DEE 3143 BASIC ELECTRICAL MACHINE & POWER SYSTEMS

CHAPTER 2
INDUCTION MOTOR

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Topic Outcomes

- TO1: Describe the concept of single-phase induction motor
- TO2: Understand the concept of three-phase induction motor
- TO3: Describe the construction of induction motor
- TO4: Analyze the principle operation of induction motor
- TO5: Understand different types of speed control

Contents

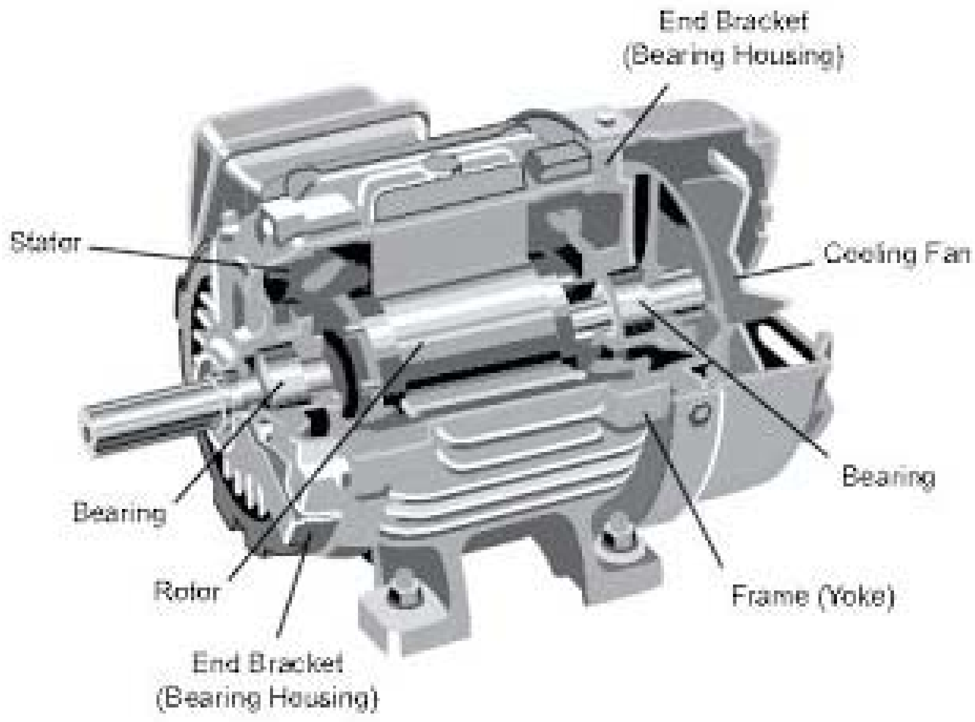
Introduction

Overview of induction motor

- Induction machine can be used either as induction motor or induction generator.
- Main features: low price and minimum maintenance cost
- Main disadvantages: difficult in speed control
- The induction motor get its name from the fact that ac voltages are induced in the rotor circuit by the rotating magnetic field of the stator

Overview of Single Phase Induction Motor

- Construction : similar to 3ϕ induction motor
- For the same kilowatt output its size is 1.5 times larger than that of 3 phase machines.
- Types of 1ϕ induction Motor
  - Split Phase Motor
  - Capacitor Start Motors
  - Capacitor Start, Capacitor Run
  - Shaded Pole Induction Motor
  - Universal Motor (ac series motors)

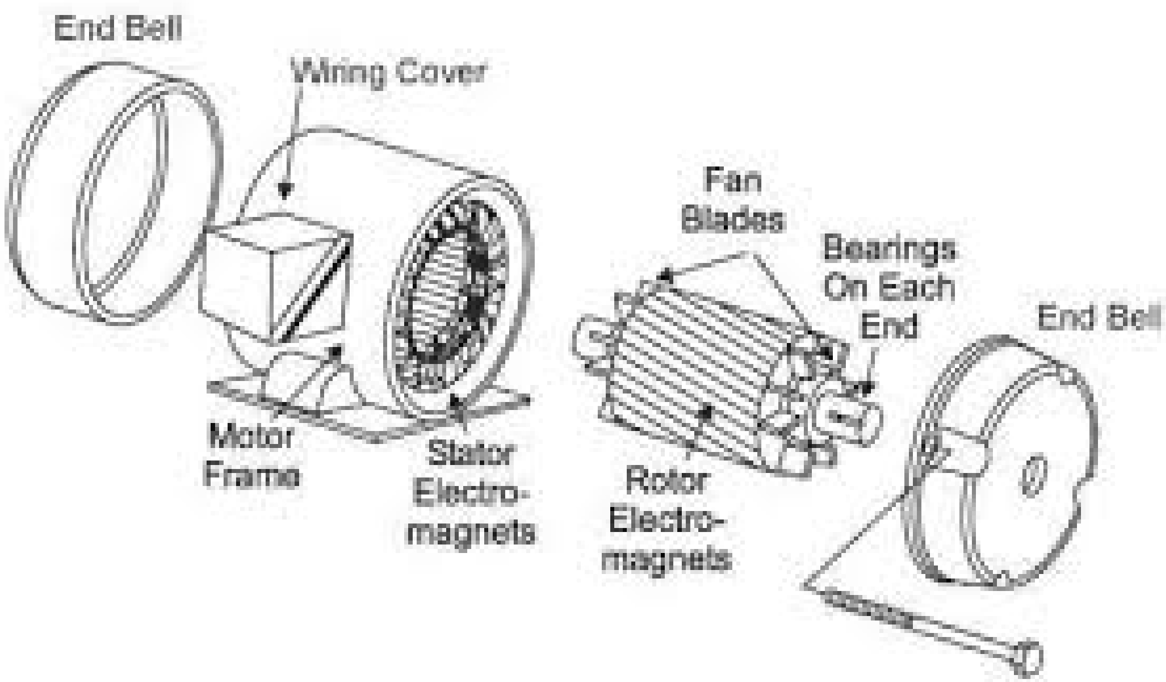


Cutaway View of Motor

Source: http://electrical-science.blogspot.my/2009/12/ac-motor-construction.html

Construction

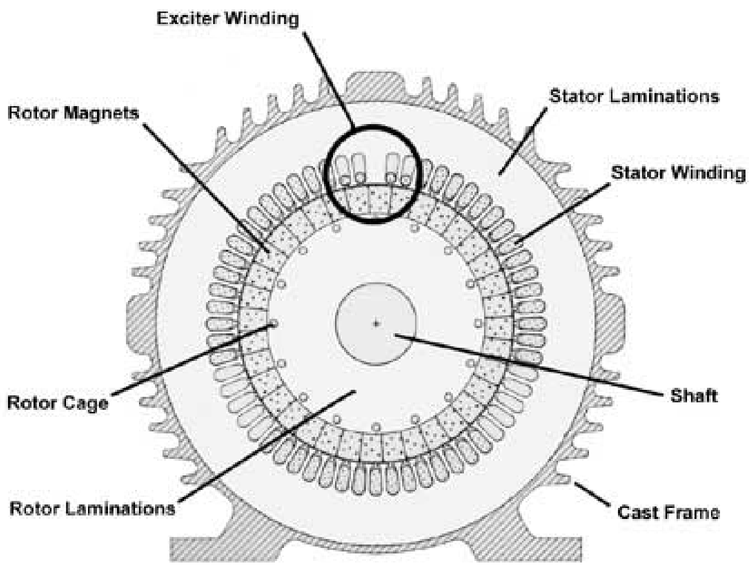
- There are three basic parts of an AC motor which are rotor, stator, and enclosure.
- The stator and rotor parts are electrical circuits that perform as electromagnets.



Source: http://what-when-how.com/motors-and-drives/ac-motors-general-principles-of-operation-motors-and-drives/

Construction (Stator construction)

- The stator is the stationary/fixed electrical part of the motor.
- 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.



Cross-Sectional Diagram
Written-Pole Single-Phase Motor

Source: http://www.meridiumpower.ca/C/c_1.html

Construction (Rotor construction)

- The rotor is the rotating/moving part of the electromagnetic circuit.
- It can be found in two types:
  - Squirrel cage (commonly used)
  - Wound rotor

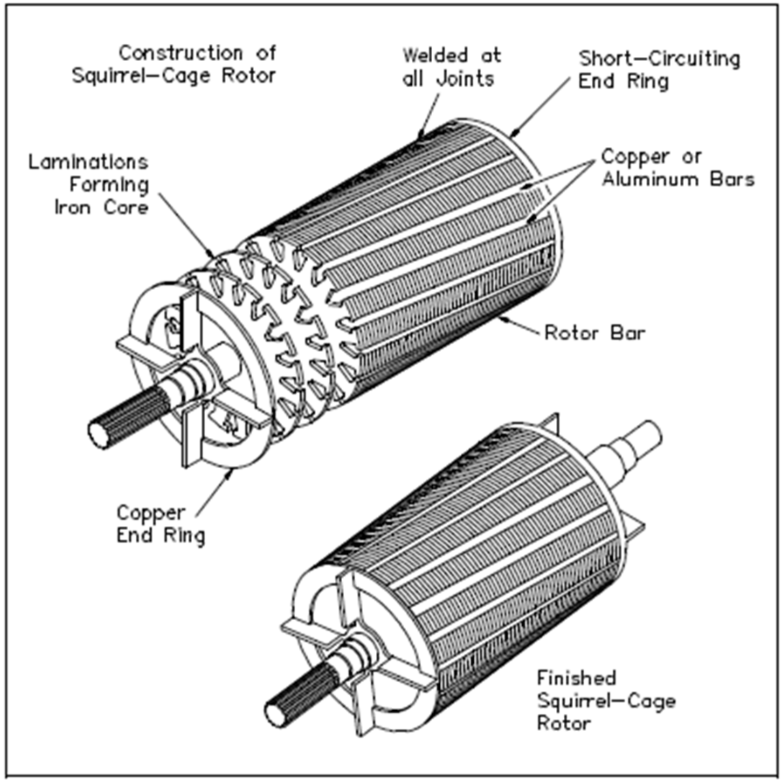


Figure 5 Squirrel-Cage Induction Rotor

Source: http://electricalengineeringbasics.blogspot.my/2010/01/squirrel-cage-motors-majoritory-of-3.html

Rotating Magnetic Field

- By connecting 3-phase voltage supply to 3-phase stator winding (3-phase current flow in the winding), it will induced 3-phase flux in the stator part.
- The speed rotation of flux is named as Synchronous Speed, n_s.
- That magnet flux is called rotating magnetic field.
- Synchronous speed: speed of rotating flux

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

- Where; *p* = number of poles
- *f* = the frequency of supply

Slip and Rotor Speed

1. Slip *s*

- Slip is the speed difference between rotor speed (induction machine) and speed of rotating magnetic field

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

- n_s = synchronous speed in rpm

  n_r = mechanical speed of rotor in rpm
- For normal conditions, the different of rotor speed and rotating magnetic field speed is small, where s= 0.01 ~ 0.05 (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 :

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

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

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

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

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

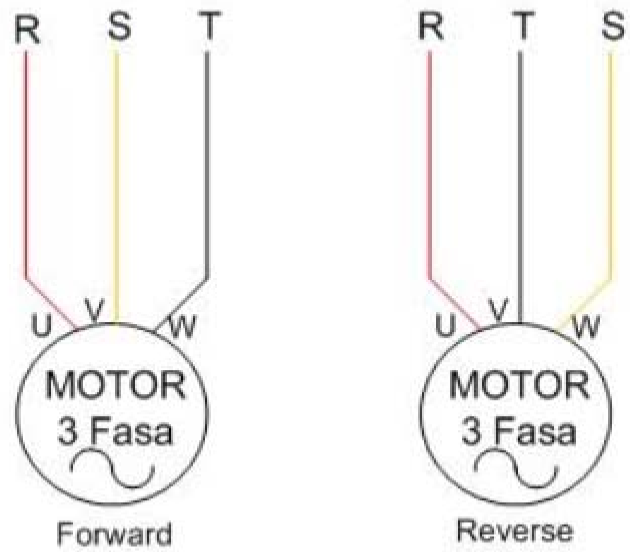
Principle of Operation

- **Torque producing mechanism**
  - By connecting 3-phase voltage supply to 3-phase stator winding (3-phase current flow in the winding), it will induced 3-phase flux in the stator part (stator part is energized).
  - The rotating flux (withing the air gap) induces rotor winding and produce voltage E_a
  - For closed circuit in rotor part, rotor current is generated due to induced voltage E_a
  - Torque – the interaction of rotor current with flux. The direction of rotor rotates with the same direction of rotating flux

Direction of Rotor Rotates

Q: How to change rotational direction?

A: By changing the power supply phase sequence



Source: http://antekel.blogspot.my/2015/10/turning-round-3-phase-induction-motors.html

Equivalent Circuit of Induction Machines

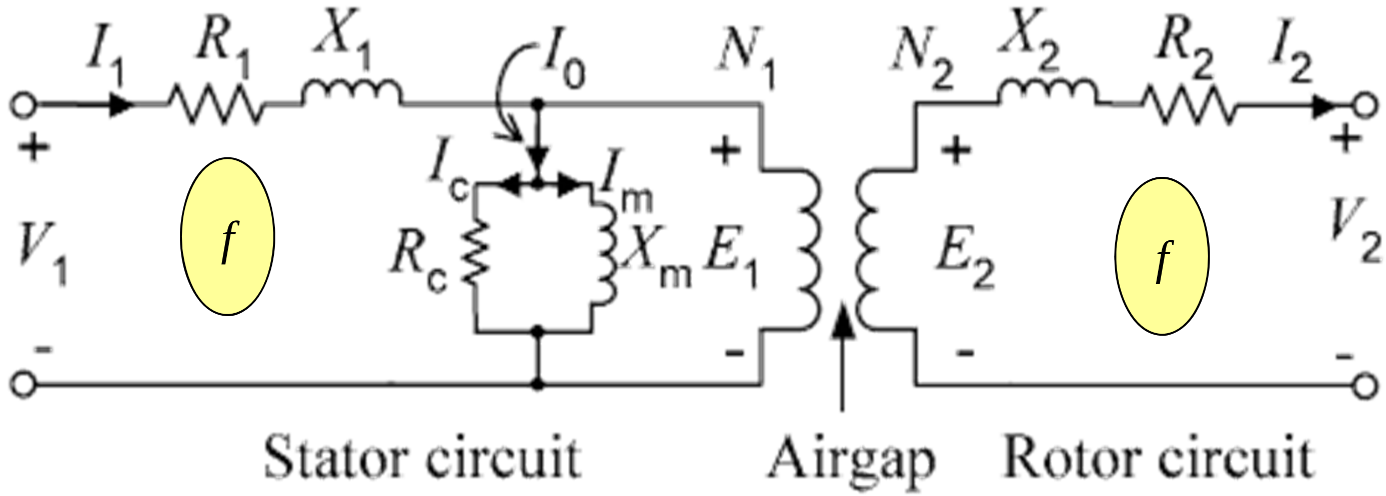
Conventional equivalent circuit

- *Note:*
  - *Modelled with per-phase equivalent model, don't modelled it with three-phase*
  - *The modelled circuit always in star connection (regardless whatever the actual motor connection)*
  - *The induction machine circuit almost similar with transformer circuit (for single-phase) which consist of rotor and stator branch*

Equivalent Circuit of Induction Machines

Step1 Rotor part in open circuit

(The rotor will not rotate)



Source: https://www.coursehero.com/file/7817197/Induction-machines/

- frequency E_2= frequency E_1 ,since the rotor is at standstill, slip (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

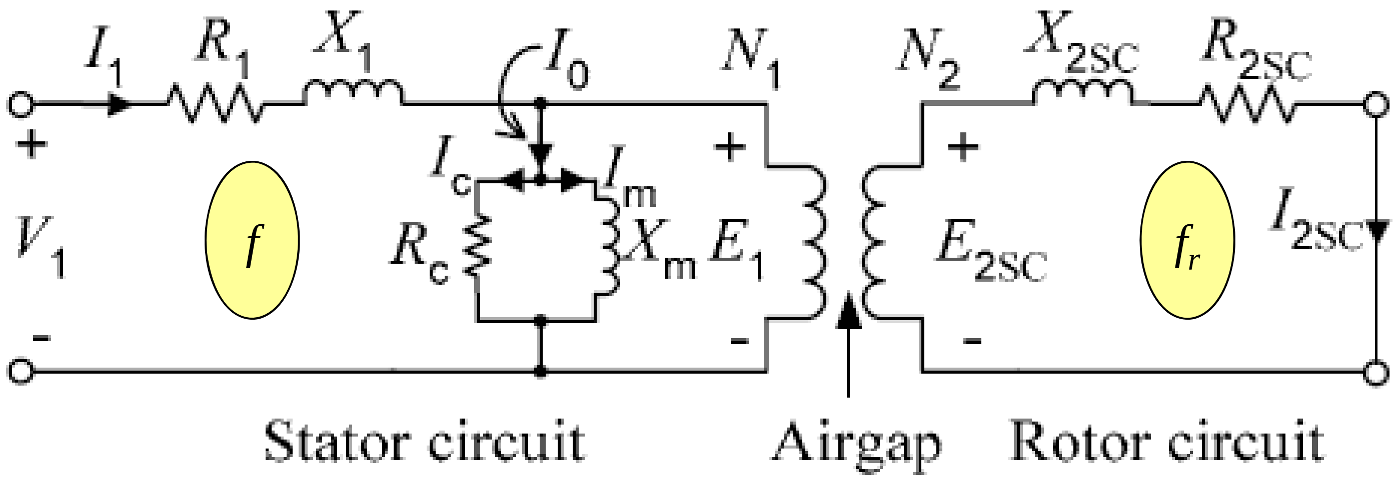
N_1, N_2 – effective number of turns of stator and rotor windings.

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

$E_2 = 4.44 f_1 N_2 \Phi$

Equivalent Circuit of Induction Machines

- **Step2 Rotor part in closed circuit**

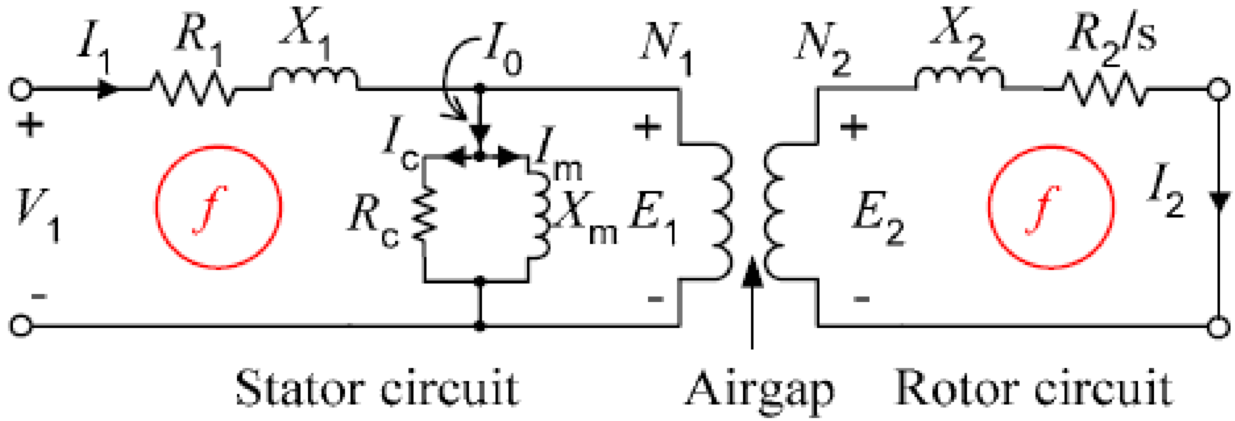


Source: https://www.coursehero.com/file/7817197/Induction-machines/

- frequency of E_2 is $f_r = sf$ due to rotating rotor.

Equivalent Circuit of Induction Machines

- **Step3 Eliminate f_2**



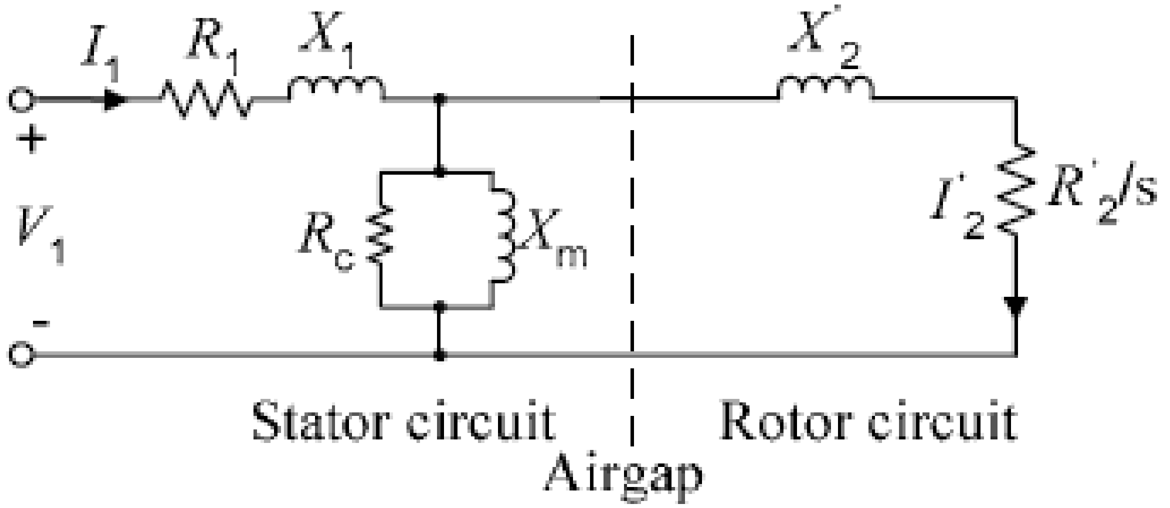
Source: https://www.coursehero.com/file/7817197/Induction-machines/

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 Refer to primary side (stator side)**



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

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

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

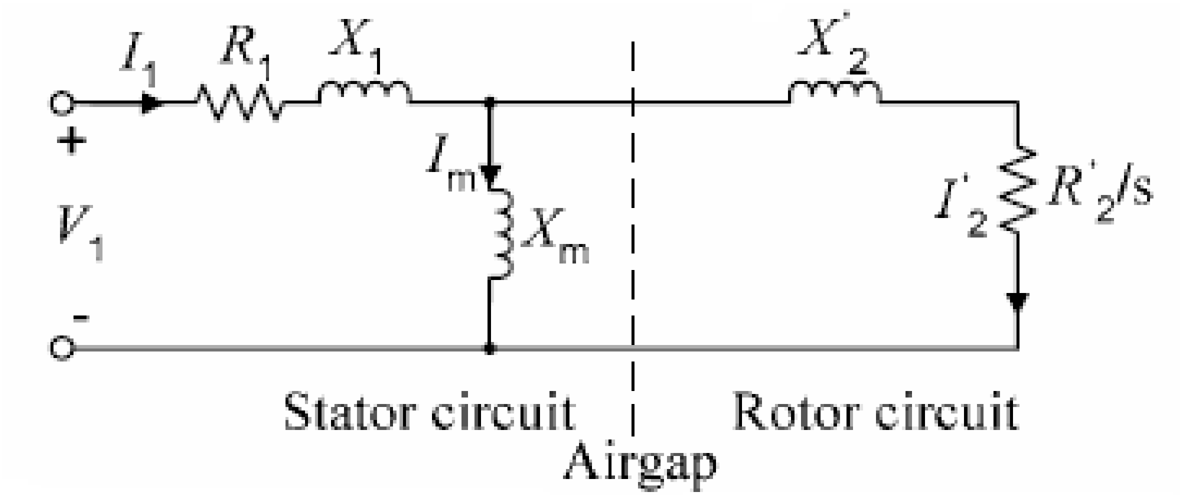
$$\text{where } a = \frac{N_1}{N_2}$$

Source: https://www.coursehero.com/file/7817197/Induction-machines/

- The value of X'_2 and R'_2 are normally mention or measured.
- Always refer the rotor side parameters to stator side.
- Typically, the circuit always refer to primary side (rotor parameter to stator side)

Equivalent Circuit of Induction Machines

- **IEEE recommended equivalent circuit**



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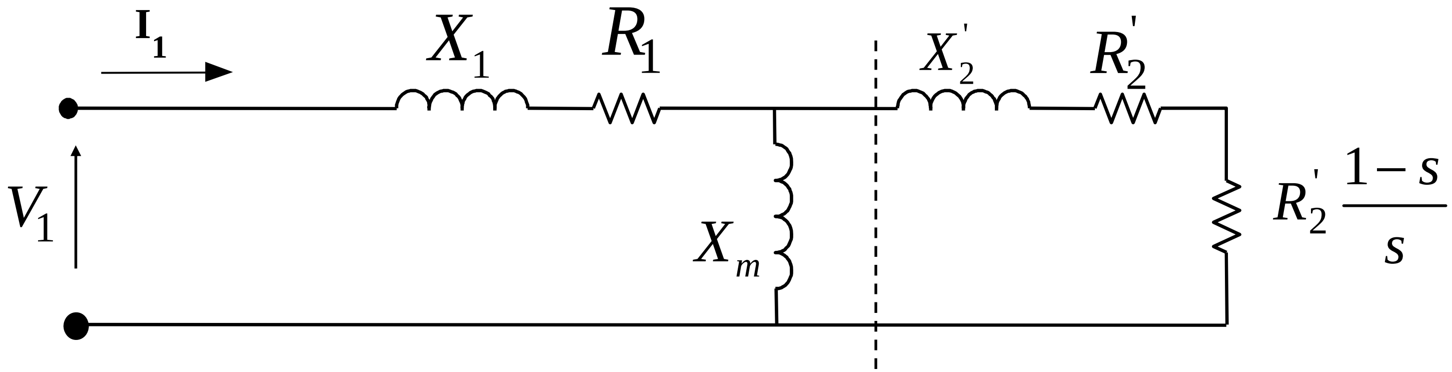
- R_c always intentionally exclude from the circuit due to core loss is combined with the rotational loss.

Equivalent Circuit of Induction Machines

IEEE recommended equivalent circuit



Source: https://www.coursehero.com/file/7817197/Induction-machines/

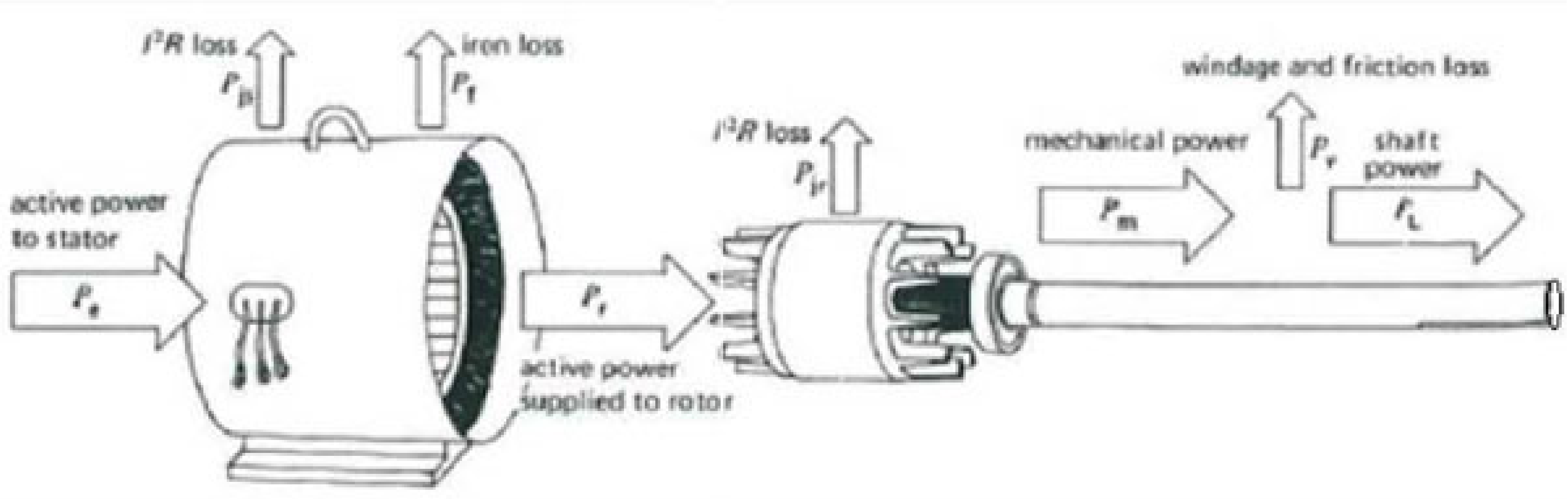
Note: $\frac{R_2}{s}$ can be separated into 2 PARTS

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

Purpose :

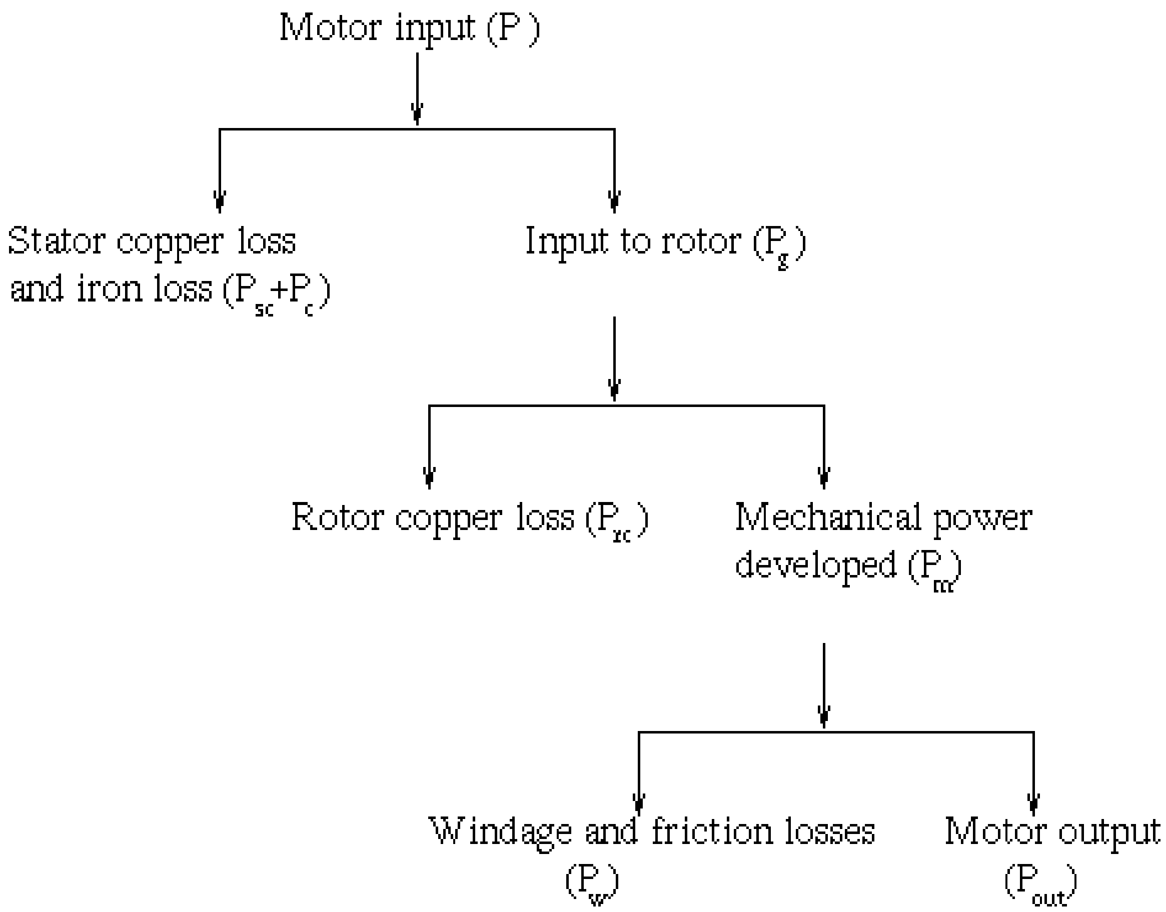
- **to obtain the developed mechanical**

Power Flow Diagram



Source: http://www.vfds.org/induction-motor-724402.html

Power Flow Diagram



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

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

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

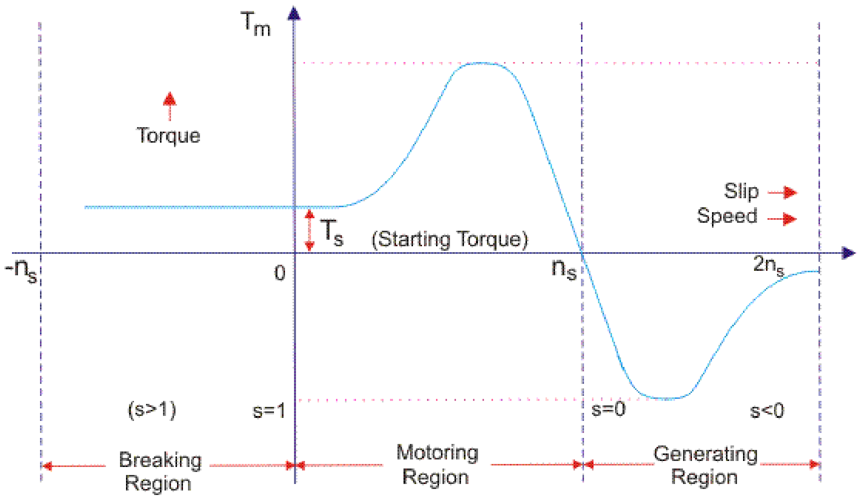
...

...

...

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

Hence, Plot T_m vs s



Torque Slip Curve for Three Phase Induction Motor

Source: https://www.electrical4u.com/torque-slip-characteristics-of-induction-motor/

Torque-Equation

$$Starting\ Torque, s = 1$$

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

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

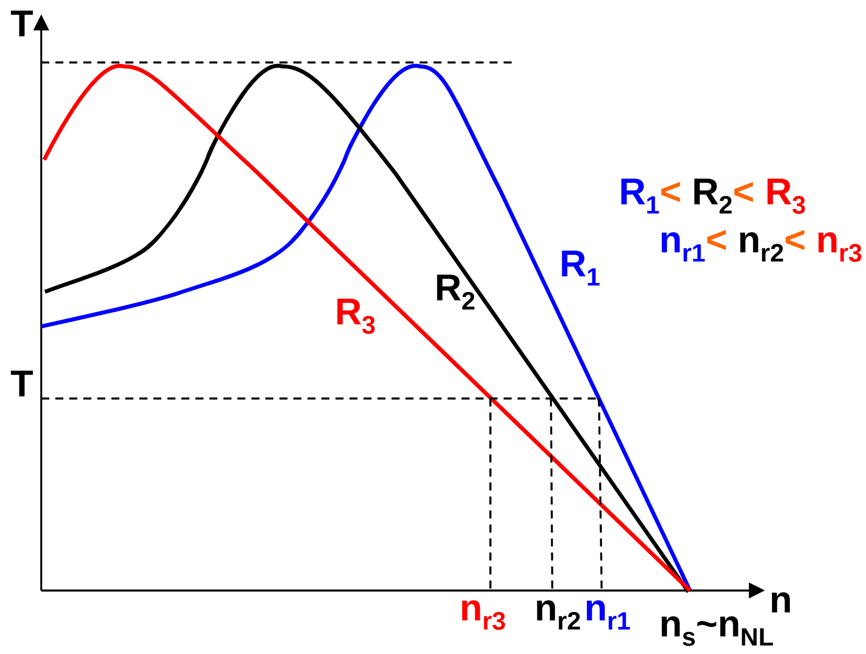
$$T_{max} = \left[\frac{3(V_{s\phi})^2}{2\left[2\pi\left(\frac{n_s}{60}\right)\right]}\right]\left[\frac{1}{R_s + \sqrt{(R_s)^2 + (X_s + X_R')^2}}\right]$$

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**

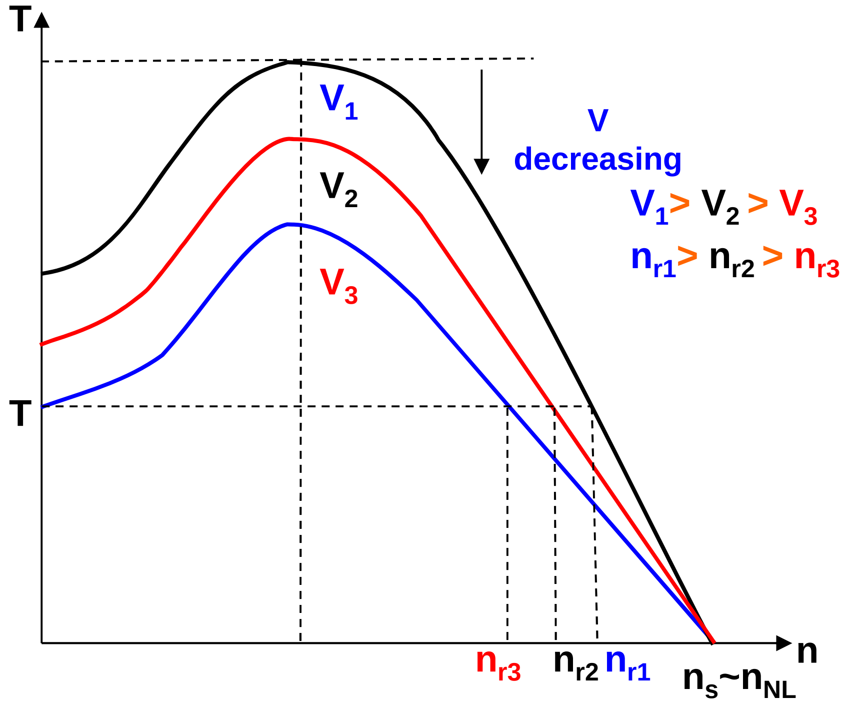
Varying Rotor Resistance

- 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



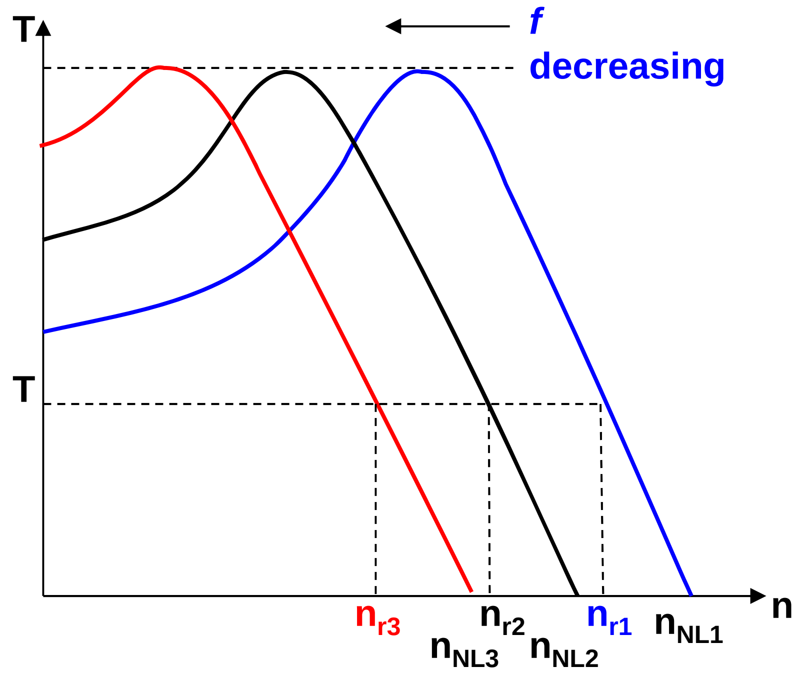
Varying Supply Voltage

- 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



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Research interest: Reliability, Distribution network, smart grid, risk asessment