Electrical Drives

Lecture 15 (12-03-2024)

INDUCTION MACHINES

- The principle of 3 phase induction machines.
- Perform an analysis on induction machines which is the most rugged and the most widely used machine in industry.

INDUCTION MACHINES

- Overview of Three-Phase Induction Motor
- Construction
- Principle of Operation
- Equivalent Circuit
  - Power Flow, Losses and Efficiency
  - Torque-Speed Characteristics

Overview of Three-Phase INDUCTION MOTORS

Induction motors are used worldwide in many residential, commercial, industrial, and utility applications.

Induction Motors transform electrical energy into mechanical energy.

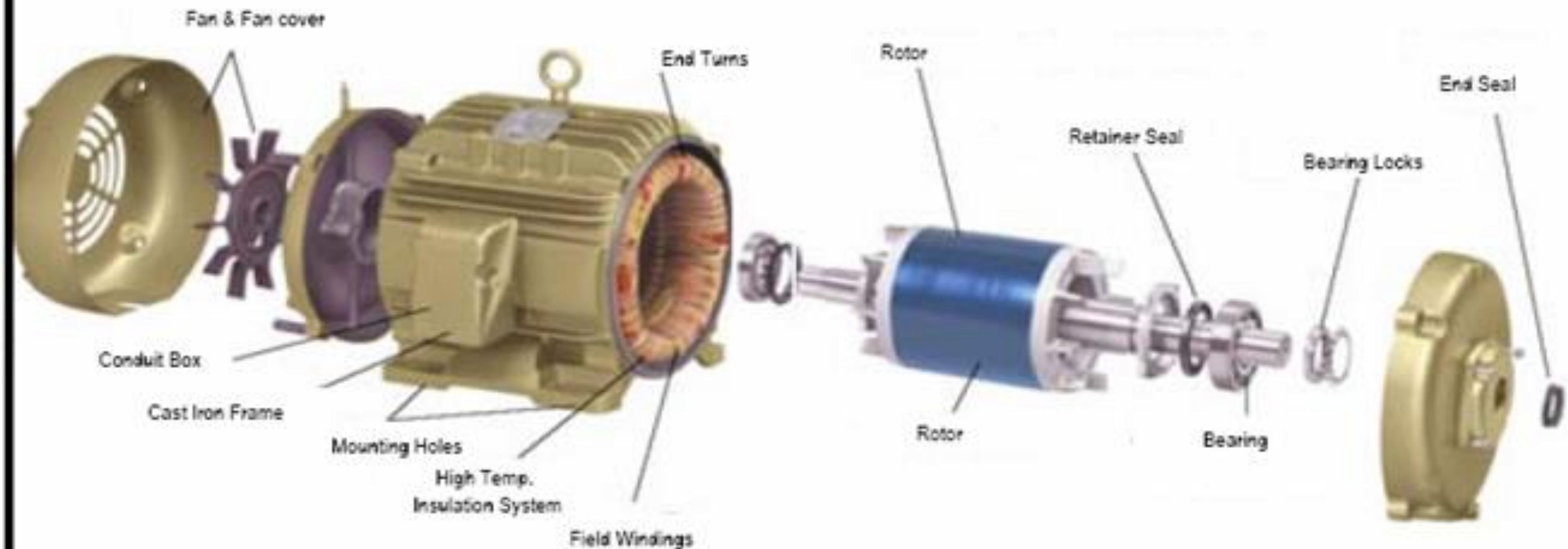
It can be part of a pump or fan, or connected to some other form of mechanical equipment such as a winder, conveyor, or mixer.

INTRODUCTION

General aspects

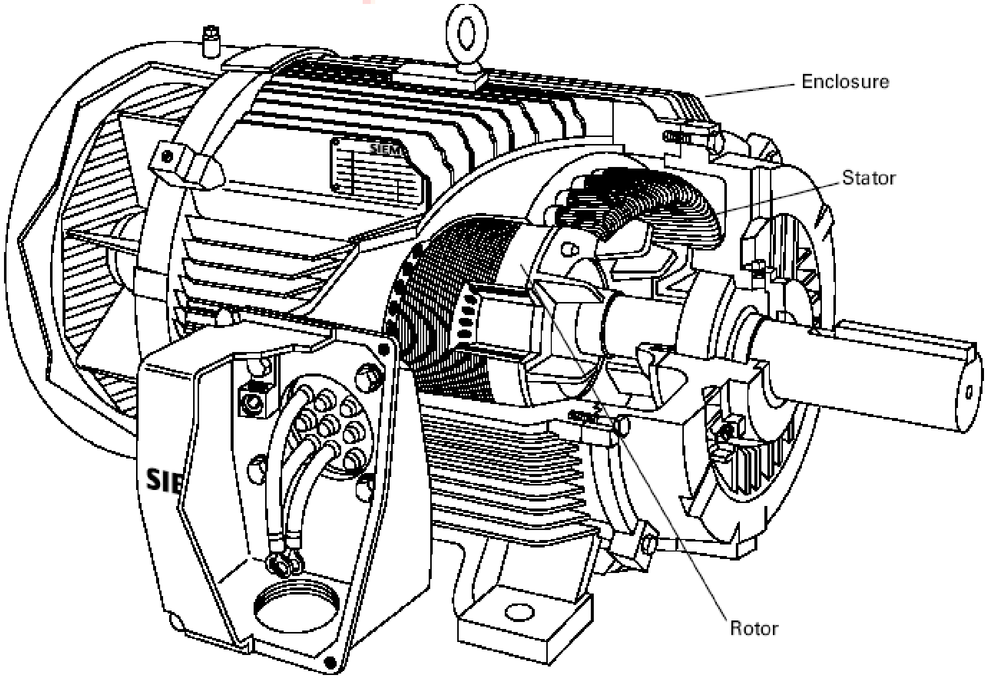
- A induction machine can be used as either a induction generator or a induction motor.
- Induction motors are popularly used in the industry
- Focus on three-phase induction motor
- Main features: cheap and low maintenance
- Main disadvantages: speed control is not easy

Parts of AC Motor



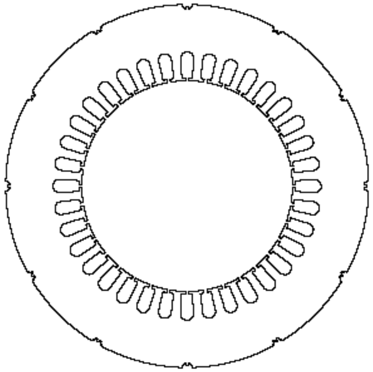
Construction

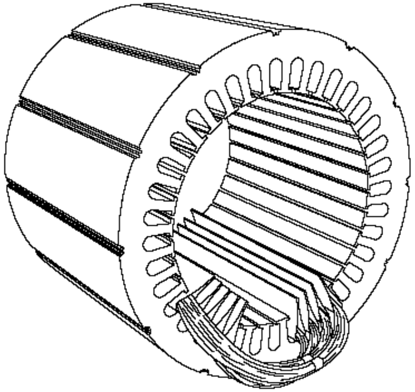
- The three basic parts of an AC motor are the rotor, stator, and enclosure.
- The stator and the rotor are electrical circuits that perform as electromagnets.

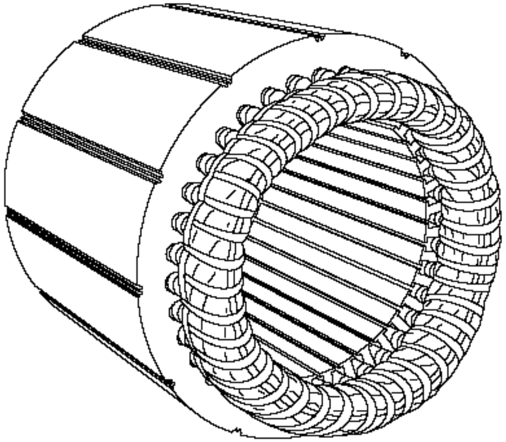


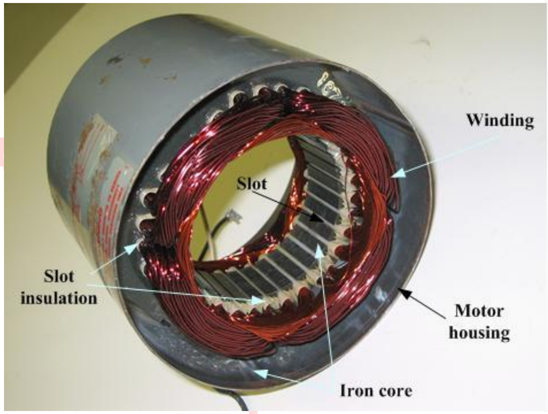
Construction (Stator construction)

- The stator is the stationary electrical part of the motor.
- The stator core of a National Electrical Manufacturers Association (NEMA) motor is made up of several hundred thin laminations.
- Stator laminations are stacked together forming a hollow cylinder. Coils of insulated wire are inserted into slots of the stator core.
- Electromagnetism is the principle behind motor operation. Each grouping of coils, together with the steel core it surrounds, form an electromagnet. The stator windings are connected directly to the power source.









Construction (Rotor construction)

- The rotor is the rotating part of the electromagnetic circuit.
- It can be found in two types:
  - Squirrel cage
  - Wound rotor
- However, the most common type of rotor is the "squirrel cage" rotor.

Construction (Rotor construction)

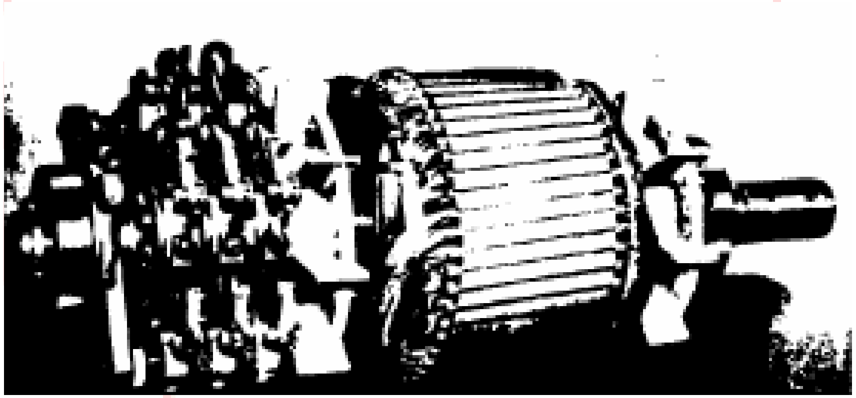
- Induction motor types:

  - **Squirrel cage type:**
    - Rotor winding is composed of copper bars embedded in the rotor slots and shorted at both end by end rings
    - Simple, low cost, robust, low maintenance

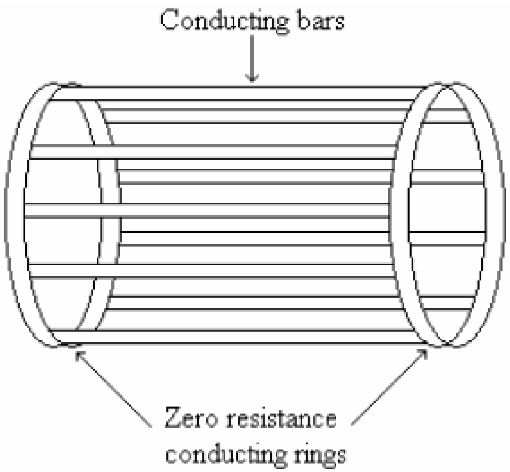
  - **Wound rotor type:**
    - Rotor winding is wound by wires. The winding terminals can be connected to external circuits through slip rings and brushes.
    - Easy to control speed, more expensive.

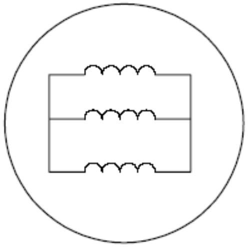
Construction (Rotor construction)

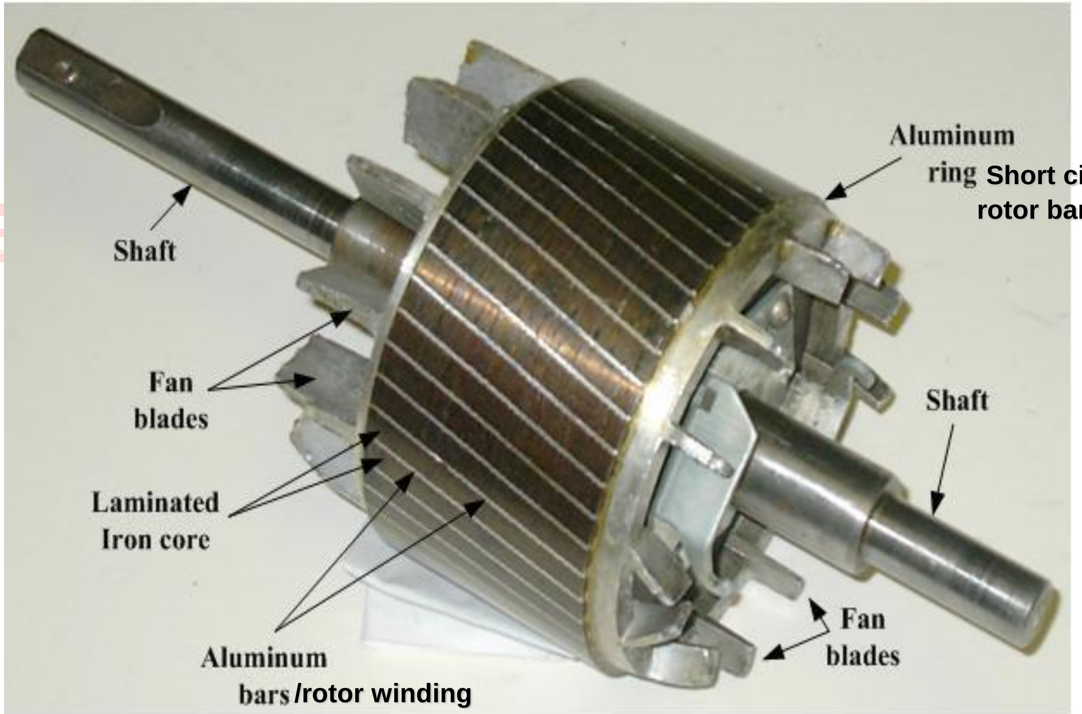
Wound Rotor



Squirrel-Cage Rotor



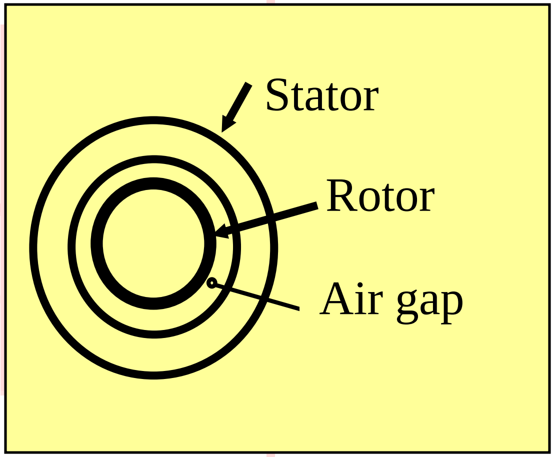




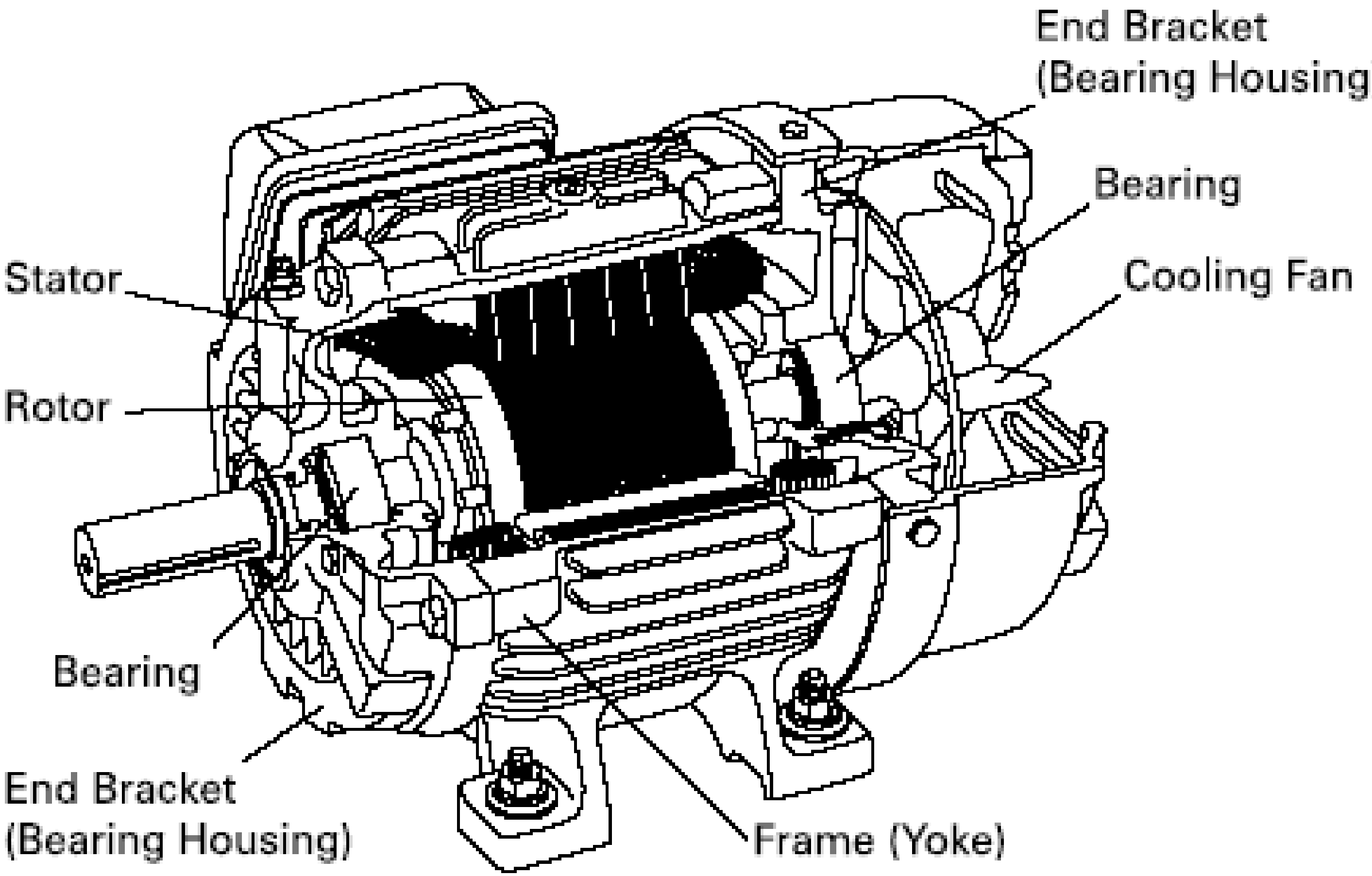
Construction (Enclosure)

- The enclosure consists of a frame (or yoke) and two end brackets (or bearing housings). The stator is mounted inside the frame. The rotor fits inside the stator with a slight air gap separating it from the stator. There is **NO** direct physical connection between the rotor and the stator.

- The enclosure also protects the electrical and operating parts of the motor from harmful effects of the environment in which the motor operates. Bearings, mounted on the shaft, support the rotor and allow it to turn. A fan, also mounted on the shaft, is used on the motor shown below for cooling.



Construction (Enclosure)



Nameplate

SIEMENS

PE•21 PLUS™ — PREMIUM EFFICIENCY

ORD.NO.	1LA02864SE41			E NO.			
TYPE	RGZESD			FRAME	286T		
H.P.	30.00			SERVICE FACTOR	1.15		3 PH
AMPS	34.9			VOLTS	460		
R.P.M.	1765			HERTZ	60		
DUTY	CONT		40°C AMB.			DATE CODE	
CLASS INSUL.	F	NEMA DESIGN	B	K.V.A. CODE	G	NEMA NOM. EFF.	93.6
SH. END BRG.	50BC03JPP3			OPP. END BRG.	50BC03JPP3		

51-770-642

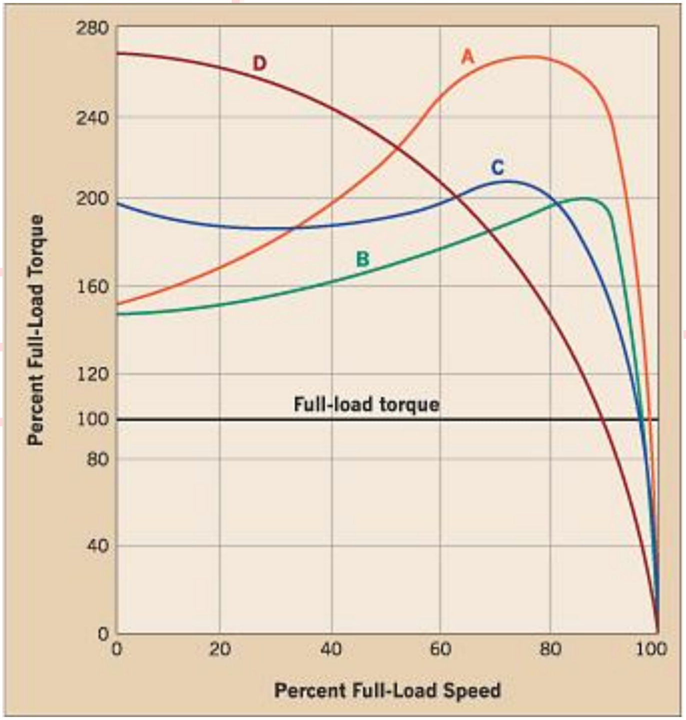
MILL AND CHEMICAL DUTY QUALITY INDUCTION MOTOR

Siemens Energy & Automation, Inc. Little Rock, AR

MADE IN U.S.A.

Service factor — Service factor (SF) is an indication of how much overload a motor can withstand when operating normally within the correct voltage tolerances. For example, the standard SF for open drip-proof (ODP) motors is 1.15. This means that a 10-hp motor with a 1.15 SF could provide 11.5 hp when required for short-term use.

NEMA design letter — Certain types of machinery may require motors with specialized performance characteristics. For example, cranes and hoists that have to start with full loads imposed may require motors with operating characteristics much different from what is required for pumps and blowers. Motor performance characteristics can be altered by design changes in lamination, winding, rotor, or any combination of these three items.

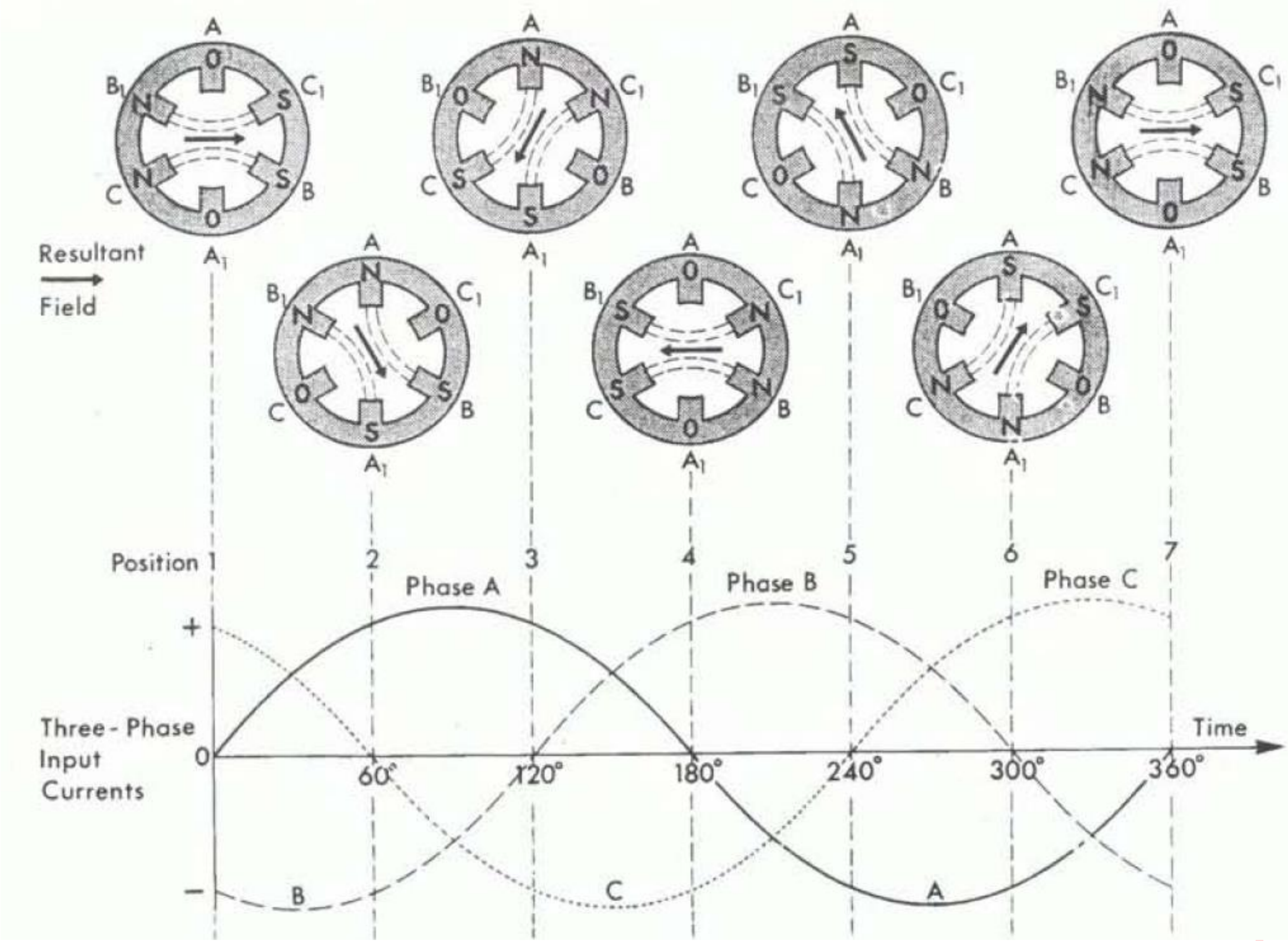


Frame size — Under the NEMA system, most motor dimensions are standardized and categorized by a frame size number and letter designation. In fractional horsepower motors the frame sizes are two digits and represent the shaft height of the motor from the bottom of the base in sixteenths of an inch. For example, a 56-frame motor would have a shaft height (“D” dimension) of 56/16 of an inch, or 3.5 inches.

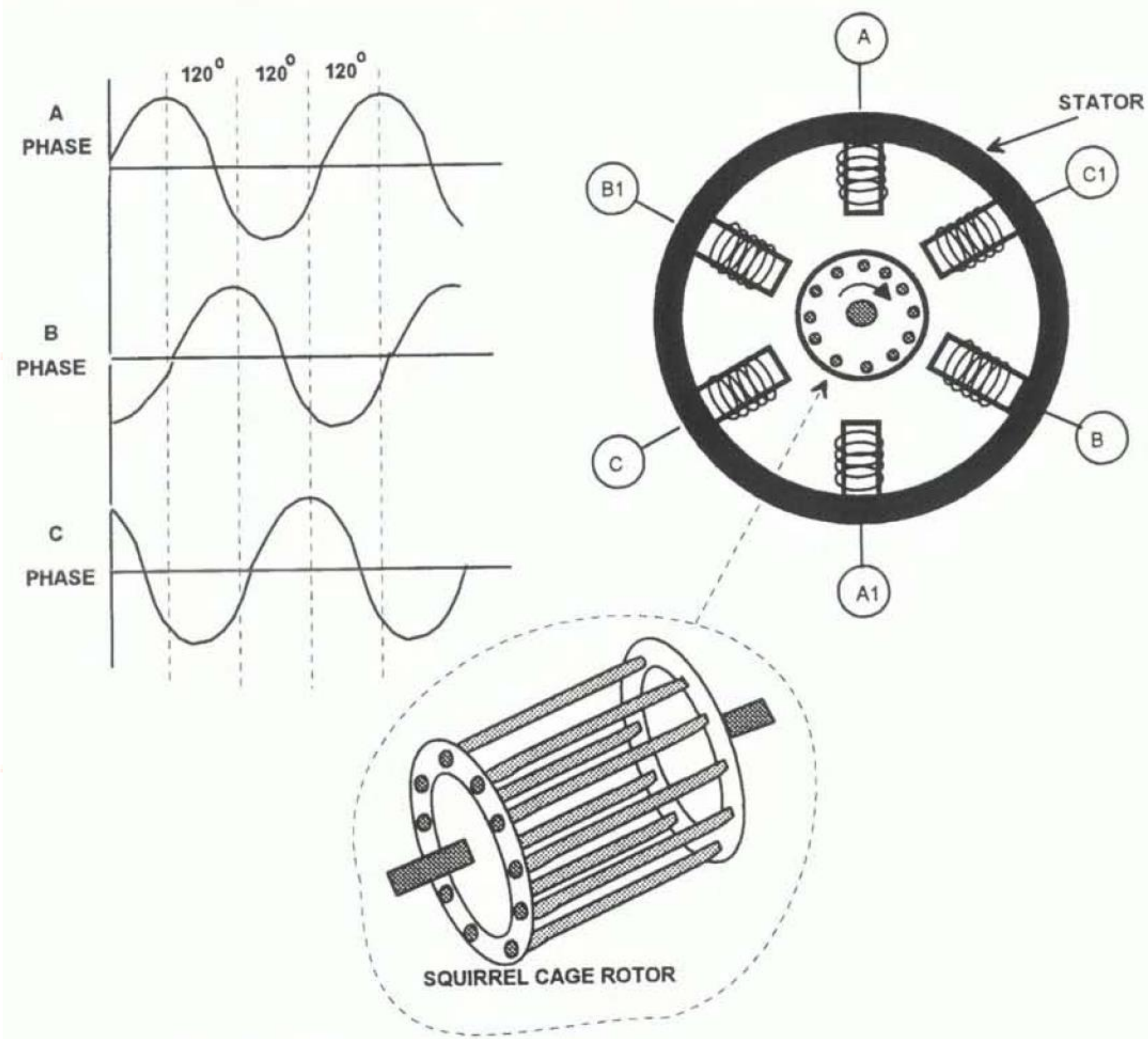
On larger 3-digit frame size motors, 143T through 449T, a slightly different system is used where the first two digits represent the shaft height in quarters of an inch. For example, a 326T frame would have a “D” dimension of 32 one-quarter inches, or 8 inches. Although no direct inch measurement relates to it, the third digit of three-digit frame sizes, in this case a 6, is an indication of the motor body's length. The longer the motor body, the longer the distance between mounting bolt holes in the base (i.e. greater “F” dimension). For example, a 145T frame has a larger F dimension than does a 143T frame.

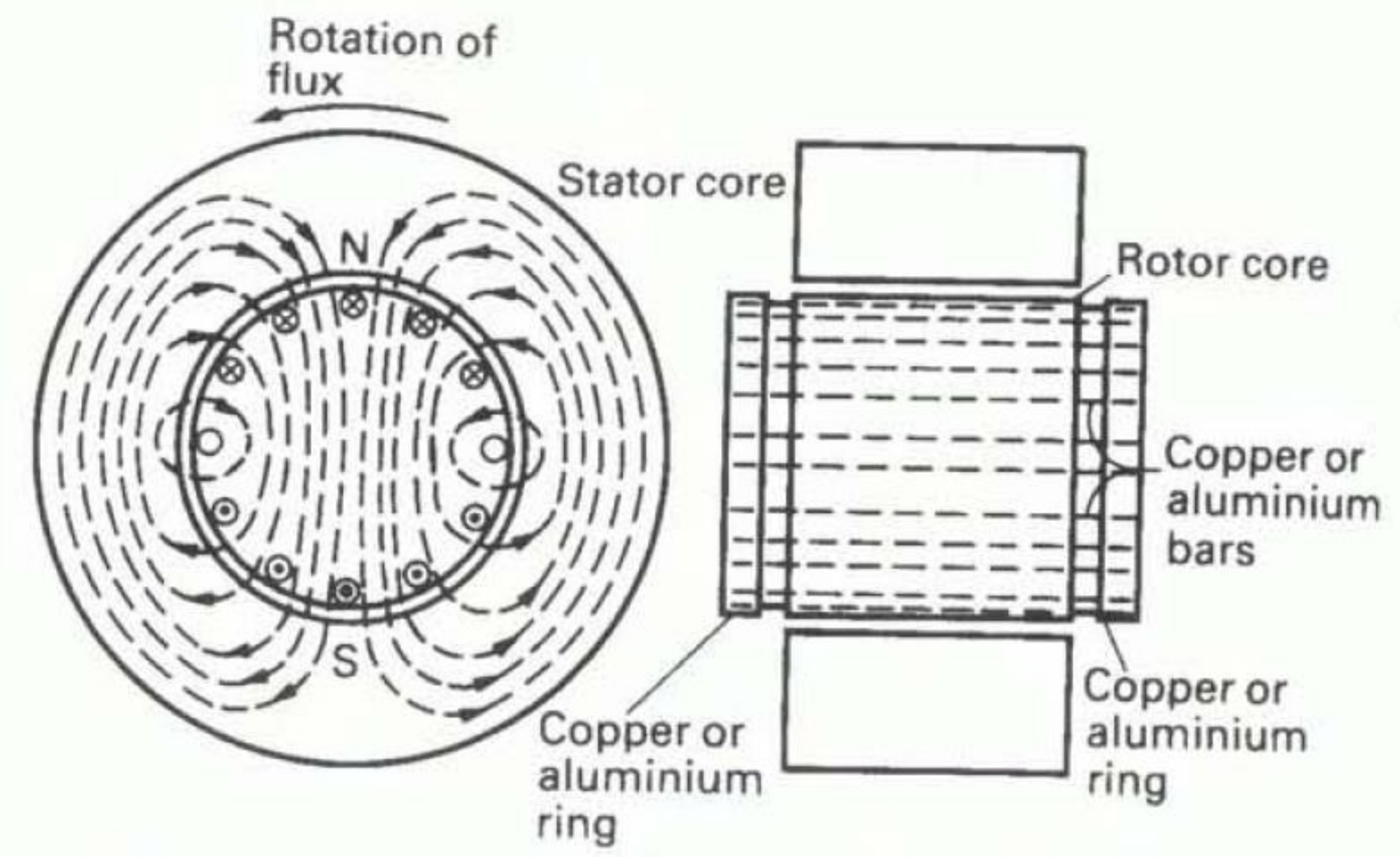
Stator-Produced Rotating Magnetic Field

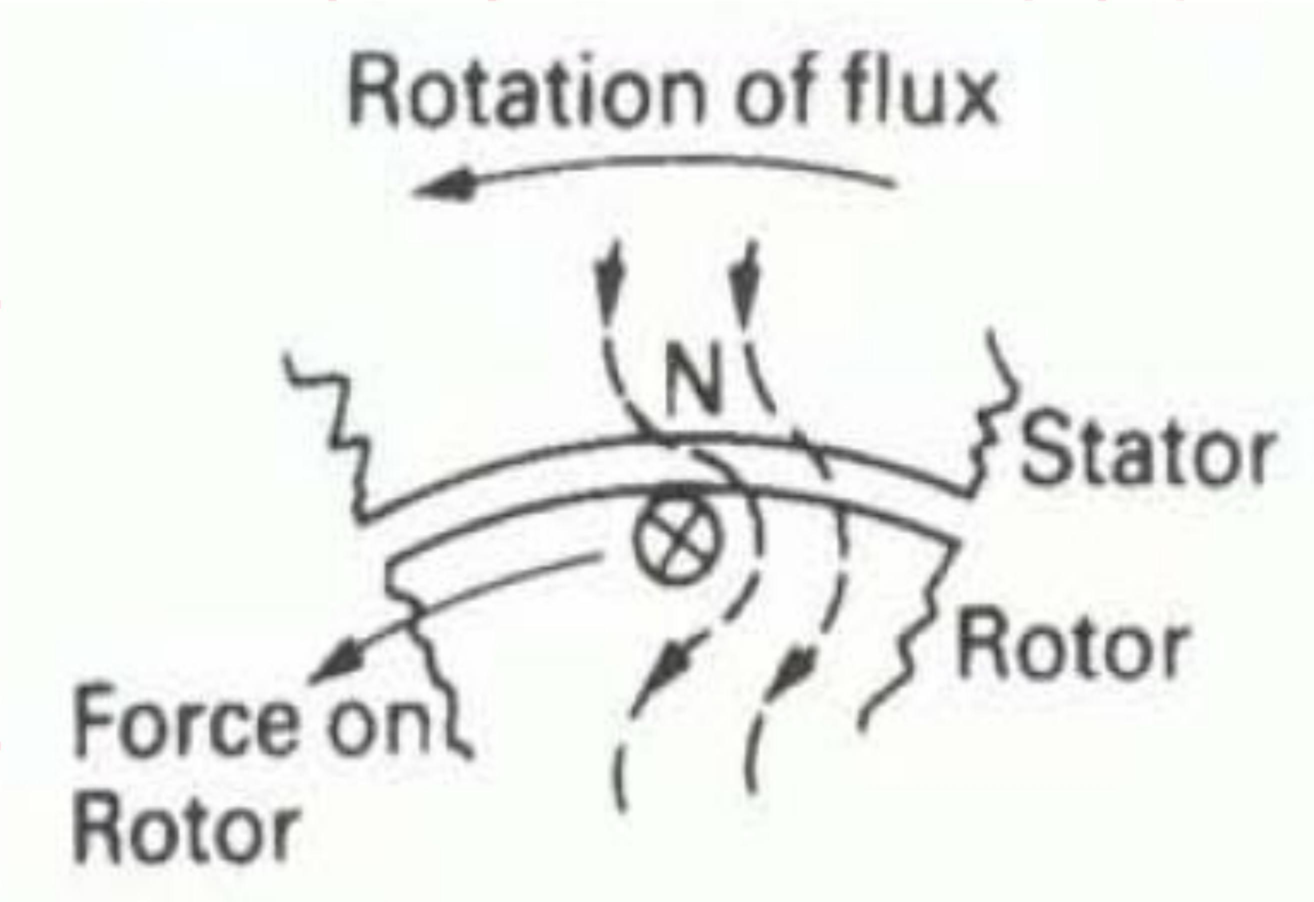
When a magnet is rotated within a three-phase stator, a three-phase voltage is produced. If this process is reversed (i.e. by connecting the three-phase supply to a three-phase stator), a rotating field is produced, as shown in the following diagram.


Resultant
Field
Position 1
2
3
4
5
6
7
Phase A
Phase B
Phase C
Three - Phase
Input
Currents
Time
0
60°
120°
180°
240°
300°
360°
+
−
B
C
A

If a rotor is then placed in the centre of the rotating magnetic field, a magnetic field is induced in it, which locks onto the rotating outer field and turns with it.


120°
120°
120°
A
PHASE
B
PHASE
C
PHASE
A
STATOR
B1
C1
C
B
A1
SQUIRREL CAGE ROTOR


Rotation of flux
Stator core
N
S
Rotor core
Copper or aluminium bars
Copper or aluminium ring
Copper or aluminium ring


Rotation of flux
N
Stator
Rotor
Force on
Rotor

When the applied torque equals the load torque, the motor runs at a speed slightly less than the stator field. The induction motor is an asynchronous machine and possesses following characteristics :

- ➢ Slip speed is the difference between the rotor speed and the synchronous (stator) speed.
- Slip Speed = Synchronous Speed - Rotor Speed
- Synchronous Speed = 60f/P
- Where
  - f = frequency of supply(Hz), and
  - P = number of pole pairs in stator

- Reversal of rotation occurs if any two of the motor phases are crossed over.

- Loss of a phase occurs when the machine is:

- Running

  The motor continues to run at a reduced torque.

- Not running

The machine does not start, and fuses or circuit breakers blow in the other two phases, causing possible damage to the motor.

Slip and Rotor Speed

Slip *s*

- The rotor speed of an Induction machine is different from the speed of Rotating magnetic field. The % difference of the speed is called slip.

$$s = \frac{n_s - n_r}{n_s} \quad OR \quad n_r = n_s(1-s)$$

- Where; n_s = synchronous speed (rpm)
- n_r = mechanical speed of rotor (rpm)
- under normal operating conditions, s= 0.01 ~ 0.05, which is very small and the actual speed is very close to synchronous speed.
- Note that : s is not negligible

Slip and Rotor Speed

- **Rotor Speed**
  - When the rotor move at rotor speed, $n_{r\,(rps)}$, the stator flux will circulate the rotor conductor at a speed of $(n_s - n_r)$ per second. Hence, the frequency of the rotor is written as:

$$f_r = (n_s - n_r)p$$
$$= sf$$

  - Where; s = slip

    f = supply frequency

Note:

$\underline{\text{At stator}}: \quad n_s = \frac{120f}{p}$

$$\therefore f = \frac{n_s p}{120} \qquad .....(i)$$

$\underline{\text{At Rotor}}: \quad n_s - n_r = \frac{120f}{p}$

$$\therefore f_r = \frac{(n_s - n_r)p}{120} \qquad .....(ii)$$

$\underline{(ii) \div (i)}: \quad f_r = s.f$

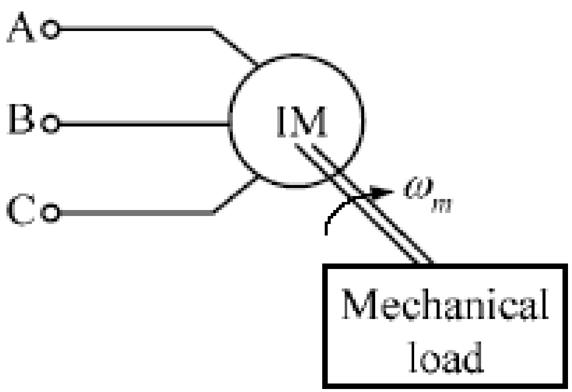
Principle of Operation

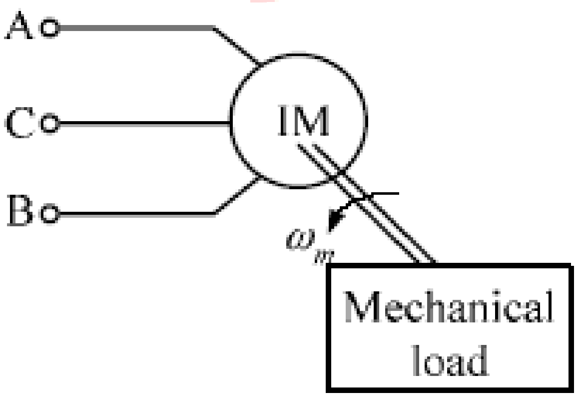
- **Torque producing mechanism**
  - When a 3 phase stator winding is connected to a 3 phase voltage supply, 3 phase current will flow in the windings, hence the stator is energized.
  - A rotating flux Φ is produced in the air gap. The flux Φ induces a voltage E_a in the rotor winding (like a transformer).
  - The induced voltage produces rotor current, if rotor circuit is closed.
  - The rotor current interacts with the flux Φ, producing torque. The rotor rotates in the direction of the rotating flux.

Direction of Rotor Rotation

Q: How to change the direction of rotation?

A: Change the phase sequence of the power supply.





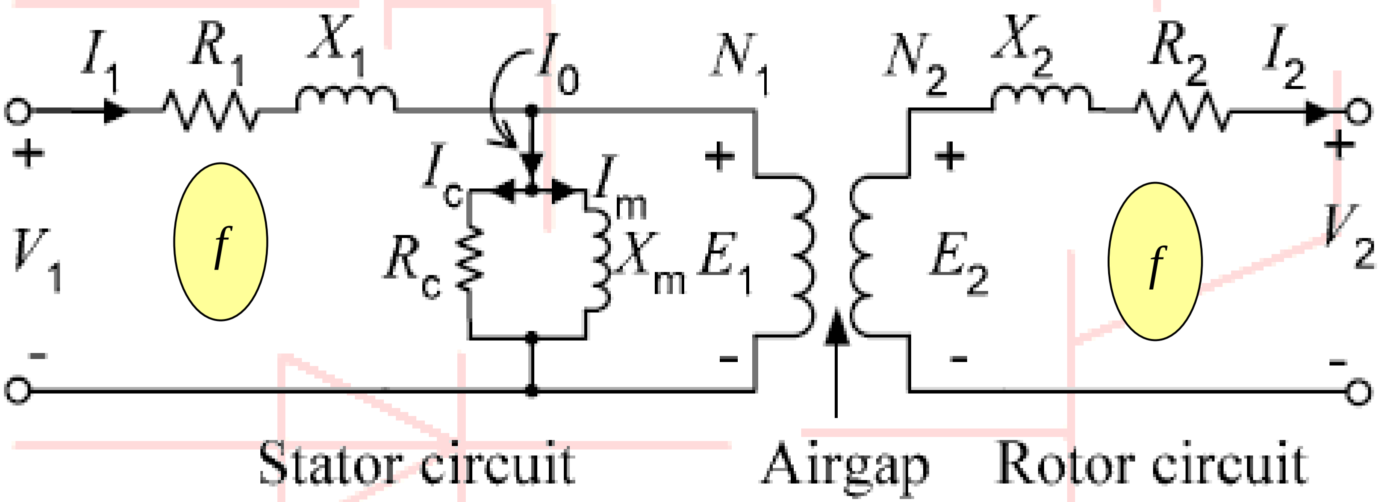
Equivalent Circuit of Induction Machines

- **Conventional equivalent circuit**
  - *Note:*
    - *Never use three-phase equivalent circuit. Always use per- phase equivalent circuit.*
    - *The equivalent circuit always bases on the Y connection regardless of the actual connection of the motor.*
    - *Induction machine equivalent circuit is very similar to the single-phase equivalent circuit of transformer. It is composed of stator circuit and rotor circuit*

Equivalent Circuit of Induction Machines

- **Step1 Rotor winding is open**

(The rotor will not rotate)



- Note:
  - the frequency of E_2 is the same as that of E_1 since the rotor is at standstill. At standstill s=1.

Equivalent Circuit of Induction Machines

V_1 – stator voltage, per phase ($V_1 = V_{LL}/\sqrt{3}$)

R_1, R_2 – stator and rotor winding resistance

$X_1 = 2\pi f_1 L_1$ – stator leakage reactance

$X_2 = 2\pi f_1 L_2$ – rotor leakage reactance

R_c – resistance representing core loss, per phase

X_m – magnetizing reactance, per phase

N_1, N_2 – effective number of turns of stator and rotor windings.

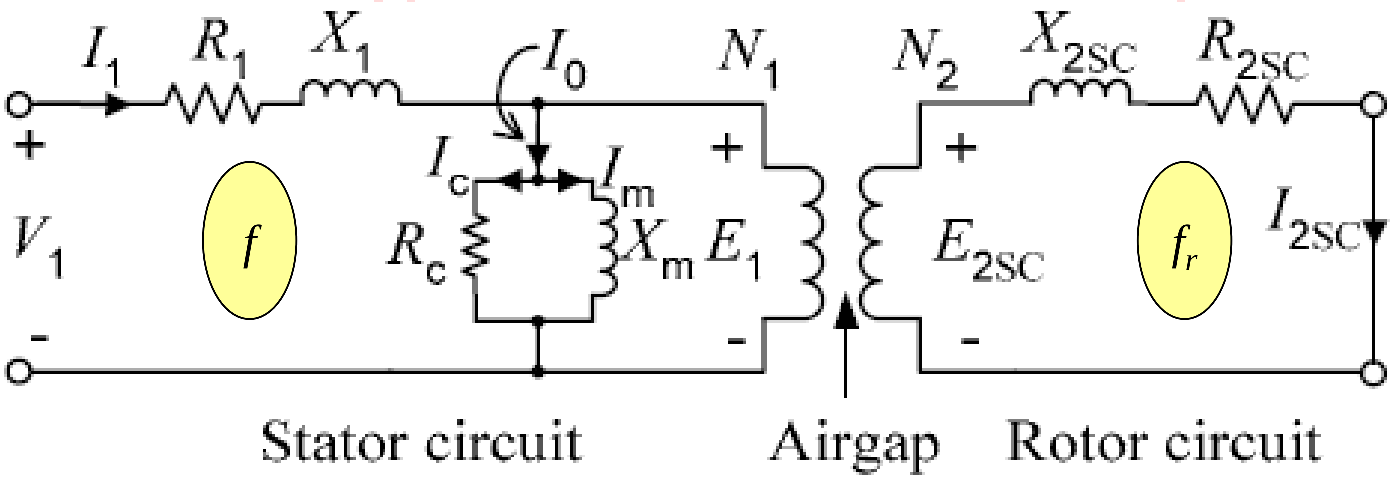
$E_1 = 4.44 f_1 N_1 \Phi$, where Φ is flux per pole

$E_2 = 4.44 f_1 N_2 \Phi$

Equivalent Circuit of Induction Machines

- **Step2 Rotor winding is shorted**

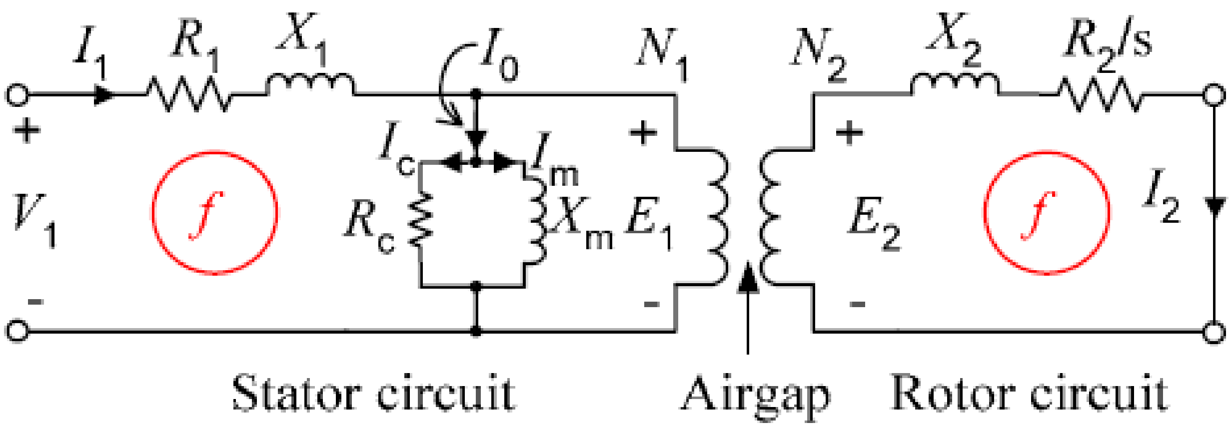
(Under normal operating conditions, the rotor winding is shorted. The slip is s)



- Note:
  - the frequency of E_2 is $f_r = sf$ because rotor is rotating.

Equivalent Circuit of Induction Machines

- **Step3 Eliminate f_2**

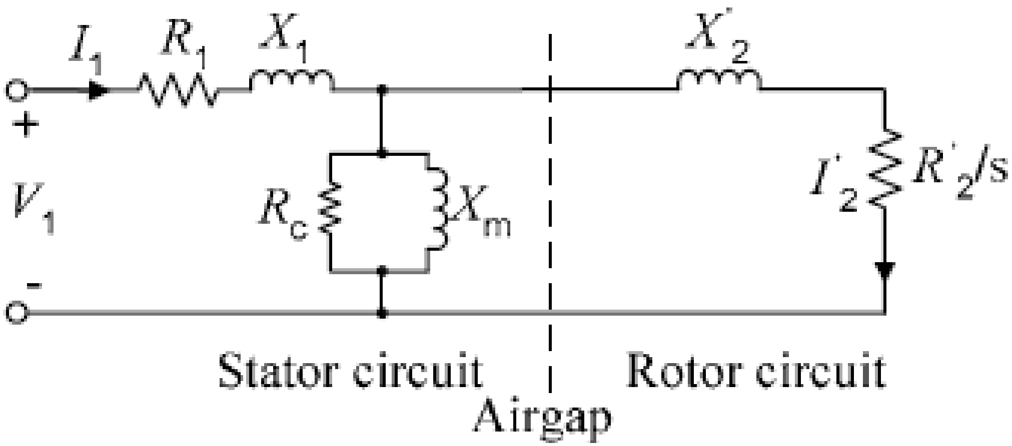


Keep tl

$$I_{2SC} = \frac{E_{2SC}}{R_{2SC} + jX_{2SC}} = \frac{sE_2}{R_2 + jsX_2} = \frac{E_2}{\frac{R_2}{s} + jX_2} = I_2$$

Equivalent Circuit of Induction Machines

- **Step 4 Referred to the stator side**



$$X_2' = a^2 X_2,$$

$$R_2' = a^2 R_2,$$

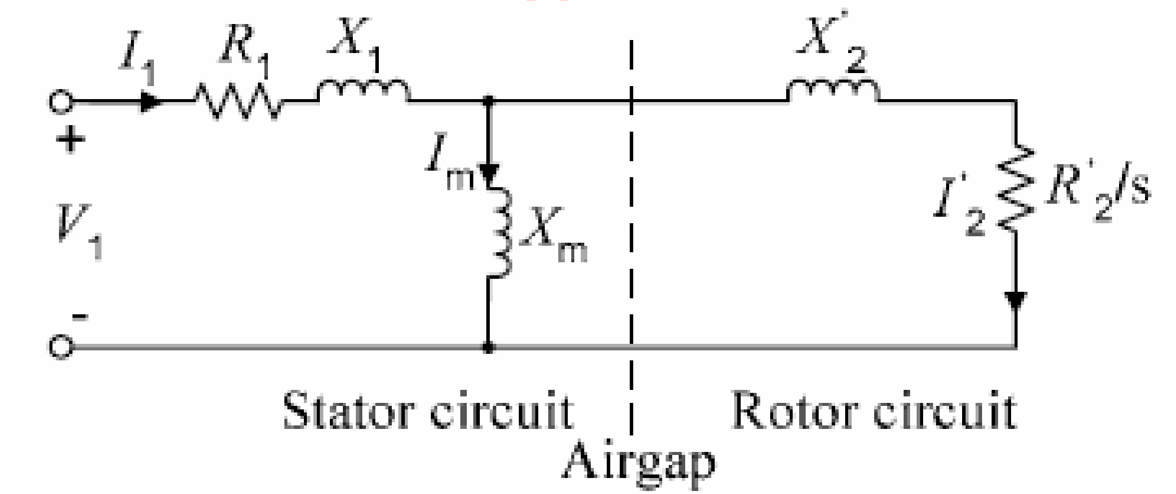
$$I_2' = \frac{1}{a} I_2,$$

$$\text{where } a = \frac{N_1}{N_2}$$

- Note:
  - X'_2 and R'_2 will be given or measured. In practice, we do not have to calculate them from above equations.
  - Always refer the rotor side parameters to stator side.
  - R_c represents core loss, which is the core loss of stator side.

Equivalent Circuit of Induction Machines

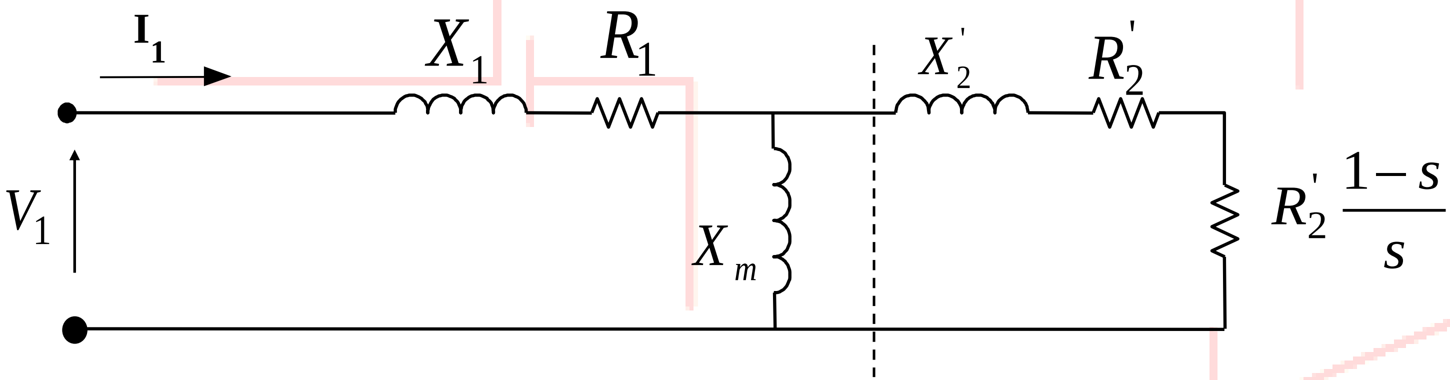
- **IEEE recommended equivalent circuit**



- Note:
  - R_c is omitted. The core loss is lumped with the rotational loss.

Equivalent Circuit of Induction Machines

- **IEEE recommended equivalent circuit**



Note: $\frac{R_2}{s}$ **can be separated into 2 PARTS**

$$\frac{R_2}{s} = R_2 + \frac{R_2(1-s)}{s}$$

- **Purpose :**
  - **to obtain the developed mechanical power**

Analysis of Induction Machines

- For simplicity, let assume

$I_s = I_1 \quad , \quad I_R = I_2$

(s=stator, R=rotor)

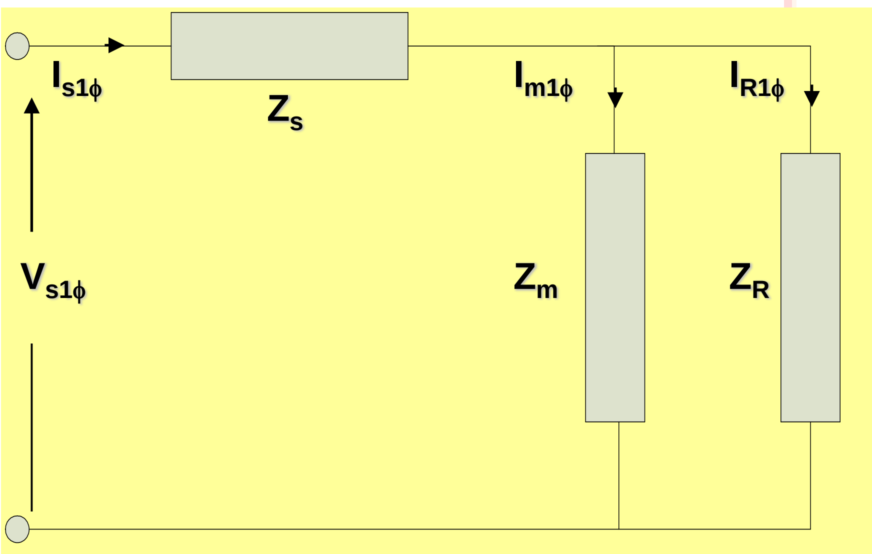
$$Z_R = \frac{R_R'}{s} + jX_R' \quad ;$$

$$Z_m = R_c \,//\, jX_m \quad ; R_c \neq neglected$$

$$Z_m = jX_m \quad ; R_c = neglected$$

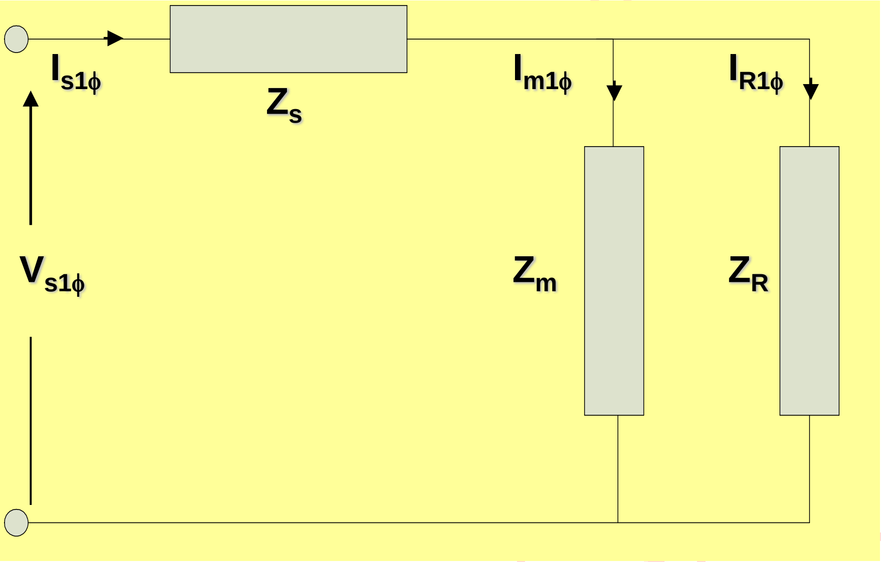
$$Z_s = R_s + jX_s \quad ;$$

$$Z_{Total} = Z_s + \left[Z_m \,//\, Z_R \right]$$



$$I_{s1\phi} = \frac{V_{s_{1\phi}}}{Z_T}$$

Analysis of Induction Machines



Note : 1hp =746Watt

Current Dividing Rules,

$$I_{m1\phi} = \left[\frac{Z_R}{Z_m + Z_R}\right] I_{s1\phi}$$

$$I_{R1\phi} = \left[\frac{Z_m}{Z_m + Z_R}\right] I_{s1\phi}$$

OR

Voltage Dividing Rules,

$$V_{RM1\phi} = \left[\frac{Z_R // Z_m}{Z_T}\right] V_{s1\phi}$$

Hence, $I_{R1\phi} = \left[\frac{V_{RM1\phi}}{Z_R}\right]$

$$I_{m1\phi} = \left[\frac{V_{RM1\phi}}{Z_m}\right]$$

Power Flow Diagram

$\sqrt{3}V_s I_s \cos\theta$

$1hp = 746W$

P_{in} (Motor)

P_{in} (Stator)

P_{in} (Rotor)

$P_{air\ Gap}$ (P_{ag})

$$3I_R'^2 \frac{R_R'}{s}$$

$P_{developed}$

$P_{mechanical}$

$P_{converted}$ (P_m)

$$3I_R'^2 R_R' \left(\frac{1-s}{s}\right)$$

P_{out}, P_o

$P_{stator\ copper\ loss}$, (P_{scu})

$$3I_s^2 R_s$$

$P_{core\ loss}$ (P_c)

$$3\left(\frac{V_{RM}}{R_c}\right)^2$$

$P_{rotor\ copper\ loss}$ (P_{rcu})

$$3I_R'^2 R_R'$$

$P_{windage,\ friction,\ etc}$ (P_μ - Given)

Power Flow Diagram

- **Ratio:**

P_{ag}	P_{rcu}	P_m
$3I_R'^2 \frac{R_R'}{s}$	$3I_R'^2 R_R'$	$3I_R'^2 R_R'\left(\frac{1-s}{s}\right)$
$\frac{1}{s}$	1	$\frac{1}{s}-1$
1	s	$1-s$

Ratio makes the analysis simpler to find the value of the particular power if we have another particular power. For example:

$$\frac{P_{rcu}}{P_m} = \frac{s}{1-s}$$

Efficiency

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$if \;\; P_{losses} \;\; are \; given,$$

$$P_o = P_{in} - P_{losses}$$

$$P_o = P_m - P_\mu$$

$$otherwise,$$

$$P_{in} = \sqrt{3} V_s I_s \cos\theta$$

$$P_{out} = x\, hp \times 746W = 746x\, Watt$$

Torque-Equation

- Torque, can be derived from power equation in term of mechanical power or electrical power.

$$Power,\ P = \omega T,\ where\ \omega = \frac{2\pi n}{60}(rad/s)$$

$$Hence,\ T = \frac{60P}{2\pi n}$$

$$Thus,$$

$$Mechanical\ Torque,\ T_m = \frac{60P_m}{2\pi n_r}$$

$$Output\ Torque,\ T_o = \frac{60P_o}{2\pi n_r}$$

Torque-Equation

- **Note that, Mechanical torque can written in terms of circuit parameters. This is determined by using approximation method**

$$P_m = 3I_R'^2 \frac{R_R'}{s}(1-s) \; and \; P_m = \omega_r T_m$$

$$\therefore T_m = \frac{P_m}{\omega_r} = \left[\frac{3I_R'^2 \frac{R_R'}{s}(1-s)}{\omega_r} \right]$$

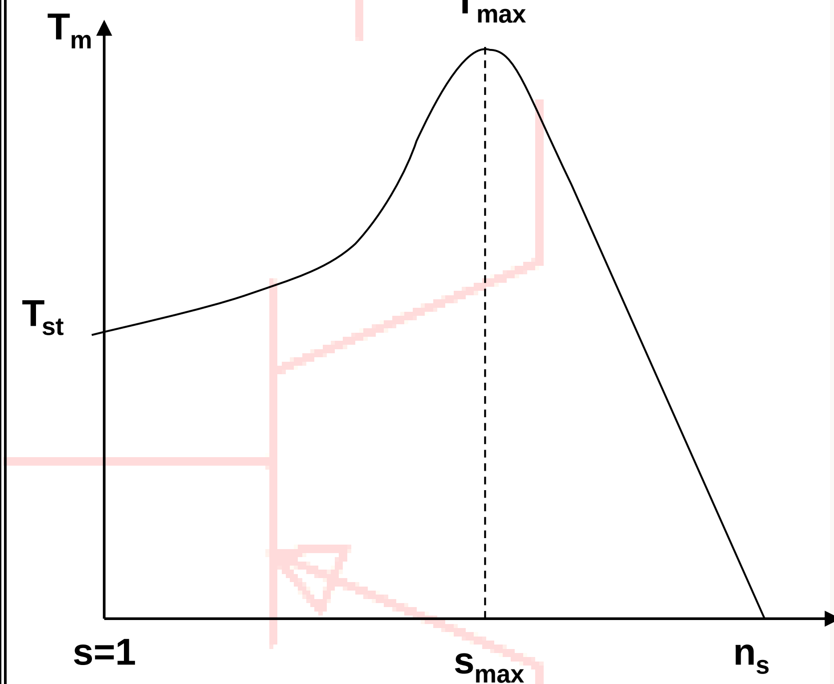
…

…

…

$$\therefore T_m = \left[\frac{3(V_{RM\phi})^2}{2\pi n_s} \right] \left[\frac{sR_R'}{(R_R')^2 + (sX_R')^2} \right]$$

Hence, Plot T_m vs s



s_{max} is the slip for T_{max} to occur

Torque-Equation

$$\textit{Starting Torque}, s = 1$$

$$\therefore T_{st} = \left[\frac{3(V_{s\phi})^2}{2\pi\left(\frac{n_s}{60}\right)}\right]\left[\frac{R_R'}{(R_s + R_R')^2 + (X_s + X_R')^2}\right]$$

$$s_{\max} = \pm\left[\frac{R_R'}{\sqrt{(R_s)^2 + (X_R')^2}}\right]$$

$$T_{\max} = \left[\frac{3(V_{s\phi})^2}{2\left[2\pi\left(\frac{n_s}{60}\right)\right]}\right]\left[\frac{1}{R_s + \sqrt{(R_s)^2 + (X_s + X_R')^2}}\right]$$