सत्यमेव जयते

# Electric Motors

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# Overview

- Introduction
- Classification of Electric Machines
- Type of Electric Motors
- Components of DC / AC Motors
- Features of DC / AC Motors
- DC Motor vs AC Motors
- Assessment of Electric Motors
- Energy Efficiency Opportunities
- KW Calculation for Pump Motor

# Introduction

- Faraday's Law of Electromagnetic Induction

  **Dynamically Induced emf**

  $e = Blv \sin\theta$

  Where

  e = induced emf (Volt)

  B = magnetic field / flux density (weber/$m^2$)

  l = length of conductor (m)

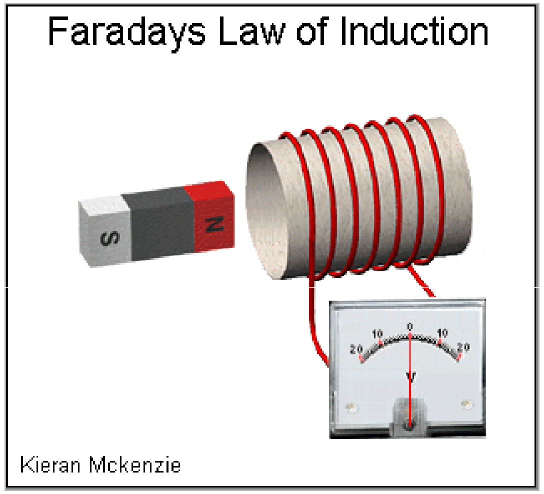
  v = velocity of conductor (m/sec)

  **Statically Induced emf**

  $e = N\, d\phi/dt$

- Fleming's RH Rule

  $1^{st}$ finger-B, Thumb-v then induced emf by $2^{nd}$ finger




# Classification of Electric Machines

## On basis of Linking Flux

- DC Machines

Moving conductor & stationary permanent magnet or dc electromagnet – all DC Generator & Motor

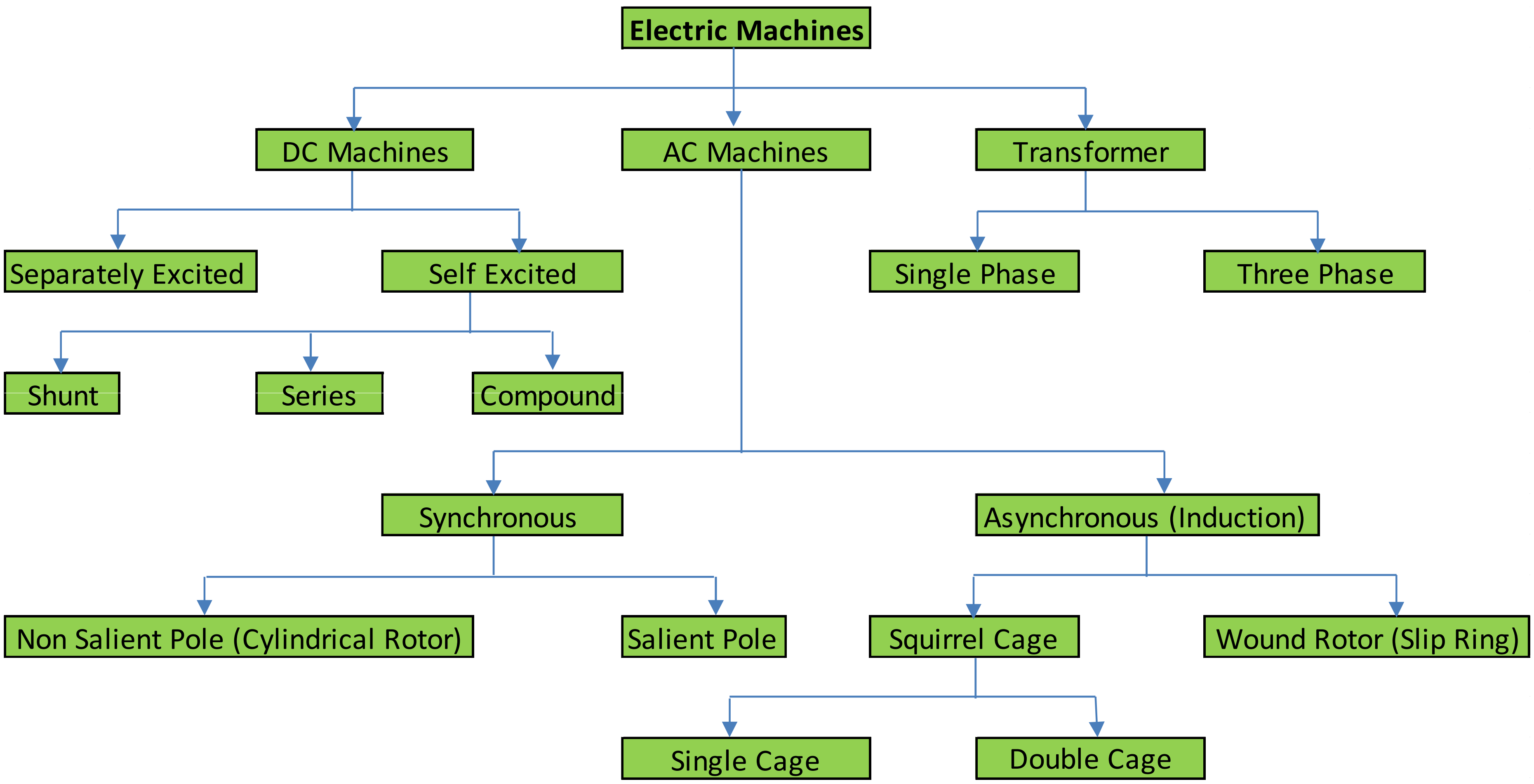
- AC Machines

Moving permanent magnet or dc electromagnet & stationary conductor – all AC Generator & Motor

- Transformers

Stationary conductor & stationary electromagnet and variation of flux by feeding ac to magnet – all Transformer

- In electro-mechanical energy conversion process exchange of energy takes place between a mechanical system and an electric system via magnetic medium.
- An electromechanical device that convert mechanical energy into electric energy is called a generator.
- An electromechanical device that convert electric energy into mechanical energy called a motor.
- An electromagnetic device that converts voltage from one level to an other is called transformer.


Electric Machines
DC Machines
AC Machines
Transformer
Separately Excited
Self Excited
Single Phase
Three Phase
Shunt
Series
Compound
Synchronous
Asynchronous (Induction)
Non Salient Pole (Cylindrical Rotor)
Salient Pole
Squirrel Cage
Wound Rotor (Slip Ring)
Single Cage
Double Cage

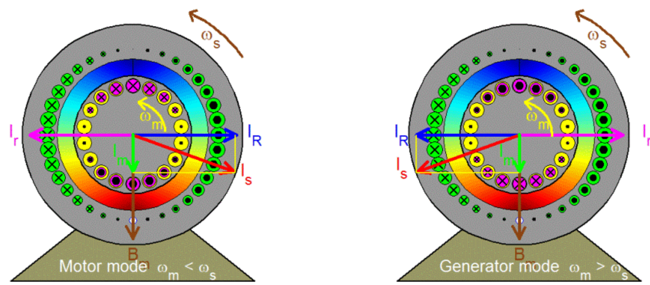
# Generator & Motor Action of Electric Machine

$e = Blv \sin\theta$

$F = BIl \sin\theta$

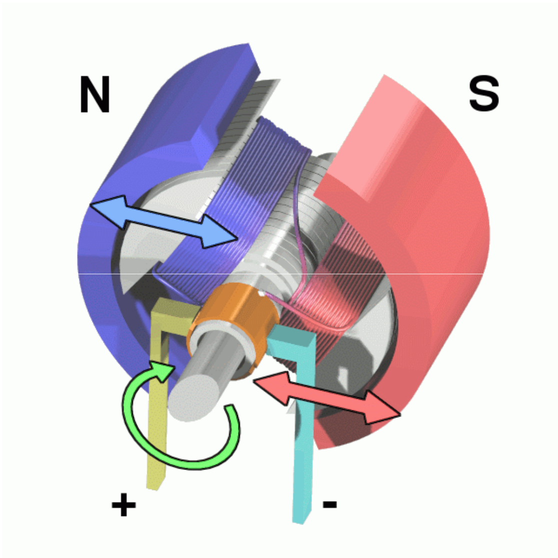
- When relative motion between conductor & magnetic field exists, an emf is induced in conductor causes current situated in magnetic field, a force is exerted on conductor. Both generator & motor actions takes place simultaneously in winding of rotating machine.
- Thus both torque & emf are produced with in winding, it is not possible to distinguish between generator & motor actions without finding the direction of power flow.

- In generator torque produced is counter torque which opposes rotation. The prime mover must overcome this counter torque.
- In motor emf generated is counter emf (back emf) which opposes the applied voltage. The supply voltage must overcome this back emf.



# Electric Motor?

An electromechanical device that converts electrical energy to mechanical energy




Mechanical energy used to e.g.

- Rotate pump impeller, fan, blower
- Drive compressors
- Lift materials

Motors in industry: 70% of electrical load

# Types of Motor Loads

| Motor loads | Description | Examples |
|---|---|---|
| Constant torque loads | Output power varies but torque is constant | Conveyors, rotary kilns, constant-displacement pumps |
| Variable torque loads | Torque varies with square of operation speed | Centrifugal pumps, fans |
| Constant power loads | Torque changes inversely with speed | Machine tools |

# How does DC Electric Motor work?

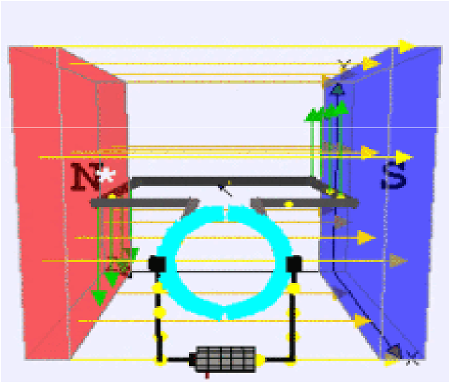
When ever a current carrying conductor is placed in a magnetic field, it experienced a force whose direction is given by Fleming's left hand rule (also called motor rule).

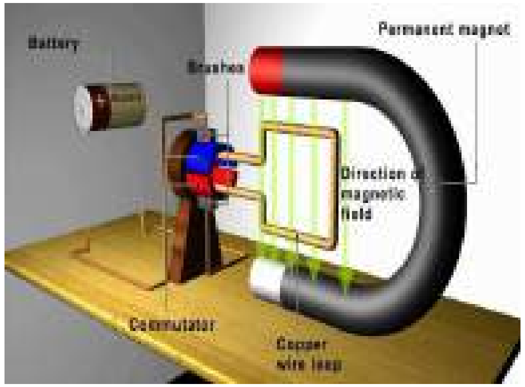
- Force on current carrying conductor

F = BIl sinθ

Where

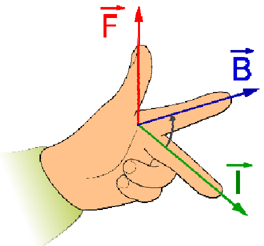
F = force on conductor
B = magnetic field
I = current
l = length of conductor




- Fleming's LH Rule

1st finger-B, 2nd finger-I then force by thumb




DC Motor invented by Frank Sprague in 1884

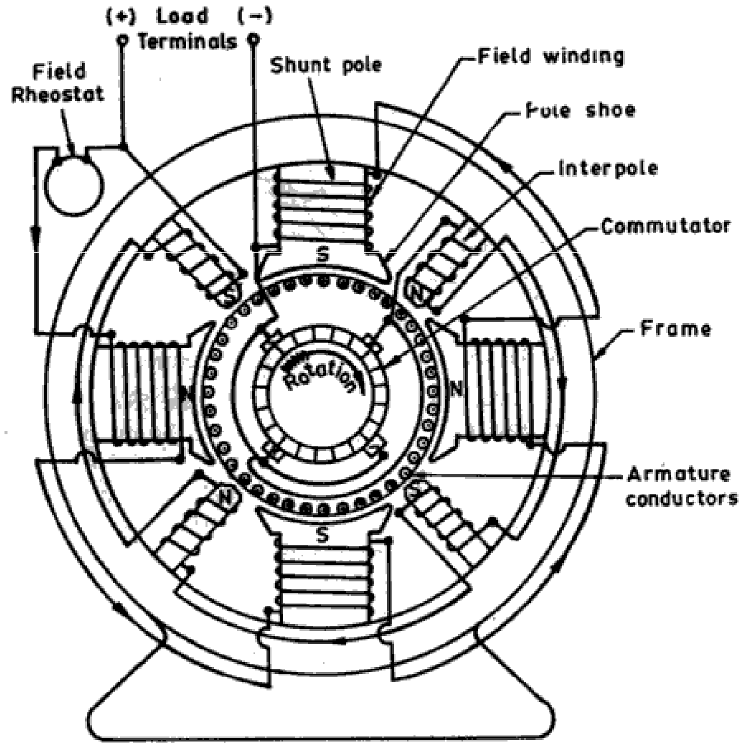
# Components of DC Motor

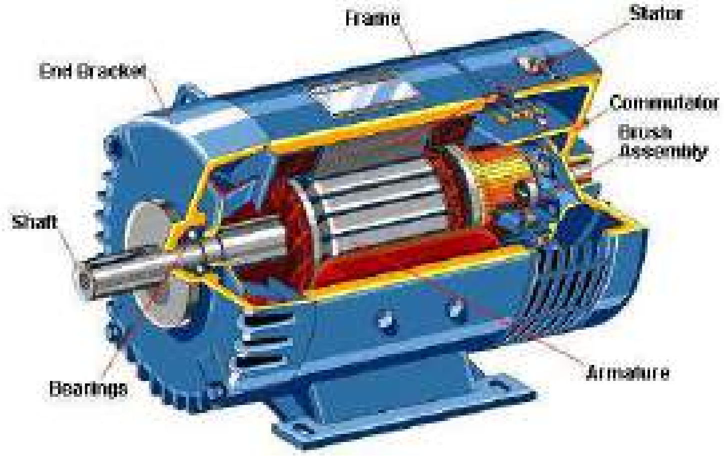
## Stator

- Yoke / Frame
- Field poles
  - ✓ Pole core
  - ✓ Pole shoe
  - ✓ Field winding

## Rotor

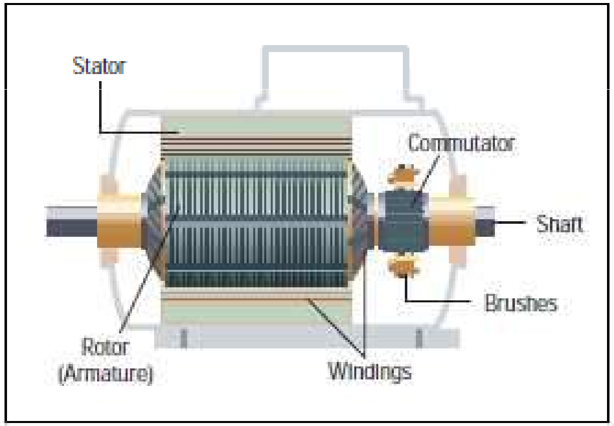
- Armature
  - ✓ Armature core
  - ✓ Armature winding
- Commutator
  - ✓ Brushes
  - ✓ Interpoles
- Shaft
- Bearings



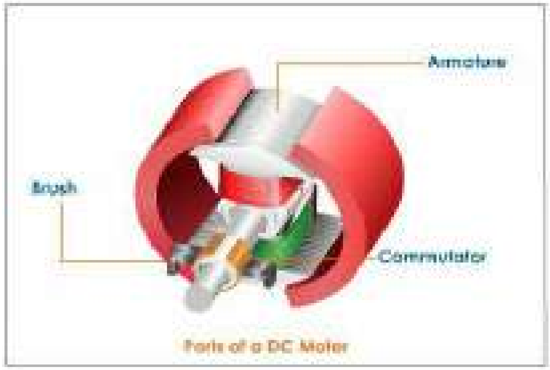
# Contd.. Components of DC Motor

- **Stator** In which field winding is placed. Field winding is excited by DC supply and it is concentrated on the pole cores on the stator.
- **Rotor** In which armature is placed. Electrical input is given to the armature in case of motor and electrical output is taken in case of generator.
- **Air Gap** Stator and rotor are separated by a small air gap (0.5 – 1.0 mm) in which flux is set up.
- **Yoke or Frame** It covers the whole machine and provides the mechanical support to the poles.
- **Pole Core** Field winding is mounted on the pole core.
- **Interpoles** These help in reducing the arcing due to commutation of current.



# Contd.. Components of DC Motor

- **Pole Shoes** The pole shoes acts as a support to the field coils and spreads out the flux over the armature periphery more uniformly.
- **Commutator** This is used for rectification (ac to dc) in case of generator and for conversion (dc to ac ) in case of motor.
- **Brushes** The function is to collect current from commutator in case of generator and feed current into commutator in case of motor. They are made of carbon/graphite.
- **Bearings** The main function of a bearing is to support the rotating parts and to allow its smooth motion with minimum friction.
- **Shaft** The shaft is made of mild steel with a maximum breaking strength.



# Types of Windings

## Lap Winding

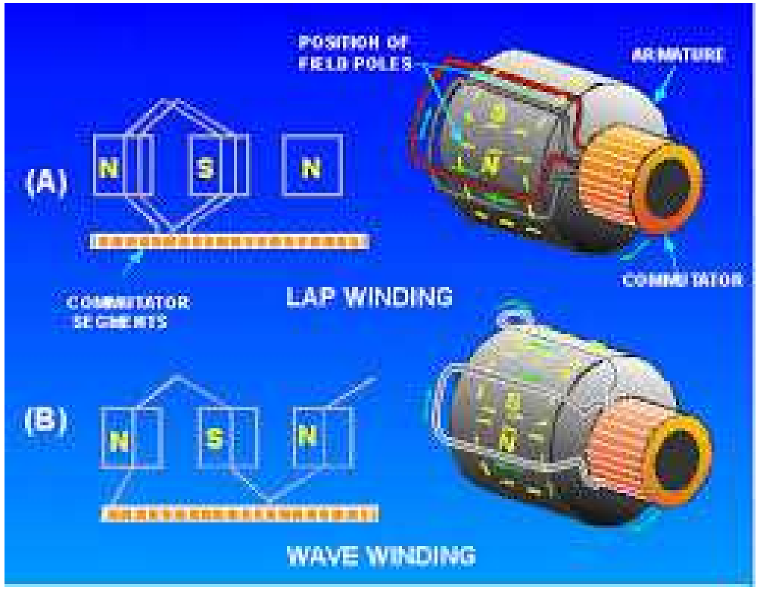
✓Finish of each coil is connected to start of next coil.

✓Equalizer rings are provided to keep circulating currents inside the section.

## Wave Winding

✓ Finish of coil is connected to start of another coil well away from first coil.

✓ One extra coil is used to maintain mechanical balance of armature, called dummy coil.



# Induced emf / Back emf & Torque developed in a Machine

$$E_b = (ZP/60A)\ \phi N$$

$$E_b = (ZP/2\pi A)\ \phi\omega \quad \ldots\ldots\ldots\ldots(1)$$

Where

Z = no. of armature conductors

P = no. of poles

A = no. of parallel path

N = speed of m/c

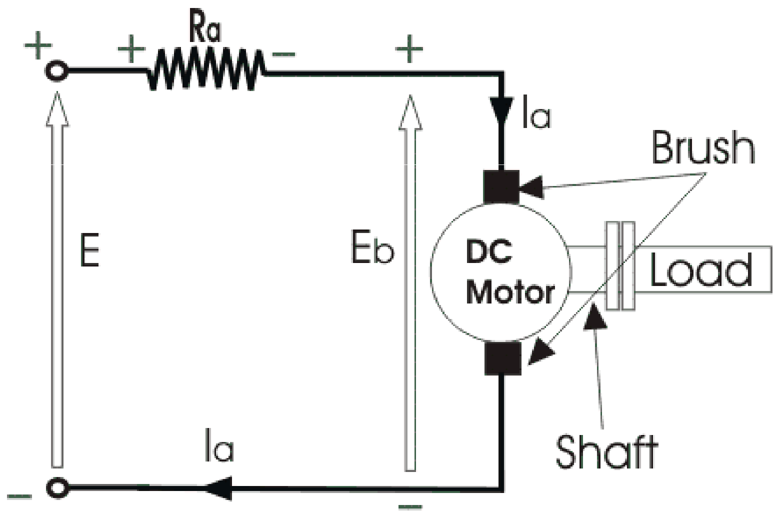
When voltage is applied to armature, motor develops a torque

$$T = (ZP/2\pi A)\ \phi I \quad \ldots\ldots\ldots\ldots(2)$$

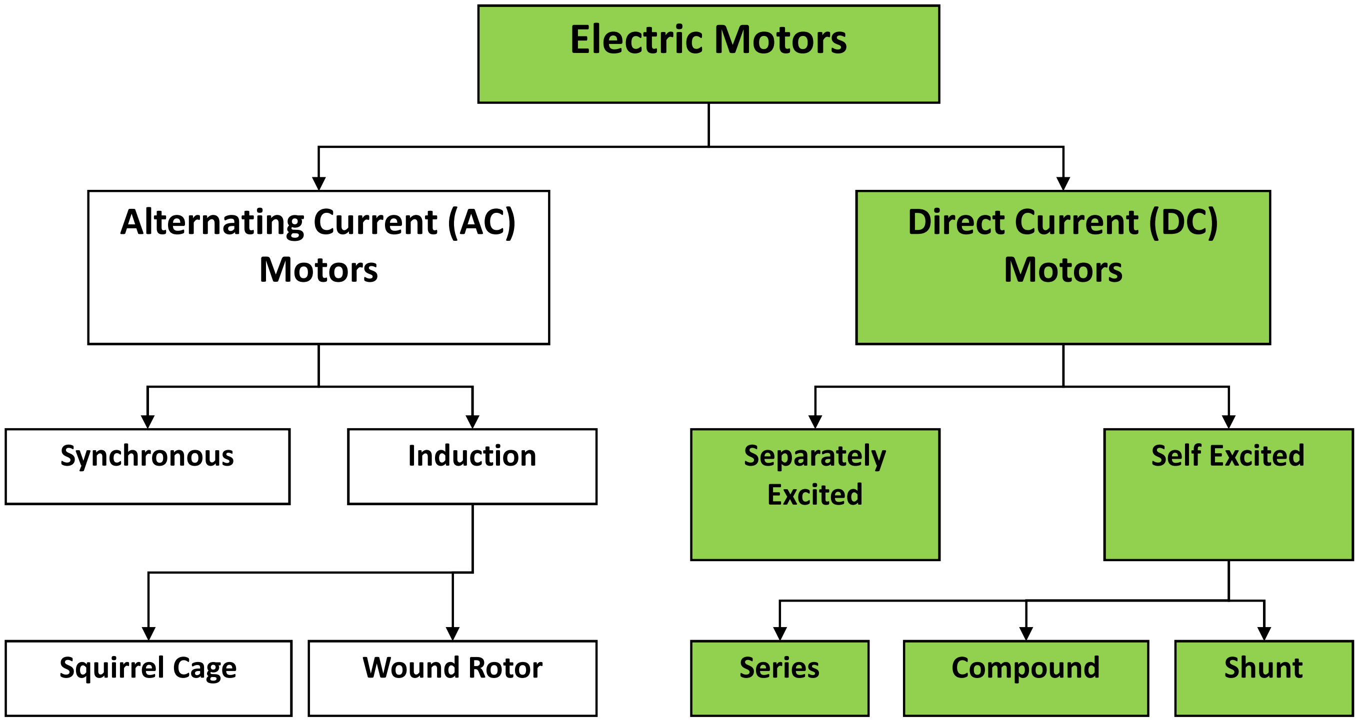
From Equation (1) & (2)

$$EI = \omega T = P$$

Electric Power = Mechanical Power



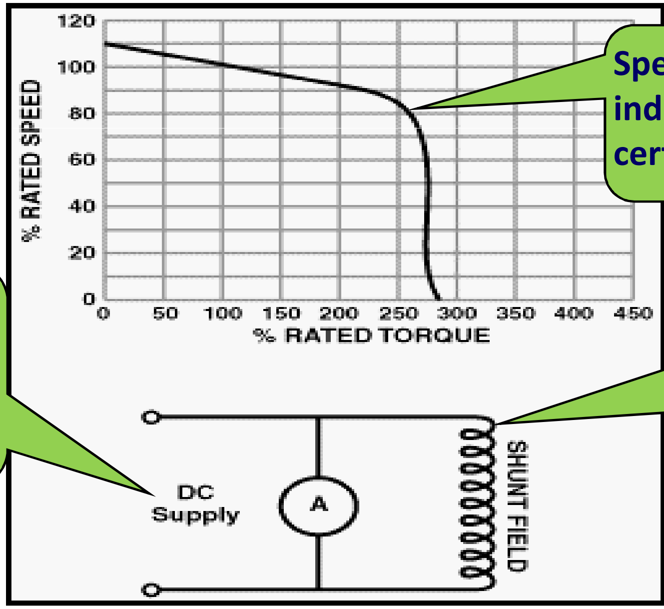
# Types of DC Electric Motors



# Contd.. Types of DC Electric Motors

Separately Excited DC motor: field current supplied from a separate source

Self-excited DC motor: Shunt Motor




**Speed constant independent of load up to certain torque**

**Field winding parallel with armature winding**
**Current = field current + armature current**

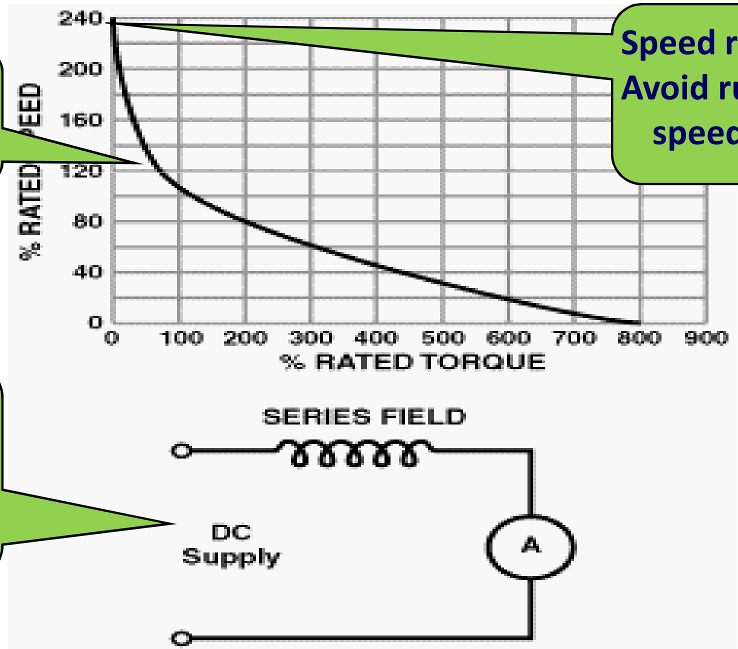
**Speed control: insert resistance in armature or field current**

# Contd.. Types of DC Electric Motors

Self-excited DC motor: Series Motor

Suited for high starting torque: cranes, hoists

Speed restricted to 5000 RPM
Avoid running with no load: speed uncontrolled



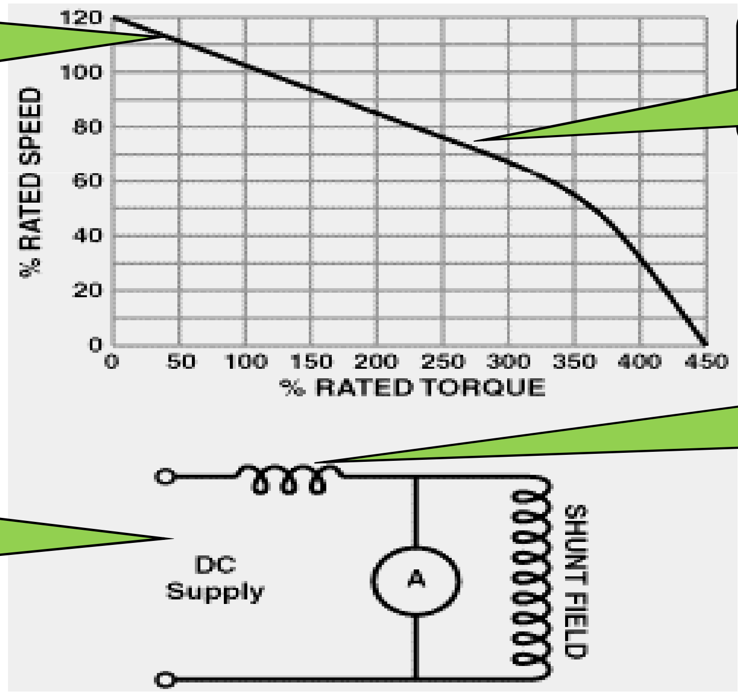

Field winding in series with armature winding
Current = Field current = armature current

# Contd.. Types of DC Electric Motors

Self-excited DC motor: Compound Motor

**Suited for high starting torque if high % compounding: cranes, hoists**

**Good torque and stable speed**




**Higher % compound in series = high starting torque**

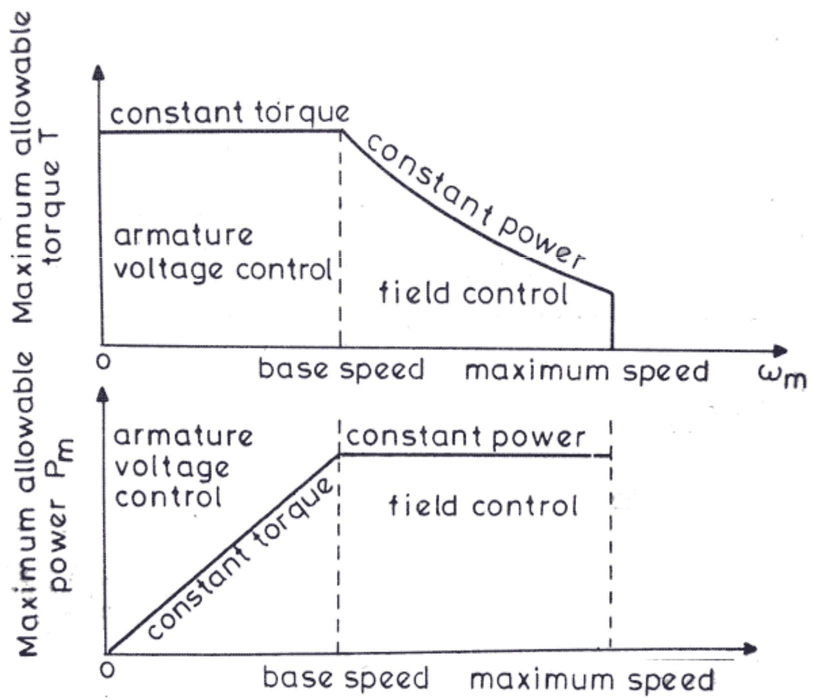
**Field winding in series and parallel with armature winding**

# Features of DC Motor

## Speed Control of DC Motor

$N = (V - I_a R_a) / K\phi$

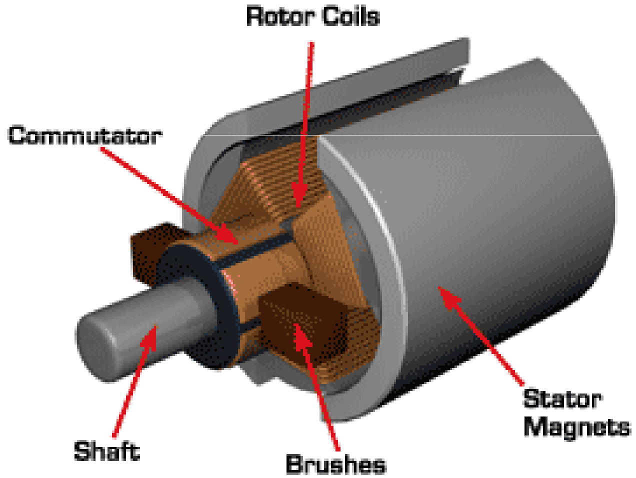
- **Armature control**
  I. Armature voltage control
  II. Armature resistance control
- ✓ Used to obtain speed below rated speed
- ✓ Applicable to constant torque drives
- **Field control**
- ✓ Used to obtain speed above rated speed
- ✓ Applicable to constant power drives



# Contd.. Features of DC Motor

## Starting of DC Motor

- $E_b = V - IR$
- At standstill N = 0 i.e. back emf $E_b = 0$
- i.e. I = V/R = 220/0.01
- This may be 20 times the rated current and may damagerous for motor
- To limit this current additional resistance in series with armature is provided.



# Contd.. Features of DC Motor

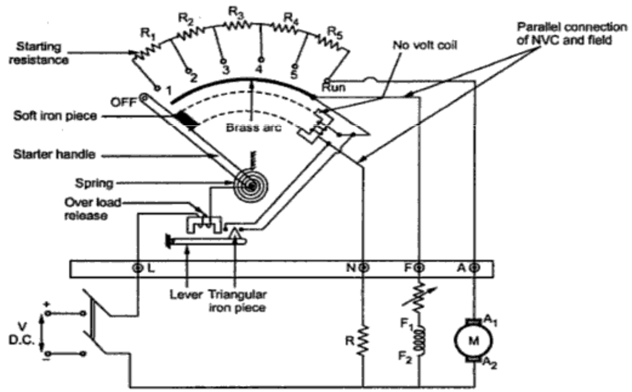
## Starting of DC Motor

- **Manual Starter**

1. DOL starter – for very small motors up to 5 KW
2. Resistance starter – for small motors
3. Three point / four point starter

- **Automatic starter**

1. Counter emf starter
2. Time delay starter




**4 point Starter**

# Contd.. Features of DC Motor

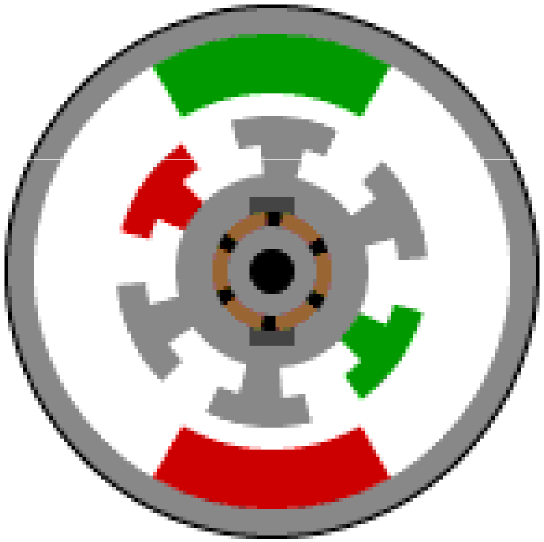
## Braking of DC Motor

- **Dynamic** – Armature disconnected from supply and braking resistance is connected to its terminals, heat is dissipated through applied resistance.
- **Plugging** – Armature connections are reversed, produced high braking torque
- **Regenerative** – Field current is increased so that induced emf becomes more than the supply voltage, armature current & torque are reversed. Motor acts as generator and feed supply back to the system.

# Contd.. Features of DC Motor

## Merits of DC Motor

1. High starting torque.
2. Speed control over a wide range, both below and above normal speed
3. Accurate seedless speed control
4. Quick starting, stopping.



## Demerits of DC Motor

1. High initial cost.
2. Increased operating and maintenance costs because of the commutator and brushes.

# Contd.. Features of DC Motor

## Application of DC Motor

- **DC shunt motor**

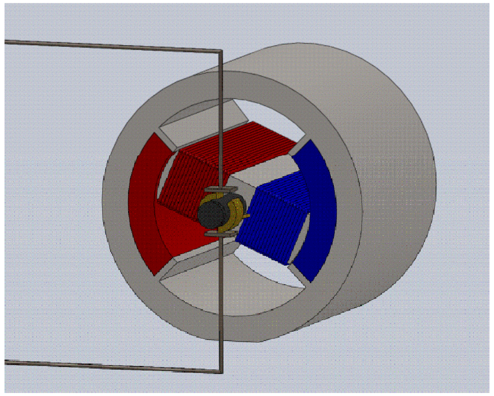
✓ Medium starting torque like pumps, fans, blowers etc.

- **DC series motor**

✓ Very high starting torque like hoists, cranes, tractions etc.

- **Compound motor**

✓ Good starting torque like pulsating loads conveyors, shears, crushers etc.



# How does Induction Motor work?

Electricity supplied to stator conductors

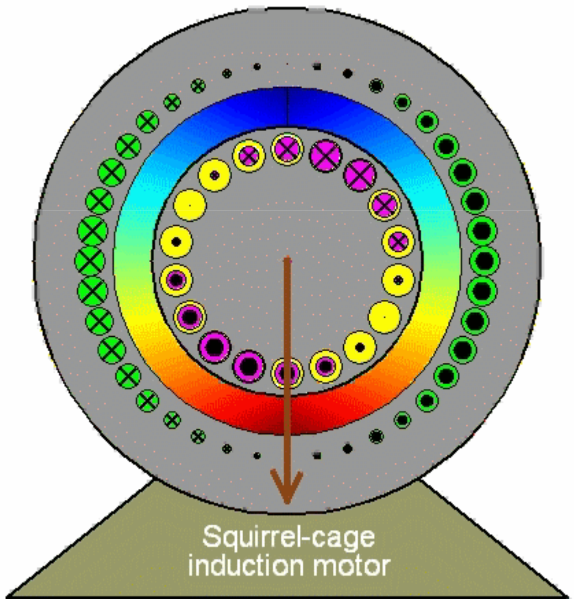
Magnetic field generated that moves around rotor

Current induced in rotor conductors

Rotor produces second magnetic field that opposes stator magnetic field

Interaction of stator & rotor fields produces a torque results to rotor starts to rotate

AC Motor invented by Tesla in 1888



# Components of AC Electric Motors

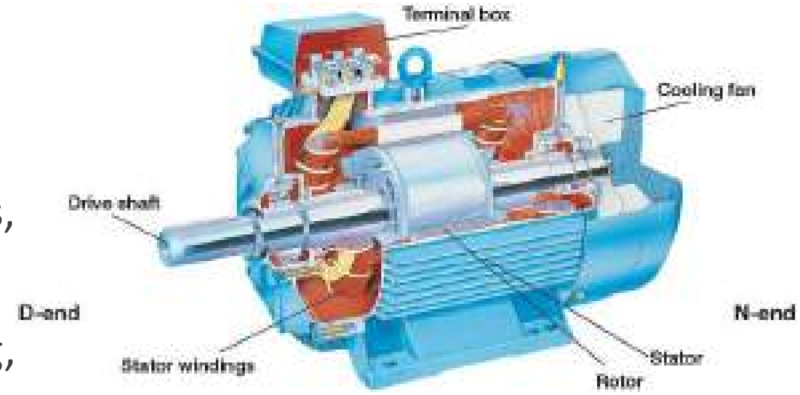
## Components

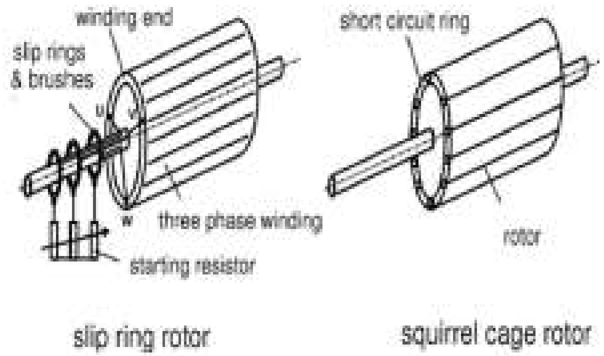
**Rotor**

- ✓Squirrel cage: conducting bars in parallel slots, low starting torque.
- ✓Wound rotor: double-layer, distributed winding, high starting torque.

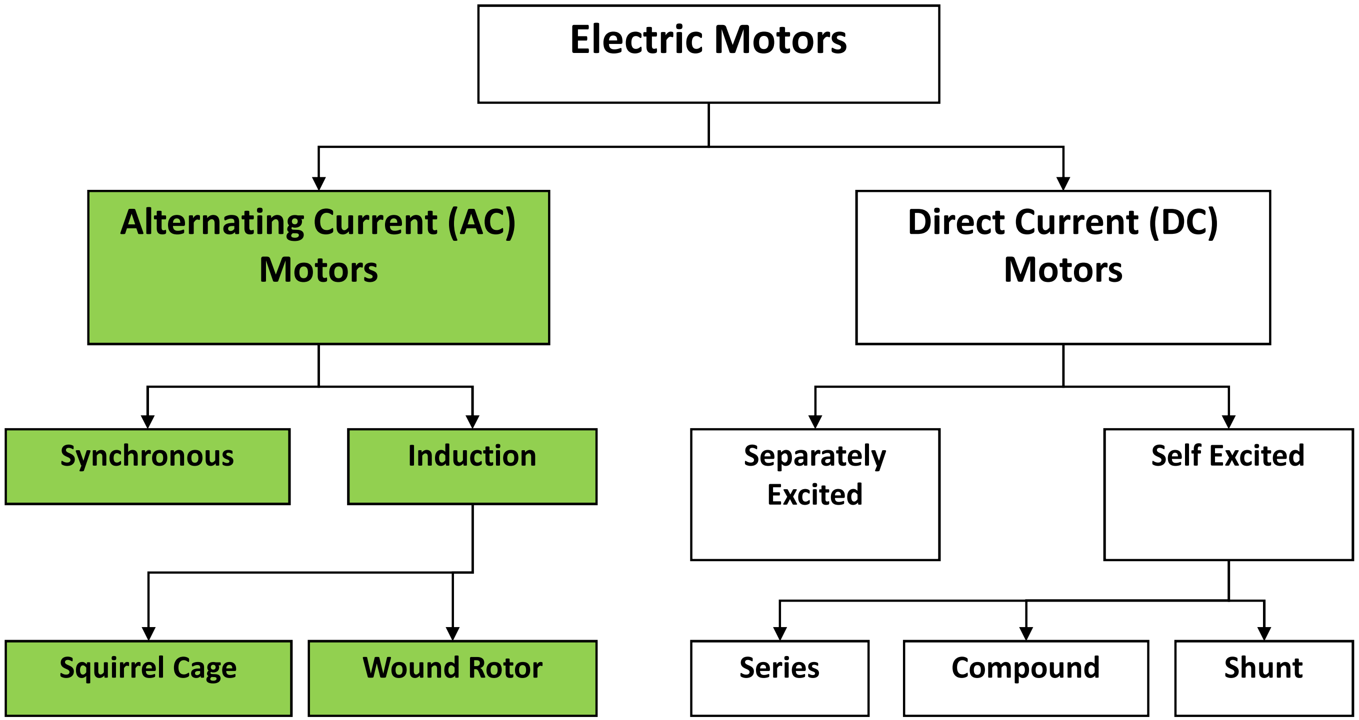
**Stator**

- ✓Stampings with slots to carry 3-phase windings
- ✓Wound for definite number of poles



# Type of AC Electric Motors



# Contd.. Type of AC Electric Motors

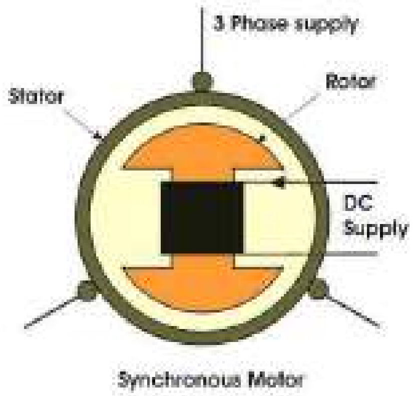
Synchronous motor armature mmf rotates in opposite direction of rotor mmf and equal to each other i.e. self starting torque is unavailable.

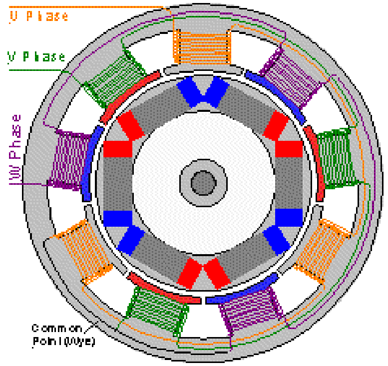
Induction motor armature mmf rotates in opposite direction of rotor mmf and must not be same for producing self starting torque i.e. rotor speed is always less than synchronous speed.

# Features of AC Electric Motor

## AC Motor – Synchronous Motor

- Constant speed fixed by system frequency
- DC for excitation
- Can improve power factor, also called synchronous condenser: suited for high electricity use systems
- Synchronous speed (Ns)




$$Ns = 120\ f\ /\ P$$

Where
f = frequency
P = no. of poles

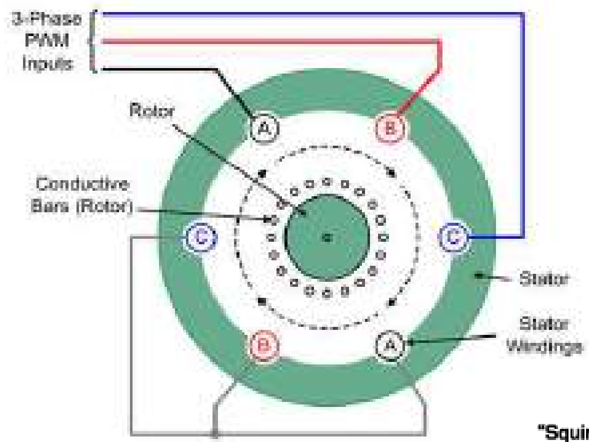
# Features of AC Electric Motor

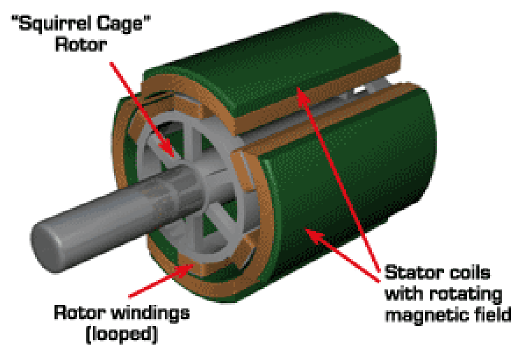
## AC Motor – Induction Motor

Most common motors in industry

Advantages:

- Simple design
- More efficient
- Inexpensive
- High power to weight ratio
- Easy to maintain
- Direct connection to AC power source



# Contd.. Features of AC Electric Motor

## AC Motors – Induction Motor

**Single-phase induction motor**

- One stator winding
- Single-phase power supply
- Squirrel cage rotor
- Require device to start motor
- 3 to 4 HP applications
- Household appliances: fans, washing machines, dryers

# Contd.. Features of AC Electric Motor

## AC Motors – Induction Motor

**Three-phase induction motor**

Three-phase supply produces magnetic field

Squirrel cage or wound rotor

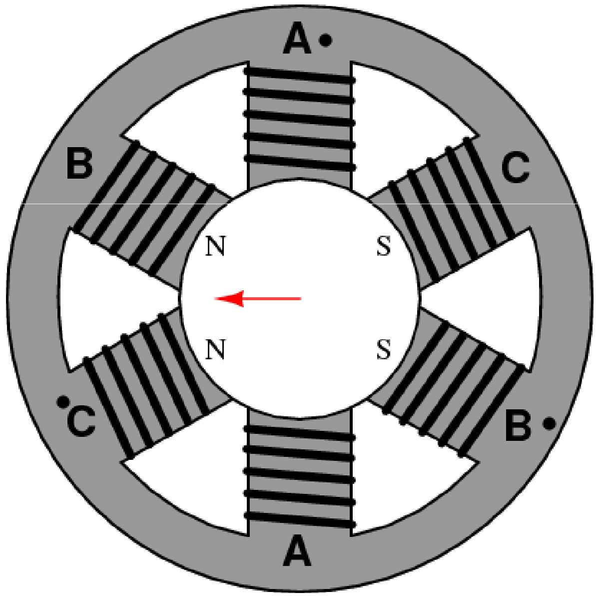
Self-starting

High power capabilities

Available in 1/3 to thousands HP rating

Applications: pumps, fans, compressors, conveyor belts etc.

70% of motors in industry!



# Contd.. Features of AC Electric Motor

## AC Motors – Induction Motor

**Speed and Slip**

Motor never runs at synchronous speed but always run lower to synchronous speed.

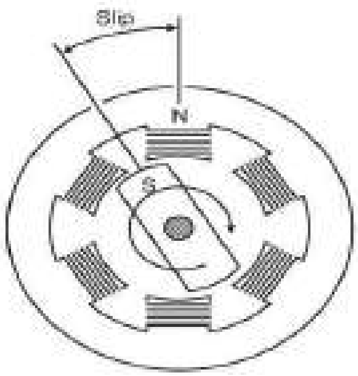
Because emf induced in rotor conductor would be zero resulting torque would be zero.

Difference is "slip"

Calculate % slip:

$$\% \text{ Slip} = \frac{Ns - Nr}{Ns} \times 100$$

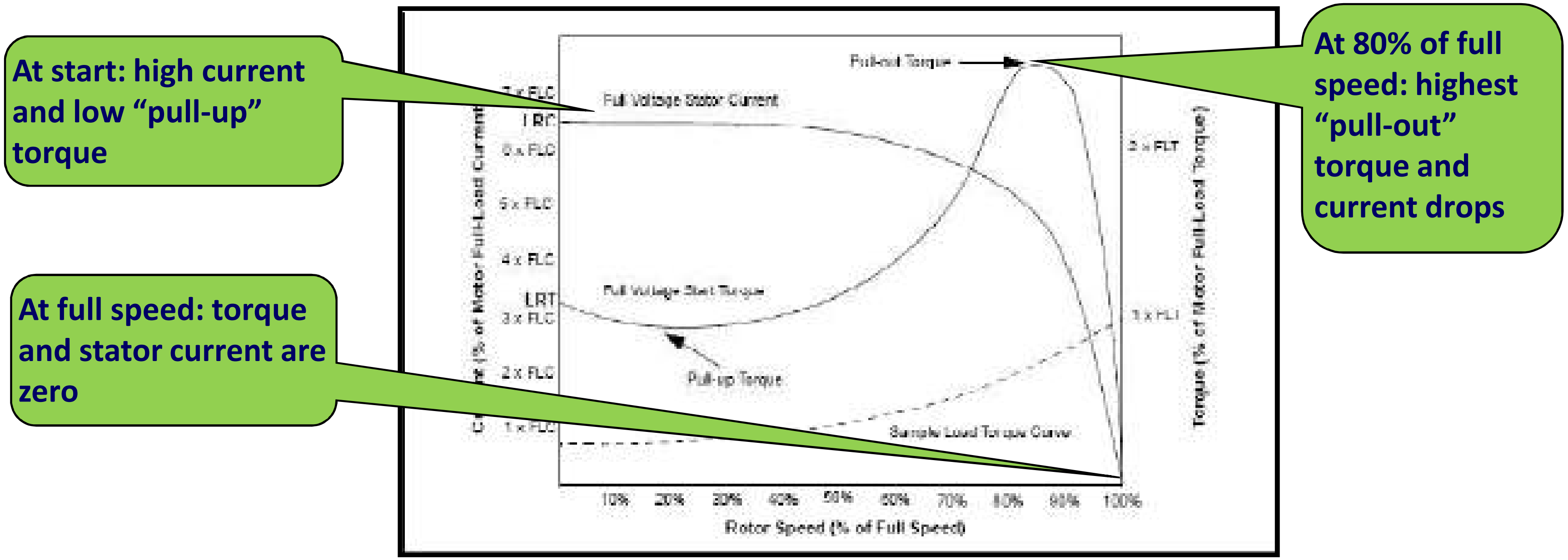
Where
Ns = synchronous speed in RPM
Nr = rotor speed in RPM



# Contd.. Features of AC Electric Motor

## AC Motors – Induction Motor

Relationship load, speed and torque



# Contd.. Features of AC Electric Motor

Induction motor vs Synchronous motor

- Starting torque – self/no
- Speed – asynchronous/synchronous
- Excitation - singly/doubly
- Power factor – lagging/adjustable
- Application - Supplying mechanical loads/power factor controller

# Contd.. Features of AC Electric Motor

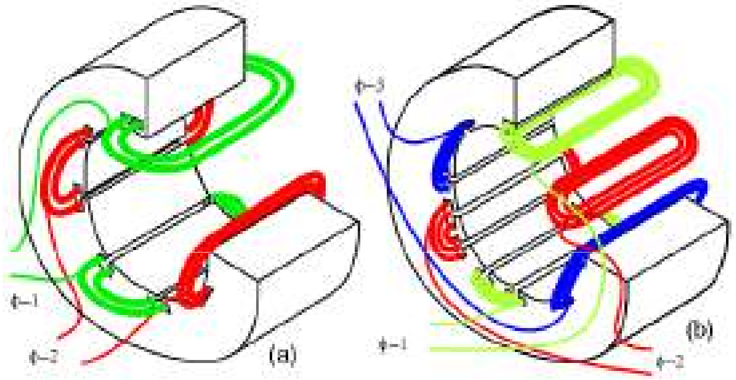
## Speed Control of Induction Motor

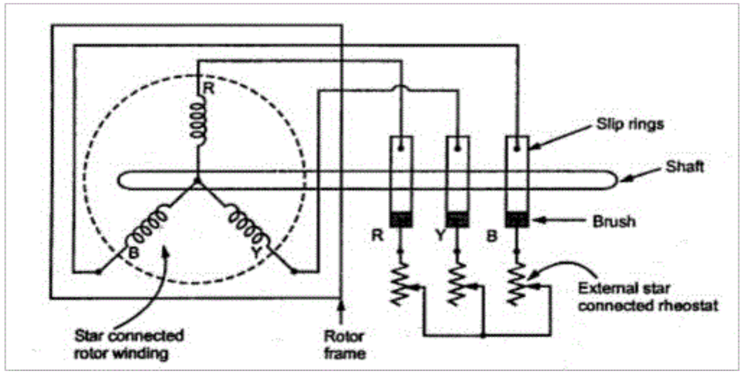
**Squirrel cage motors**

- Pole changing
- Stator voltage control (T$\alpha$ $V^2$)
- Eddy current coupling (Dynodrive)
- Frequency control (VFD)
- Cascade connection

**Wound rotor motors**

- Rotor resistance control
- Slip power recovery

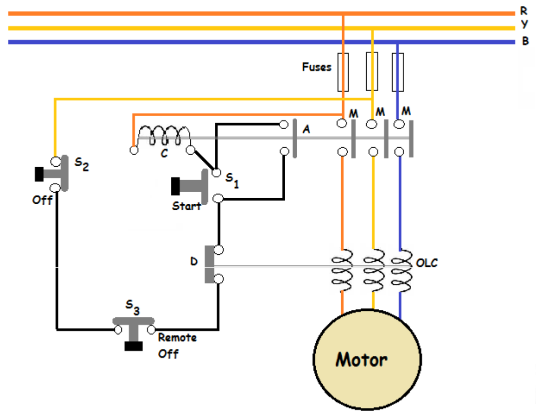


# Contd.. Features of AC Electric Motor

## Starting of Induction Motors

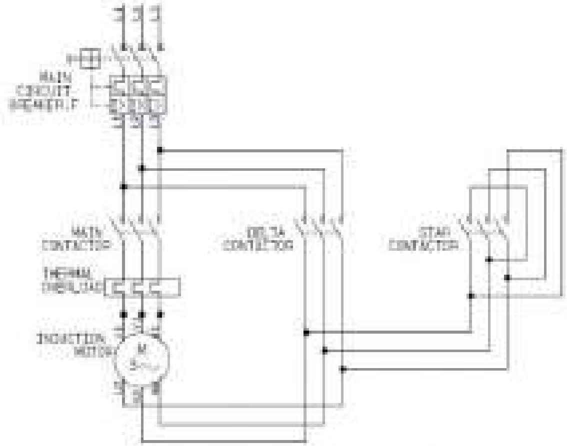
It takes 5 to 8 times full load current if starts at rated voltage. Large current at low pf drawn by motor is objectionable because considerable voltage drop in supply voltage occurs & affect performance of other equipment connected to same supply.



Direct On Line (DOL) Starter Wiring Diagram

### Squirrel cage motors

- Direct on line starters
- Star-delta starters
- Auto transformers



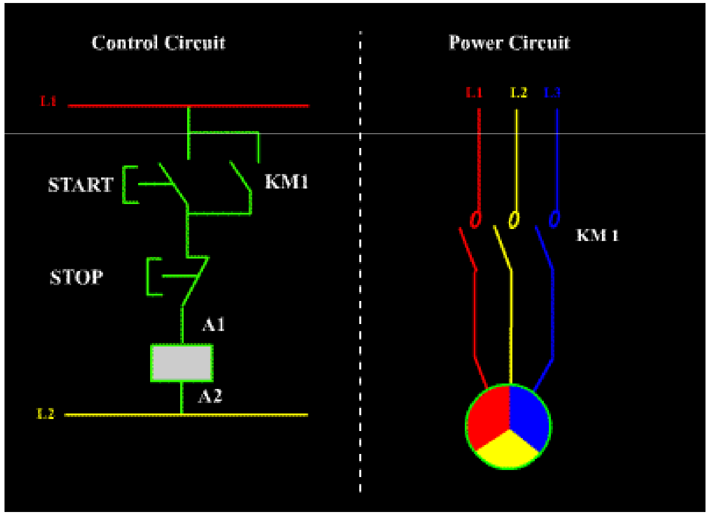
### Wound rotor motors

- Rotor resistance method

# Contd.. Features of AC Electric Motor

## Braking of Induction Motor

- **Dynamic** – Armature disconnected from supply and braking resistance is connected to its terminals, heat is dissipated through applied resistance.
- **Plugging** – Armature connections are reversed, produced high braking torque
- **Regenerative** – Motor acts as generator and feed supply back to the system.



# Contd.. Features of AC Electric Motor

## Single Phasing of Induction Motor

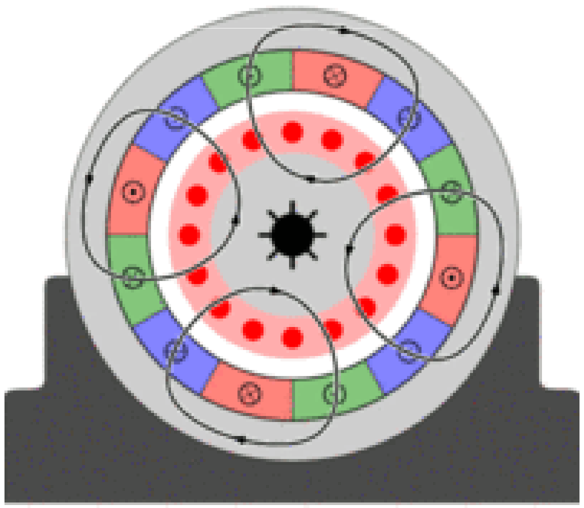
- In case of full load, the motor may stall.
- In case of light loading, the motor may continue operating but with poor performance. Both stator & rotor will get overheated and resulting failure of the motor insulation.

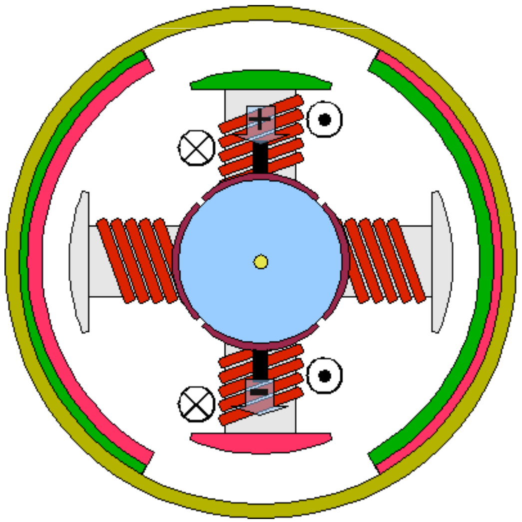
## Cogging & Crawling Phenomena

- In squirrel cage IM, motor may not starts when number of stator slots are equal to rotor slots - Cogging.
- For some other ratio it may run at very low speed - Crawling.

# DC motor vs AC motor

- AC motor are cheaper, more rugged / robust and requires lesser maintenance because of absence of commutator & carbon brushes like to dc motor
- DC motor has improved system power factor than AC motor. But DC drive has very poor PF in range 0.4-0.85.

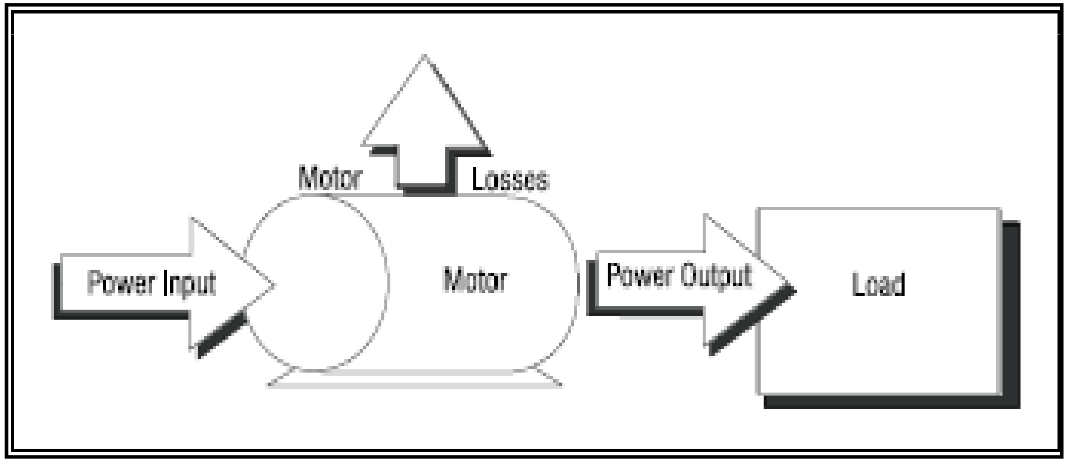




# Assessment of Electric Motor

## Efficiency of Electric Motor

- Efficiency of motor = (Power input – Losses) / Power input



# Contd.. Assessment of Electric Motor

## Losses in Electric Motor

- **Copper loss – 50%**
  - Armature copper loss – 30%
  - Field copper loss – 20%
- **Iron / core / no-load / magnetic loss – 20 %**
  - Hysteresis loss
  - Eddy current loss
- **Mechanical loss – 30%**
  - Friction loss / bearing friction
  - Windage loss / air friction loss
  - Stray load loss / distorted armature reaction

# Contd.. Assessment of Electric Motor

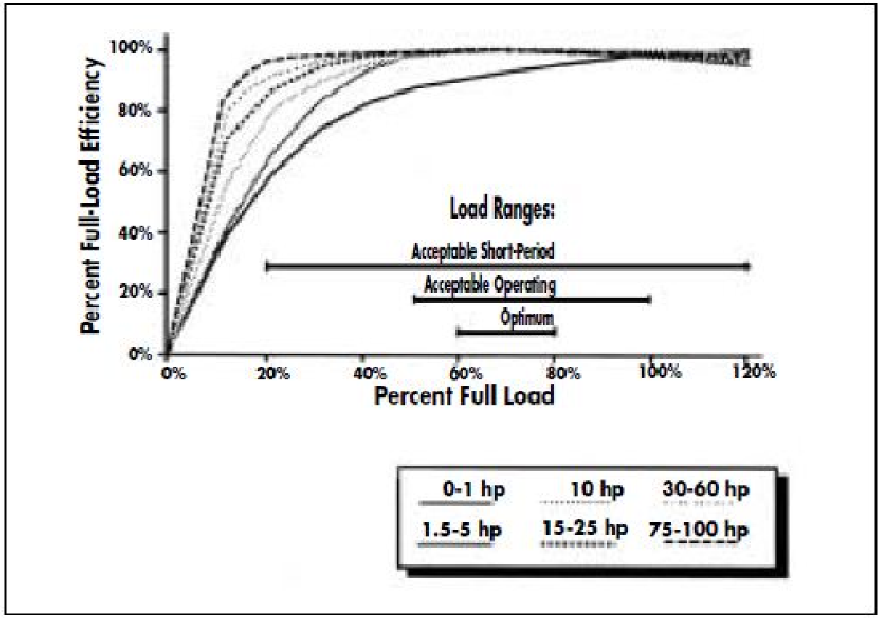
## Factors influencing efficiency of Electric Motor

- Age
- Capacity
- Speed
- Type
- Temperature
- Rewinding
- Load

# Contd.. Assessment of Electric Motor

## Assessment by efficiency calculations

- ✓Designed for 50-100% load
- ✓Most efficient at 75% load
- ✓Rapid drop below 50% load




Motor Part-Load Efficiency (as a Function of % Full-Load Efficiency)

# Contd.. Assessment of Electric Motor

## Motor load

Motor load is indicator of efficiency

Equation to determine load:

$$\text{Load} = \text{Pi} \times \eta \ \text{HP} \times 0.746$$

Where

| | |
|---|---|
| Load | = Output power as a % of rated power |
| Pi | = Three phase power in kW = √3.V.I.Cosϕ/100 |
| η | = Motor operating efficiency in % |
| HP | = Nameplate rated horse power |

# Contd.. Assessment of Electric Motor

## Motor Load

| Result | Action |
| --- | --- |
| 1. Significantly oversized and under loaded | → Replace with more efficient, properly sized models |
| 2. Moderately oversized and under loaded | → Replace with more efficient, properly sized models when they fail |
| 3. Properly sized but standard efficiency | → Replace most of these with energy-efficient models when they fail |

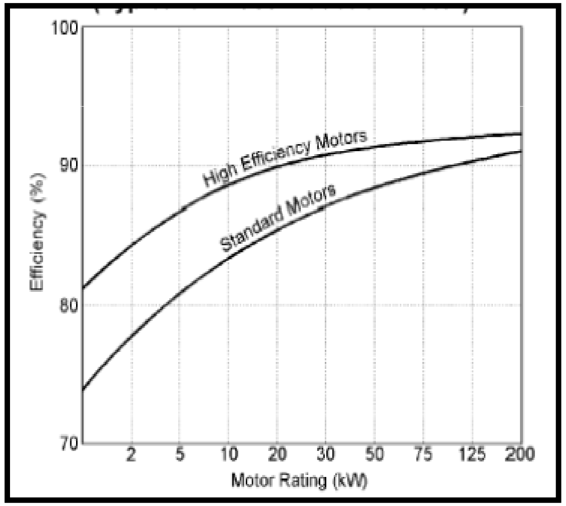
# Energy Efficiency Opportunities

1. Use energy efficient motors
2. Reduce under-loading (and avoid over-sized motors)
3. Sizing to variable load
4. Improve power quality
5. Rewinding
6. Power factor correction by capacitors
7. Improve maintenance
8. Speed control of electric motor

# Contd.. Energy Efficiency Opportunities

## 1. Use Energy Efficient Motors

- Reduce intrinsic motor losses
- Efficiency 3-7% higher
- Wide range of ratings
- More expensive but rapid payback
- Best to replace when existing motors fails



# Contd.. Energy Efficiency Opportunities

## Contd.. Use Energy Efficient Motors

- IS 12615:2004 (based on CEMEP:2000-European Committee of Manufacturers of Electric Machines and Power Electronics)
  - Eff2 - Improved efficiency
  - Eff1 – High efficiency
- IS 12615:2011 (based on IEC 60034-30:2008 – International Electrotechnical Commission)
  - IE1 - Standard efficiency
  - IE2 – High efficiency
  - IE3 – Premium efficiency

# Contd.. Energy Efficiency Opportunities

## 2. Reduce Under-loading

Reasons for under-loading

- Large safety factor when selecting motor
- Under-utilization of equipment
- Maintain outputs at desired level even at low input voltages
- High starting torque is required

Consequences of under-loading

- Increased motor losses
- Reduced motor efficiency
- Reduced power factor

# Contd.. Energy Efficiency Opportunities

## Contd.. Reduce Under-loading

Replace with smaller motor

- If motor operates at <50%
- Not if motor operates at 60-70%

Operate in star mode

- If motors consistently operate at <40%
- Inexpensive and effective
- Motor electrically downsized by wire reconfiguration
- Motor speed and voltage reduction but unchanged performance

# Contd.. Energy Efficiency Opportunities

## 3. Sizing to Variable Load

Motor selection based on

X • Highest anticipated load: expensive and risk of under-loading

✓ • Slightly lower than highest load: occasional overloading for short periods

(Motor should have service factor 15% above rated load)

But avoid risk of overheating due to

- Extreme load changes
- Frequent / long periods of overloading
- Inability of motor to cool down

# Contd.. Energy Efficiency Opportunities

## 4. Improve Power Quality

### Motor performance affected by

Poor power quality: too high fluctuations in voltage and frequency

Voltage unbalance: unequal voltages to three phases of motor

Keep voltage unbalance within 1%

- Balance single phase loads equally among three phases
- Segregate single phase loads and feed them into separate line/transformer

# Contd.. Energy Efficiency Opportunities

## 5. Rewinding

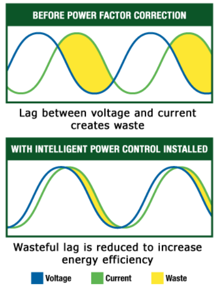
Rewinding: sometimes 50% of motors

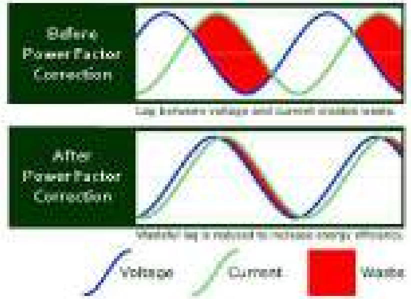
Can reduce motor efficiency

Maintain efficiency after rewinding by

- Using qualified/certified firm
- Maintain original motor design
- Replace 40HP, >15 year old motors instead of rewinding
- Buy new motor if costs are less than 50-65% of rewinding costs

# Contd.. Energy Efficiency Opportunities



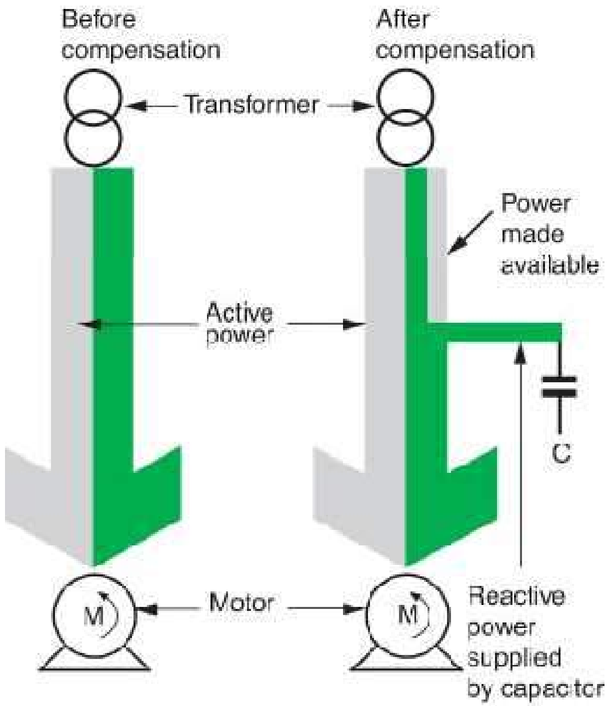

## 6. Improve Power Factor (PF)

Use power factor capacitors for induction motors

Benefits of improved PF

- Reduced kVA demand
- Reduced losses
- Improved voltage regulation
- Increased efficiency of plant electrical system

Capacitor size not >90% of no-load kVAR of motor



# Contd.. Energy Efficiency Opportunities

## 7. Maintenance

Checklist to maintain motor efficiency

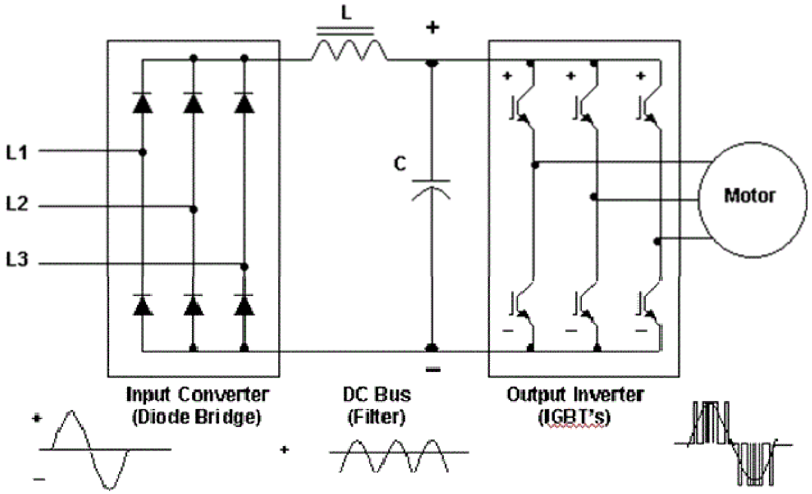
- Inspect motors regularly for wear, dirt/dust
- Checking motor loads for over/under loading
- Lubricate appropriately
- Check alignment of motor and equipment
- Ensure supply wiring and terminal box and properly sized and installed
- Provide adequate ventilation
- Proper earthing of motor

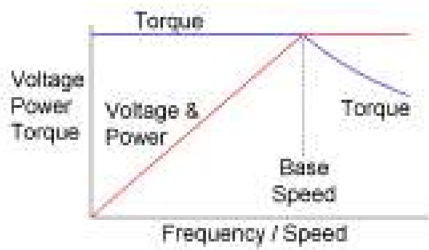
# Contd.. Energy Efficiency Opportunities

## 8. Speed Control of Induction Motor

Variable frequency drives (VFDs)

- Most common method for speed controlling
- Can be installed in existing system
- Reduce electricity consumption by >30% in fans and pumps
- Convert 50 Hz incoming power to variable frequency and voltage: change speed



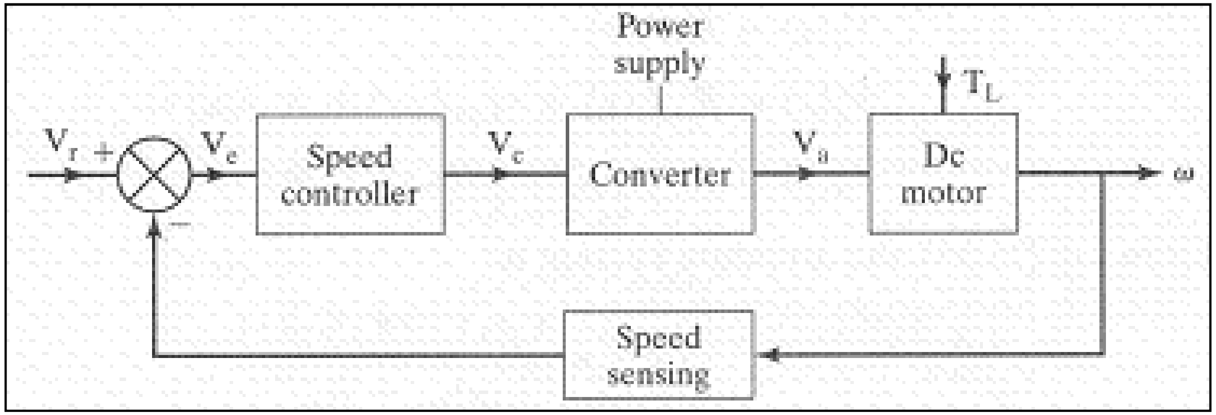



# Contd.. Energy Efficiency Opportunities

## 8. Speed Control of DC Motor

Direct Current Drives

- Oldest form of electrical speed control
- Consists of
  - DC motor: field windings and armature
  - Controller & Convertor: regulates DC voltage to armature that controls motor speed
  - Tacho-generator: gives feedback signal to controlled



# Contd.. Energy Efficiency Opportunities

## 8. Speed Control of DC Motor

- Direct current (dc) motors have variable characteristics and are used extensively in variable-speed drives.
- DC motors can provide a high starting torque and it is also possible to obtain speed control over a wide range.
- The methods of speed control are normally simpler and less expensive than those of AC drives.
- Both series and shunt DC motors are normally used in variable-speed drives, but series motors are traditionally employed for traction applications.
- Due to commutators, DC motors are not suitable for very high speed applications and require more maintenance than to AC motors.

# KW Calculation for Pump Motor

## KW Rating Equation

$$KW = QxHxSG / 270x1.36x\eta$$

Where

Q = Capacity of pump ($m^3/hr$)

H = Pumping head (m)

SG = Specific Gravity of fluid

$\eta$ = Pump efficiency (%)

| Fluid | Specific Gravity |
|---|---|
| Fresh Water | 1.000 |
| Salted Water | 1.024 |
| Lube Oil | 0.850 |
| Diesel Oil | 0.850 |
| Cane Juice | 1.060 |
| Molasses | 1.400 |

# Contd.. KW Calculation for Pump Motor

## Example

A seawater service pump installed in the engine room at a 50 °C ambient. Calculate the kilowatt rating of the motor, when the pump capacity is 80 m3/hr at 100 m pressure head, at 80% pump efficiency (ç), and motor efficiency (ç) is 92%.

**Steps:**

*Motor Killowatt = QxHxSG / 270x1.36xη*

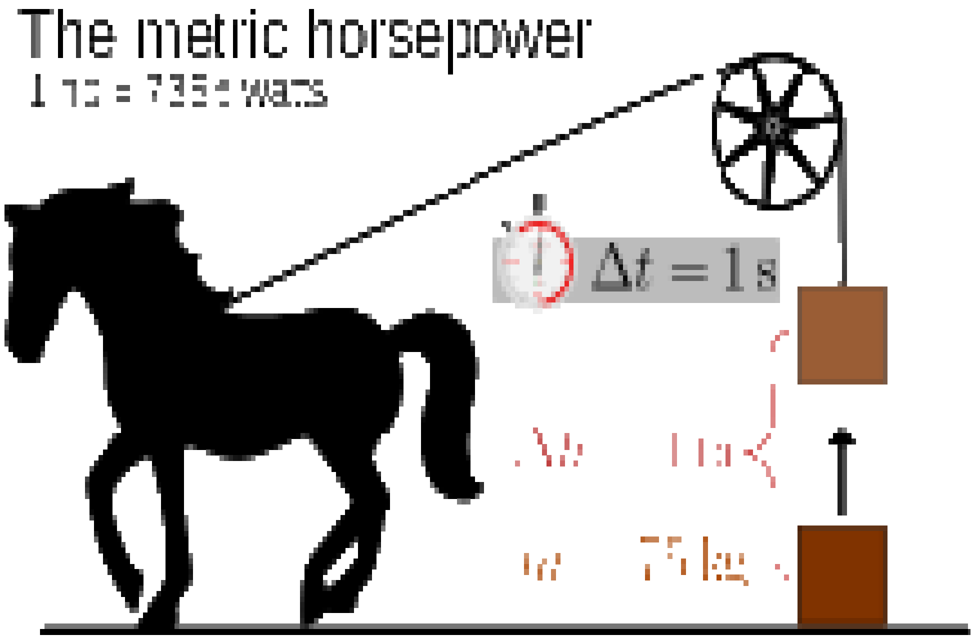
*= 80x100x1.024 / 270x1.36x80*

*= 27.90 KW*

*At 92% Efficiency Motor KW = 27.90 / 0.92 = 30.32 KW ≈ 30 KW*

# KW & HP Rating of Electric Motor

One metric horsepower is needed to lift 75 kilograms (avg. body weight of a person) by 1 meter (3.28 feet) in 1 second.



# Thank You


DC Motor Video

Induction Motor Video