3-Phase Induction Motors.

- A 3-phase induction motor is a Singly-excited a.c. machine.
  - ↳ Only Stator is given 3-phase a.c. supply.
  - ↳ The rotor is not given any supply.

- An induction motor runs at a speed other than the synchronous speed. So, it is also known as asynchronous motor.
- It works on the principle of electromagnetic induction

Constructional Features.

- The two main parts of the induction motor are :-
  - (i) Stator
  - (ii) Rotor.

(i) Stator :- The stator of an induction motor consists of

- (a) Stator frame
- (b) Stator core
- (c) Stator winding → 3-phase distributed winding
- (d) End-covers
- (e) Bearings etc.

- The stator of 3-phase induction motor is similar to the stator of synchronous machine.

- Stator frame is made up of cast-iron and it holds the stator core.

- Stator core is made up of thin sheets of steel laminations ; stacked together. The stator core has slots for providing three-phase distributed a.c. windings in it.

- The two end-covers are also made up of cast-iron.

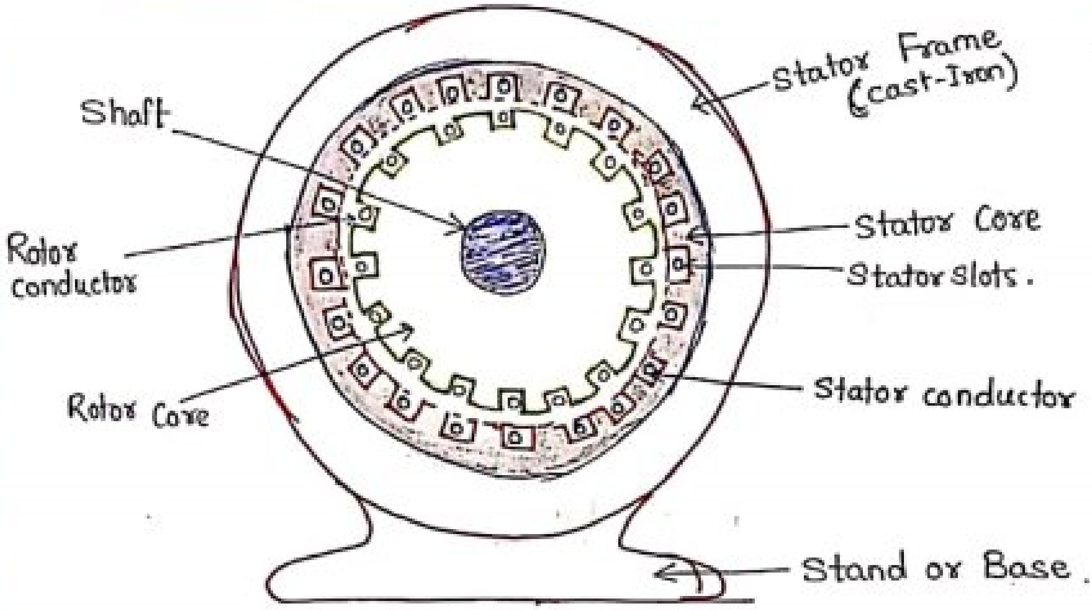
- The stator windings consists of insulated copper wire. The windings are three-phase distributed winding. The three phases are connected in either star or delta fashion.

- The stator windings are done for specific number of poles, as per our requirement. Greater is the number of poles, lesser is the speed.

$$\because \quad N_s = \frac{120f}{P}$$

- When a 3-phase ac supply is given to a 3-phase distributed winding, a rotating magnetic field is set-up in space.

- This rotating magnetic field induces emf in the rotor by electro-magnetic induction, which produces a torque, resulting in rotation of motor.



Constructional features of Induction motor

- The air-gap between the stator and rotor should be as small as practically possible.
  - ↳ (i) It reduces the leakage flux between stator and rotor.
  - ↳ (ii) It improves the operating power factor of the induction motor.

(ii) Rotor

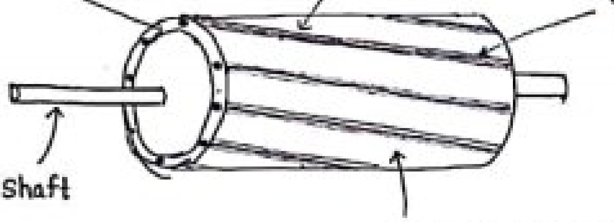
- Rotor is a hollow laminated core, having slots.
- The rotor core is mounted on the shaft.
- The rotor in the induction motor can be classified into two types, depending upon construction.

~~(a) Squirrel type~~

(i) Squirrel cage type.
(ii) Wound type or Slip ring type.

(i) Squirrel cage type.

- In this, copper or aluminium bars are placed in the slots on the rotor core.
- These bars are short-circuited at both the ends, using end-rings.
- In many small size squirrel cage induction motor, the rotor bars, the end-rings and the cooling fan are cast at the same time, using a mould.
- If the rotor core is removed, the whole structure of rotor bars and end-rings, looks like the cage of a squirrel and hence the name.
- The rotor slots are skewed, to ensure smooth and quiet operation of induction motor.



Squirrel cage Rotor.

(ii) Wound type rotor or Slip-ring induction motor.

- In this, the rotor contains windings similar to that used on the stator.
- So, the rotor windings are also 3-phase distributed windings.
- The rotor windings are usually connected in star.
- The three terminals of the star-connected windings, are connected to the three slip-rings (or collector rings). The slip rings are on the shaft, but are insulated from it.
- Slip rings allow for connection of external resistance, in series with the rotor windings, using carbon brushes.

- Advantages of connecting external resistance
  - ↳ (a) It allows speed control of induction motor
  - ↳ (b) It also provides control over starting torque.

- comparision of both types of induction motor

Squirrel cage induction motor	Wound-type induction motor
i) Economical and simpler in construction	(i) Costly.
(ii) More rugged, so requires less maintenance.	(ii) Need more maintenance
(iii) No control over starting torque	(iii) Starting torque can be controlled using external resistance connection.
(iv) Speed cannot be controlled using resistance	(iv) Easy control of speed using external resistance.

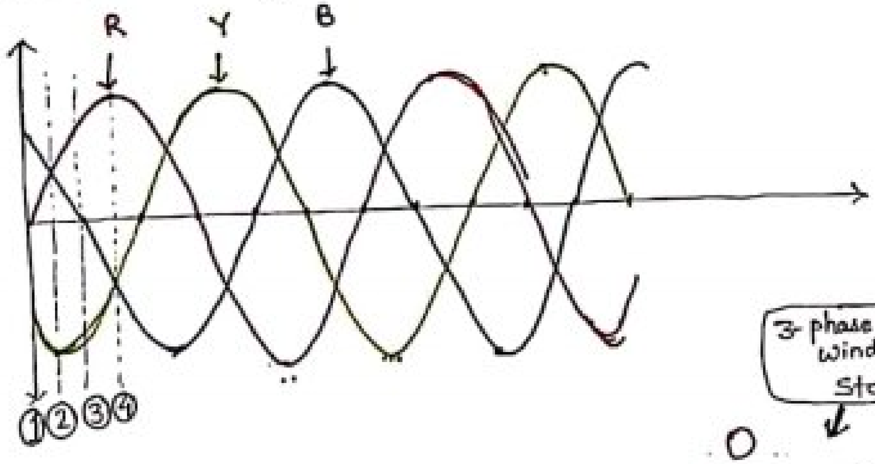
Rotating Magnetic field.

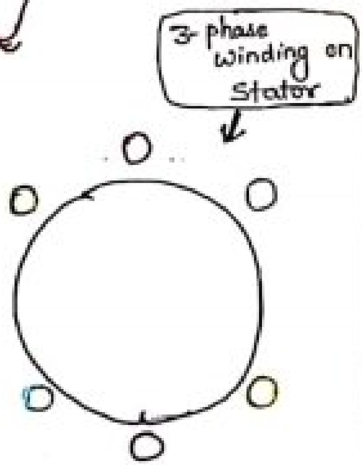
- When a three-phase ac supply is given to a three-phase distributed windings, a rotating magnetic field is created.

- Rotating magnetic field means that the poles on the stator are not stationary, but rotating in space.

- Proof for production of rotating magnetic field :-
  - A two-pole, three-phase distributed winding is taken on stator.
  - A balanced three-phase supply is given to it.

3-phase ac supply :-





$\phi_R = \phi_m \sin \omega t$

$\phi_Y = \phi_m \sin(\omega t - 120^\circ)$

$\phi_B = \phi_m \sin(\omega t - 240^\circ)$

At instant 1.

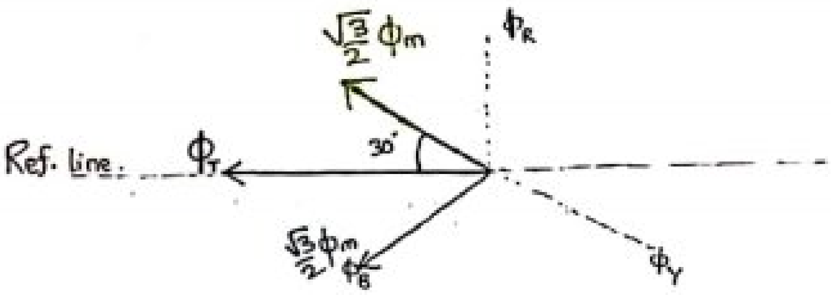
$\omega t = 0^\circ$

So,

$\phi_R = 0$

$\phi_Y = \phi_m \sin(-120^\circ) = -\frac{\sqrt{3}}{2}\phi_m.$

$\phi_B = \phi_m \sin(-240^\circ) = \frac{\sqrt{3}}{2}\phi_m.$



$\vec{\phi}_{Total} = \vec{\phi}_R + \vec{\phi}_Y + \vec{\phi}_B$

$= 0 + \frac{\sqrt{3}}{2}\cos 30^\circ + \frac{\sqrt{3}}{2}\cos 30^\circ$

$= 1.5\phi_m.$

So, resultant flux is 1.5 times of the maximum flux, and at instant 1, it is directed along reference line.

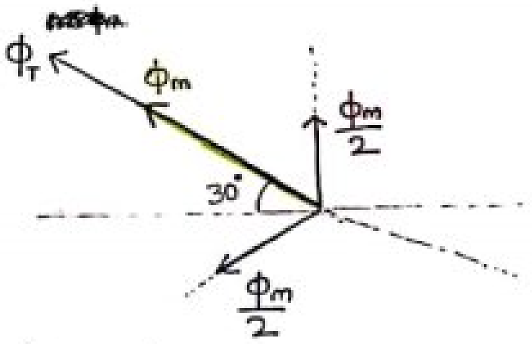
At instant 2.

$\omega t = 30^\circ$

So, $\phi_R = \phi_m \sin 30^\circ = \frac{\phi_m}{2}$

$\phi_Y = \phi_m \sin(-90^\circ) = -\phi_m.$

$\phi_B = \phi_m \sin(-210^\circ) = \frac{\phi_m}{2}$



$$\vec{\phi}_{Total} = \vec{\phi}_R + \vec{\phi}_Y + \vec{\phi}_B$$

$$= \frac{\phi_m}{2}\cos 60° + \phi_m + \frac{\phi}{2}\cos 60°$$

$$= 1.5\,\phi_m$$

So, resultant flux is again 1.5 times of maximum flux, and at instant 2, it is directed at angle of 30° from reference, in clock-wise direction.

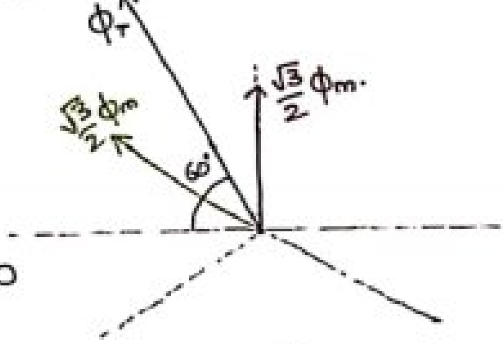
At instant 3.

$\omega t = 60°$

So, $\phi_R = \phi_m \sin 60° = \frac{\sqrt{3}}{2}\phi_m.$

$\phi_Y = \phi_m \sin(-60°) = -\frac{\sqrt{3}}{2}\phi_m.$

$\phi_B = \phi_m \sin(-180°) = 0.$



$$\phi_{Total} = \vec{\phi}_R + \vec{\phi}_Y + \vec{\phi}_B$$

$$= \frac{\sqrt{3}}{2}\cos 30° + \frac{\sqrt{3}}{2}\cos 30° + 0$$

$$= 1.5\,\phi_m$$

So, resultant flux is 1.5 times of maximum flux, and is directed at 60° from reference in clockwise dir^n.

- So, from above phasor diagrams, we see that a rotating magnetic field of constant magnitude ($1.5\phi_m$) is setup, when a 3-phase balanced supply is given to 3-phase distributed windings.

- The speed at which the magnetic field rotates is known as synchronous speed, denoted by N_s.

Slip.

- The difference between the synchronous speed, N_s, and actual rotor speed is called Slip. It is usually expressed as a fraction or percentage.

$$\% \text{ Slip}, s = \frac{N_s - N_r}{N_s} \times 100$$

Principle of operation of induction motor.

- Induction motor works on the principle of electro-magnetic induction.

- When a 3-phase ac supply is given to 3-phase distributed winding, a rotating magnetic field is created.

↓

∴ This rotating magnetic field cuts the rotor conductors, inducing an emf in it.

↓

This induced emf causes a current to flow in the rotor, as rotor circuit is short-circuited.

↓

As per lenz's law, the effect opposes the cause.

↓

The ~~cause~~ effect is the :- current in the rotor, and the cause is the :- flux cutting by the rotating magnetic field.

↓

So, this cause of flux cutting can be reduced, if the relative speed between the rotating magnetic field and rotor conductors decreases.

⇓

So, a torque is ~~prop~~ produced, which rotates the rotor in the same direction, as that of rotating magnetic field. This reduces the relative flux cutting, as relative speed of flux cutting decreases.

- If we inter-change two supply phases, the direction of rotation of magnetic field reverses and so the rotation of induction motor also reverses.

<u>NOTE</u>:- The rotor of induction motor can never attain synchronous speed, N_s as in that case relative speed will be zero and there will be no flux-cutting. So there will be no induced emf and no developed torque in this case.

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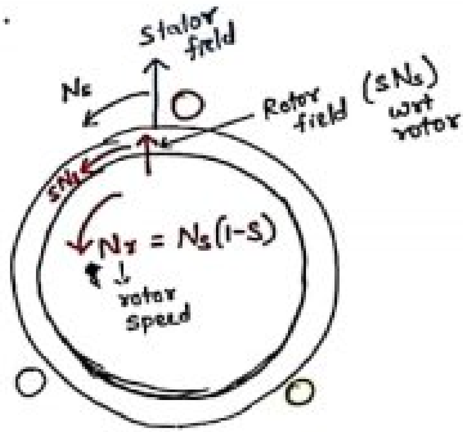
Working of Induction motor.



- Speed of stator field, rotating in space, (w.r.t stator) $= N_s$.

- Speed of rotor of induction motor $= N_r$
$= N_s(1-s)$

- Relative speed between stator field and rotor conductors $= N_s - N_r$
$= sN_s$.

→ Since flux cutting is at speed $N_s - N_r = sN_s$.
So, frequency of induced emf in rotor $= f_r = sf$

→ Now, current in the rotor (at freq. sf), causes a flux, which rotates at a speed of sN_s, w.r.t. the rotor body.
↳ ∵ Speed of rotor field w.r.t. rotor $= sN_s$

∴ Speed of rotor field w.r.t. stator $= N_s$

- So, Stator field and rotor field rotate at same speed N_s, thus creating a constant torque.

→ Torque and Power Equations.

→ Power flow in induction motor.

P_{in} → P_g → P_{dev} → P_{out}

- P_{in} → P_g: — Stator Cu loss, — Stator core loss
- P_g → P_{dev}: — Rotor Cu loss
- P_{dev} → P_{out}: — F & W loss

P_{in}: Power input to stator

P_g: Air-gap power or Power input to rotor

P_{dev}: Mechanical power developed in rotor

P_{out}: Power output at shaft.

> **NOTE:-** ① Rotor core loss is not taken separately here, but is included in F&W loss itself. So, iron loss given in question refers only to stator iron loss.

— Similarly, corresponding torques can be defined.

$$\tau_g = \frac{P_g}{\omega_{sm}}$$

τ_g → Air-gap torque.

ω_{sm} → synchronous speed in mechanical radian/sec.

$$\tau_d = \frac{P_{dev}}{\omega_r} = \frac{P_g}{\omega_{sm}}$$

τ_d → Developed torque.

$$\tau_{out} = \frac{P_{out}}{\omega_r}$$

τ_{out} → Shaft torque

ω_r → rotor speed in mec·radn/sec.

> ② Friction and windage loss is also known as mechanical loss or rotational loss.
>
> ③ Losses at no-load include — Stator core loss and Friction and Windage loss.

For plotting torque-slip characteristics, we see relation between τ and s.

Case 1:- At starting and during initial running (also during braking region)

↳ Slip is high.

↳ $\left(\frac{R_2'}{s}\right)^2 << X_2'^2$

↳ $\boxed{\tau \propto \frac{1}{s}}$ → Hyperbolic relation

Case 2:- Under normal running condition

↳ Slip is low

↳ $\left(\frac{R_2'}{s}\right)^2 >> X_2'^2$

↳ $\boxed{\tau \propto s}$ → Linear relation.

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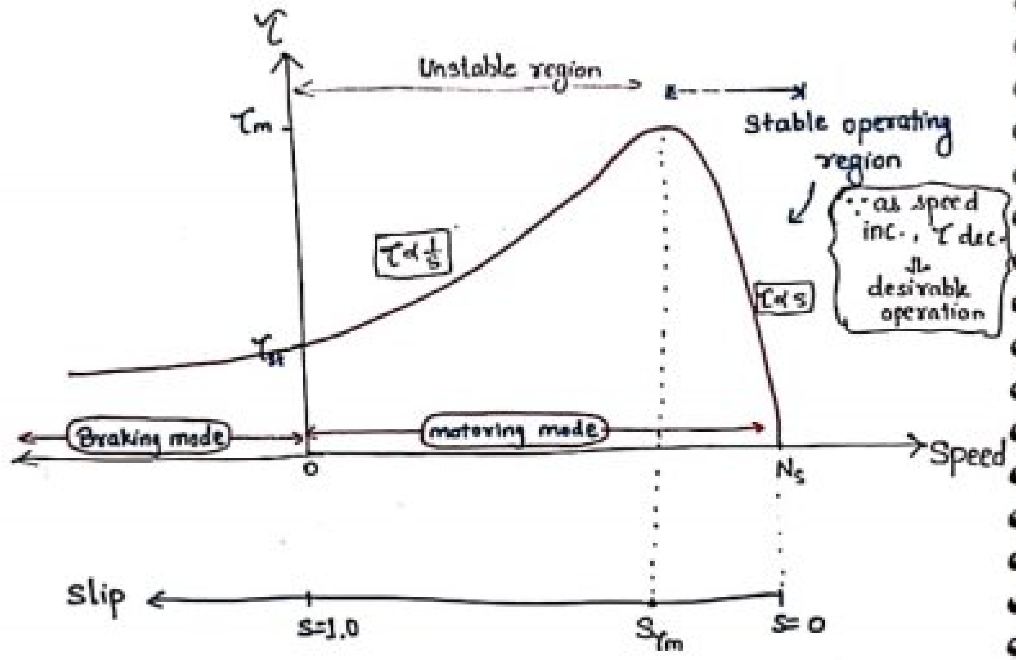


Maximum air-gap torque. (τ_m)

- It is the maximum value of air-gap torque τ_g.
- It is also referred as
  - → maximum - internal torque or
  - → pull-out torque or
  - → stalling - torque or
  - → breakdown - torque.
- condition required for obtaining maximum torque can be obtained by differentiating $\tau_{g3\phi}$ w.r.t. s and equating to zero.

Q.1 A 3 phase 4 pole induction motor is supplied from 3 phase 50 Hz ac supply. Calculate

(i) The synchronous speed $N_s = \frac{120f}{P} = 1500$

(ii) The rotor speed when slip is 4% $N_r = (1-s)N_s$

(iii) The rotor current frequency or slip frequency when rotor runs at 600 rpm

(iii) $N_r = N_s(1-s)$

$$1-s = \frac{N_r}{N_s} = \frac{600}{1500}$$

$$s = 1 - \frac{600}{1500}$$

$$s = 0.6$$

rotor current frequency $= s f_s$

$= s \times 50$

$= 0.6 \times 50$

$= 30.0$ Hz

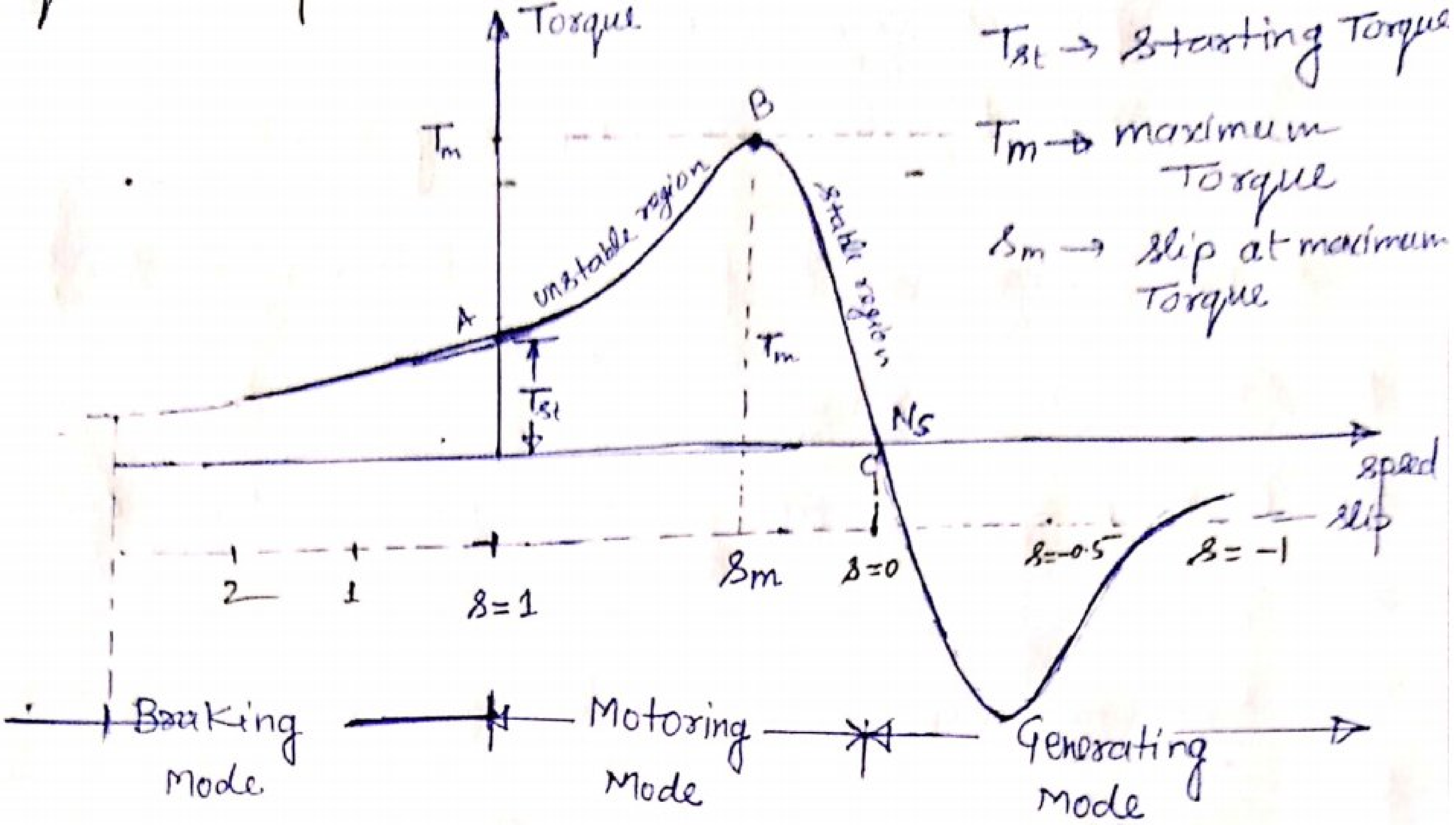
(IV) find relative speed b/w stator field and rotor conductor if the rotor speed is 900 rpm

$(N_s - N_r) =$

(V) find relative speed b/w the stator field and rotor field.

Ans- 0

Torque - Slip Characteristics :-



3 phase induction motor operates in 3 modes—

1. Motoring Mode :- [0 < s < 1]
In this mode of operation, supply is given to the stator sides and the motor always rotates below the synchronous speed. The induction motor torque varies from zero to full load torque as the slip varies.

2. Generating Mode [- s < 0] :-
In this mode of operation induction motor runs above the synchronous speed and it should be driven by a prime mover. The stator winding is connected to a Three phase supply in which it supplies electrical energy. Actually, in this case, the torque and slip both are negative so the motor receives mechanical energy and delivers electrical energy.

3. Braking Mode [s > 1] :- In the Braking mode, the two leads or the polarity of the supply is changed so that the motor starts to rotate in the reverse direction and as a result the motor stops.

Application of 3 phase induction motor :-

1. Electric train engine
2. cooling of large alternators i.e. used as cooling fan
3. Printing machines
4. Rolling mills
5. In ~~pums~~ water pump motor
6. In hydraulic for pumping the fluid
7. Drilling machine
8. Grinding machine
9. Motor of refrigerator
10. cooler motors
11. industrial drives
12. Agricultural and industrial pumps
13. ~~Ceiling fan~~