Basic Electrical Engineering

Chapter-5: Electric Machines

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Introduction

- Induction machine is a **rotating electrical machine operated by AC** voltage source or which **generates AC voltage.**
- It also known as **asynchronous machine**, because it never operates at synchronous speed.
- It can be used **as generator as well as motor.**
    - The mode of operation of the machine is determined by the **speed of the rotating field in relation to the motor.**
- **Speed is frequency dependent and consequently these motors are not easily adapted to speed control.**
- The distinguishing feature of such a motor is that it is a **singly excited machine**, although such machines are equipped with both field & armature windings.
- Currents are made to flow in the armature (or rotor) conductors **by induction** which interact with the field produced by the field (or stator) winding and thereby produce a net unidirectional torque.
- An asynchronous machine may be considered to be a transformer in the sense that the **power is transferred from the stator (primary) to the rotor (secondary) winding only by mutual induction.** For this reason, such a machine is often called the **induction machine.**

Basic constructional details of induction machine

An induction machine has three major parts namely-

- **stator,**
- **rotor**
- **yoke.**

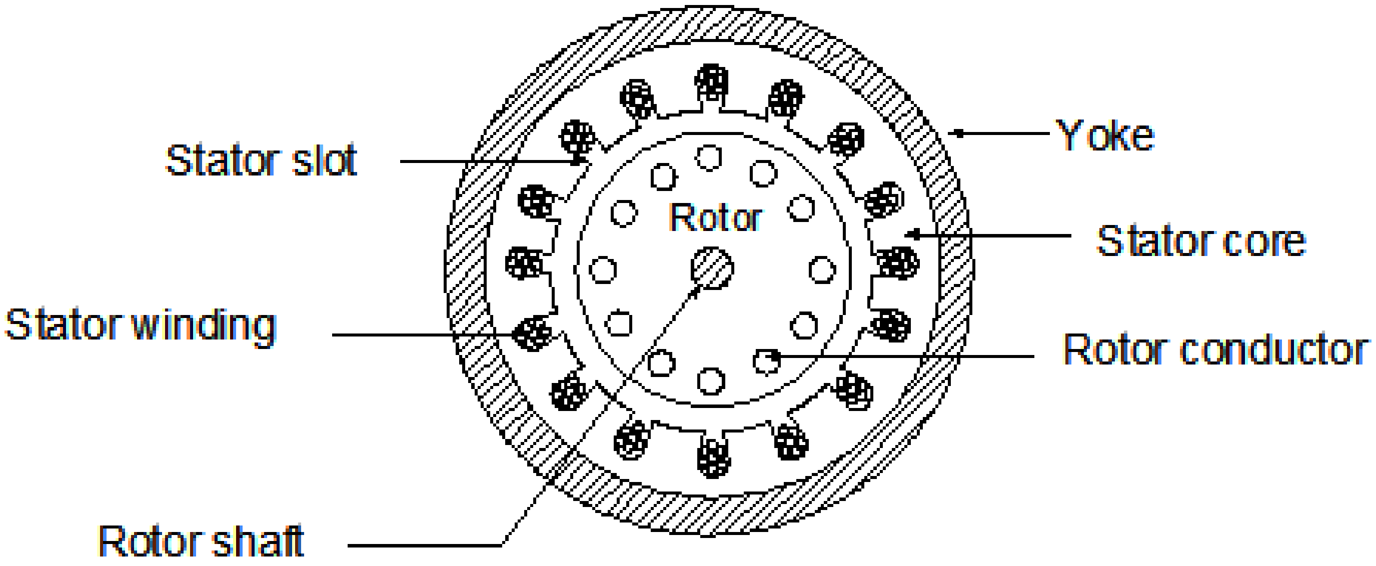
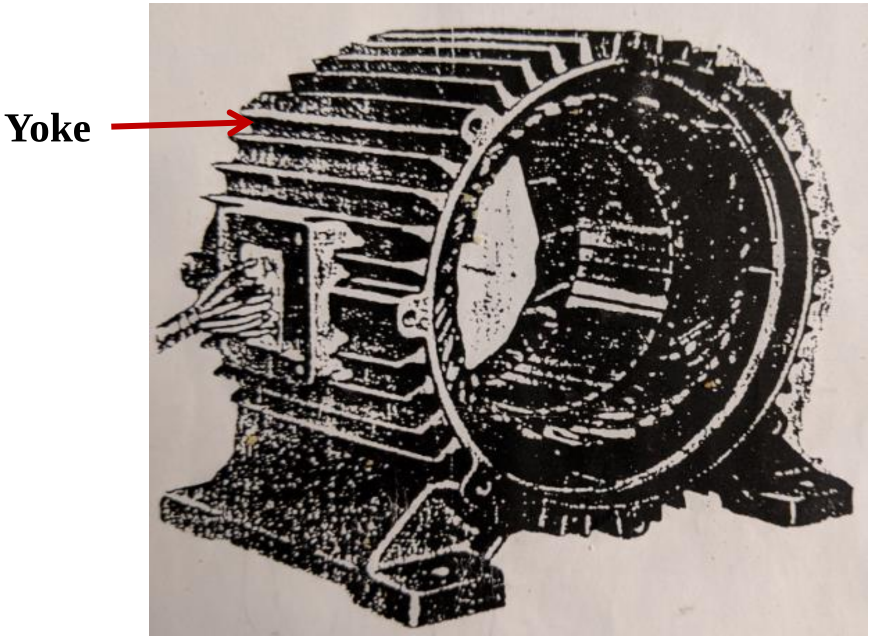


Fig.5.1 Cross-sectional view of induction machine

a) Yoke:

- It is the outermost frame of the machine. It houses the stator core and provides mechanical protection of the whole machine.



Basic constructional details of induction machine

b) Stator:

- It is the **stationary part** of the machine in cylindrical form with hollow space at the center.
- The stator core is made of **laminated silicon steel.**
- The inner circumference of the stator core has **alternate number of slots and teeth.**
- The **slots are provided with stator windings** made of enamel insulated copper wire.
- In case of **three-phase induction machine**, the stator winding is three-phase distributed winding with **each phase spaced 120^0 electrically apart.**
- The windings are insulated from the slots with insulating paper.
- When the **stator windings are supplied by three-phase voltage**, the winding **creates definite number of magnetic poles on the stator core.**

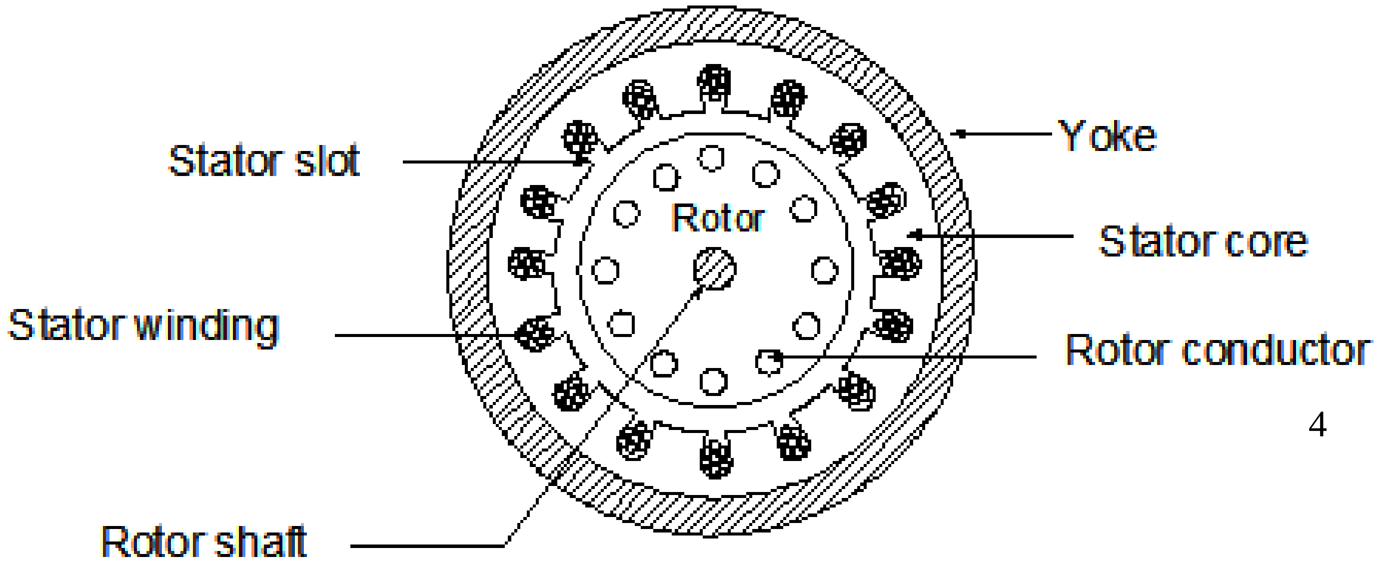


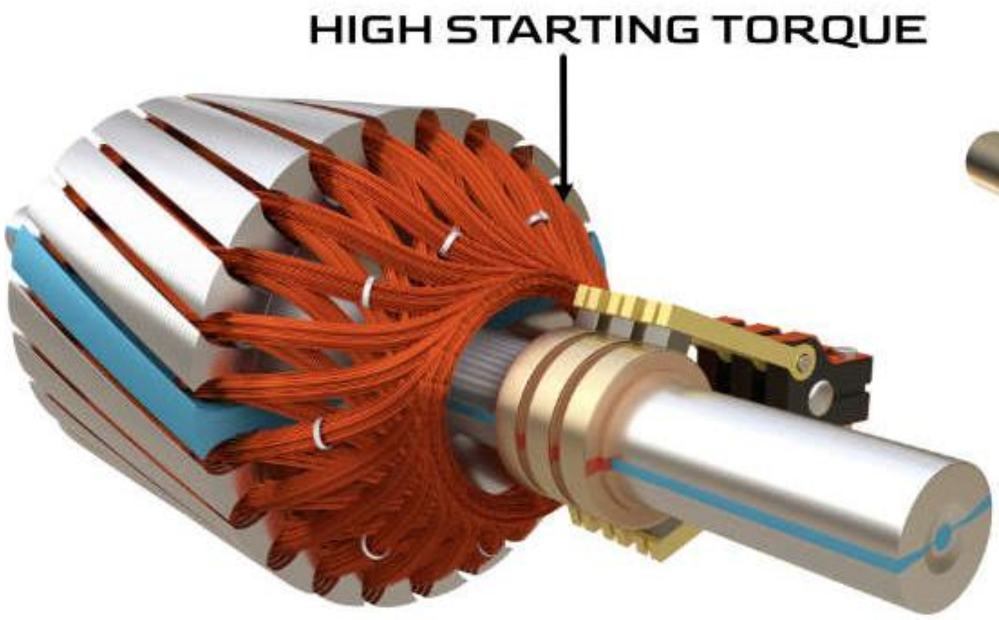
Fig.5.1 Cross-sectional view of induction machine

Basic constructional details of induction machine

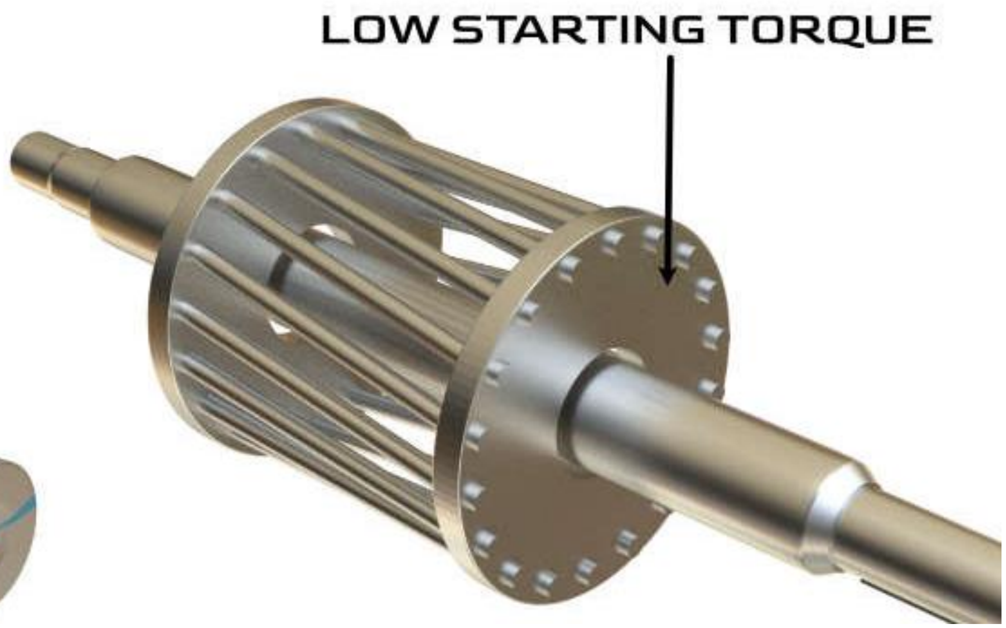
c) Rotor:

- It is the **rotating part** of the machine.
- It is **cylindrical in shape with a central shaft.**
- The shaft is supported by bearing at both end so that it can rotates freely keeping a small air gap of about 1 to 4 mm between rotor and stator.
- It is made of **laminated silicon steel sheet.**
- There are two types of rotor

i) Squirrel cage rotor and ii) Phase wound rotor



Phase wound rotor



Squirrel cage rotor

i) Squirrel cage rotor:

- made of **cylindrical laminated core with parallel slots** near by outer circumference as shown in Fig.5.3.
- These **parallel slots carry rotor conductors and ends of these conductors are short circuited by copper rings known as end rings.**

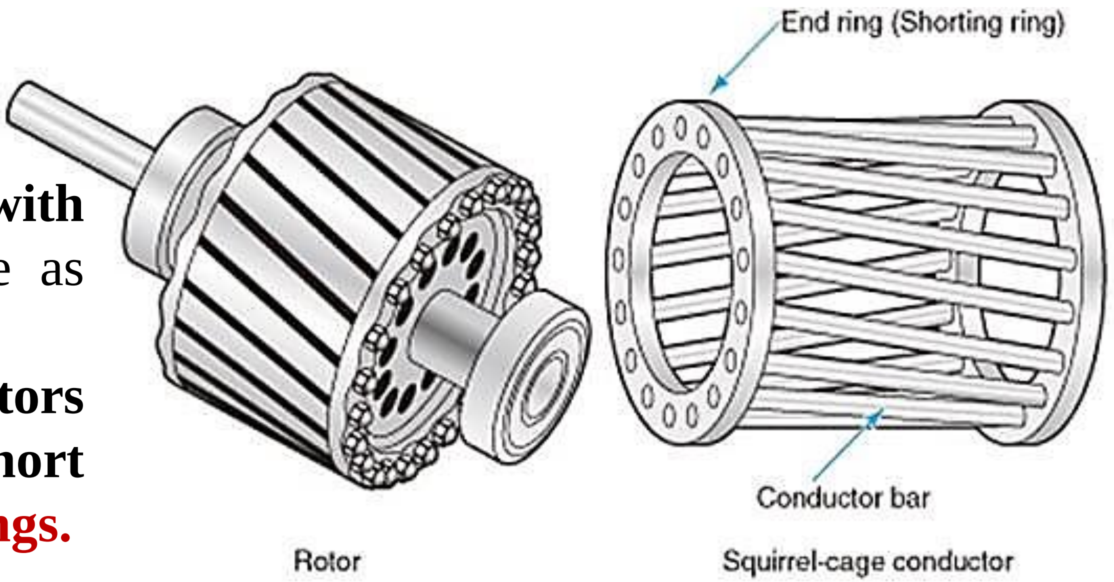


Fig.5.3 Squirrel cage rotor

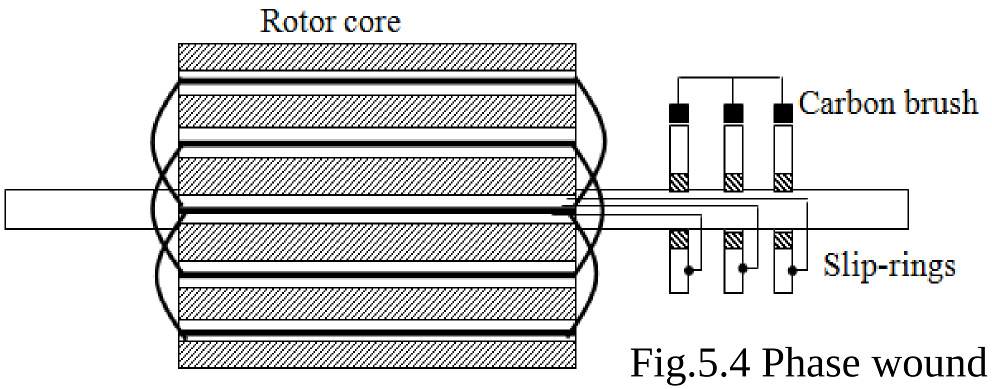


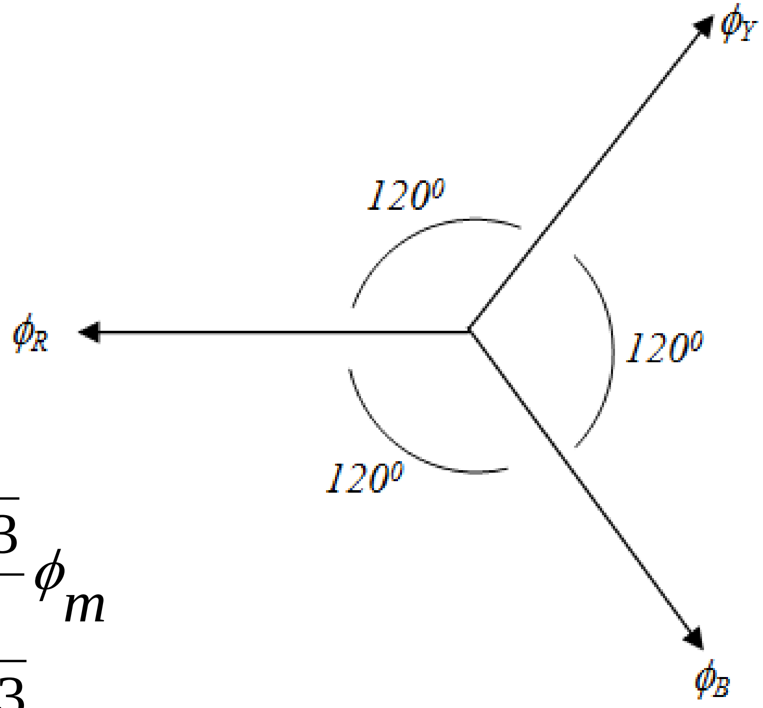
Fig.5.4 Phase wound rotor

ii) Phase wound rotor:

- made of **cylindrical laminated silicon steel core**, but it has **open slots** along the outer circumference.
- The **three-phase rotor windings are connected in star** and three ends of rotor windings are **connected to the three separate slip-rings mounted on the shaft** and the **slip-rings are short circuited by the carbon brushes with or without external resistance** as shown in Fig.5.4.
- The slip-rings are electrically insulated from the shaft. The **slip-rings rotates along with the shaft**, but the **carbon brushes are fixed and always touching over the slip-rings.**

Operating principle of three-phase induction motor

- When the three phase **stator windings are supplied by three phase balanced ac voltage source**, three phase currents will flow through the stator windings.
- The three-phase stator **currents produce their own magnetic flux**, whose nature will be same that of three phase stator currents.
- The **stator winding will magnetized the stator core.**
- The **net air-gap magnetic flux is the sum of three individual magnetic flux** produced by individual phase current.

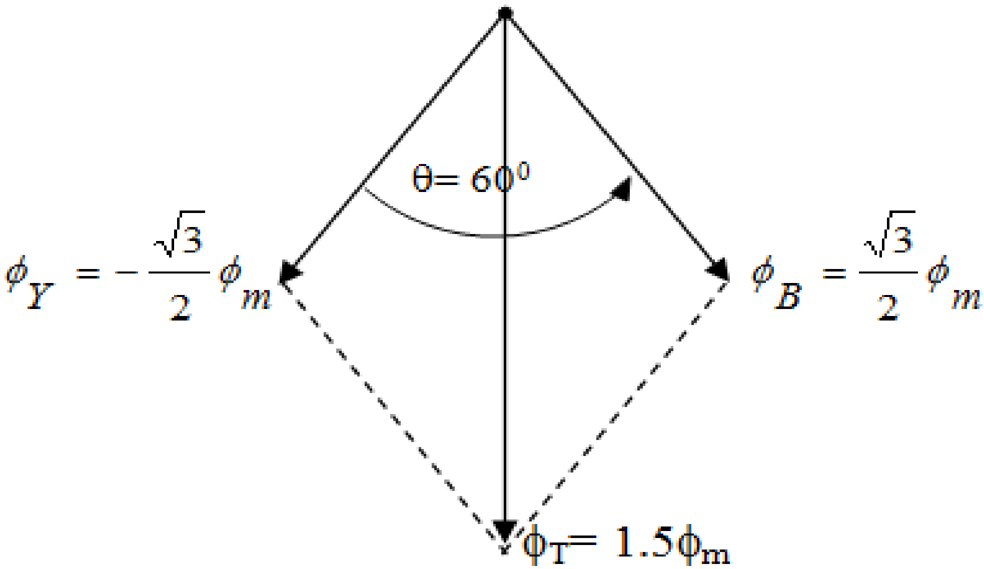


$$\phi_R = \phi_m \, \text{Sin}\omega t$$
$$\phi_Y = \phi_m \, \text{Sin}(\omega t - 120^0)$$
$$\phi_B = \phi_m \, \text{Sin}(\omega t - 240^0)$$

<u>When $\omega t = 0^0$</u>

$$\phi_R = \phi_m \, \text{Sin}\omega t = 0$$
$$\phi_Y = \phi_m \, \text{Sin}(\omega t - 120^0) = \phi_m \, \text{Sin}(0^0 - 120^0) = -\frac{\sqrt{3}}{2}\phi_m$$
$$\phi_B = \phi_m \, \text{Sin}(\omega t - 240^0) = \phi_m \, \text{Sin}(0^0 - 240^0) = +\frac{\sqrt{3}}{2}\phi_m$$

Operating principle of three-phase induction motor



When $\omega t = 0^0$

$$\phi_R = 0 \;;\phi_Y = -\frac{\sqrt{3}}{2}\phi_m \;;\phi_B = +\frac{\sqrt{3}}{2}\phi_m$$

The total air-gap flux is given by:

$$\phi_T = \sqrt{\phi_Y^2 + \phi_B^2 + 2.\phi_Y.\phi_B.Cos\theta}$$

$$\text{OR}\;\; \phi_T = \sqrt{(\frac{\sqrt{3}}{2}\phi_m)^2 + (\frac{\sqrt{3}}{2}\phi_m)^2 + 2.\frac{\sqrt{3}}{2}\phi_m\frac{\sqrt{3}}{2}.\phi_m.Cos60^0} = 1.5\,\phi_m$$

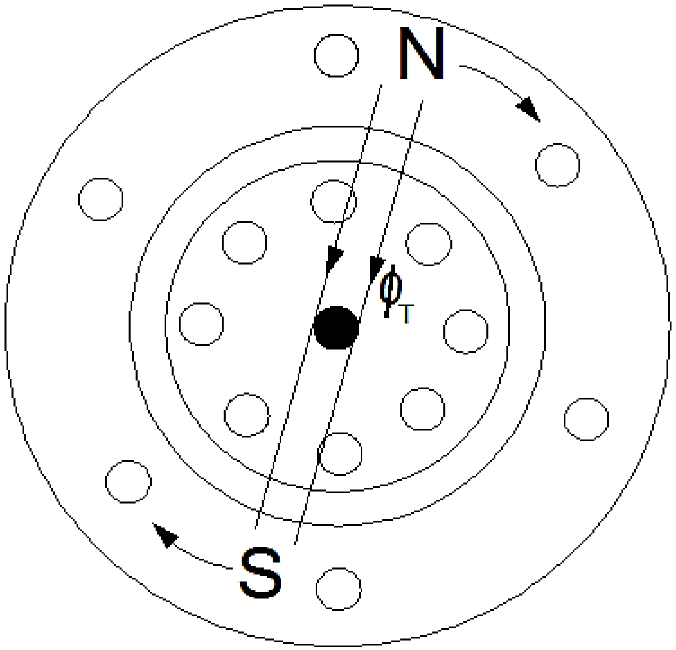
- Hence, it is clear from the above mathematical and phasor analysis that the net air gap flux has a constant magnitude of **1.5 ϕm** at any instant and its direction is rotating in clockwise direction with a constant speed.
- Such a magnetic field is known as **rotating magnetic field**. The speed of the rotating magnetic field is known as **synchronous speed** and is given by:

$$N_S = \frac{120.f}{P}$$

f = Frequency of voltage applied to the stator winding
P = Number of magnetic pole for which the stator winding is wound.

Operating principle of three-phase induction motor

- The **rotating magnetic field** produced by the stator currents **cuts the rotor conductor (which are at rest at starting).**
- Therefore, **according to Faraday's law of electromagnetic induction**, **emf will induced in the rotor conductors.**
- As the **rotor conductors are short circuited by end rings at both ends**, **there is a closed path and current will circulate** through the rotor conductors.
- Now the current carrying rotor conductors are lying in the magnetic field, hence **force developed on the rotor conductors starts rotor rotation.**



Operating principle of three-phase induction motor

- The **direction of rotation** is such that it **opposes the cause of induced current in the rotor circuit** **(i. e. relative speed between the rotor and the rotating magnetic field),** as described by **Lenz's law.**
- That means, the **rotor rotates in the same direction as the rotating magnetic field trying to catch – up the synchronous speed** of the rotating magnetic field, but it never success to do so.
    - If the rotor rotates with synchronous speed, there will no relative speed between magnetic field and rotor conductors, hence no emf and current will induce in the rotor conductors and no force will develop on the rotor conductors.
    - Therefore, the rotor always rotates at a speed less than the synchronous speed. That is why an induction motor is also known as asy**nchronous motor.**

Let N = speed of the rotor (in RPM)

$\dfrac{Ns - N}{Ns}$ is a factor indicating the fraction by which the speed of the rotor is less than the synchronous speed. This factor is known as **'Slip'.**

$$\boxed{\therefore \quad \text{Slip} \quad s = \frac{Ns - N}{Ns} \qquad (5.3)}$$

Operating principle of three-phase induction motor

- At starting, the electric circuit of induction motor is similar to that of a transformer.
  - **Stator winding acts as primary winding**
  - **Rotor conductors acts as secondary winding.**

$$E_2 = \frac{N_2}{N_1} E_1 \qquad (5.4)$$

Where,

E_2 = emf induced in the rotor winding per phase
E_1 = emf induced in the stator winding per phase
N_1 = Number of turn per phase in the stator winding
N_2 = Number of turn per phase in the rotor winding

At starting, the frequency of emf induced E_2, will be equal to the frequency of applied input voltage just like in transformer given as:

$$\boxed{N_S = \frac{120.f}{P} \quad \text{OR} \quad f = \frac{Ns.P}{120}}$$

When the rotor rotates, the **relative speed between rotating magnetic field and rotor conductors decreases.** Therefore, the magnitude of emf induced in the rotor conductors reduces to:

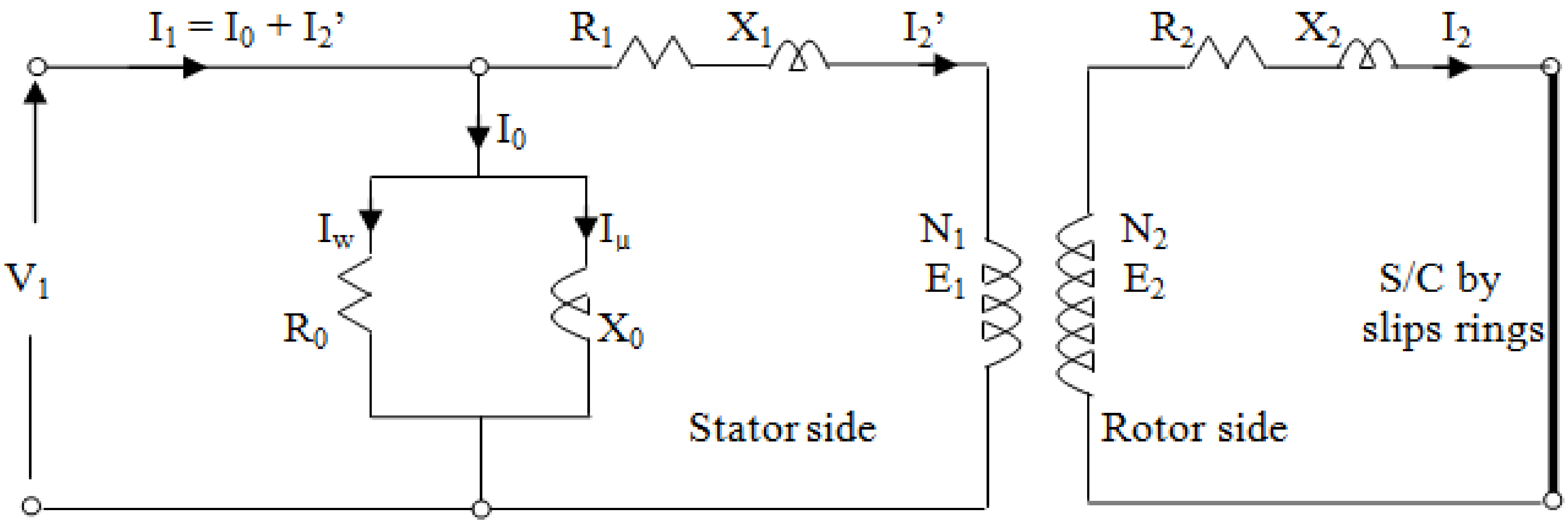
$$\boxed{E_R = s.E_2 \qquad (5.5)}$$

Similarly, **frequency of emf induced in rotor circuit also decreases to:**

$$f_R = \frac{(Ns. - N)P}{120} \quad \text{OR} \quad \frac{f_R}{f} = \frac{(N_s - N)P/120}{N_s.P/120} = \frac{(N_s - N)}{N_s.} = s$$

$$\boxed{\textbf{or,} \quad f_R = s.f \qquad \textbf{(5.6)}}$$

Analogy of an induction motor with a Transformer



$$I_2 = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$$

I_2 lags E_2 by a phase angle of ϕ_2.

$$\text{Where, } cos\Phi_2 = \frac{R_2}{\sqrt{R_2^2+X_2^2}}$$

Here, V_1 = Supply voltage to stator winding per phase
I_1 = Stator current per phase
I_0 = No-load stator current per phase
E_1 = Stator emf per phase
E_2 = Rotor emf at stand-still per phase
R_1 = Stator winding resistance per phase
X_1 = Stator winding leakage reactance per phase
R_2 = Rotor winding resistance per phase
X_2 = Rotor winding leakage reactance per phase at standstill
I_2 = Rotor current per phase at stand-still

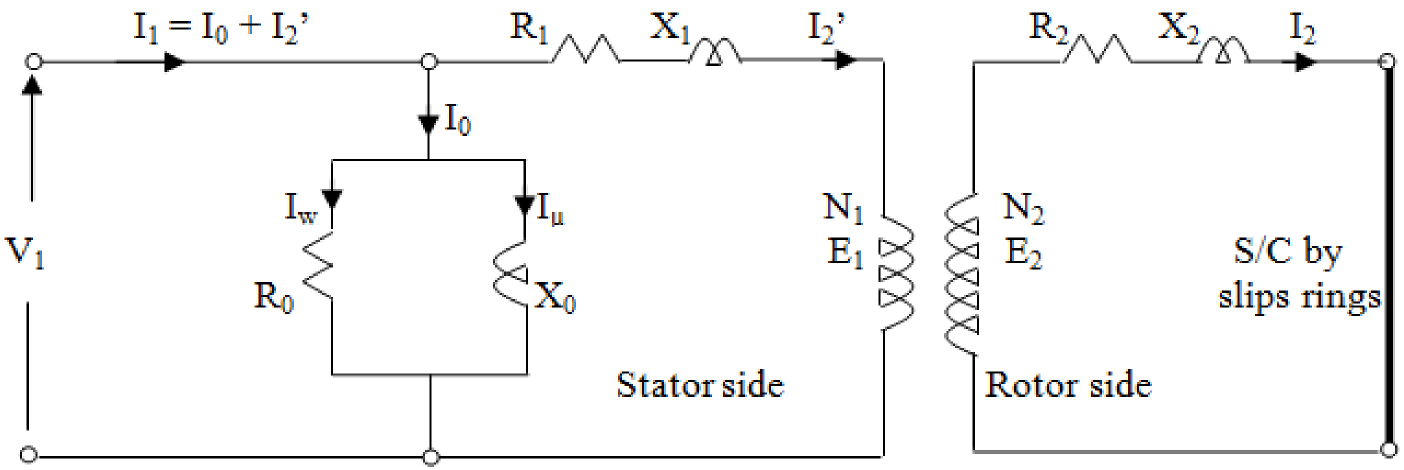
Analysis of stand-still condition of induction motor

Rotor current per phase at stand-still is given by:

$$I_2 = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$$

I_2 lags E_2 by a phase angle of ϕ_2.

Where, $cos\Phi_2 = \frac{R_2}{\sqrt{R_2^2+X_2^2}}$



- The **torque developed** by the rotor at stand-still (T_S) is **proportional to the flux per pole and active component of I_2.**

$$T_S = k.\ \phi.\ I_2 \cos \varphi_2, \quad \text{Where } \phi = \text{Flux per pole.}$$

- Like in transformer, the magnetic flux per pole (ϕ) remains constant irrespective of change in I_1 and I_2. It only depends on $I\mu$ Or V_1 or E_1.

Since,

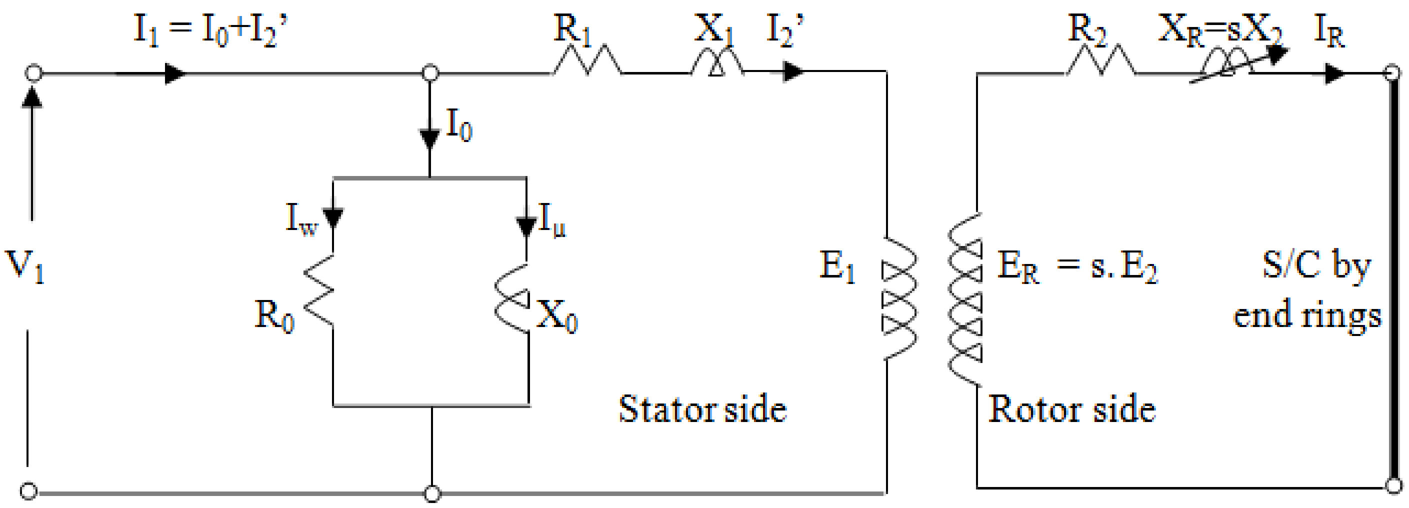
$$E_2 \propto \phi \quad \therefore \quad T_S = K_1.E_2 \frac{E_2}{\sqrt{R_2^2 + X_2^2}} \times \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

$$\boxed{\text{Or, } T_s = k_1 . \frac{E_2^2 R_2}{R_2^2+X_2^2}}$$

Analysis of running condition of induction motor

Here, X_R is shown variable, because its value changes with speed. The rotor current at running condition is given by:

$$I_R = \frac{s.E_2}{\sqrt{R_2^2 + (s.X_2)^2}}$$



I_R lags E_R (i.e. $s.E_2$) by a phase angle of ϕ_R.

Where, $Cos\phi_R = \frac{R_2}{\sqrt{R_2^2+(s.X_2)^2}}$

The **torque developed** by the rotor at running condition (T_R) is **proportional to the flux per pole and active component of I_R.**

$T_R = k.\ \phi.\ I_R\ Cos\ \varphi_R$, Where ϕ = Flux per pole.

$$\therefore \quad T_R = K_1.E_2 \frac{s.E_2}{\sqrt{R_2^2 + s^2 X_2^2}} \times \frac{R_2}{\sqrt{R_2^2 + s^2 X_2^2}}$$

$$\boxed{\text{Or, } T_R = k_r.\frac{s.E_2^2.R_2}{R_2^2+(s.X_2)^2}}$$

Uses of Induction Machines

- It can be used **as generator as well as motor**. The **mode of operation** of the machine is **determined by the speed of the rotating field in relation to the motor.**
- They **run at essentially constant speed** from no-load to full-load, the **speed is frequency dependent** and consequently these motors are not easily adapted to speed control.
  - We usually prefer d.c. motors when large speed variations are required.
- The **polyphase induction motor** is, by a very considerable margin, the **most widely used AC motor** (almost more than 90% of the mechanical power used in industry is provided by 3- phase induction motor).
  - The reasons are its **low cost, simple & rugged construction, absence of commutator, good operating characteristics (reasonably good power factor, sufficiently high efficiency and good speed regulation).**
  - An induction motor of a medium size may have an **efficiency as high as 90% & a power factor of 0.89.**
  - The **physical size** of such a motor **for a given output rating is relatively small** as compared with other types of motors.
- The 3-phase induction motors are **simple, robust, low-priced, easy to maintain and can be manufactured with characteristics to suit most industrial as well as domestic requirements.**