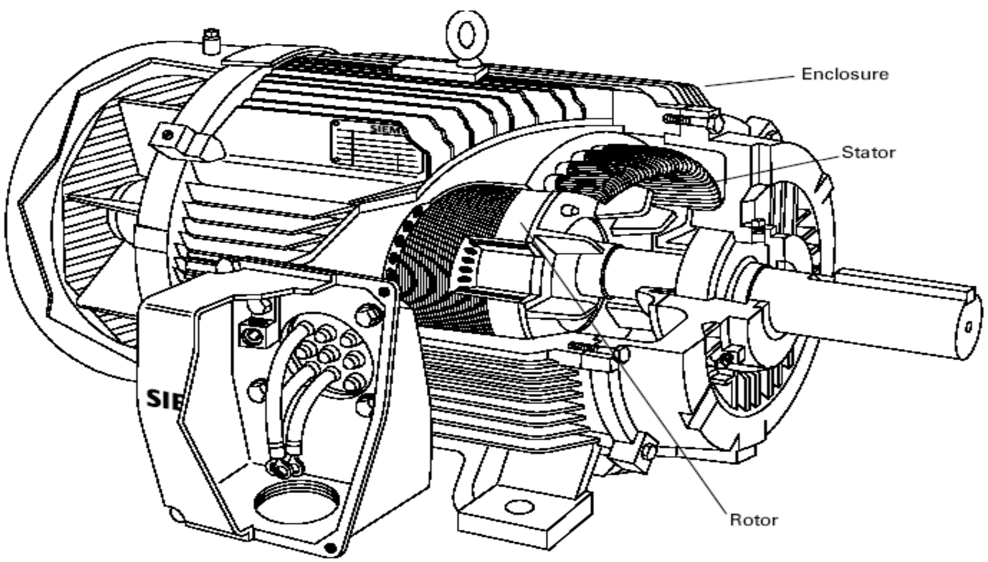
INDUCTION MOTOR

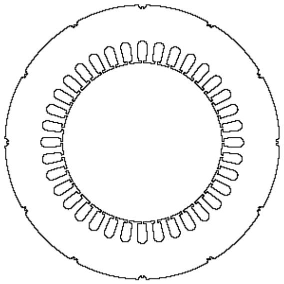
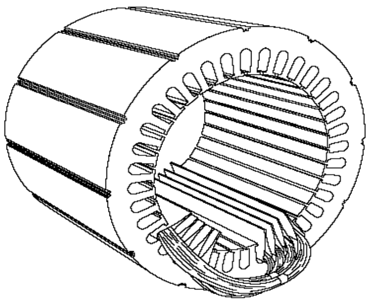
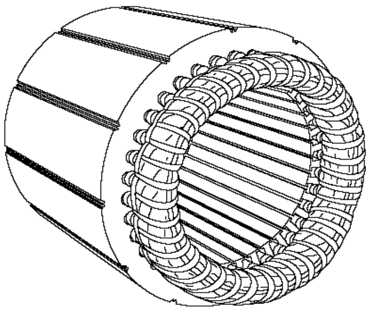
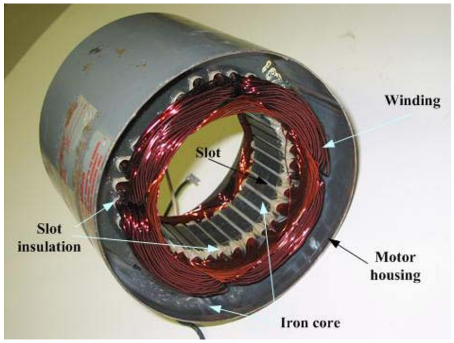
CONSTRUCTION

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



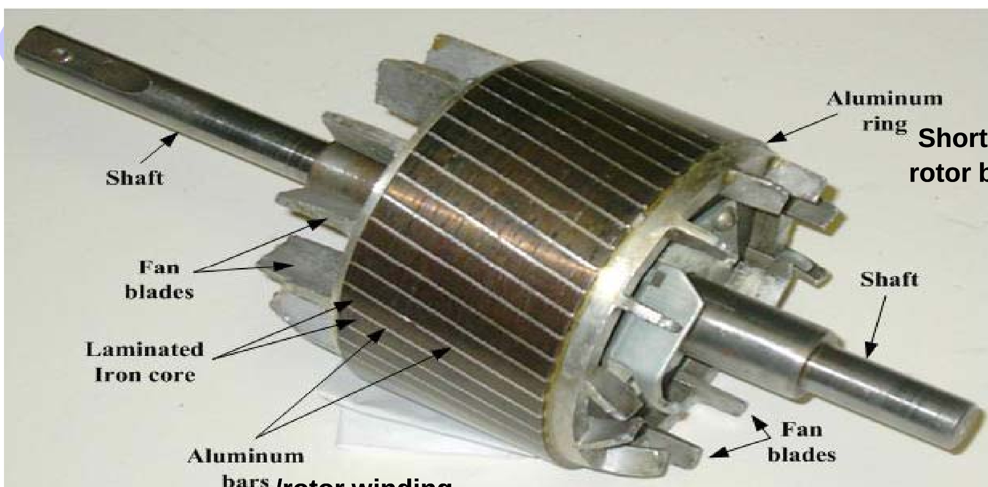
CONSTRUCTION (stator)

- The stator - stationary part of the motor.
- Stator laminations are stacked together forming a hollow cylinder.
- Coils of insulated wire are inserted into slots of the stator core.
- Each grouping of coils, together with the steel core it surrounds, form an electromagnet.

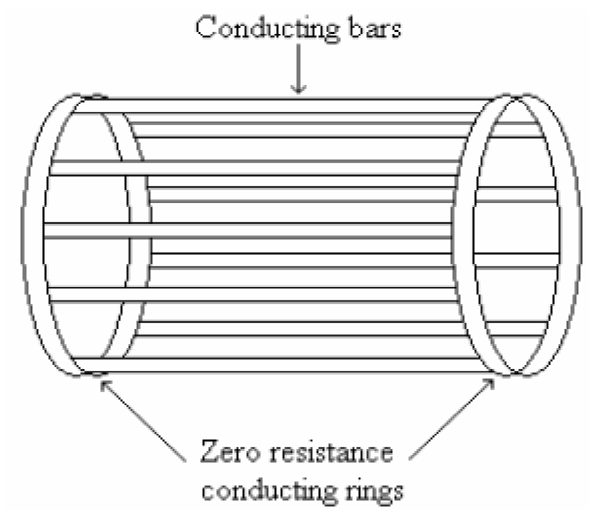
CONSTRUCTION (rotor)

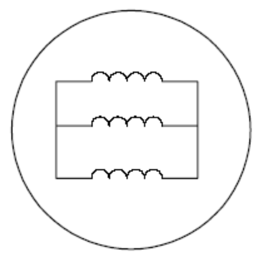
- The rotor is the rotating part of the motor
- It can be found in two types:
  - Squirrel cage (most common)



CONSTRUCTION (rotor)

- **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

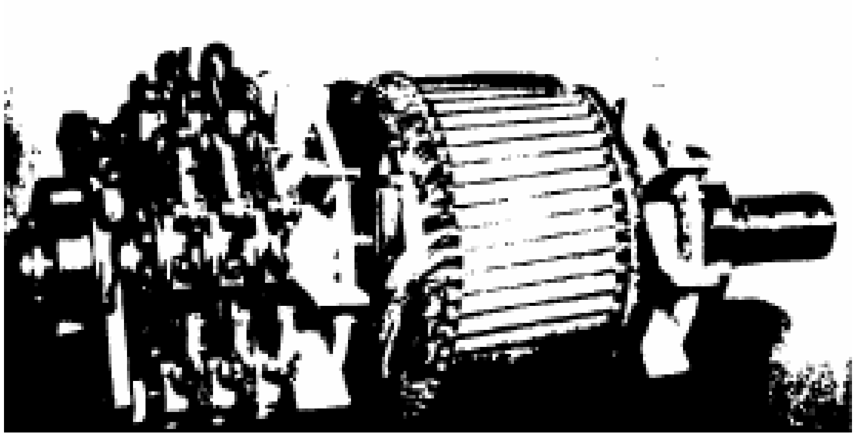




CONSTRUCTION (rotor)

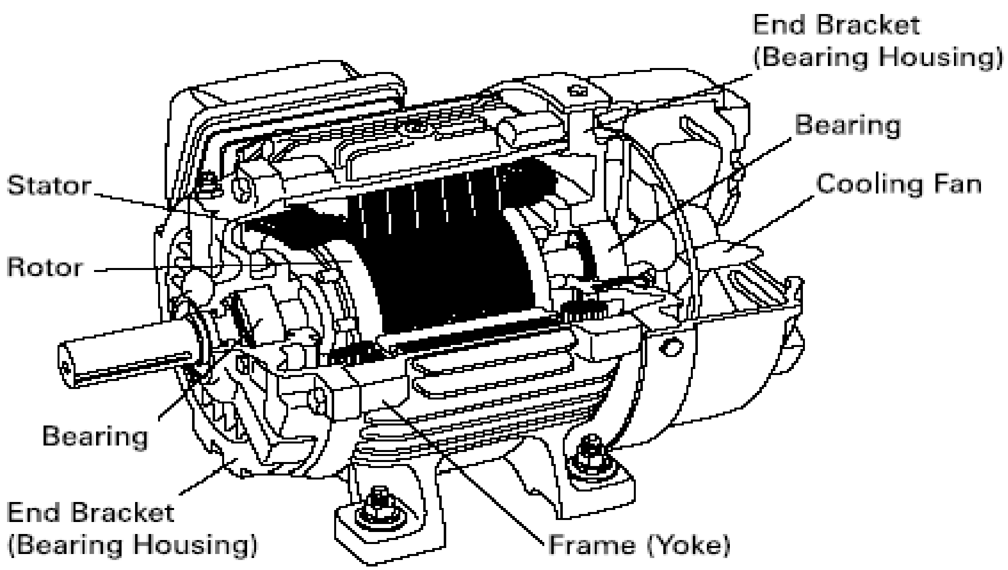
- **Wound rotor type:**
  - Rotor winding is wound by wires. The winding terminals can be connected to external circuits through slip rings and brushes.

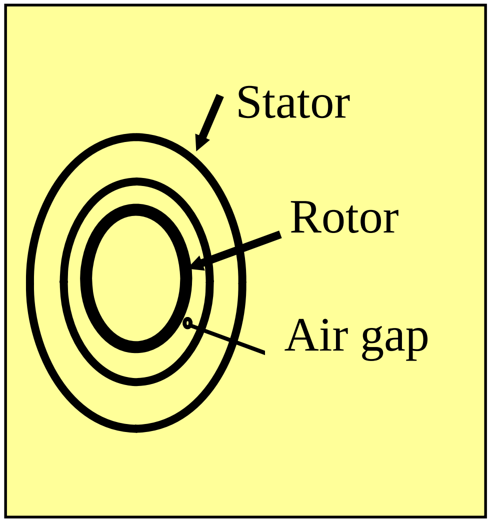
    (similar with DC motor, with the coils connected together that make contact with brushes)
  - Easy to control speed, more expensive.



CONSTRUCTION (enclosure)

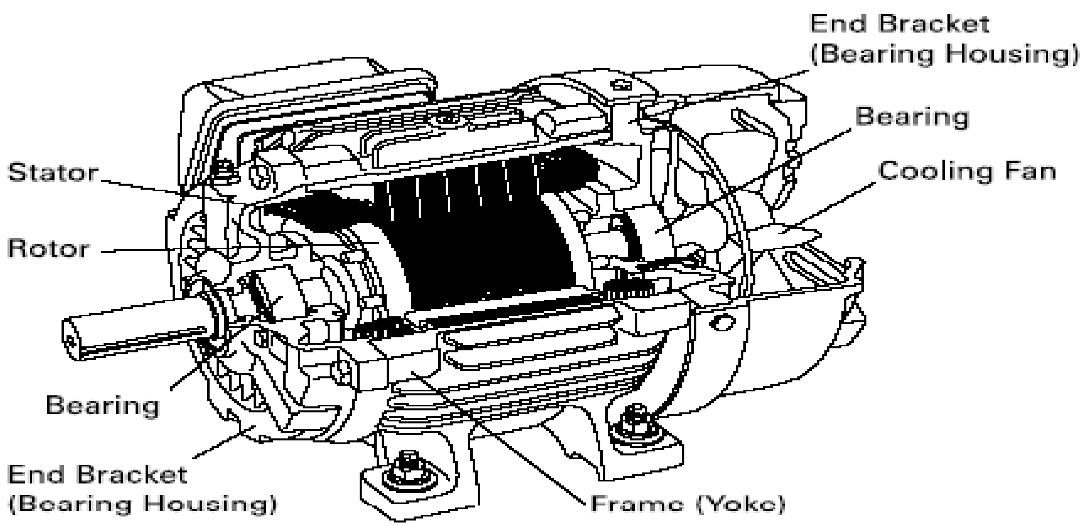
- The enclosure consists of a frame (or yoke) and two end brackets (or bearing housings). The stator is mounted inside the frame. The rotor fits inside the stator with a slight air gap separating it from the stator (**NO** direct physical connection)





CONSTRUCTION (enclosure)

- The enclosure 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.



Rotating Magnetic Field

- When a 3 phase stator winding is connected to a 3 phase voltage supply, 3 phase current will flow in the windings, which also will induce 3 phase flux in the stator.
- These flux will rotate at a speed called a Synchronous Speed, n_s. The flux is called as Rotating magnetic Field
- Synchronous speed: speed of rotating flux

$$n_s = \frac{120 f}{p}$$

- Where; p = is the number of poles, and
  f = the frequency of supply

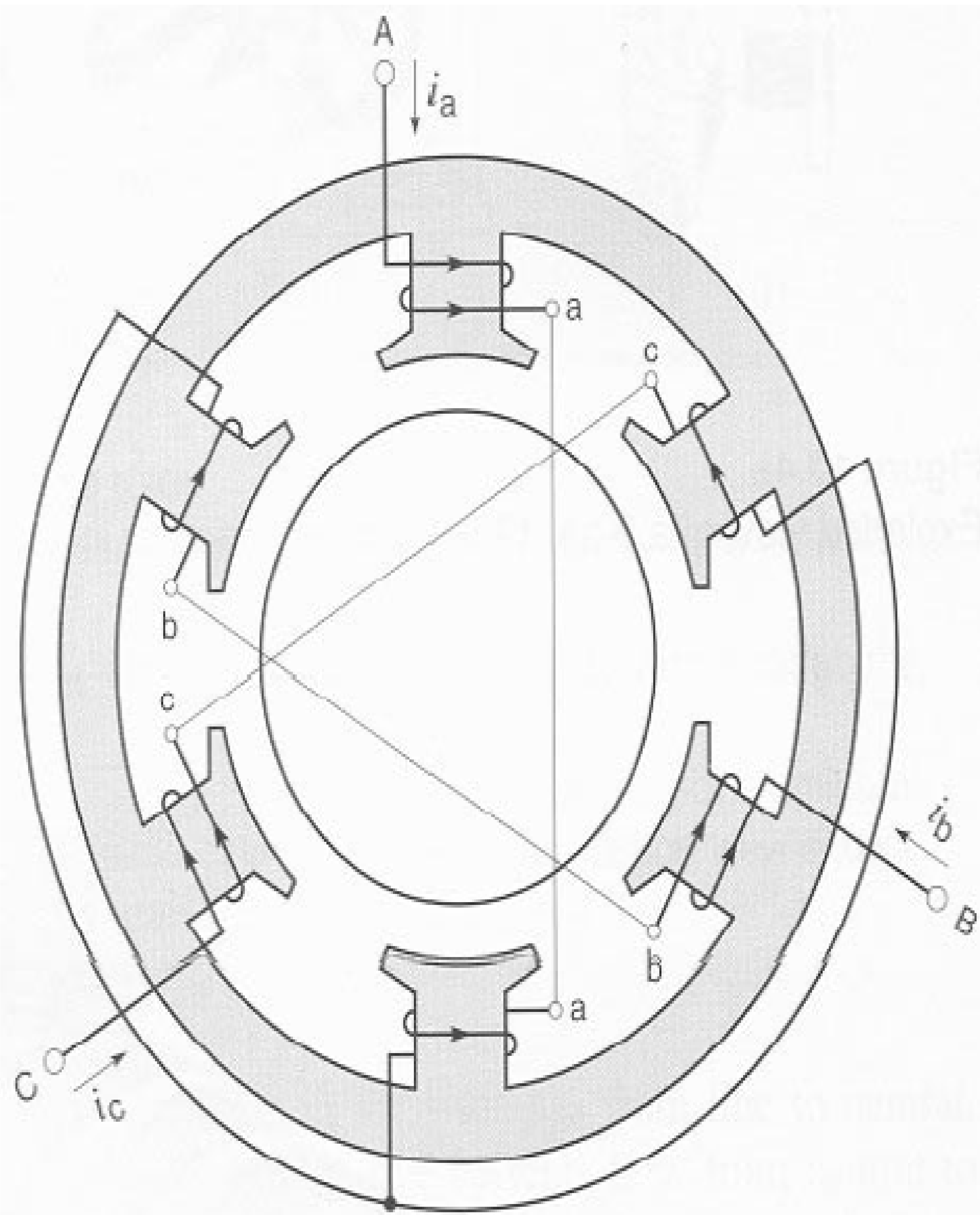
Slip and Rotor Speed

1. **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.

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

- 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


A
i_a
a
c
b
c
i_b
B
b
a
C
i_c
N

Induction Motor: Rotating Field

- Consider a simple stator with 6 salient poles - windings AN, BN, CN.
- The windings are mechanically spaced at 120° from each other.
- The windings are connected to a 3-phase source.
- AC currents Ia, Ib and Ic will flow in the windings, but will be displaced in time by 120°.
- Each winding produces its own MMF,which creates a flux across the hollow interior of the stator.
- The 3 fluxes combine to produce a magnetic field that rotates at the same frequency as the supply

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:

<u>*At stator*</u>: $n_s = \frac{120f}{p}$

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

<u>*At Rotor*</u>: $n_s - n_r = \frac{120f}{p}$

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

<u>$(ii) \div (i)$</u>: $f_r = s.f$

Principle of Operation

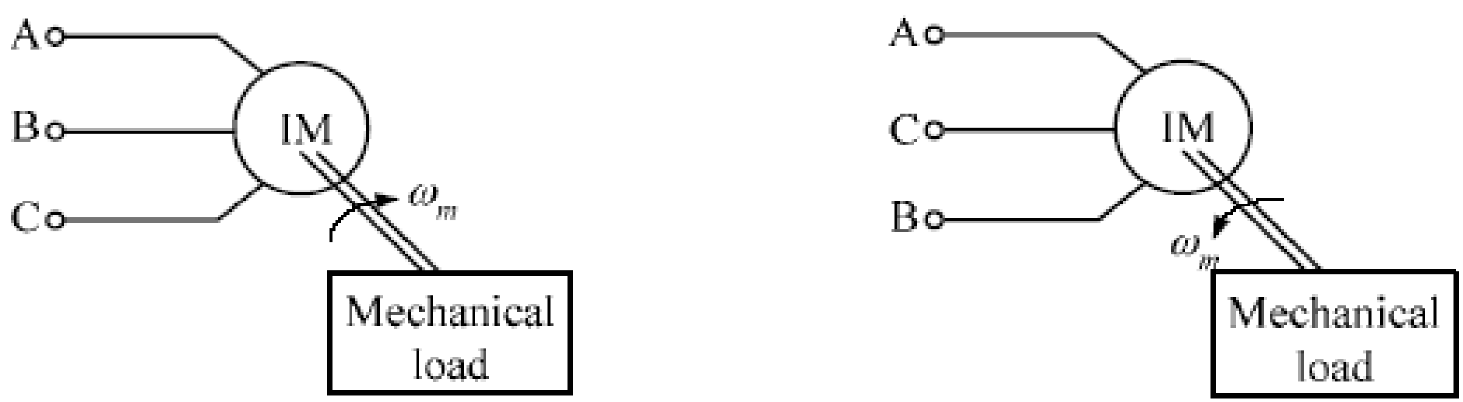
Torque producing mechanism

- 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 Rotates

- Q: How to change the direction of
- rotation?
- • A: Change the phase sequence of the
- power supply.



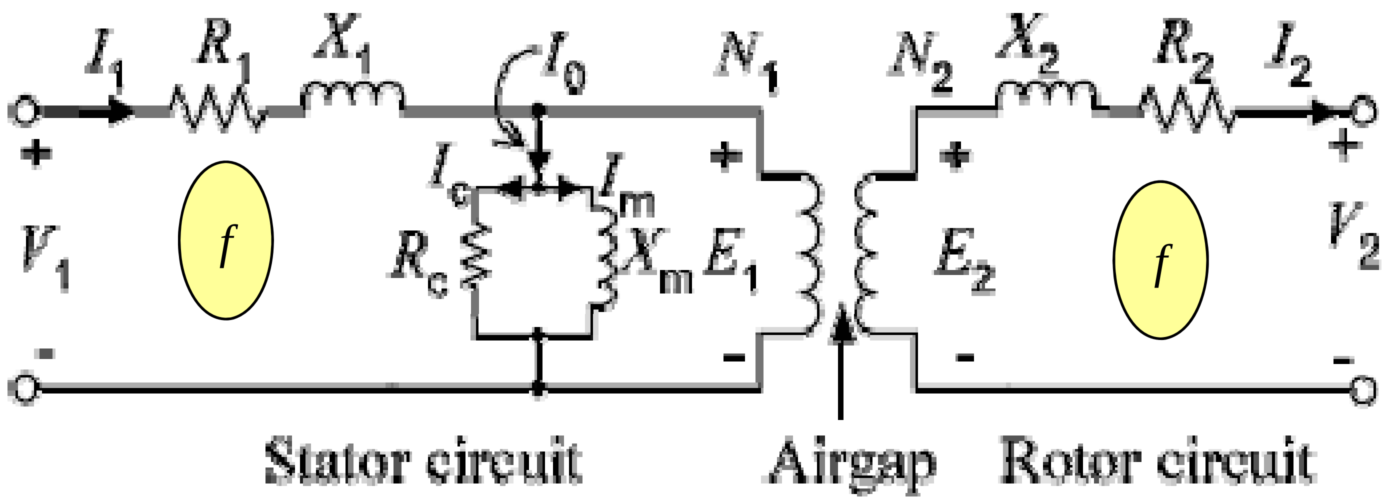
Equivalent Circuit of Induction Machines

- **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.

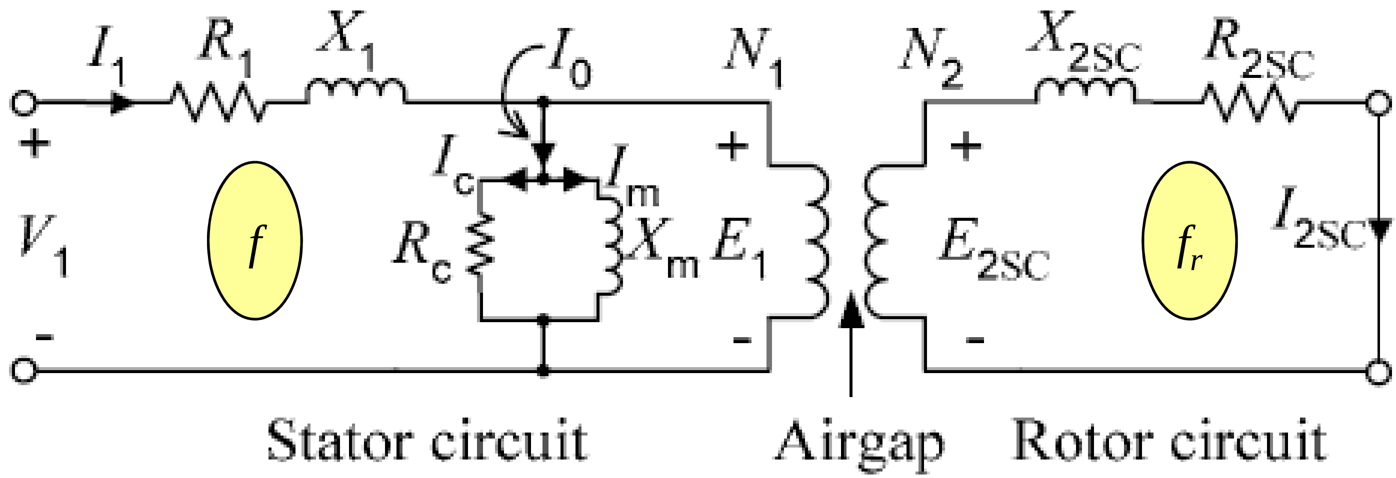
$E_1 = 4.44 f_1 N_1 \Phi$, where Φ is flux per pole

$E_2 = 4.44 f_1 N_2 \Phi$

Equivalent Circuit of Induction Machines

- **Step2 Rotor winding is shorted**

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

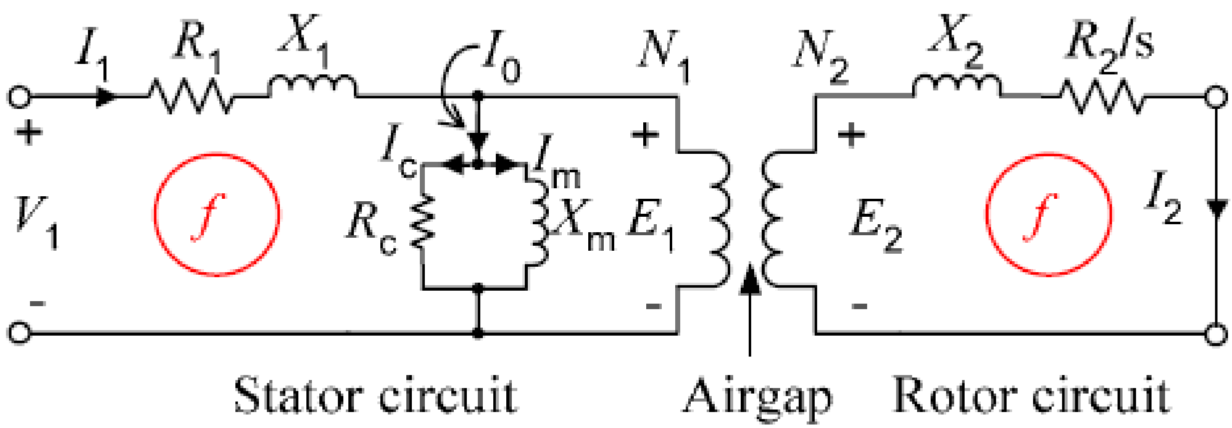


- Note: the frequency of E_2

is $f_r = sf$ because rotor is rotating.

Equivalent Circuit of Induction Machines

- **Step3 Eliminate f_2**

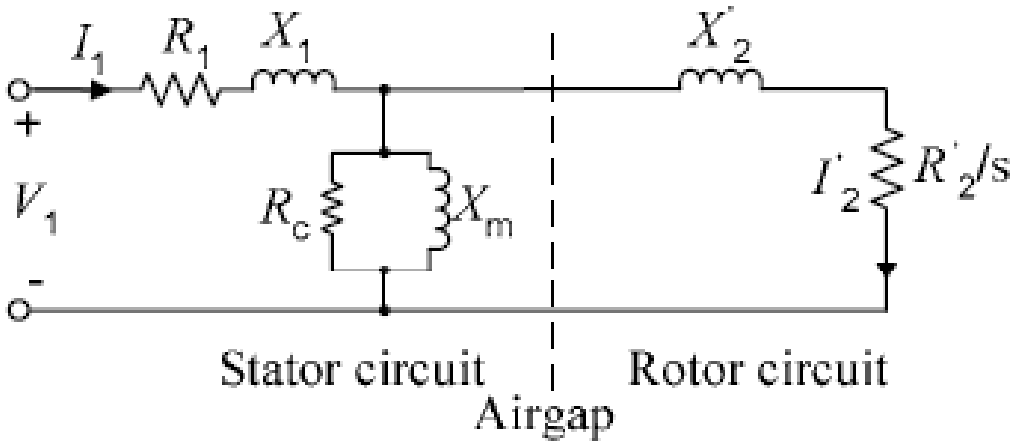


Keep the rotor current same:

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

Equivalent Circuit of Induction Machines

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



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

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

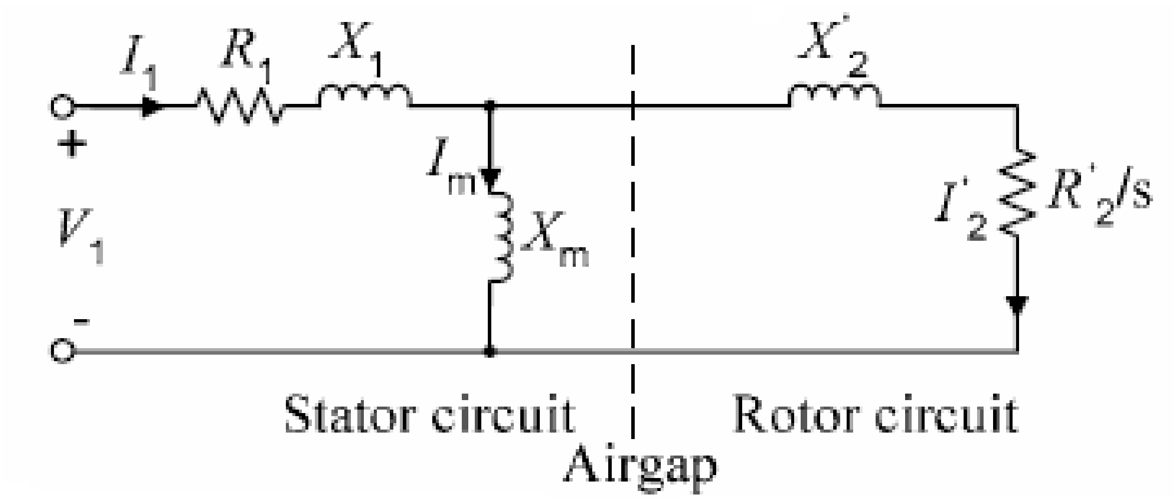
$$I_2' = \frac{1}{a} I_2,$$

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

- 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.

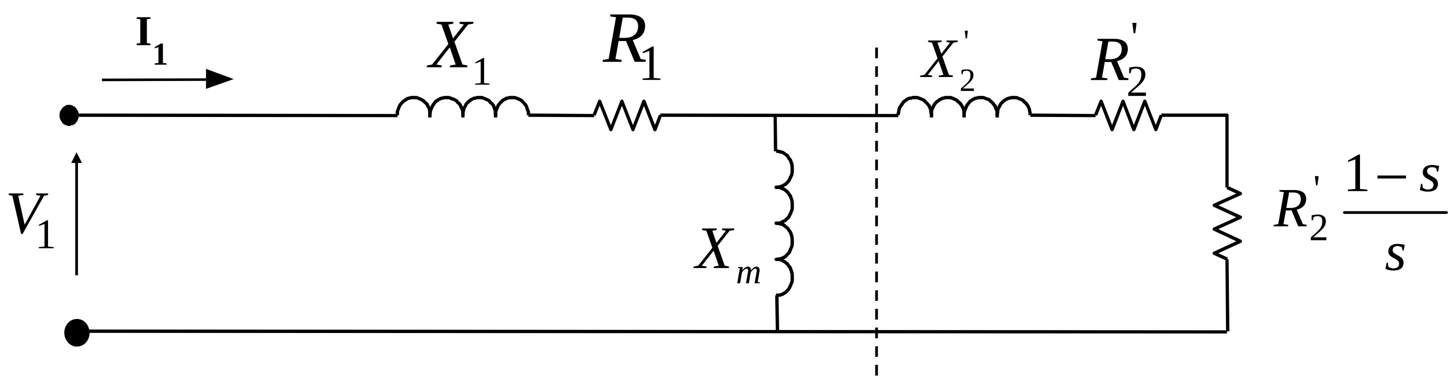
Equivalent Circuit of Induction Machines

- **IEEE recommended equivalent circuit**



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 Flow Diagram

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

$1hp = 746\,W$

P_{in} (Motor)

P_{in} (Stator)

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

$3 I_s^{\,2} R_s$

$P_{core\ loss}$ (P_c)

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

P_{in} (Rotor)

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

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

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

$3 I_R'^2 R_R'$

$P_{developed}$

$P_{mechanical}$

$P_{converted}$ (P_m)

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

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

P_{out}, P_o

Torque-Equation

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

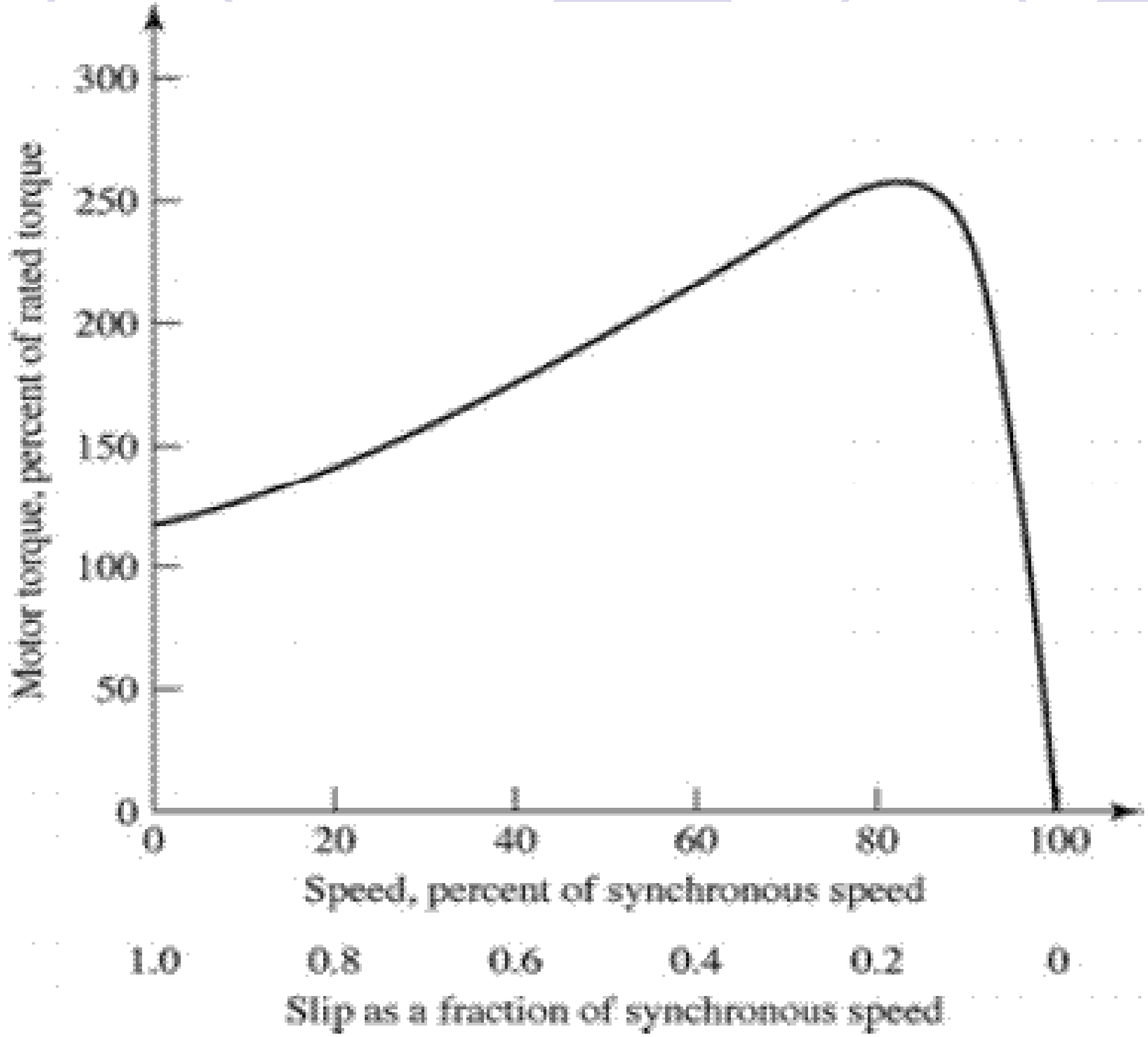
$$Power, P = \omega T, where \omega = \frac{2\pi n}{60} (rad/s)$$

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

$$Thus,$$

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

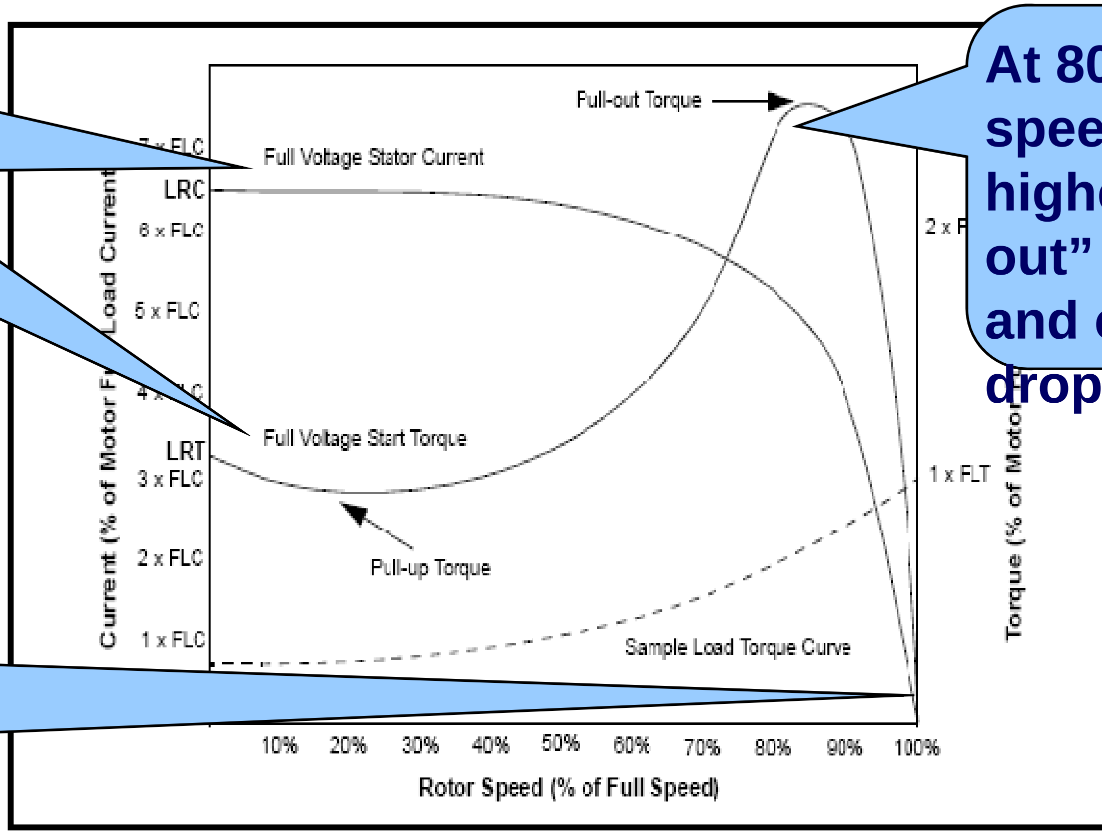
$$Output \ \ Torque, T_o = \frac{60 P_o}{2\pi n_r}$$


Motor torque, percent of rated torque
300
250
200
150
100
50
0
0
20
40
60
80
100
Speed, percent of synchronous speed
1.0
0.8
0.6
0.4
0.2
0
Slip as a fraction of synchronous speed

Type of Electric Motors

AC Motors – Induction motor

Relationship load, speed and torque



At start: high current and low "pull-up" torque

At 80% of full speed: highest "pull-out" torque and current drops

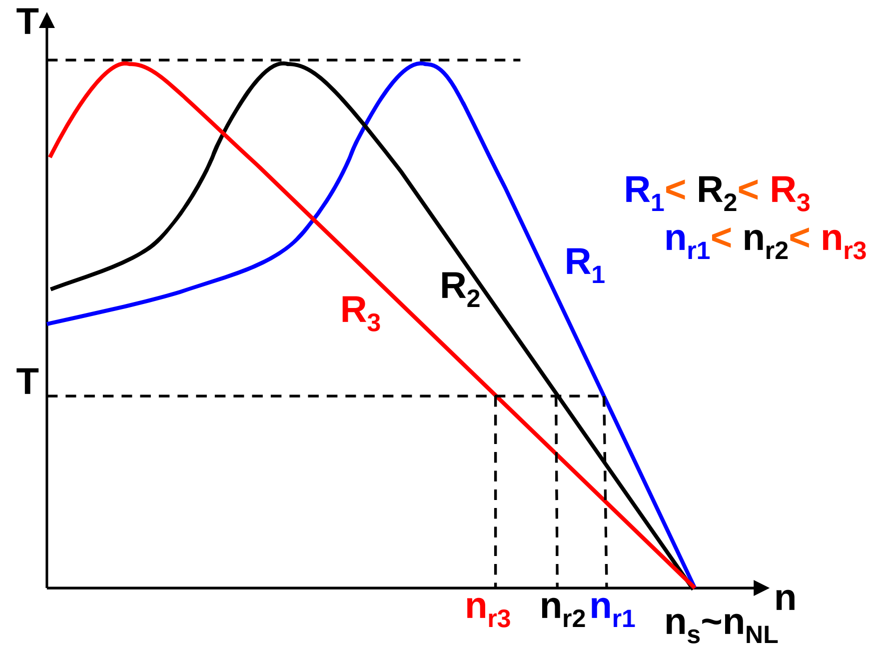
At full speed: torque and stator current are zero

Speed Control

- There are 3 types of speed control of 3 phase induction machines
  i. **Varying rotor resistance**
  ii. **Varying supply voltage**
  iii. **Varying supply voltage and supply frequency**

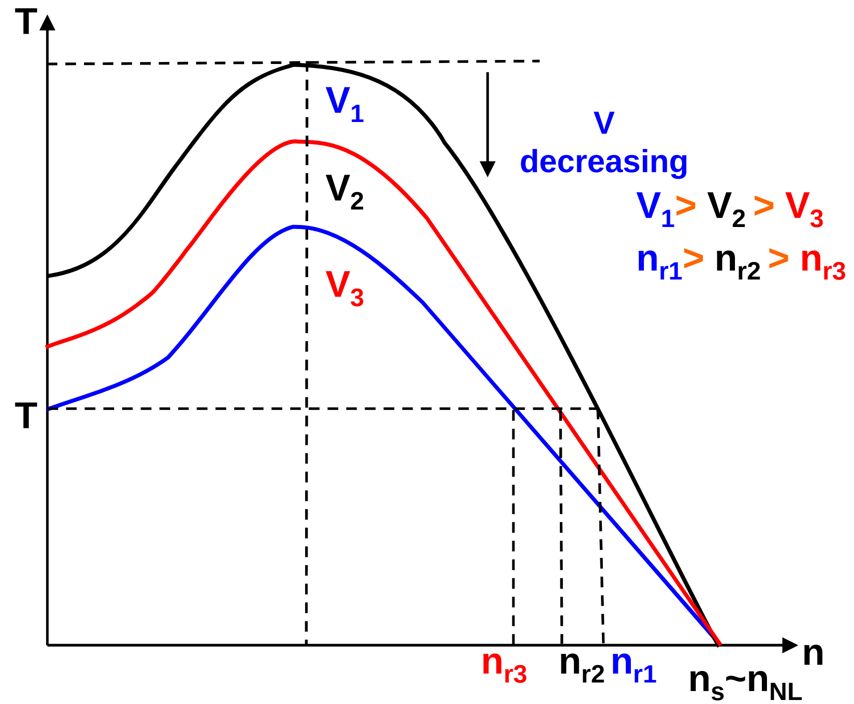
Varying rotor resistance

- For wound rotor only
- Speed is decreasing
- Constant maximum torque
- The speed at which max torque occurs changes
- Disadvantages:
  - large speed regulation
  - Power loss in R_{ext} – reduce the efficiency



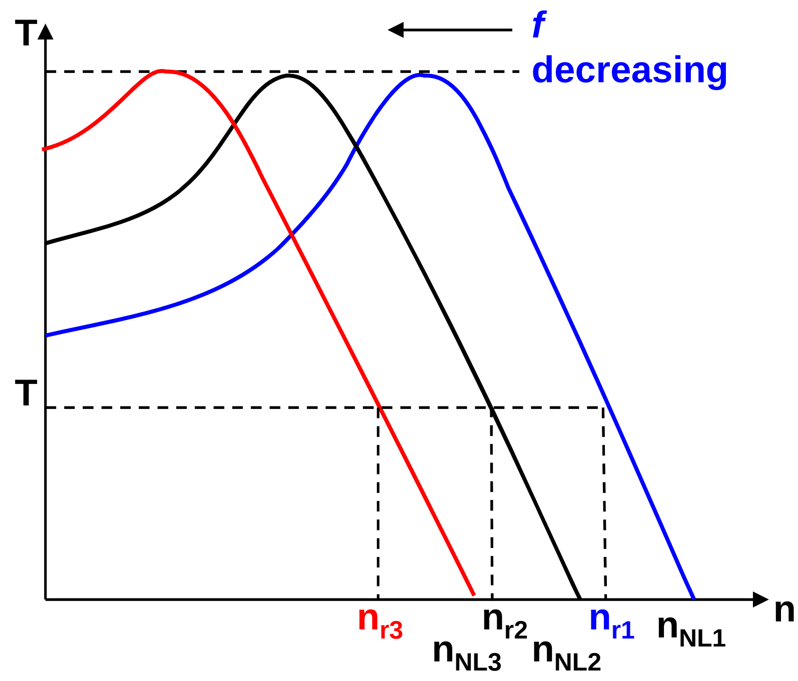
Varying supply voltage

- Maximum torque changes
- The speed which at max torque occurs is constant (at max torque, $X_R = R_R/s$
- Relatively simple method – uses power electronics circuit for voltage controller
- Suitable for fan type load
- Disadvantages :
  - Large speed regulation since ~ n_s



Varying supply voltage and supply frequency

- The best method since supply voltage and supply frequency is varied to keep V/f constant
- Maintain speed regulation
- uses power electronics circuit for frequency and voltage controller
- Constant maximum torque



Torque-Equation

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

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

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

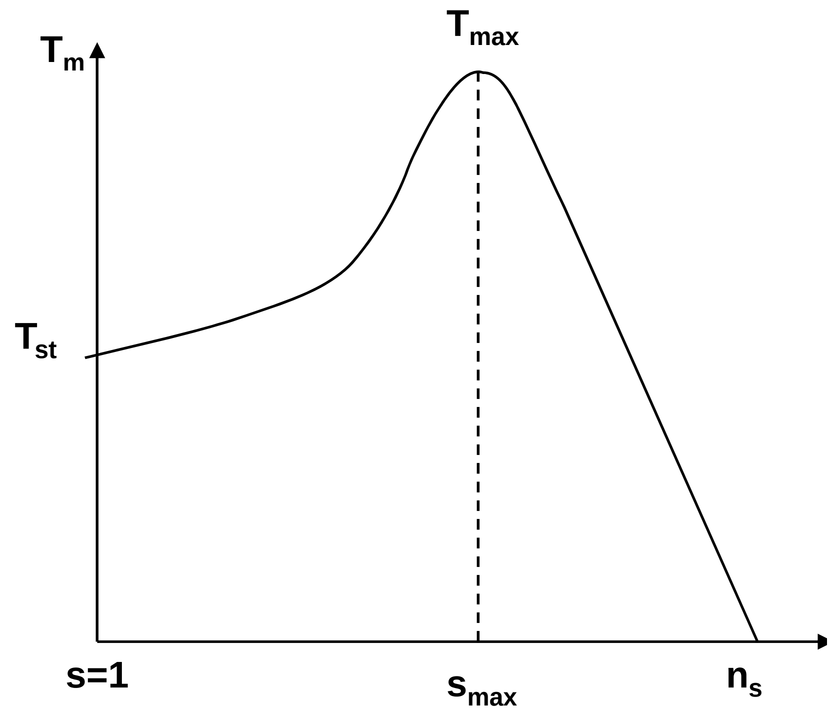
…

…

…

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

Hence, Plot T_m vs s



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

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:

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

Torque-Equation

Starting Torque, $s = 1$

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

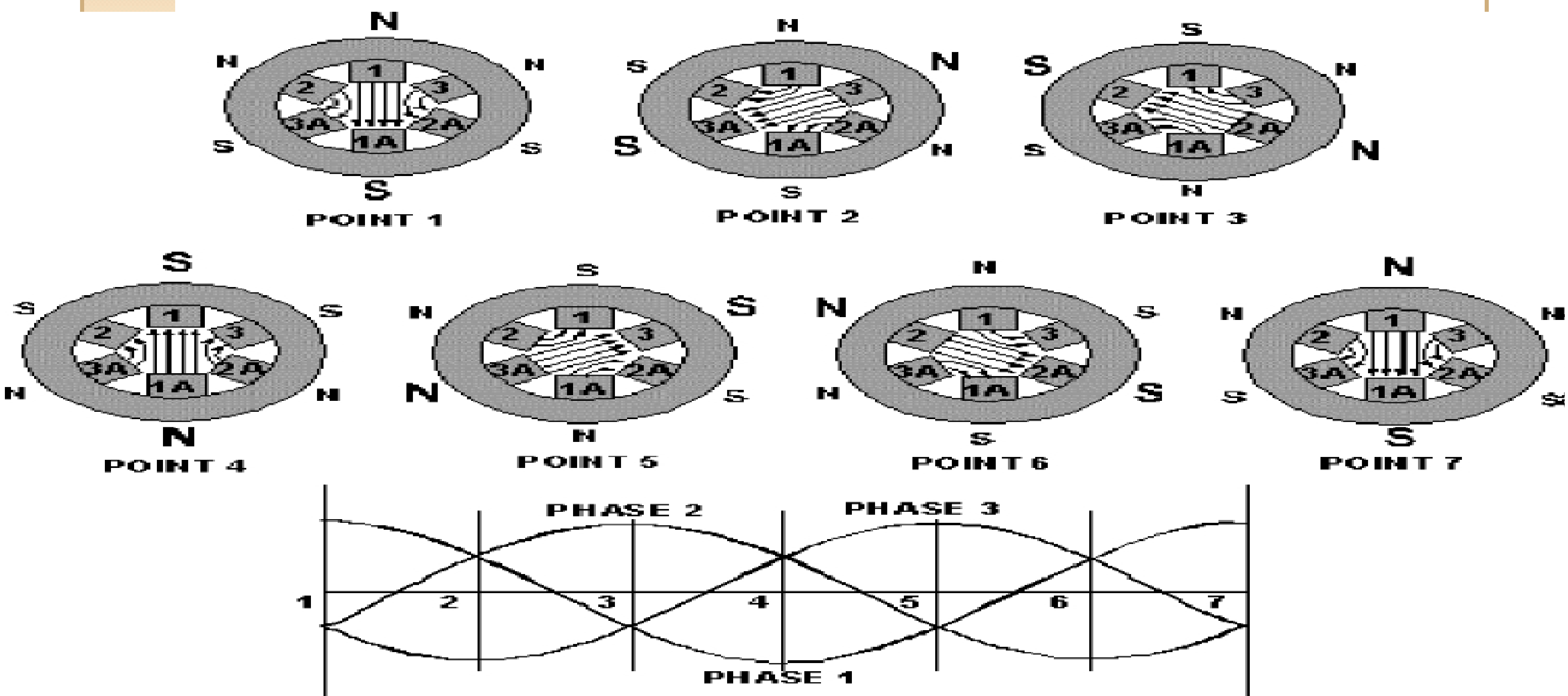
$$s_{\max} = \pm\left[\frac{R_R'}{\sqrt{(R_s)^2 + (X_R')^2}}\right]$$

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

COGGING AND CRAWLING

- When rotor bars are made to run parallel with stator , the torque rises & falls correspondingly causing more pulsations. This is termed as cogging in other words magnetic locking. This is reduced by making the rotor bars run at an angle to the stator i.e crawling in order to make the torque uniform. Crawling on the other hand signifies running of motor at almost one seventh of the rated spped due to interference of seventh harmonics.

ROTATING FIELD



OVERVIEW OF SINGLE PHASE IM

- Home air conditioners
- Kitchen fans
- Washing machines
- Industrial machines
- Compressors
- Refrigerators

OVERVIEW OF SINGLE PHASE IM

- Types of 1ϕ induction Motor
  - Split Phase Motor
  - Capacitor Start Motors
  - Capacitor Start, Capacitor Run
  - Shaded Pole Induction Motor
  - Universal Motor (ac series motors)