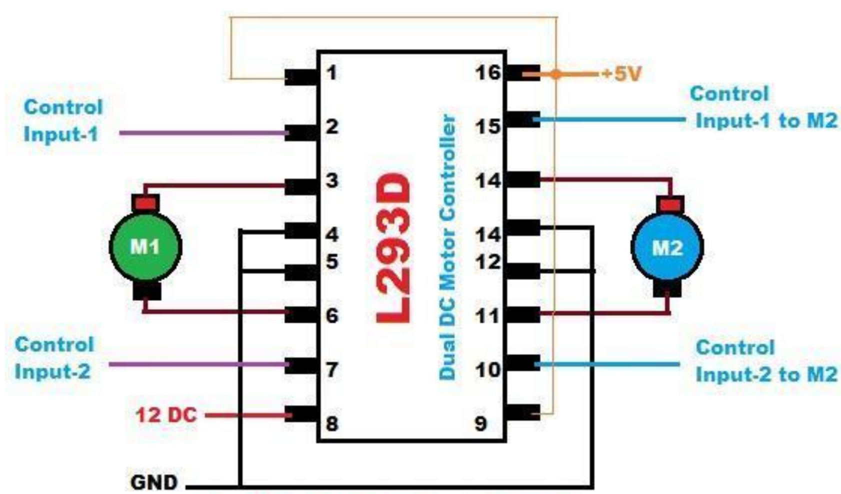
Control of DC Motors

- Switch ON-OFF
- Speed
- Direction



L293D H Bridge

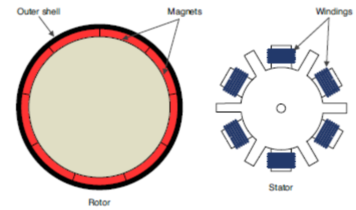




Dual H-Bridge Circuit using L293D

All inputs Low: Motor M1 & M2 = OFF.
Input-1 is High and Input-2 is Low: Motor M1 = Forward Direction.
Input-1 is Low and Input-2 is High: Motor M1 = Backward Direction.

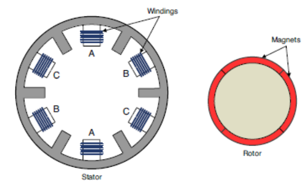
Brushless DC Motors



BLDCs are more complex and more expensive than brushed motors, but because there's no mechanical contact between the rotor and stator, they're more reliable and efficient.

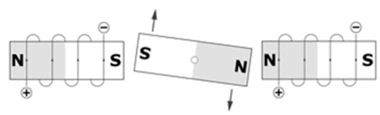
The controller delivers positive and negative current to different windings in a sequence, and the rotor spins to follow the change in current.

The windings' names are important because windings with the same name are connected. That is, both windings named A receive current at the same time, as do both windings named B and both windings named C. In this manner, the controller only has to deliver three inputs to the motor. For this reason, this BLDC is called a *three-phase motor* . More phases are possible, but most BLDCs are three-phase motors.



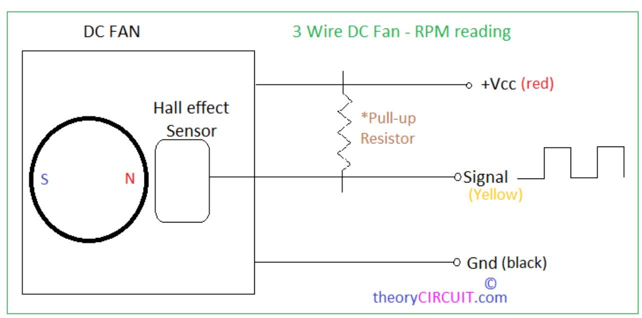
BLDCs can be divided into two categories depending on the relative positions of the rotor and stator.

- If the rotor turns inside the stator, the motor is an inrunner.
- If the rotor turns outside the stator, it's an outrunner.



Brushless DC Motors

- Applications
  - CPU cooling fans
  - CD/DVD Players
  - Electric automobiles
- Pros
  - Higher efficiency
  - Longer lifespan, low maintenance
  - Clean, fast, no sparking/issues
- Cons
  - Higher cost
  - More complex circuitry and requires a controller



Controlling BLDC

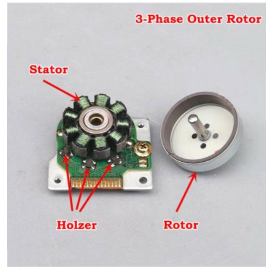
A three-phase BLDC has three inputs that deliver current to the windings. At any time, one input will be set high (V+), one will be set low (V-), and one will be left floating.

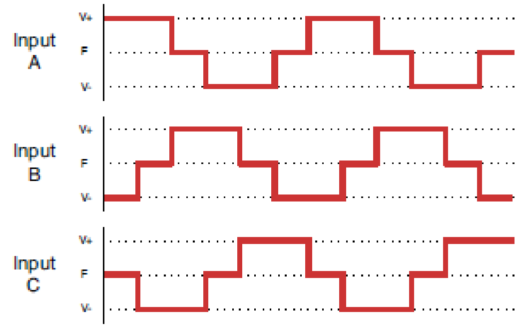
For a three-phase BLDC, there are only six unique phase states before they repeat. As the controller energizes the windings through these states, the rotor makes a complete rotation (360°). Therefore, each phase state corresponds to one-sixth of the complete turn, or 60°.

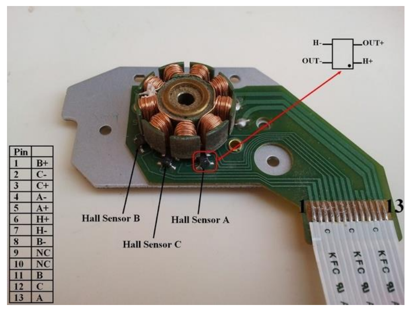
If the controller delivers more current, the motor will exert more torque as it rotates. If the pulses' order and timing is reversed, the motor will turn in the reverse direction. For this reason, BLDC control circuits don't require the H bridges needed to reverse brushed motors.

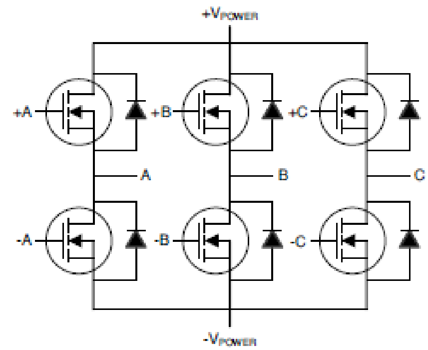
BLDCs receive power through special switching circuits called voltage source inverters, usually shortened to *inverters*

Sensored motor control is easier to implement and more reliable than sensorless control, but sensored BLDCs require additional circuitry, which means larger motors and higher cost.





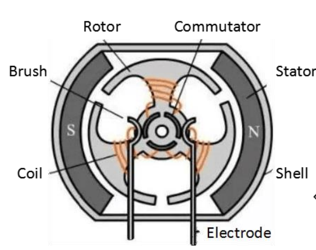




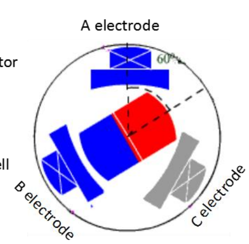
DC Motors Comparison

Feature	Brushless DC Motor	Brushed DC Motor
Commutation	Electronic commutation based on Hall position sensors	Brushed commutation
Maintenance	Less or no maintenance	Periodic maintenance
Life	Longer	Shorter
Speed / Torque	Enable operations on all speeds with rated load	At higher speeds, brush friction increases and reduce torque
Efficiency	High	Moderate
Speed Range	Higher – No mechanical limitation due to contact	Lower – Mechanical limitations due to brushes
Electric Noise Generation	Low – because it has permanent magnets on the rotor, improves dynamic response	Arcs in the brushes will generate electric noise

Brushed DC Motor



Brushless DC Motor



AC MACHINERY FUNDAMENTALS

Chapter 5

Table of Content

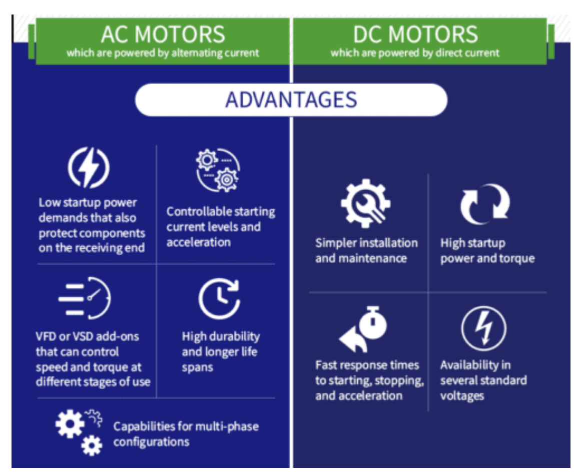
- Introduction
- Poly-Phase Circuits

Introduction

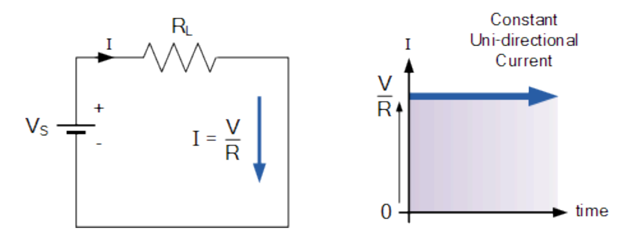
- AC induction motor is the most widely used type of electric motor in the modern world.
- AC motors are primarily used as a source of constant-speed mechanical power but are increasingly being used in variable speed-control applications.
- Advantages: They are popular because they can provide rotary power with high efficiency, low maintenance, and exceptional reliability all at relatively low cost.
- Disadvantages: there is a problem with using AC motors in control systems: These high-efficiency AC motors are by nature constant speed, and control systems usually require the motor speed to be controllable.

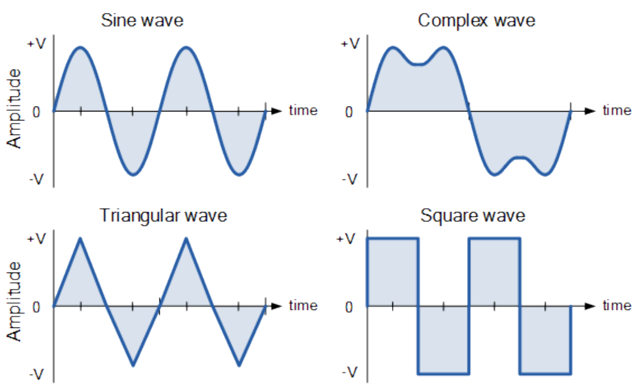
DC/AC Comparison

- AC motors can use the AC power “right off the lines.”—DC motors require the added expense of a rectifier circuit;
- Most AC motors do not need brushes as DC motors do. In most cases, the AC power is connected only to the motor’s stationary field windings. The rotor gets its power by electromagnetic induction, a process that does not require physical electrical contact.
- Maintenance is reduced because brushes do not have to be periodically replaced. Also, the motor tends to be more reliable and last longer because there are fewer parts to go wrong and there is no “brush dust” to contaminate the bearings or windings
- The speed of a DC motor can be controlled by simply adjusting the applied voltage. For complete speed control of an AC motor, both voltage and frequency must be adjusted, which requires using special electronic speed-control circuitry, such as the volts-per-hertz (V/Hz) drive or the vector drive



AC Basics





AC Waveform Characteristics

- The Period, (T) is the length of time in seconds that the waveform takes to repeat itself from start to finish. This can also be called the Periodic Time of the waveform for sine waves, or the Pulse Width for square waves.
- The Frequency, (f) is the number of times the waveform repeats itself within a one second time period. Frequency is the reciprocal of the time period, (f = 1/T) with the unit of frequency being the Hertz, (Hz).
- The Amplitude (A) is the magnitude or intensity of the signal waveform measured in volts or amps.

$$\text{Frequency}, (f) = \frac{1}{\text{Periodic Time}} = \frac{1}{T} \text{ Hertz}$$

or

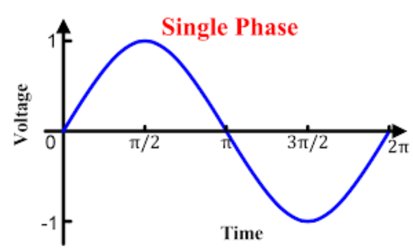
$$\text{Periodic Time}, (T) = \frac{1}{\text{Frequency}} = \frac{1}{f} \text{ seconds}$$

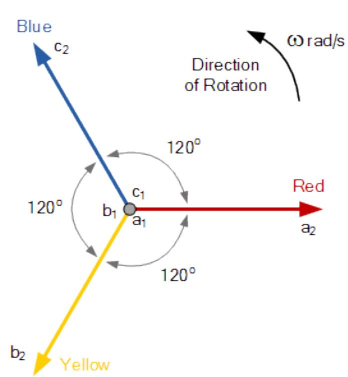
$$\text{Radians} = \left(\frac{\pi}{180^0}\right) \times \text{degrees}$$

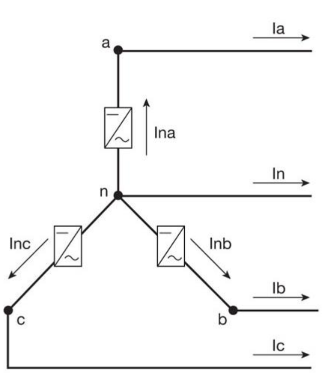
$$\text{Degrees} = \left(\frac{180^0}{\pi}\right) \times \text{radians}$$

$$\omega = 2\pi f \quad (\text{rad/sec})$$

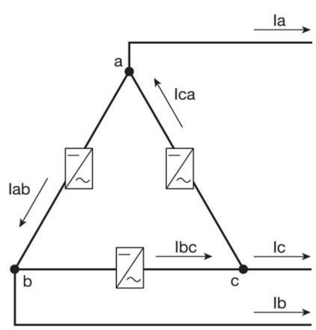
Poly-Phase Circuits



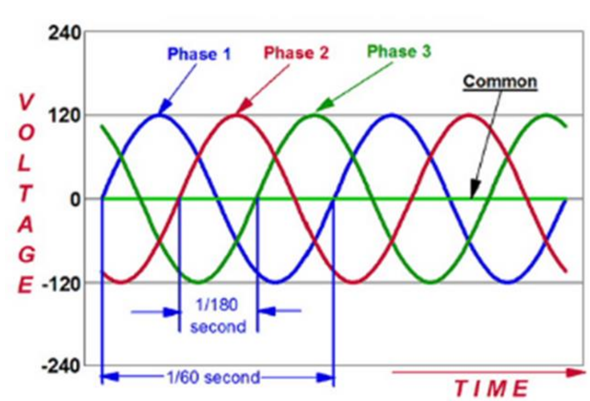




Wye diagram

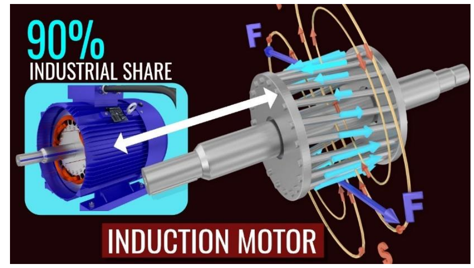


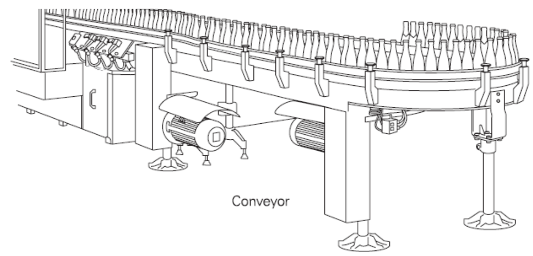
Delta diagram



AC Motor Applications

- AC motors are used worldwide in many residential, commercial, industrial, and utility applications.
- Motors transform electrical energy into mechanical energy.
- An AC motor may be part of a pump or fan, or connected to some other form of mechanical equipment such as a conveyor, or mixer.
- AC motors are found on a variety of applications from those that require a single motor to applications requiring several motors.



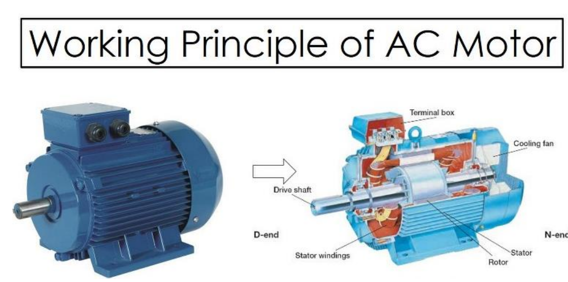


AC Motor - How it Works

Principles of Operation

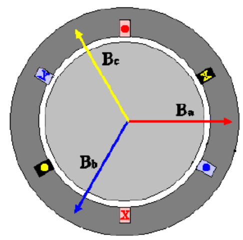
The principle of operation for all AC motors relies on the interaction of a revolving magnetic field created in the stator by AC current, with an opposing magnetic field either induced on the rotor or provided by a separate DC current source. The resulting interaction produces usable torque, which can be coupled to desired loads throughout the facility in a convenient manner.

Two major classes of machines:
- (i) Synchronous machines.
- (ii) Induction machines.



Rotating Magnetic Field

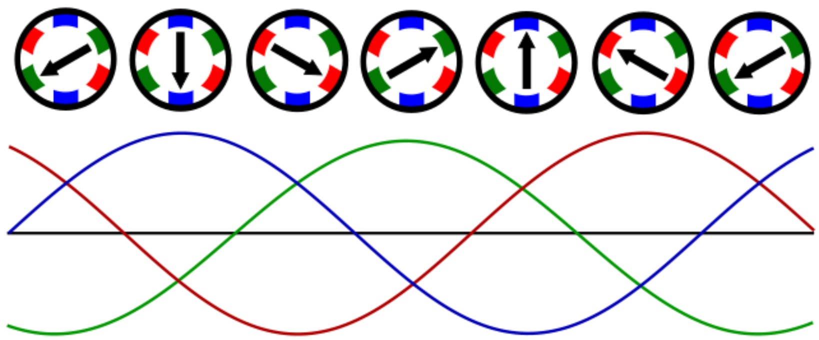
- Balanced three phase windings, i.e. mechanically displaced 120 degrees form each other, fed by balanced three phase source
- A rotating magnetic field with constant magnitude is produced, rotating with a speed



Synchronous speed

P	50 Hz	60 Hz
2	3000	3600
4	1500	1800
6	1000	1200
8	750	900
10	600	720
12	500	600

$$n_{sync} = \frac{120 f_e}{P} \qquad (rpm)$$

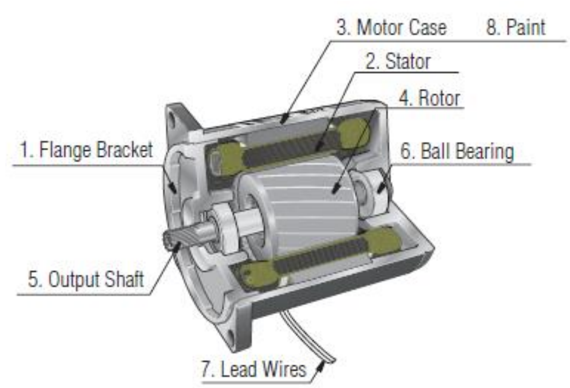


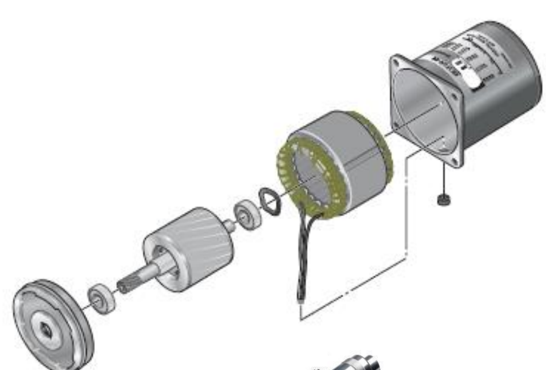
Where f_e is the supply frequency and P is the no. of poles and n_{sync} is called the synchronous speed in *rpm*

(revolutions per minute)

Construction of an AC Motor

1. **Flange bracket** die cast aluminium bracket with a machined finish, press-fitted into the motor case
2. **Stator** comprised of a stator core made from electromagnetic steel plates.
3. **Motor case** made from die cast aluminium with a machined finish inside
4. **Rotor** electromagnetic steel plates with die cast aluminium
5. **Output shaft** available in round shaft type and pinion shaft type.
6. **Ball bearing**
7. **Lead wires** with heat-resistant coating
8. **Painting** baked finish of acrylic resin.



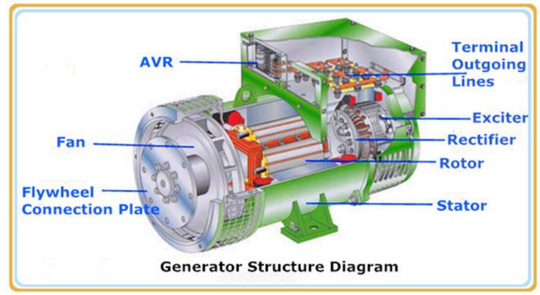


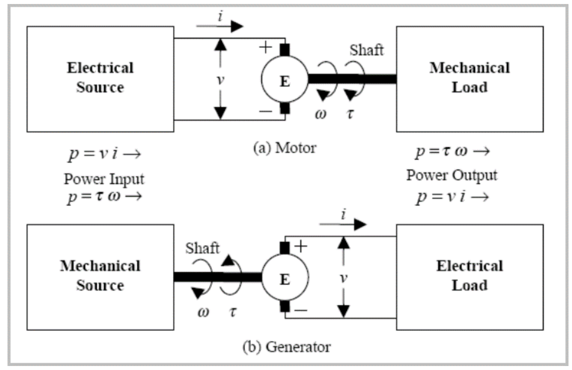
Introduction to a Synchronous Generators

- Synchronous generators or alternators are synchronous machines used to convert mechanical power to ac electric power, depending on the mode of operation of the machine.
- A machine has two modes of operation;

(a) motor : an electric motor converts electrical energy into mechanical energy.

(b) generator: an electric generator is used to convert mechanical energy into electrical energy. For this reason, electric machines are also called electromechanical energy converters.





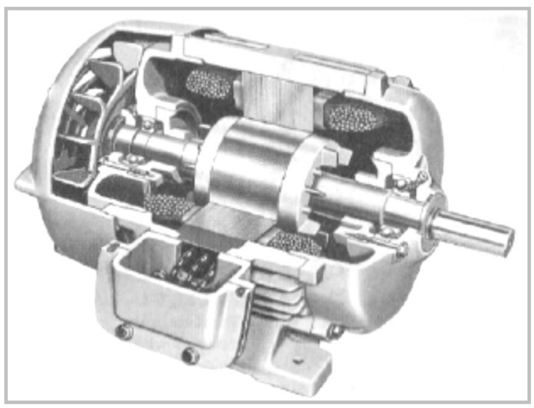
Induction Motors

Chapter 6

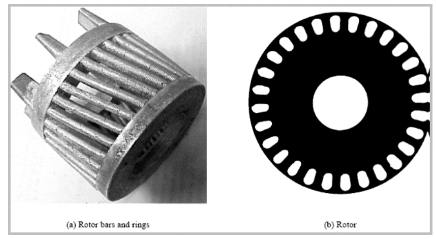
Table of Content

Introduction

- The machines are called induction machines because of the rotor voltage which produces the rotor current and the rotor magnetic field is induced in the rotor windings.
- No dc field current is required to run the machine.
- Induction generator has many disadvantages and low efficiency. Therefore induction machines are **usually referred** to as **induction motors**.



Induction Motor Types


(a) Rotor bars and rings (b) Rotor

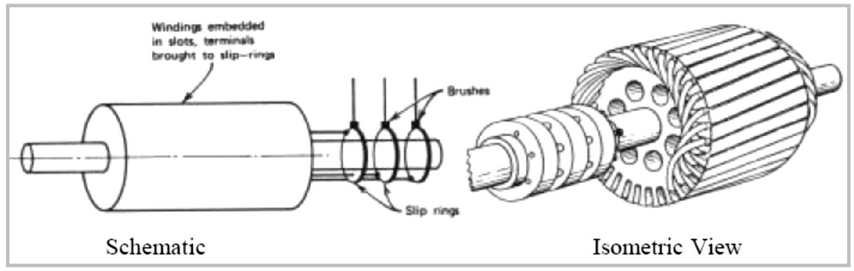
Induction motor has the same physical stator as a synchronous machine, with a different rotor construction.

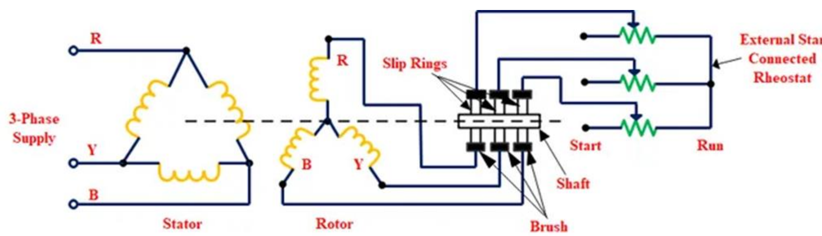
There are two different types of induction motor rotors ;

(a) Squirrel Cage rotor: Cage induction Motor rotor consists of a series of conducting bars laid into slot carved in the face of rotor and shorted at either end by large shorting ring

(b) Wound rotor: A wound rotor has a complete set of three-phase winding that are mirror images of the winding on the stator.

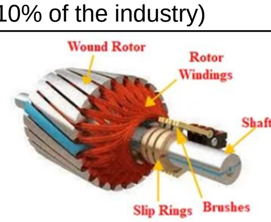
The three phases of the rotor windings are usually Y-connected, the end of the three rotor wires are tied to slip ring on the rotor shaft. Rotor windings are shorted through brushes riding on the slip rings. Wound-rotor induction motors are more expansive than the cage induction motors, they required much more maintenance because the wear associated with their brushes and slip rings.



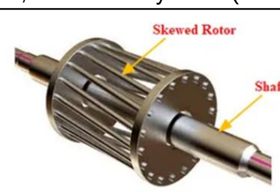


Wound-rotor vs Squirrel cage

	Wound-rotor or slip ring induction motor	Squirrel cage induction motor
Construction	Complicated due to the presence of slip rings and brushes	Simple due to the absence of slip rings and brushes
Starting Method	The motor requires slip rings, brush gear, short-circuiting device and starting resistance, etc.…	The motor can be started with a star-delta starter.
Starting Torque	High starting torque can be obtained due to the presence of external resistance in the rotor circuit.	Poor starting torque and cannot be improved.
Rotor	The rotor is wound rotor type with its terminal ends connected to 3 slip rings on the output shaft.	The rotor is skewed rotor type with its terminals are short-circuited at end rings.
Speed Control	Speed control by rotor resistance method is possible	Speed cannot be controlled by the rotor resistance method
Maintenance	Frequent maintenance is required due to the presence of brushes and slip rings	Less maintenance is required
Copper Losses	High	Less
Efficiency	Low due to power loss in external resistance	High
Cost	High Cost	Cheaper in cost
Applications	Used where high starting torque required such as cranes, hoist, elevator, etc.… Rarely used (about 5%-10% of the industry)	Used in lathe machines, drilling machines, blowers, fan, etc.…Widely used (about 90% of the industry)



Wound Rotor or Slip Ring Induction Motor

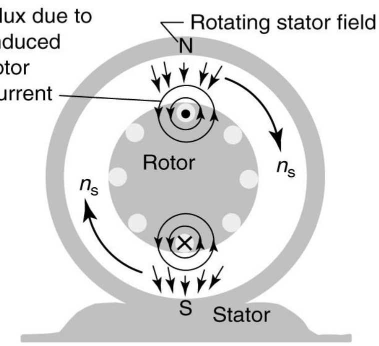


Squirrel Cage Induction Motor

Basic Induction Motor Concept

The Development of Induce Torque in an Induction Motor.

The three-phase of voltages has been applied to the stator, and three-phase set of stator current is flowing . These currents produce a magnetic field B_s, rotating counter clockwise direction.



The speed of the magnetic field's rotation is given by;

$$n_{sync} = \frac{120 f_e}{P}$$

where, f_e is the system frequency in hertz. and P is the number of poles in the machine.

The rotating magnetic field B_s passes over the rotor bars and induce a voltage in them.

The voltage induced in a given rotor bar is given by the equation;

$$e_{ind} = (v \times B) \bullet l$$

where, v = velocity of the bar relative to the magnetic field, B = magnetic flux density vector and l = length of conductor in the magnetic field.

The relative motion of the rotor compared to the stator magnetic field that produces induce voltage in a rotor bar.

The induce torque in the machine is given by;

$$\tau_{ind} = kB_R \times B_S$$

The rotor induced torque in counter clockwise, the rotor accelerates in that direction.

Rotor Slip

The voltage induced in a rotor bar of an induction motor depends on the speed of the rotor relative to the magnetic field.

Slip speed is defined as the difference between synchronous speed and rotor speed;

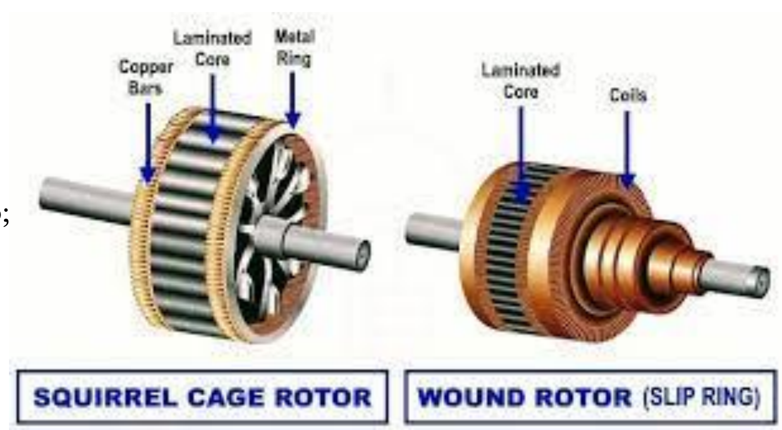
$$n_{slip} = n_{sync} - n_m$$

Where,

n_{slip} = slip speed of the machine.

n_{sync} = speed of the magnetic fields.

n_m = mechanical shaft speed of motor.



Another term used to describe the relative motion is slip;

$$s = \frac{n_{slip}}{n_{sync}} \times 100\%$$

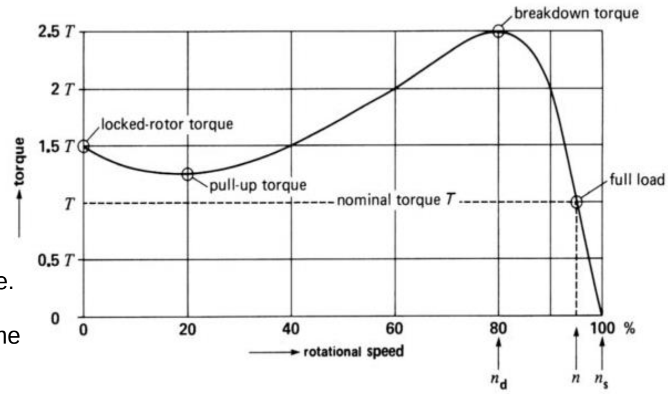
$$s = \frac{n_{slip} - n_m}{n_{sync}} \times 100\%$$

Torque Speed Characteristic

- There is a finite upper limit to the motor speed.
- If the induction motor rotor were tuning at synchronous speed, then the rotor bar would be stationary relative to the magnetic field (no induce voltage).
- If e_{ind} is zero, there would be;
  - no rotor current,
  - no rotor magnetic field,
  - the induce torque is zero,
  - and the rotor would slow down as a result of friction lost.
- The induction motor works by inducing voltages and current in the rotor of the machine.
- If the rotor of a motor is locked so that it cannot move, the rotor will have the same frequency as the stator.
- If the rotor turns at synchronous speed, the frequency on the rotor will be zero.
- For n_m= 0 r/min & the rotor frequency $f_r = f_e$ → slip, s = 1

  $n_m = n_{sync}$ & the rotor frequency $f_r = 0$ → slip, s = 0
- For any speed in between, the rotor frequency is directly proportional to the difference between the speed of the magnetic field n_{sync} and the speed of the rotor n_m.

Torque-speed characteristics



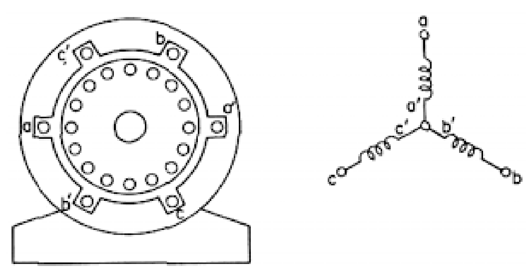
Typical torque-speed characteristics of induction motor

$$f_r = sf_e$$

Example 1

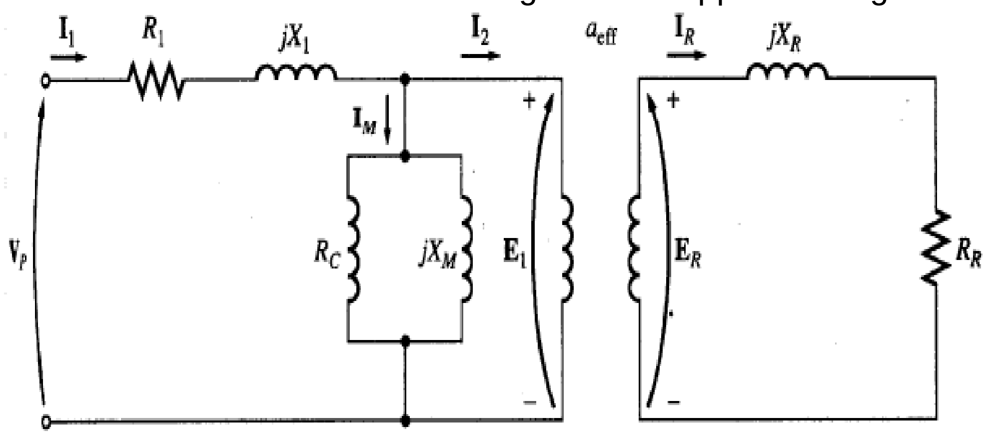
A 208-V, 10-hp, four-pole, 60-Hz, Y- connected induction motor has a full-load slip of 5 percent.

- What is the synchronous speed of this motor?
- What is the rotor speed of this motor at the rated load?
- What is the rotor frequency of this motor at the rated load?
- What is the shaft torque of this motor at the rated load?



The Equivalent Circuit of an Induction Motor

- The induction motor is similar to the transformer with the exception that its secondary windings are free to rotate
- As we noticed in the transformer, it is easier if we can combine these two circuits in one circuit but there are some difficulties
- R1 is the stator resistance and X1 is the stator leakage reactance.
- The flux in the machine is related to the integral of the applied voltage E1.



The Equivalent Circuit of an Induction Motor

Now as we managed to solve the induced voltage and different frequency problems, we can combine the stator and rotor circuits in one equivalent circuit

Where

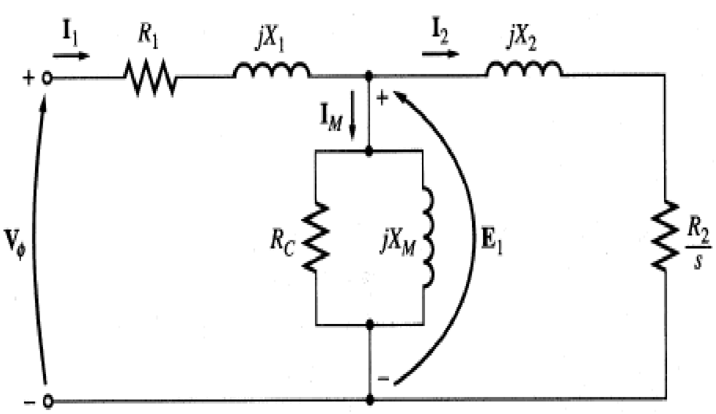
$$X_2 = a_{eff}^2 X_{R0}$$

$$R_2 = a_{eff}^2 R_R$$

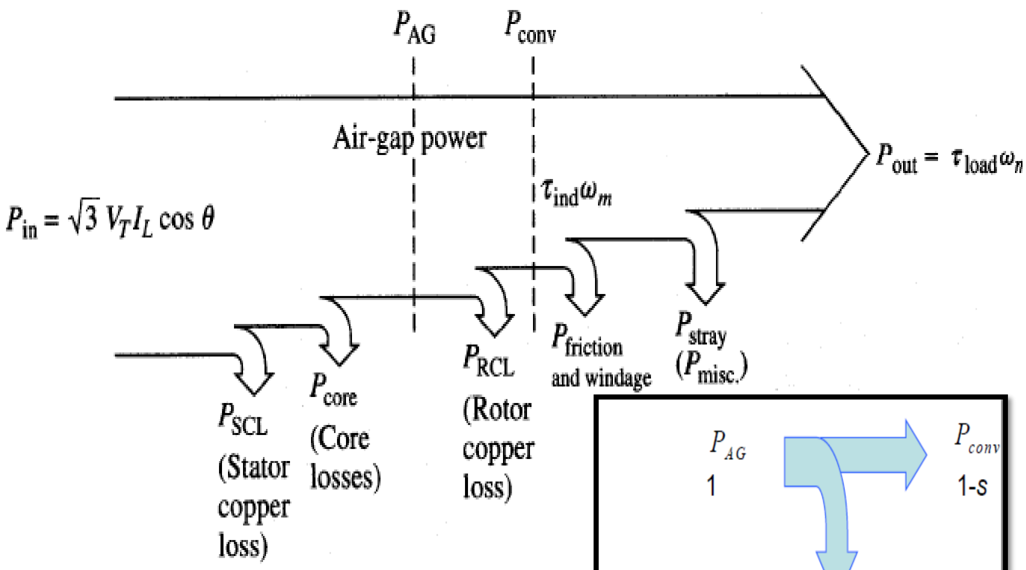
$$I_2 = \frac{I_R}{a_{eff}}$$

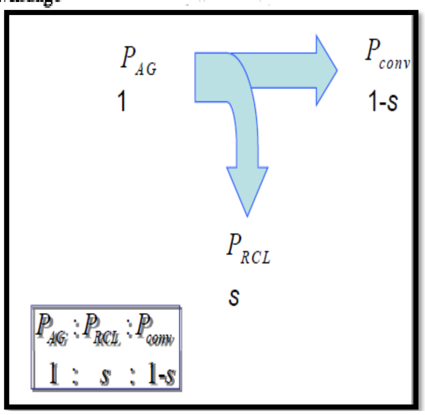
$$E_1 = a_{eff} E_{R0}$$

$$a_{eff} = \frac{N_S}{N_R}$$



Power flow in induction motor





Power relations

$$P_{in} = \sqrt{3}\, V_L I_L \cos\theta = 3\, V_{ph} I_{ph} \cos\theta$$

$$P_{SCL} = 3\, I_1^2 R_1$$

$$P_{AG} = P_{in} - (P_{SCL} + P_{core})$$

$$P_{RCL} = 3 I_2^2 R_2$$

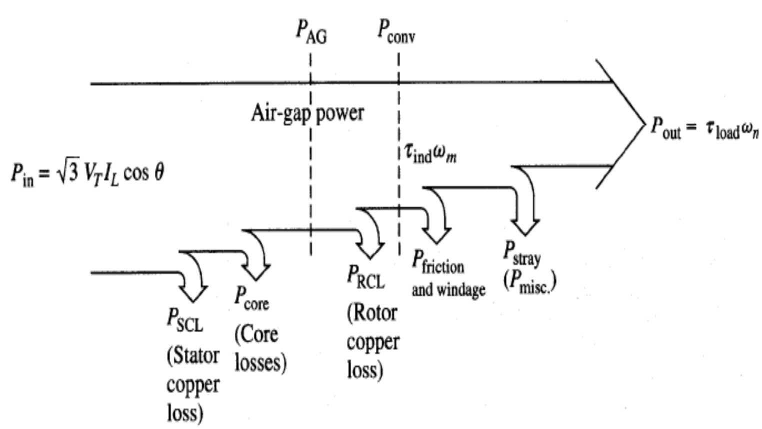
$$P_{conv} = P_{AG} - P_{RCL}$$

$$P_{out} = P_{conv} - (P_{f+w} + P_{stray})$$

$$\tau_{ind} = \frac{P_{conv}}{\omega_m}$$

Example 2

- A 480-V, 60 Hz, 50-hp, three phase induction motor is drawing 60A at 0.85 PF lagging. The stator copper losses are 2 kW, and the rotor copper losses are 700 W. The friction and windage losses are 600 W, the core losses are 1800 W, and the stray losses are negligible.
- Find the following quantities:
  1. The air-gap power P_{AG}.
  2. The power converted $_{Pconv}$.
  3. The output power P_{out}.
  4. The efficiency of the motor.



Example 3

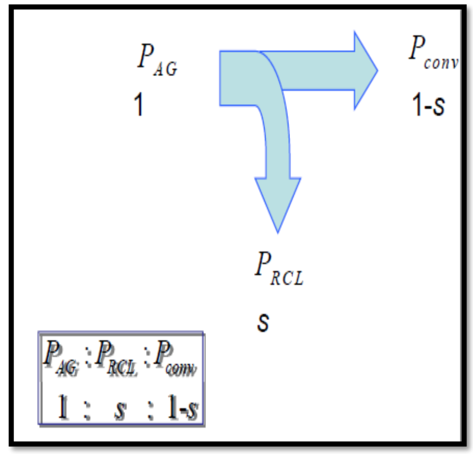
If the frequency of the source in example 2 is 60Hz, and the machine has four poles, fine

1- The slip,

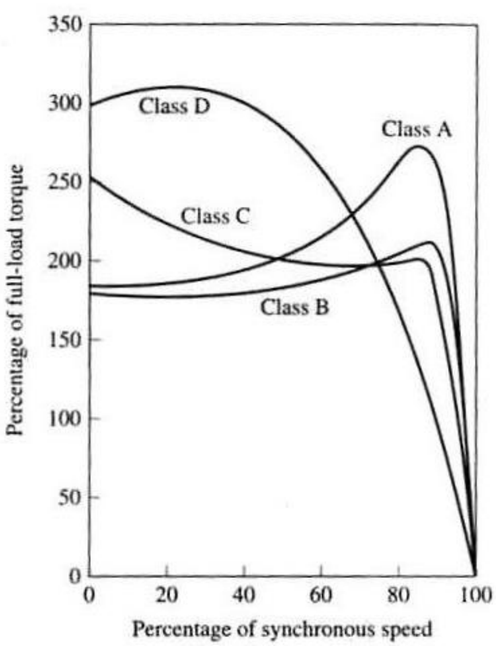
2- The operating speed,

3- The developed torque,

4- The output torque.



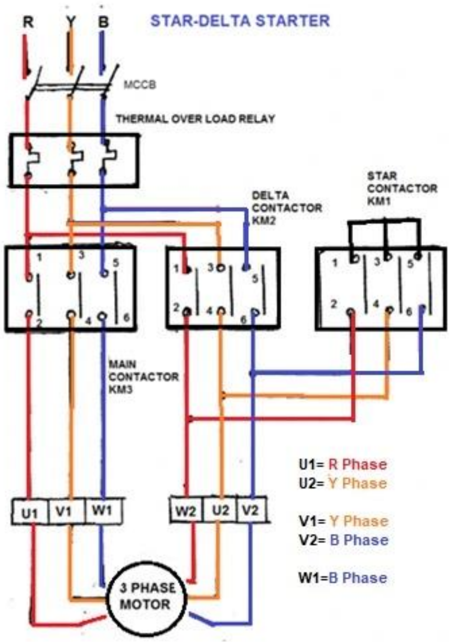
NEMA Classification based on Speed Torque Curve



- NEMA = National Electrical Manufacturers Association
- Classification based on T-ω characteristics
- **Class A & B** – general purpose
- **Class C** – higher T_{start} (eg: driving compressor pumps)
- **Class D** – provide high T_{start} and wide stable speed range but **low efficiency**

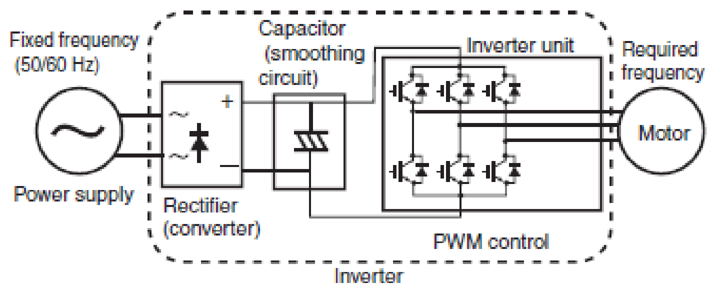
Starting Induction Motor

- We know that the induction motor is self starting (i.e when the supply is given to the motor it starts to rotate without any external help).
- When an induction motor is started as there is no resistance initially (i.e, during starting), there is a tendency of huge current flow through the rotor circuit which may damage the circuit permanently.
- To overcome this problem various methods have been introduced to limit the starting current. one of the methods is Star delta starter
- The induction motor drives are normally designed to run on delta connection, but during starting the supply is given from star connection because then the starter voltage and current reduces by $1/\sqrt{3}$ times than the delta connection. When the motor reaches a steady state speed the connection changes from star to delta connection.



Variable-Speed Control of AC Motors

- In order to fully control the speed of an AC motor, you must be able to change the frequency.
- This can be done with off-the-shelf power-conversion units that are capable of converting the line voltage at 60 Hz into a wide range of voltages and frequencies.
- A motor-control unit (or the control unit plus the motor) is called a drive (inverter).

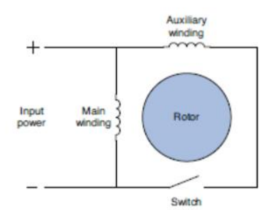


Single Phase Induction Motor

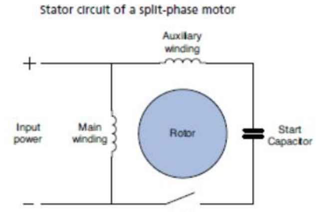
- A single-phase induction motor comprises a single-phase distributed winding on the stator and normal squirrel-cage rotor.
- Availability of a wide variety of small-size motors of fractional kilowatt ratings.
- Motors are employed in fans, refrigerators, mixers, vacuum cleaners; washing machines, other kitchen equipment, tools, small farming appliances, etc.
- Behaviour of single-phase induction motor can be explained on the basis of double-field revolving theory and cross magnetic field theory.
- Single phase induction motors are simple, robust, reliable and cheaper for small ratings. They are available up to 1 KW rating

Single Phase Induction Motor Types

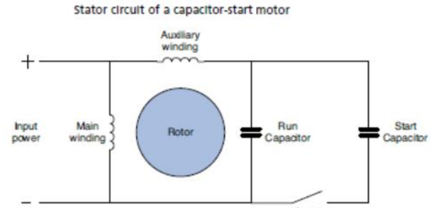
1. Split phase induction motor
2. Capacitor start induction motor
3. Capacitor start capacitor run induction motor



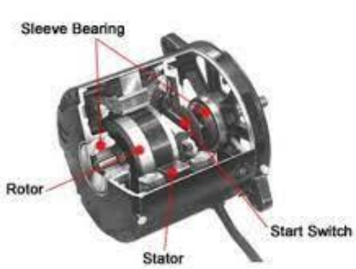
Stator circuit of a split-phase motor



Stator circuit of a capacitor-start motor



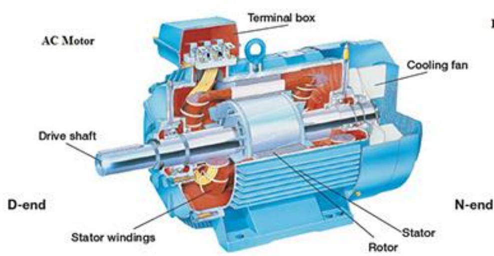
Stator circuit of a capacitor-run motor

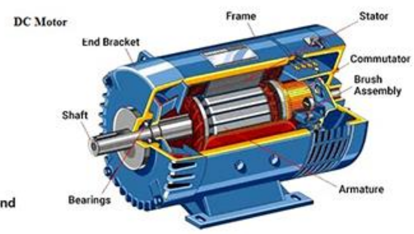


SPLIT PHASE MOTOR

AC-DC Motors Comparison

AC Motors	DC Motors
Ac motors are powered from AC current.	DC motors are powered from DC current.
AC motors can be single-phase or three phases.	All DC motors are single phase.
Repairing of DC motors is costly.	Repairing of AC motors is not costly.
AC motor does not use brushes.	DC motor uses brushes.
AC motors have a longer life span.	DC motors have not longer life span.
The speed of AC motors is simply controlled by varying the frequency of the current.	The speed of DC motors is controlled by varying the armature winding's current.
AC motors require effective starting equipment like a capacitor to start operation.	DC motors do not require any external help to start operation.





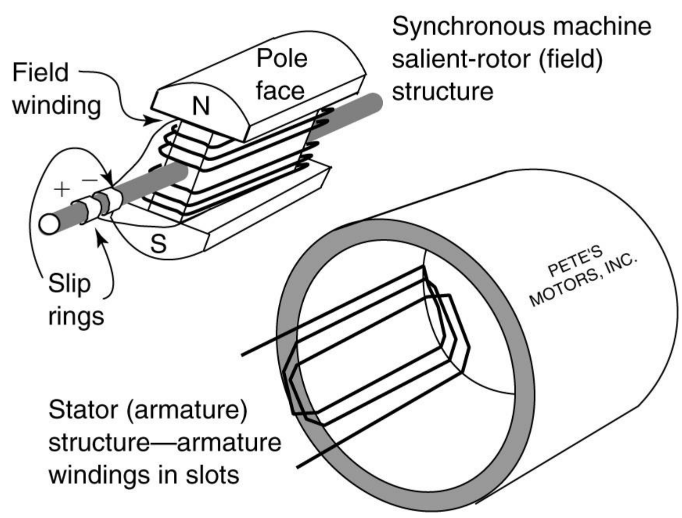
Synchronous Machines

Chapter 7

Table of Content

Introduction

- Alternating current (ac) is the primary source of electrical energy.
- It is less expensive to produce and transmit alternating current (ac) than direct current (dc).
- For this reason, and because ac voltage is induced into the armature of all generators, ac machines are generally more practical.
- May function as a generator (mechanical to electrical) or a motor (electrical to mechanical)
- The ability to control the power factor is one of the major advantages of the synchronous motor..
- In the synchronous motor, the speed remains constant irrespective of the loads. This characteristic helps in industrial drives where constant speed required irrespective of the load it is driving.

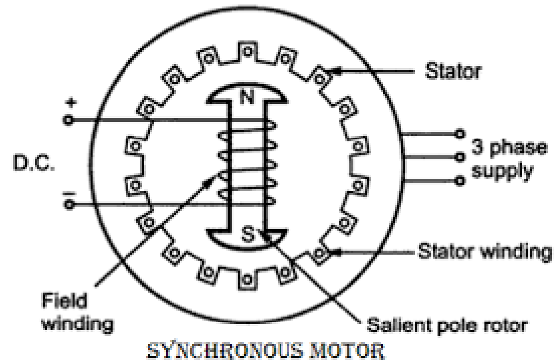


Synchronous Machines

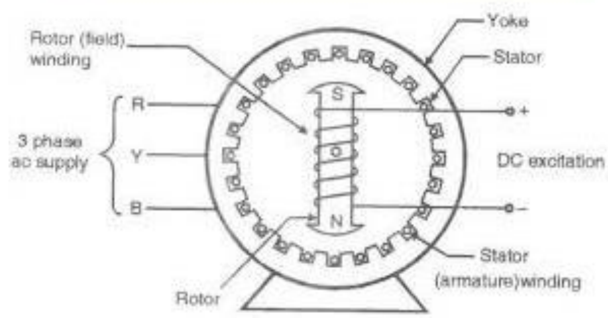
- Origin of name: syn = equal, chronos = time
- Synchronous machines are called '***synchronous***' because their mechanical shaft speed is directly related to the power system's line frequency.
- The rotating air gap field and the rotor rotate at the same speed, called the **synchronous speed.**
- Synchronous machines are ac machine that have a field circuit supplied by an external dc source.
  - DC field winding on the rotor,
  - AC armature winding on the stator

$$n_S = \frac{120 \cdot f_e}{P} \quad (rpm)$$

- Synchronous machines are used primarily as generators of electrical power, called synchronous generators or alternators.
- They are usually large machines generating electrical power at hydro, nuclear, or thermal power stations.
- *Synchronous motors* are built in large units compare to induction motors (Induction motors are cheaper for smaller ratings) and used for constant speed industrial drives
- Application as a motor: pumps in generating stations, electric clocks, timers, and so forth where constant speed is desired.

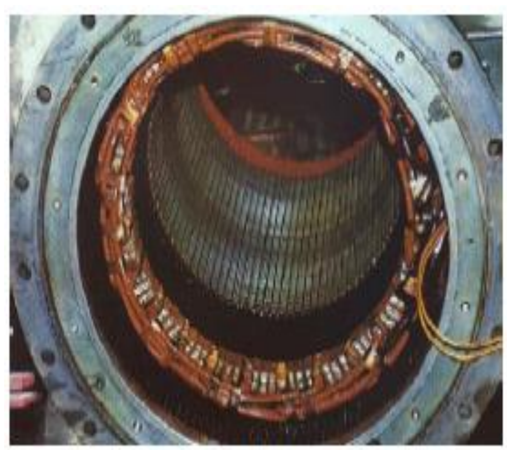


Synchronous Generator Construction



Synchronous Machine Construction (Stator)

- The main part in the synchronous machines are
  i) Rotor
  ii) Stator
- AC windings are mounted on the (stationary) stator resulting in three-phase AC stator voltages and currents
  - The stator of a synchronous machine carries the armature or load winding which is a three-phase winding.
  - The armature winding is formed by interconnecting various conductors in slots spread over the periphery of the machine's stator.
  - Often, more than one independent three phase winding is on the stator. An arrangement of a three-phase stator winding.



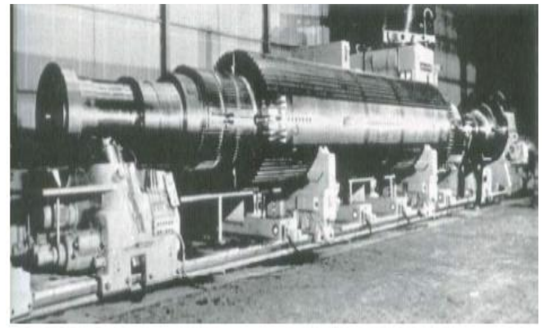
Stator

Synchronous Machine Construction (Rotor)

- DC field windings are mounted on the (rotating) rotor which is thus a rotating electromagnet
- There are two types of rotors used in synchronous machines:

i) Cylindrical (or round) rotors: Machines with cylindrical rotors are typically found in higher speed higher power applications such as turbogenerators. Using 2 or 4 poles, these machines rotate at 3600 or 1800 rpm (with 60hz systems).

ii) Salient pole rotors: Salient pole machines are typically found in large (many MW), low mechanical speed applications, including hydrogenerators, or smaller higher speed machines (up to 1-2 MW). Salient pole rotors are less expensive than round rotors.

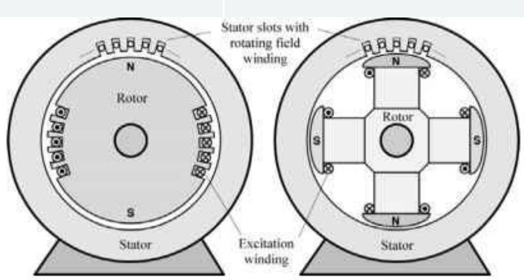


Cylindrical rotor

SALIENT POLE ROTOR

Salient Pole vs Cylindrical Pole

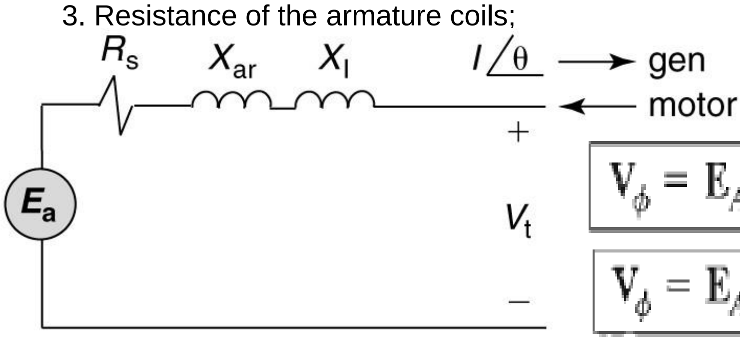
Salient Pole Alternator	Cylindrical Pole Alternator
The air gap is non-uniform.	The air gap is uniform due to the smooth cylindrical periphery.
Diameter is high and the axial length is small.	Small diameter and the large axial length is the feature.
Mechanically weak.	Mechanically strong.
This is preferred for low-speed alternators ranging from 125 rpm to 500 RPM	This is preferred for high-speed alternators ranging from 1500 rpm to 3000 RPM.



Cylindrical Rotor Salient Pole Rotor

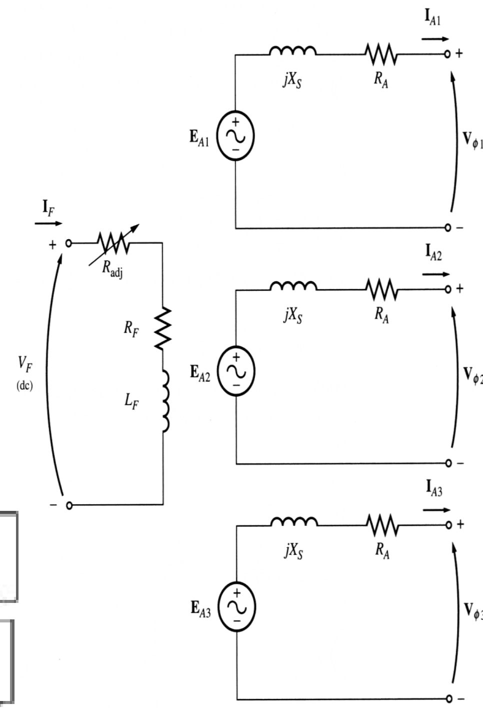
Equivalent Circuit of Synchronous Machine

- The internally generated voltage in a single phase of a synchronous machine E_A is not usually the voltage appearing at its terminals.
- It equals to the output voltage V_Φ only when there is no armature current in the machine.
- The reasons that the armature voltage E_A is not equal to the output voltage V_Φ are:
  1. Distortion of the air-gap magnetic field caused by the current flowing in the stator (armature reaction);
  2. Self-inductance of the armature coils;
  3. Resistance of the armature coils;



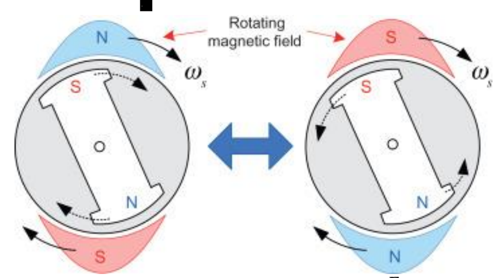
$$\mathbf{V}_\phi = \mathbf{E}_A - jX_S\mathbf{I}_A - R_A\mathbf{I}_A$$

$$\mathbf{V}_\phi = \mathbf{E}_A + jX_S\mathbf{I}_A + R_A\mathbf{I}_A$$

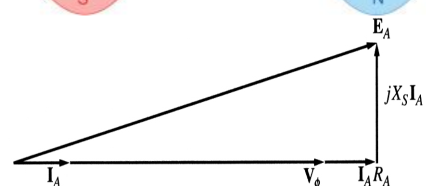


Basic Synchronous Machine Concept

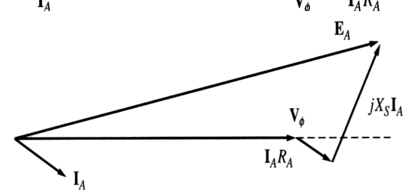
$$\mathbf{V}_\phi = \mathbf{E}_A - jX_S\mathbf{I}_A - R_A\mathbf{I}_A$$



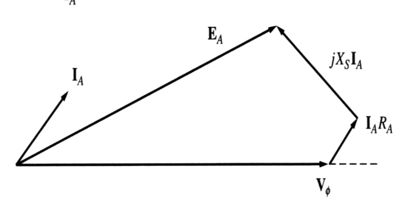
- The voltages in a synchronous generator are AC voltages, they are usually expressed as phasors.
- A vector plot of voltages and currents within one phase is called a phasor diagram.
  - A phasor diagram of a synchronous generator with a unity power factor (resistive load)



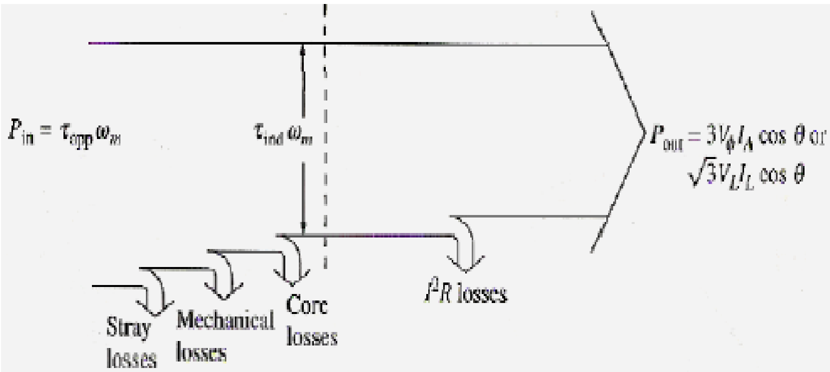
  - Lagging power factor (inductive load): a larger than for leading PF internal generated voltage *EA* is needed to form the same phase voltage.

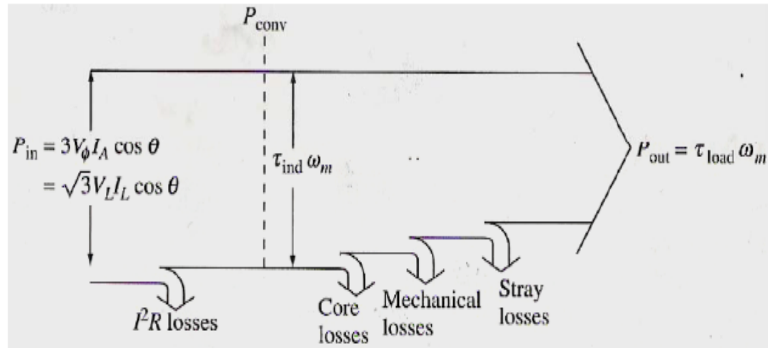


  - Leading power factor (capacitive load).



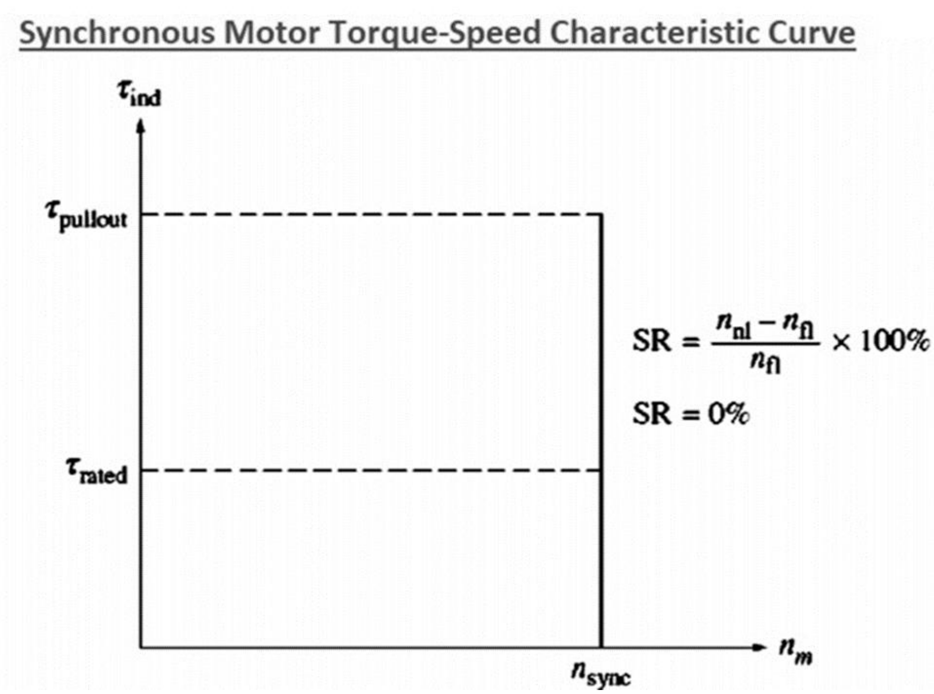
Power flow in Synchronous Machines



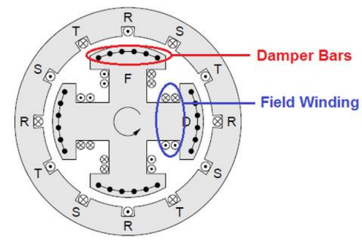


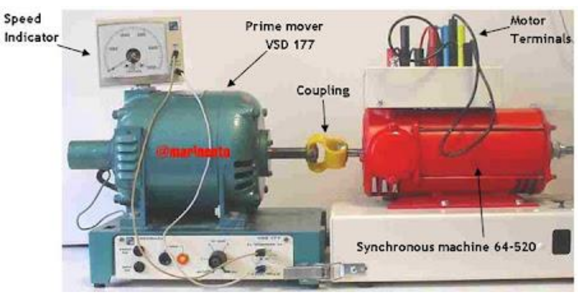
$$P_{out} \approx \frac{3V_\phi E_A \sin\delta}{X_S}$$

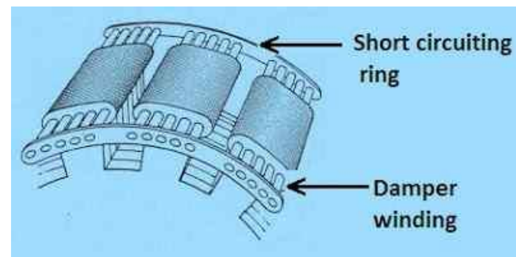
Torque Speed Characteristic



Starting Synchronous Motor







Synchronous and Asynchronous Motor Comparison

BASIS	SYNCHRONOUS MOTOR	ASYNCHRONOUS MOTOR
Definition	Synchronous motor is a machine whose rotor speed and the speed of the stator magnetic field is equal. N= NS = 120f/P	Asynchronous motor is a machine whose rotor rotates at the speed less than the synchronous speed. N < NS
Slip	Does not have slip. The value of slip is zero.	Have slip therefore the value of slip is not equal to zero.
Additional power source	It requires an additional DC power source to initially rotate the rotor near to the synchronous speed.	It does not require any additional starting source.
Slip ring and brushes	Slip ring and brushes are required	Slip ring and brushes are not required.
Cost	Synchronous motor is costly as compared to Asynchronous motor	Less costly
Efficiency	Efficiency is greater than Asynchronous motor.	Less efficient
Power factor	By changing excitation the power factor can be adjusted accordingly as lagging, leading or unity.	Asynchronous motor runs only at a lagging power factor.
Current supply	Current is given to the rotor of the synchronous motor	The rotor of Asynchronous motor does not require any current.
Speed	The Speed of the motor does not depend on the variation in the load. It is constant.	The Speed of the Asynchronous motor decreases with the increasing load.
Self starting	Synchronous motor is not self starting	It is self starting
Affect in torque	Change in applied voltage does not affect the torque of the synchronous motor	Change in applied voltage does affect the torque of the Asynchronous motor
Operational speed	They operate smoothly and relatively good at low speed that is below 300 rpm.	Above 600 rpm speed motor operation is excellent.
Applications	Synchronous motors are used in Power stations, manufacturing industries etc. it is also used as voltage controller.	Used in Centrifugal pumps and fans, blowers, paper and textile mills, compressors and lifts. etc

SPECIAL-PURPOSE MOTORS

Chapter 8

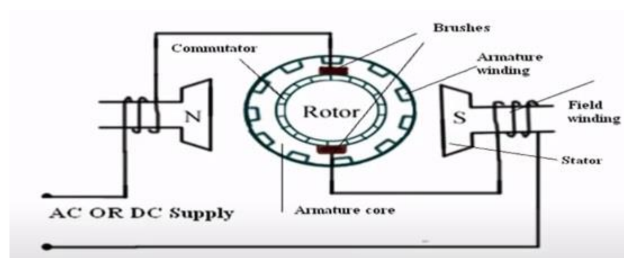
Table of Content

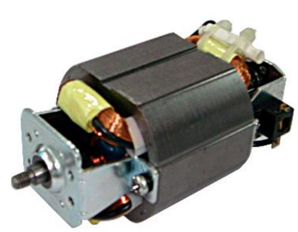
Introduction

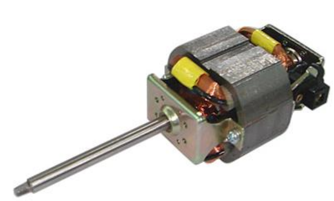
- Motors and generators of *three-phase* ac machines are the most common ones in larger commercial and industrial settings.
- However, most homes and small businesses do not have three-phase power available. For such locations, all motors must run from single phase power sources.

Universal Motors

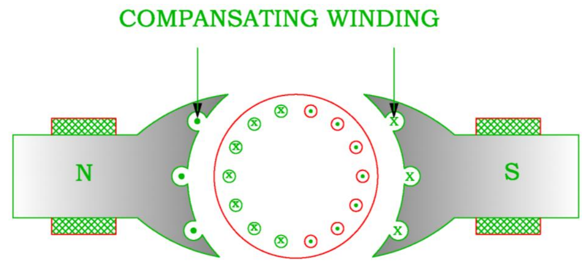
- The universal motor is a type of electric motor that can operate on either AC or DC power.
- It is a commutated series brushed DC motor where the stator's field coils are connected in series with the rotor windings through a commutator.
- It is often referred to as an AC series motor.
- The universal motor is very similar to a DC series motor in construction, but is modified slightly to allow the motor to operate properly on AC power.
- Universal motors have high starting torque, can run at high speed, and are lightweight and compact.
- They are commonly used in portable power tools and equipment, as well as many household appliances.
- However, the commutator has brushes that wear, so they are much less often used for equipment that is in continuous use. In addition, universal motors are typically very noisy.





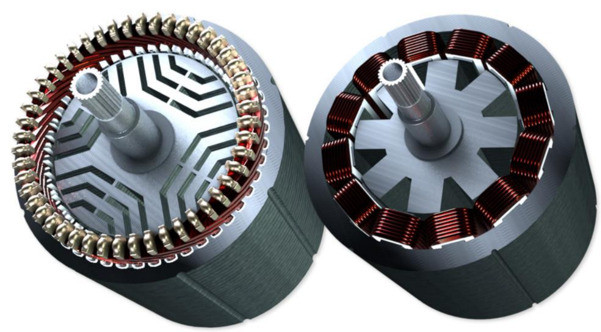


Universal Motors

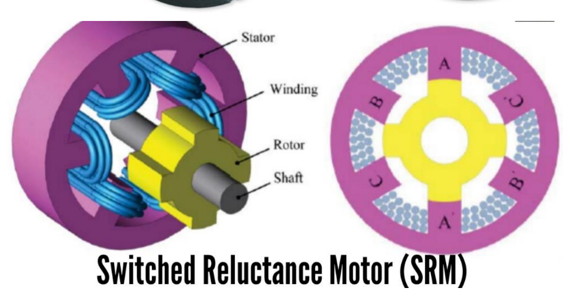


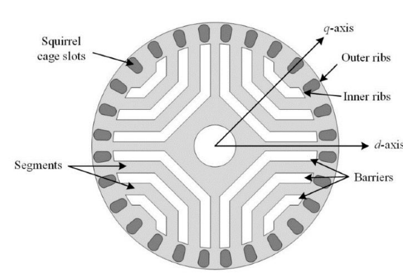
- If an ordinary series wound DC motor were connected to an AC supply, it would run very poorly.
- The universal motor is modified in several ways to allow for proper AC supply operation.
  - There is a compensating winding typically added, along with laminated pole pieces, as opposed to the solid pole pieces found in DC motors.
  - A universal motor's armature typically has far more coils and plates than a DC motor, and hence fewer windings per coil.

Reluctance Motors

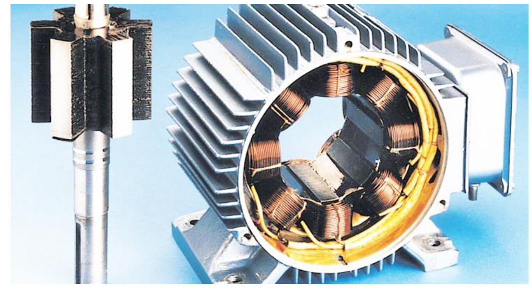


- A reluctance motor is a type of electric motor that induces non-permanent magnetic poles on the ferromagnetic rotor. The rotor does not have any windings. It generates torque through magnetic reluctance.
- Reluctance motor types:
  - Switched Reluctance or Variable Reluctance
    - The most fundamental form of SRM has the lowest construction cost of any electric motor because of its simple structure, and even industrial motors may have some cost reduction due to the lack of rotor winding or permanent magnets.
    - Common uses include applications where the rotor must be held stationary for long periods, and in potentially explosive environments such as mining because it operates without mechanical commutator.
  - Synchronous Reluctance
    - Synchronous reluctance motors have an equal number of stator and rotor poles. The projections on the rotor are arranged to introduce internal flux “barriers”, holes that direct the magnetic flux along the so-called direct axis.
    - The rotor operates at synchronous speeds without current-conducting parts. Rotor losses are minimal compared to those of an induction motor.
- Until the early twenty-first century, their use was limited by the complexity of designing and controlling them.
- Microcontrollers use real-time computing control algorithms to tailor drive waveforms according to rotor position and current/voltage feedback. Before the development of large-scale integrated circuits, the control electronics were prohibitively costly.



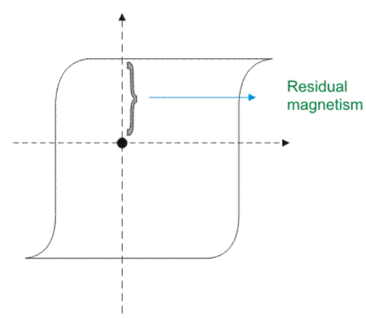


Reluctance Motors

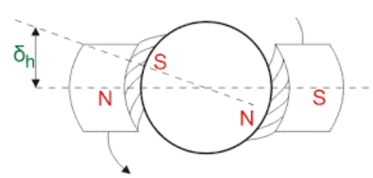


- The stator consists of multiple projecting (salient) electromagnet poles, similar to induction motor.
- The rotor consists of soft magnetic material, such as laminated silicon steel, which has multiple projections acting as salient magnetic poles through magnetic reluctance.
- Reluctance motors can deliver high power density at low cost, making them attractive for many applications. Disadvantages include high torque ripple (the difference between maximum and minimum torque during one revolution) when operated at low speed, and noise due to torque ripple.

Hysteresis Motors



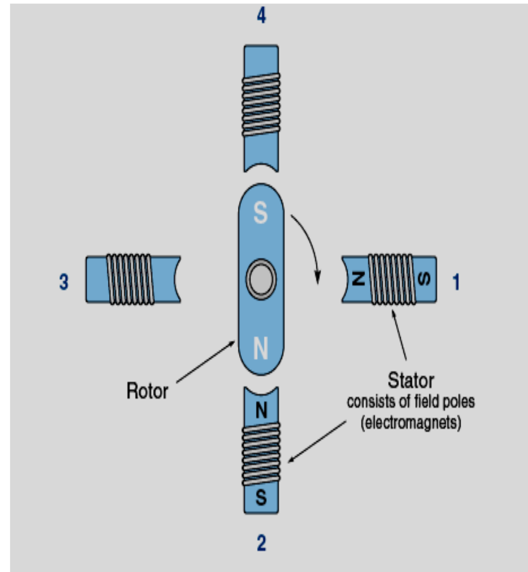
Hysteresis loop for rotor material



- The hysteresis motor is an alternating current motor of rotating magnetic field type.
- A Hysteresis motor is self-starting synchronous motor with a uniform air gap and without excitation that uses the hysteresis characteristics of magnetic materials to make torque.
- It widely finds use in synchronous motor applications where very smooth soft torque and simple construction with conventional three phase stator windings are required.
- A Hysteresis motor is a type of synchronous motor in which the rotor consists of central nonmagnetic core upon which rings of magnetically hard material are mounted.
- Hysteresis motors are durable and reliable in operation and are noiseless and capable of running at various speeds.

Stepper Motors

- A stepper motor is a special electrical machine which rotates in discrete angular steps in response to a programmed sequence of input electrical pulses.
- A stepper motor is a unique type of DC motor that rotates in fixed steps of a certain number of degrees.
- Step size can range from 0.9 to 90°.
- It consists of a rotor and stator.
- The rotor could be permanent magnet, and the stator is made up of electromagnets (field poles).
- The rotor will move (or step) to align itself with an energized field magnet.
- If the field magnets are energized one after the other around the circle, the motor can be made to move in a complete circle.



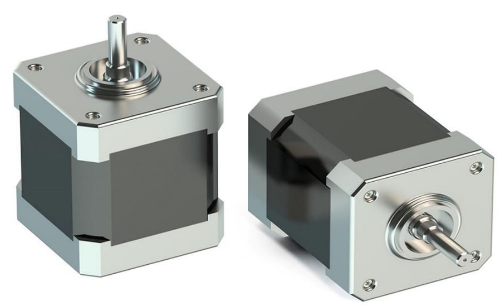
Importance of Stepper Motor in Control Application

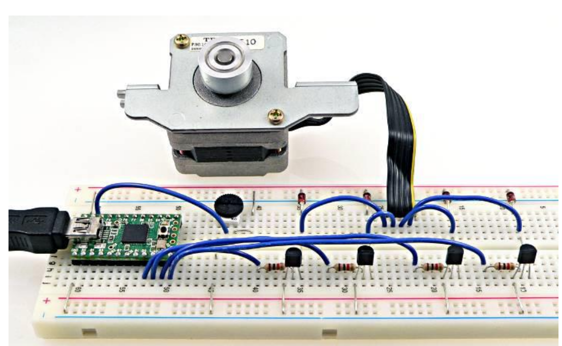
Can know the exact position of the motor shaft without the need of position sensors. This is done by simply counting the number of steps taken from a known reference position.

Most stepper motor systems operate open-loop—that is, the controller sends the motor a determined number of step commands and assumes the motor goes to the right place. A common example is the positioning of the read/write head in a floppy disk drive.

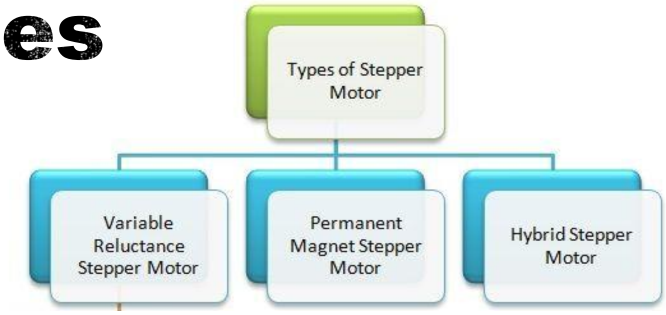
Steppers have inherently low velocity and therefore are frequently used without gear reductions. A typical unit driven at 500 pulses/second rotates at only 150 rpm.

Stepper motors can easily be controlled to turn at 1 rpm or less with complete accuracy.





Stepper Motor Types

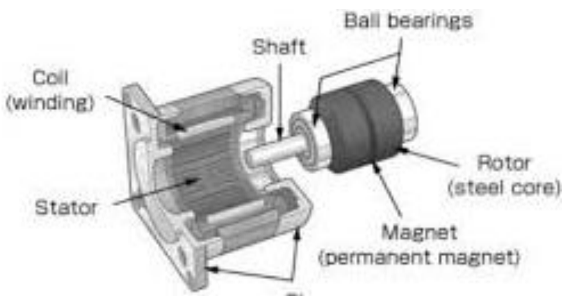


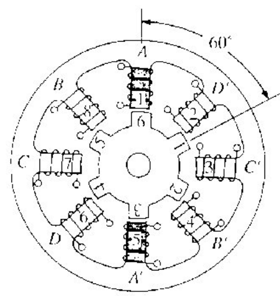
There are three types of stepper motors:

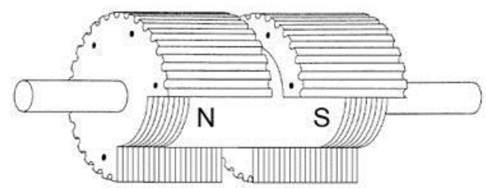
1 -Permanent Magnet.

2- Variable Reluctance.

3- Hybrid.





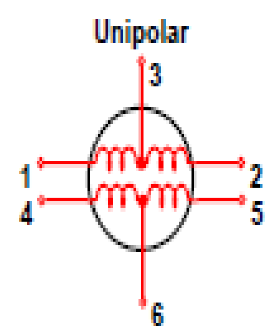


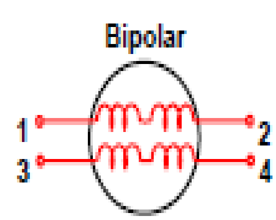
Hybrid Stepper Motor Rotor

Unipolar and Bipolar

- **Stepper Motors can be further subdivided:**

- **Unipolar**
  -- A centre tap added between the two leads
  -- Unidirectional current flow
- **Bipolar**
  -- Each lead taken separately
  -- Bidirectional current flow through entire winding





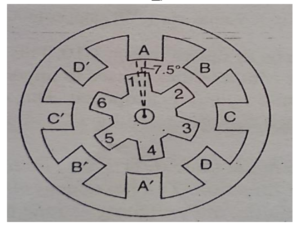
Modes of Control (Excitation)

a) 1 Phase ON

b) Two phase ON mode

c) 2-1-2-1-Phase ON (Half Stepping)

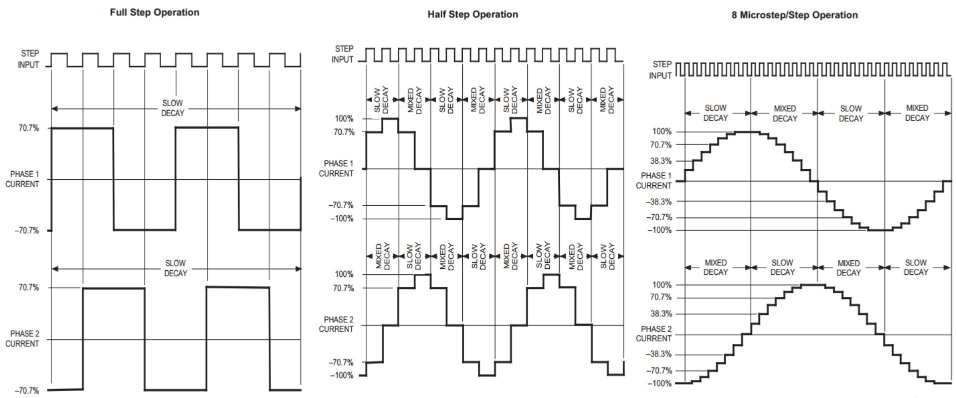
d) Micro-stepping



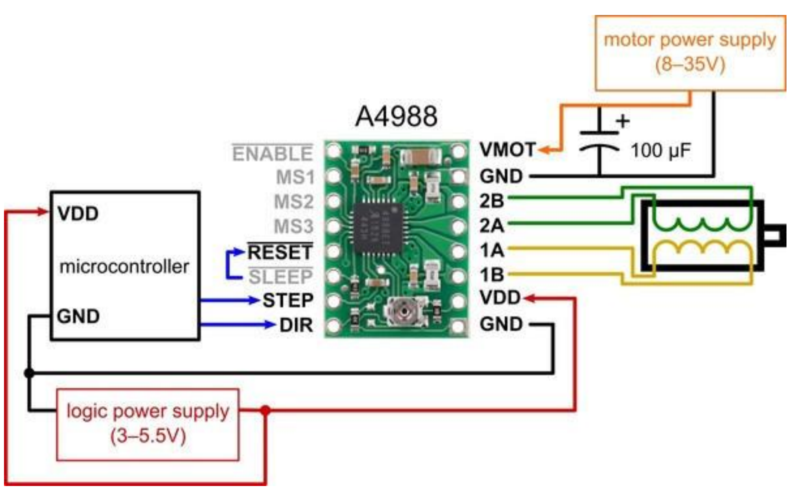
	1- Phase ON (Full Stepping)									
Clock State -->	R	1	2	3	4	5	6	7	8	9
Phase A	1	1				1				1
Phase B			1				1			
Phase C				1				1		
Phase D					1				1	
Step (Degrees)	0	0	15	30	45	60	75	90	105	120
			Steps of 15							

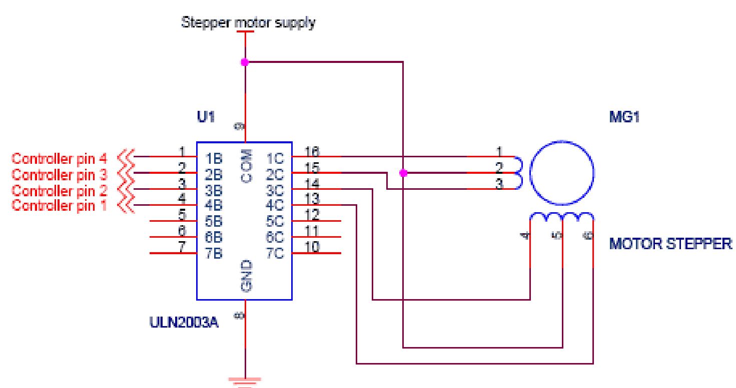
2-Phase ON									
R	1	2	3	4	5	6	7	8	9
0	7.5	22.5	37.5	52.5	67.5	82.5	97.5	112.5	127.5
	Steps of 15								

2-1-2-1-Phase ON (Half Stepping)									
R	1	2	3	4	5	6	7	8	9
1	1						1	1	1
	1	1	1						1
			1	1	1				
					1	1	1		
0	7.5	15	22.5	30	37.5	45	52.5	60	67.5
Steps of 7.5									



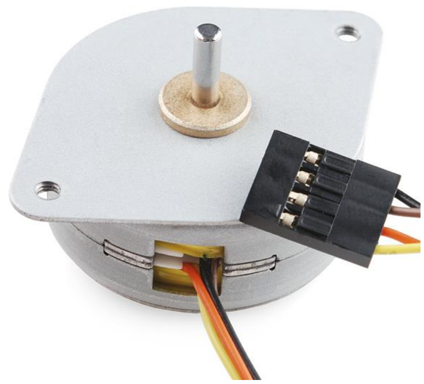
Stepper Motor Control Circuits





EXAMPLE

A 15°/step stepper motor is given 64 steps CW (clockwise) and 12 steps CCW (counter clock wise). Assuming it started at 0°, find the final position.



Servo Motors

The word "servo" are used for the situation that objects move to the target position or follow a moving objective.

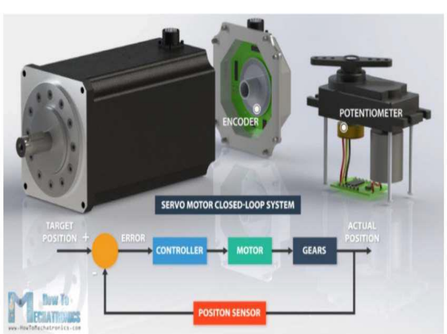
The word "servo" comes from the Latin word, servos, which means slave, and a "servomechanism"("servo" for short).

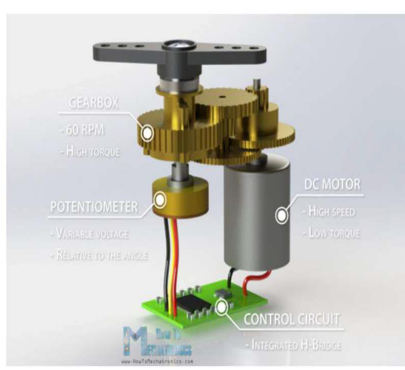
Servo is a control system that control machine as issued commands.

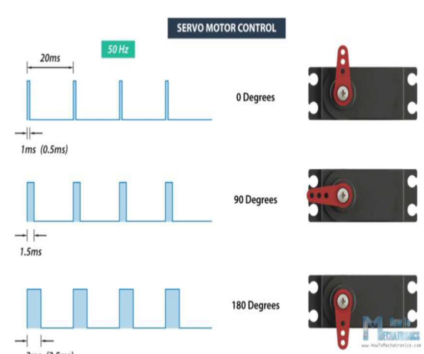
Servo mechanism enables the position, speed, torque control or combinations of these controls.

A Servo Motor is a DC (or AC) motor which uses a feedback control system to move to specific angles of rotation.

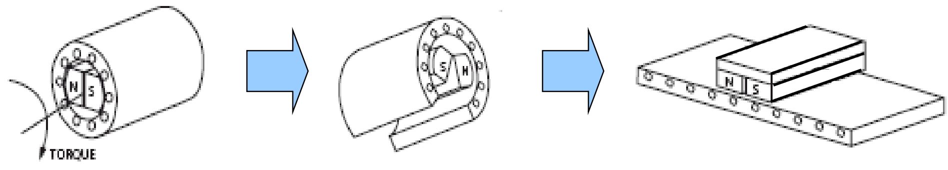
A Servo Motor requires a PWM signal to move the rotor to a particular angle.



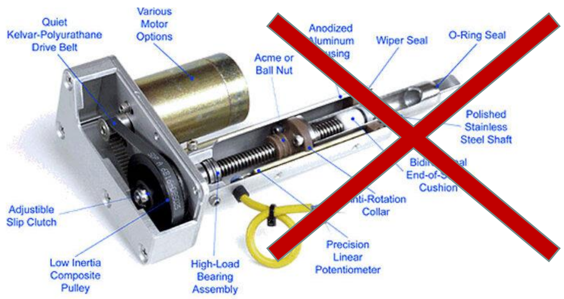




Linear Motors

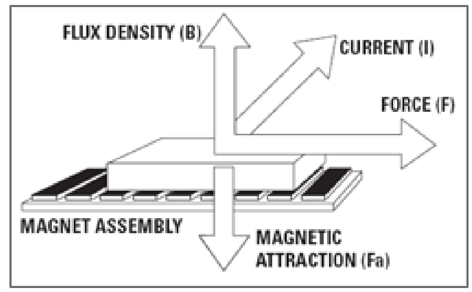


Analogous to Unrolled DC Motor



Force (F) is generated when the current (I) (along vector L) and the flux density (B) interact

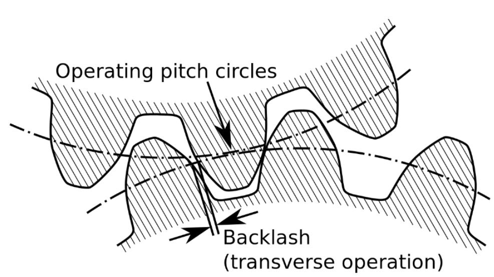
$$F = LI \times B$$



Advantages and Disadvantages of Linear Motors

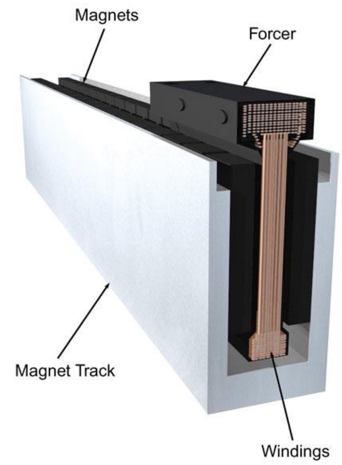
- High Maximum Speed
  - Limited primarily by bus voltage, control electronics
- High Precision
  - Accuracy, resolution, repeatability limited by feedback device, budget
  - Zero backlash: No mechanical transmission components.
- Fast Response
  - Response rate can be over 100 times that of a mechanical transmission → Faster accelerations, settling time (more throughput)
- Durable
  - Modern linear motors have few contacting parts → no wear

- Cost
  - Low production volume (relative to demand)
  - High price of magnets
  - Linear encoders (feedback) are much more expensive than rotary encoders, cost increases with length
- Higher Bandwidth Drives and Controls
- Heating issues
  - Forcer is usually attached to load → I^2R losses are directly coupled to load



Components of Linear Motors

- **Forcer (Motor Coil)**
  - Windings (coils) provide current (I)
  - Windings are encapsulated within core material
  - Mounting Plate on top
  - Usually contains sensors (hall effect and thermal)
- **Magnet Rail**
  - Iron Plate / Base Plate
  - Rare Earth Magnets of alternating polarity provide flux (B)
  - Single or double rail



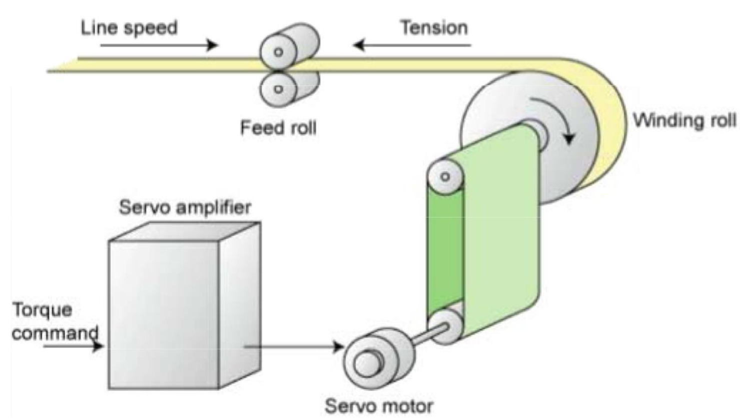
Motor Sizing Principles

Chapter 9

Table of Content

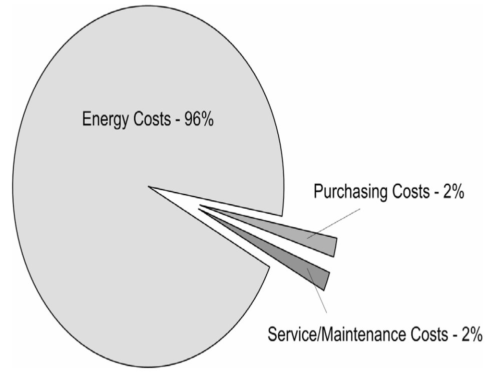
Introduction

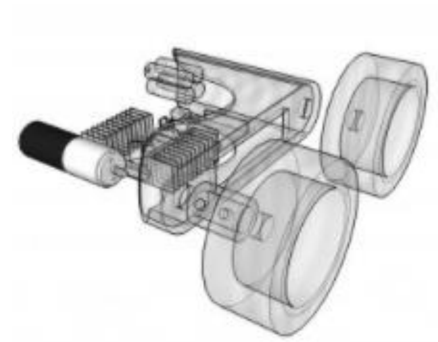
- The vast majority of automated manufacturing systems involve the use of sophisticated motion control systems that, besides mechanical components, incorporate electrical components such as servo motors, amplifiers and controllers.
- The first straightforward task for the motion system design engineer, before tuning and programming the electrical components, is to specify preferably **the smallest - motor and drive combination that can provide the torque, speed and acceleration as required by the mechanical set up**.
- The importance of motor sizing should not be underestimated. Proper motor sizing will not only result in significant cost savings by saving energy, reducing purchasing and operating costs, reducing downtime, etc.; it also helps the engineer to design better motion control systems.



Why Motor Sizing?

- The motor represents the most influential cost factor in the motion control system design, not only during the purchasing process, but especially during operation.
- A high-torque motor will require a stronger and thus more expensive amplifier than smaller motors.
- The combination of higher torque motor plus amplifier results not only in higher initial expenses, but will also lead to higher operational costs, in particular increased energy consumption.
- It is estimated, that the purchase price represents only about 2% of the total life cycle costs; about 96% is electricity.
- Oversizing a motor is naturally more common than under sizing. An undersized motor will consequently not be able to move the load adequately (or not at all) and, in extreme cases, may overheat and burn out, especially when it can't dissipate waste heat fast enough. Larger motors will stay cool, but if they are too large they will waste energy during inefficient operation. After all, the motor sizing process can also be seen as an energy balancing act.
- The main reasons to oversize a motor are:
  - Uncertain load requirements
  - Allowance for load increase (e.g. due to aging mechanical components)
  - Availability (e.g. inventory)

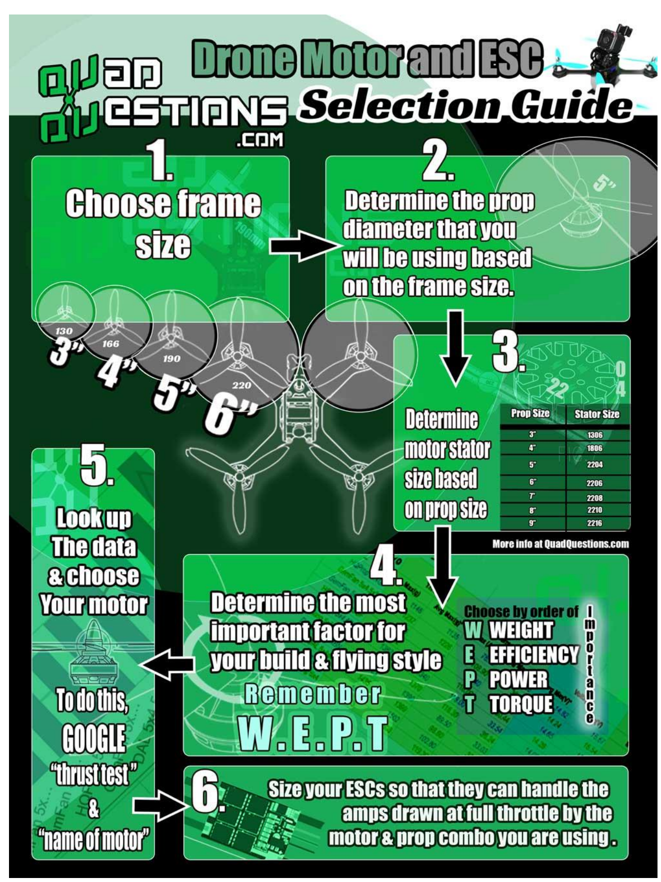




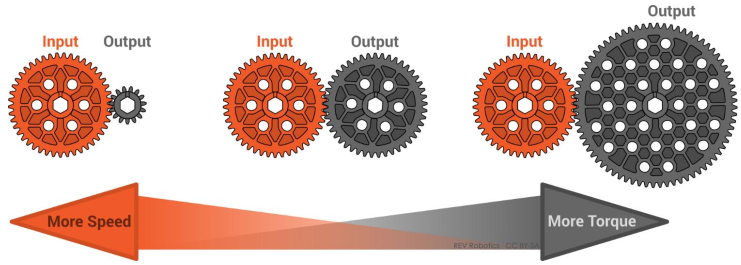
Sizing Process

The sizing process involves the following steps:

1. Establishment of motion objectives
2. Selection of mechanical components
3. Definition of a load (duty) cycle
4. Load calculation
5. Motor selection



Sizing Process

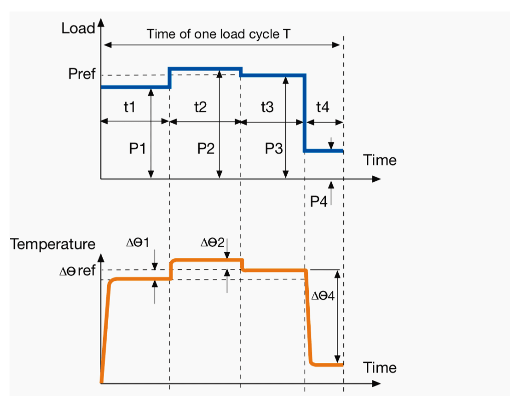


1. **Establishment of motion objectives**
   - Required positioning accuracy ?
   - Required position repeatability ?
   - Required velocity accuracy ?
   - Linear or rotary application ?
   - If linear application: Horizontal or vertical application?
   - Thermal considerations – Ambient temperature ?
   - What motor technologies are best suited for the application

2. Selection of mechanical components: The engineer must decide which mechanical components are required for the application. For instance, a linear application may require a leadscrew or a conveyor. For speed transmission a gear or a belt drive may be used.

- Direct Drive ?
- Special application or standard mechanical devices ?
- If linear application: Use of linear motor or leadscrew, conveyor, etc. ?
- Reducer required – Gearbox, belt drive, etc. ?
- Check shaft dimensions – select couplings
- Check mechanical components for speed and acceleration limitations

Sizing Process

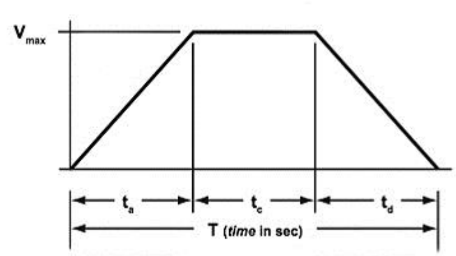


3. Definition of a load (duty) cycle

- Define critical move parameters such as velocity, acceleration rate
- Triangular, trapezoidal or other motion profile ?
- Does the load change during the duty cycle ?
- Holding brake applied during zero velocity ?

4. Load calculation

- Calculate inertia of all moving components
- Determine inertia reflected to motor
- Determine velocity, acceleration at motor shaft
- Calculate acceleration torque at motor shaft
- Determine non-inertial forces such as gravity, friction, pre-load forces, etc.
- Calculate constant torque at motor shaft



Sizing Process

5. Motor Selection

- Decide the motor technology to use (DC brush, DC brushless, stepper, etc.)
- Select a motor/drive combination
- Use rotor inertia to calculate system (motor plus mechanical components) acceleration (peak) and RMS torque
- Does the motor's performance curve (torque over speed) support the torque and speed requirements?.
- use of a gearbox or increase the transmission ratio of the existing gearbox. Servo motors should not be operated over a ratio of 10:1.

Motor Sizing Design Considerations

✓**Power Source**

-AC (120V, 220V…)

-DC (batteries, etc)

✓ **Torque Requirements (Power)**

-Constant Torque

-Variable Torque

-Stall torque characteristics

✓ **RPM Requirements**

-Built in gear reduction

-External gear reduction

✓ **Controls**

-How will the motor be controlled?

-To what extent will control be an issue?

✓**Positioning during Rotation**

-Precision

-Braking

-Reversibility

✓**Operating Environment**

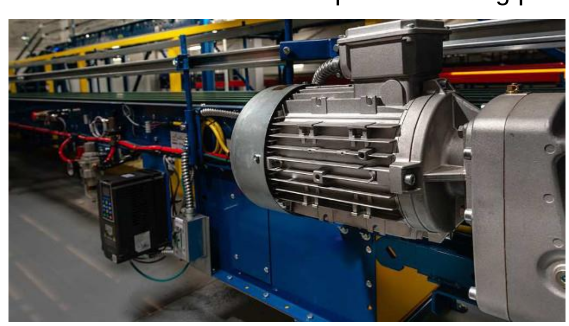
- Temperature
- What atmosphere will the motor be operating in?

✓**Physical size / Mounting position**

- length
- diameter
- What mounting options are there?

✓**Continuous or Discontinuous Operation**

- Will the motor operate for long periods of time?



Choosing the Right Motor

Some points to consider when specifying a new motor:

- Horsepower
- Speed (poles)
- Voltage
- Efficiency
- Torque (design letter)
- Dimensional constraints (frame size)
- Unusual service conditions
- Enclosure
- Coupling vs. Pulley drive

Motor Nameplate Data

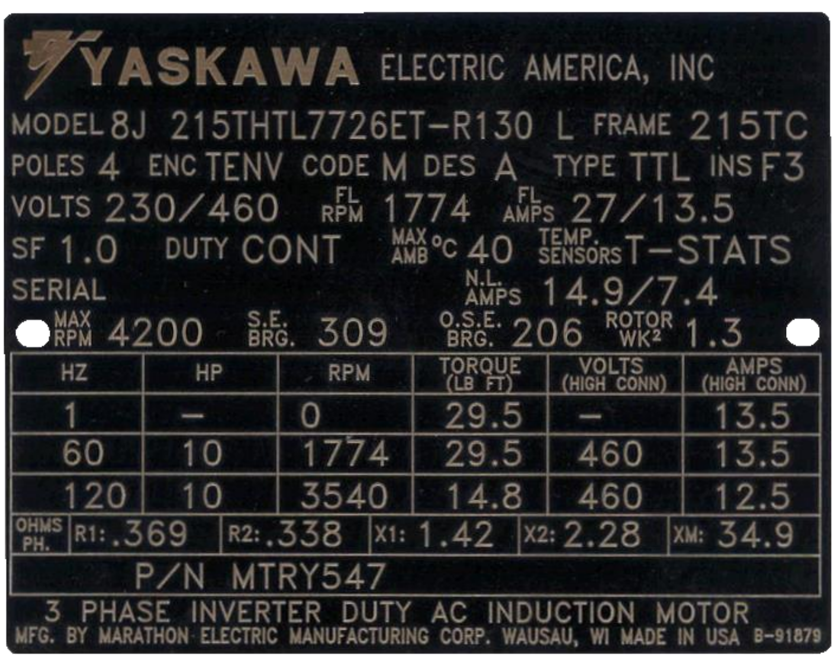
HP- Horsepower

Voltage

Amps

NEMA Design

RPM



S.F. - Service Factor

- The number by which the horsepower rating is multiplied to determine the maximum safe load that a motor may be expected to carry continuously
- Example - a 10HP motor with a service factor of 1.15 will deliver 11.5 horsepower continuously without exceeding the allowable temperature rise of its insulation class

Motor Nameplate

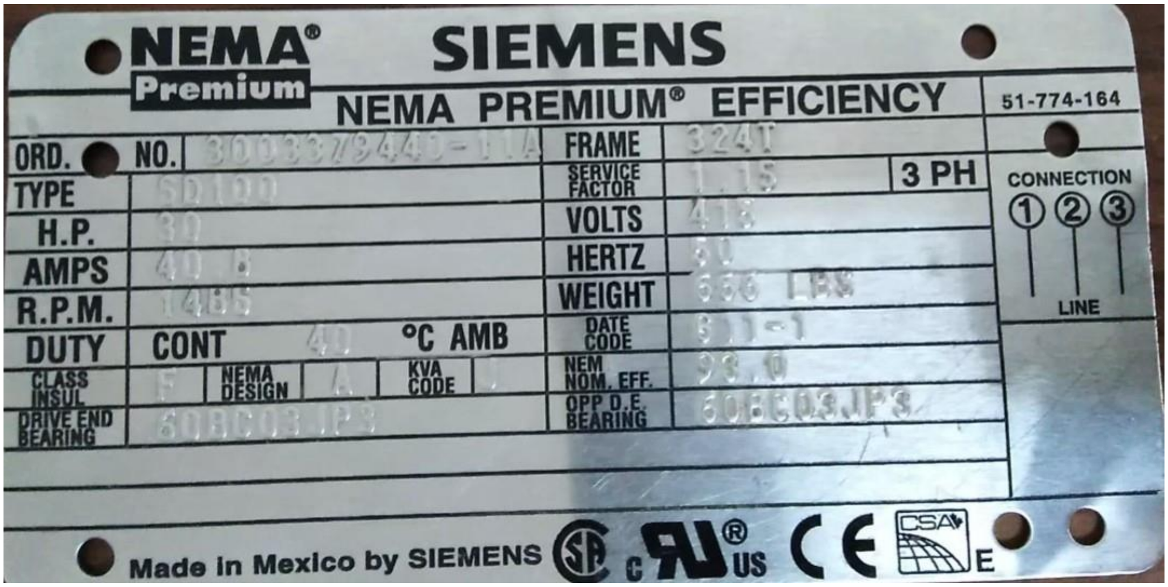
HP- Horsepower

Voltage

Amps

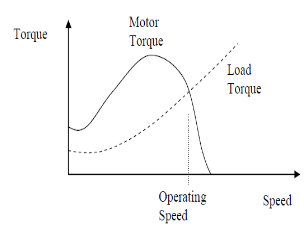
NEMA Design

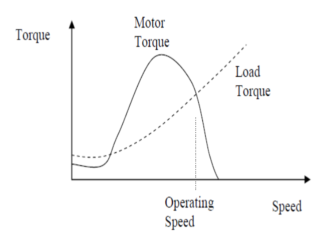
RPM

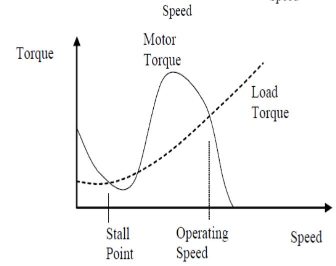


When the motor can start the load?

- In order to get the load up to speed the motor must start off from zero speed and accelerate the load up to desired speed.
- Torque is what causes acceleration.
- The motor torque will cause the load to accelerate but the load produces its own torque which resists acceleration.
- The torque produced by a motor varies with speed and the torque produced by a load also varies with speed.
- If the motor torque is greater than the load torque then the load will accelerate.
- If the load torque is greater than the motor torque then the load will decelerate.
- Accelerating Torque: = $T_{motor} - T_{load}$
- In order for the motor to start the load and get it up to correct speed then the motor torque must be higher than the load torque at zero speed (starting torque) and at every speed up to the desired operating speed.
- If the load torque ever exceeds the motor torque at any intermediate speed the motor will stall at that speed and the system will not start up correctly.







Example

The following load torque profile was measured for a constant speed load. Choose an appropriately sized motor to drive this load assuming a service factor of 20%. You do not need to consider starting performance.

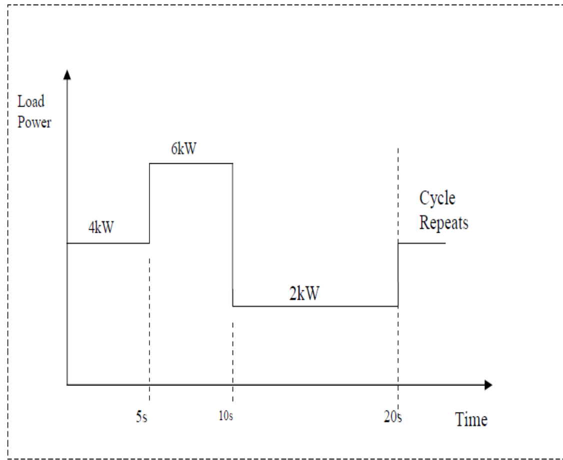
Sizing the motor

1. Peak Load Power requirement = 6kW.
   Peak load power must be less than Rated Motor Power x Service Factor
   => $6kW < P_{motor} \times 1.2$
   => $P_{motor} > 6/1.2 = 5kW$

2. The RMS load power should ideally be between 75% and 100% of Rated Motor Power.

$$RMSLoadpower = \sqrt{\frac{P_1^2 t_1 + P_2^2 t_2 + P_3^2 t_3 + ... + P_n^2 t_n}{t_1 + t_2 + t_3 + ... + t_n}} = \sqrt{\frac{4^2 \times 5 + 6^2 \times 5 + 2^2 \times 10}{5 + 5 + 10}} = 4.16kW$$

If we choose P_{motor}=5kW then RMS load power = 4.16/5*100% = 83% of P_{motor} which is acceptable.



Answer: Choose a 5kW motor.