Basics of Electrical Engineering

[*Subject Code*-25EL101]

UNIT – 4

Electrical Machines

Syllabus

- **DC Machines:** Construction, working principle, types, EMF equation and numerical related to EMF equation, torque equation of motor and applications.
- **Three-phase Induction Motors:** Operating principle, concept of slip and numerical problems related to slip, applications of three phase induction motor.
- **Single-phase Induction Motors:** working principle and applications.

Contents

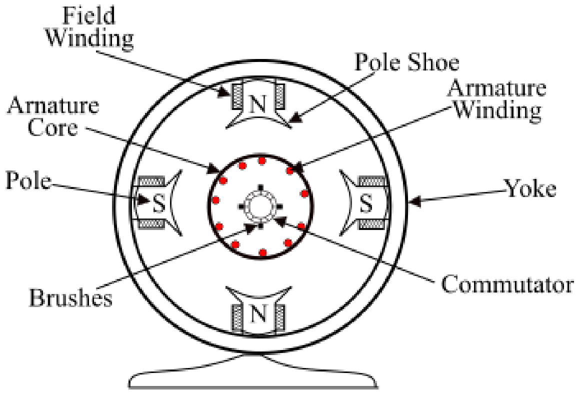
Prepared by:

Sumit Maheshwari,

Assistant Professor (ELCE)

ABES Engineering College, Ghaziabad

DC Machine Construction



Stator: It is the non-moving part of the electric motor that produces a magnetic field, usually manufactured by a permanent magnet or an electromagnet.

Rotor (Armature): It is the rotating part of the DC motor which holds the armature winding from which the current flows.

Commutator: A commutator is a rotary mechanical rectifier which converts the direct current input to the motor from the DC source into alternating current in the armature winding. The commutator is made of wedge-shaped copper segments insulated from each other and from the shaft by mica sheets. Each segment of commutator is connected to the ends of the armature coils.

Carbon Brush: Brushes maintain electrical contact with the commutator, allowing the current to flow into the armature. The brushes are mounted on the commutator and are used to inject the current from the DC source into the armature windings. The brushes are made of carbon and are supported by a metal box called brush holder. The pressure exerted by the brushes on the commutator is adjusted and maintained at constant value by means of springs. The current flows from the external DC source to the armature winding through the carbon brushes and commutator.

Shaft: It is the part which directly connects to the rotor, transmitting the mechanical energy produced by the motor.

Armature Windings: The insulated conductors are put into the slots of the armature core. The conductors are suitably connected. This connected arrangement of conductors is known as armature winding. There are two types of armature windings are used – wave winding and lap winding.
In wave winding, coil ends are connected to commutator segments a distance apart from each other, creating a continuous progression, wave-like pattern. While, in lap winding, Coil ends are connected to adjacent commutator segments, forming overlapping or "lapped" loops. This creates multiple parallel paths for the armature current.

Field Windings: Windings are the coil in the stator with numerous turns. Current flows through these coils to produce a magnetic field.

Working Principle of DC Generator

DC generator lies a fundamental principle of electromagnetic induction discovered by Michael Faraday. In essence, a DC generator ingeniously converts mechanical energy into direct current (DC) electrical energy by rotating a coil of wire within a magnetic field.

- **Generation of magnetic field**: The field windings of the stator create a constant magnetic field.
- **Armature rotation and EMF induction:** As an external source of mechanical energy rotates the armature, the conductors of the armature windings cut through the magnetic field. **According to Faraday's Law**, this induces an EMF in these conductors. The magnitude of this induced EMF is directly proportional to the rate at which the magnetic flux is cut, which in turn depends on the speed of rotation and the strength of the magnetic field.

  The voltage equation of a DC Generator: $E_g = V_t + I_a \mathrm{R_a}$

- **The nature of the induced current:** It is important to note that the current initially induced in the rotating armature is alternating in nature. But Commutator "rectifies" the alternating current, ensuring that the current flowing through the external circuit is always in the same direction, thus producing a direct current.
- **Armature reaction:** When the armature carries current, it creates its own magnetic field (armature flux) that interacts with the main magnetic field from the poles (main flux). This interaction distorts and weakens the main field flux, causes cross-magnetizing and demagnetizing effect.

Working Principle of DC Motor

The DC Motor working is based on the principle of electromagnetism, in which when a current-carrying conductor is placed within a magnetic field, the conductor experiences a force that causes motion in the conductor.

- When a DC voltage is applied, current flows through the brushes to the commutator and into the armature coil. This current flowing through the coil, which is situated within the magnetic field of the stator, generates a force on both sides of the coil according to Fleming's Left-Hand Rule. These forces are in opposite directions on each side of the coil, called the Lorentz force. The interaction between the magnetic field of both the armature and stator creates a force, producing torque or the force that rotates the armature casing motion.
- The commutator reverses the current direction in the armature windings as it rotates. Hence, the current will be reversed by the commutator, ensuring continuous rotation in the same direction.
- **Back emf:** As the armature coils rotate within the main magnetic field, they cut through the magnetic flux lines. Just like in a generator, this induces an electromotive force (EMF) in the armature conductors. According to **Lenz's Law**, this induced EMF opposes the cause by which producing it means the supply voltage. For this reason, it is called **Back EMF** or **Counter EMF.**

The voltage equation of a DC Motor: $E_b = V_t - I_a \, R_a$

DC machine EMF equation

When the armature rotates in the magnetic field, each conductor cuts flux and an emf is induced that **opposes** the applied voltage (Lenz's law). That induced emf in the motor is termed as **back emf** E_b.

P: Total No. of poles,
Z: Total armature conductors,
A: No. of parallel paths,
Φ: flux\pole (flux per pole) Wb
N: speed (rpm), ω: rad/s

In one revolution, a conductor cuts total flux PΦ
Time for one revolution = 60/N sec
Average emf induced in one conductor:

$$Emf_{conductor} = \frac{\text{(flux cut per revolution)}}{\text{(time per rev)}} = \frac{P\ \Phi}{\left({}^{60}/_{N}\right)}$$

$$Emf_{conductor} = \frac{P\ \Phi\ N}{60}$$

Each parallel path has Z/A series conductors, so the total emf :

$$Emf_{total} = Emf_{conductor} \times \frac{Z}{A}$$

$$Emf_{total} = \frac{P\ \Phi\ N}{60} \times \frac{Z}{A}$$

$$Emf_{total} = \frac{NPZ\Phi}{60\ A}$$

for a simplex wave winding $A = 2$.

$$Emf_{total} = \frac{NPZ\Phi}{120}$$

for a simplex lap winding $A = P$.

$$Emf_{total} = \frac{NZ\Phi}{60}$$

DC motor Torque Equation

The torque produced by a DC motor is a direct result of the force experienced by the current-carrying conductors in its armature when they are subjected to the magnetic field of the stator. The derivation builds from the fundamental principle of the Lorentz force.

The force (F) on a single conductor of length (l) carrying a current (I_c) within a magnetic field of flux density (B) is given by:

$$F = B.I_c.l$$

Torque (τ) is the rotational equivalent of force and is calculated as the force multiplied by the perpendicular distance from the axis of rotation (the radius, r)

$$\tau_{\text{conductor}} = F.r = (B.I_c.l).r$$

A practical DC motor armature has many conductors. To find the total torque, we need to consider all of them. The total armature current (Ia) is split among these parallel paths. Therefore, the current in a single conductor (Ic) is:

$$I_c = \frac{I_a}{A}$$

Now, we can express the total torque (τ_{total}) by multiplying the torque from a single conductor by the total number of conductors (Z):

$$\tau_{\text{total}} = Z.\tau_{\text{conductor}} = Z.(B.I_c.l).r$$

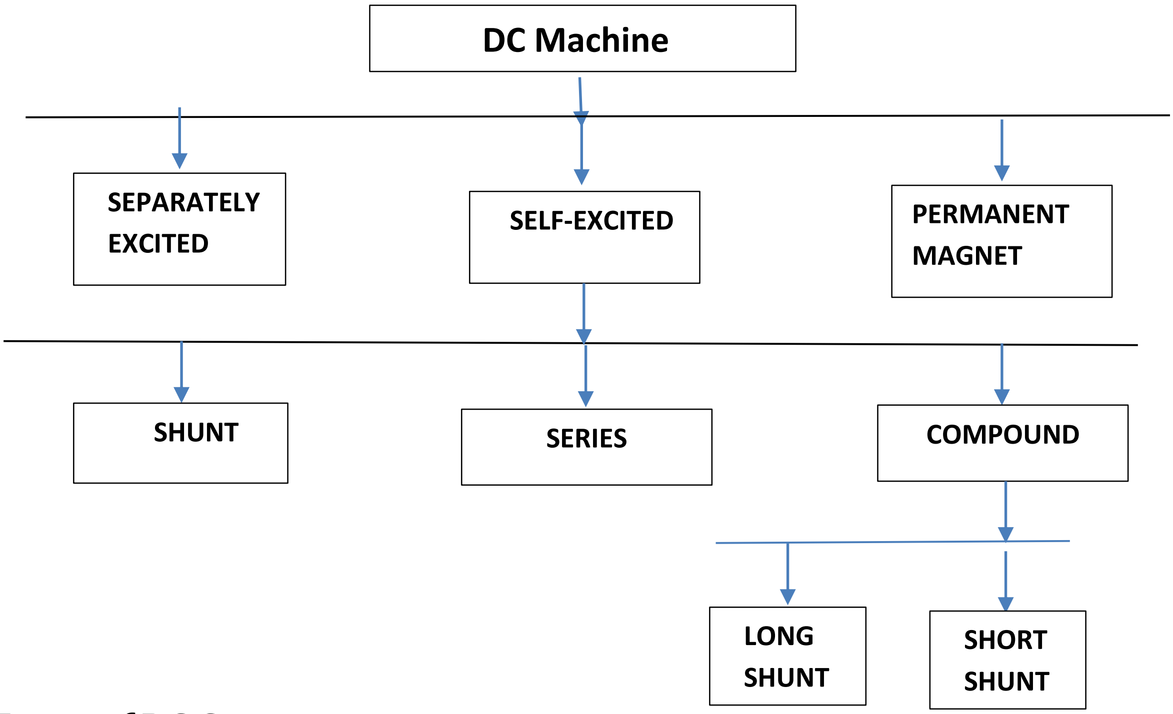
$$= Z.(B.\frac{I_a}{A}.l).r$$

Z be the total number of armature conductors
A be the number of parallel paths in the armature winding
B be the magnetic flux density

$$\tau_{\text{total}} = Z.(\frac{\phi}{Area\ per\ pole}.\frac{I_a}{A}.l).r = Z.(\frac{\phi}{\left(\frac{2\pi rl}{P}\right)}.\frac{I_a}{A}.l).r$$

$$\boxed{\tau_{\text{total}} = Z.\mathrm{P}.\phi\,\frac{I_a}{2\pi.A} = 0.159\,Z.\mathrm{P}.\phi\,\frac{I_a}{A}}$$

Classification of DC Machines:

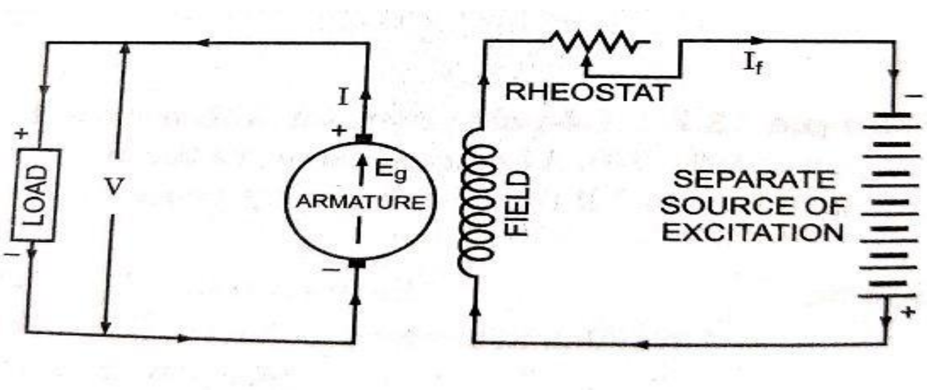


Types of DC Generators

DC Generators are classified on the basis of their excitation system (i.e. working flux is produced). There are three methods of excitation, and thus three main types of DC generators

Permanent Magnet DC Generators – Pieces of permanent magnet are placed around armature to develop working flux. No Field poles or coils are required hence compact in size but still rarely used in industry due to constant field strength and low rating. Used in vehicles as dynamo for charging battery and in techometers.

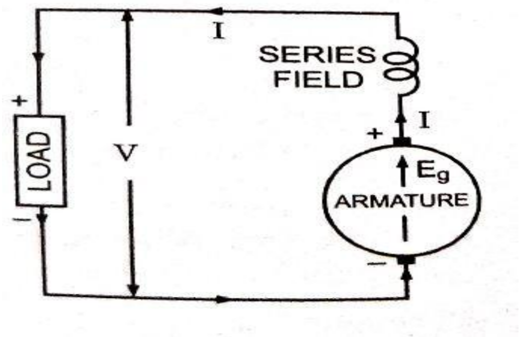
Separately Excited DC Generators – In separately excited dc machines, the field winding is supplied from a separate power source. That means the field winding is electrically separated from the armature circuit. Shown in Fig. below

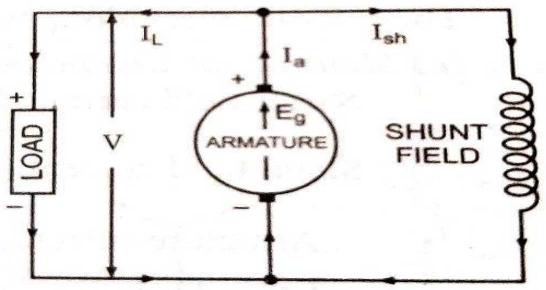


Separately Excited DC Generators

Self-Excited DC Generators –In a self-excited type of DC generator, the field winding is energized by the current produced by themselves. A small amount of flux is always

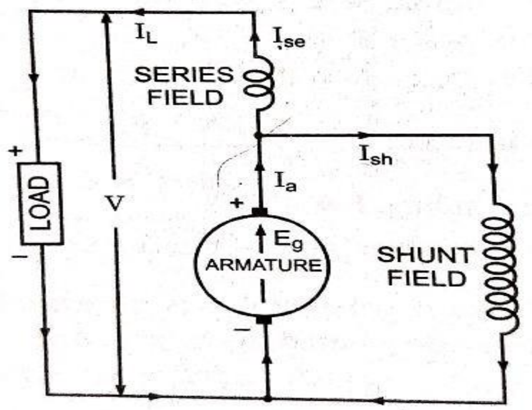
present in the poles due to the residual magnetism. So, initially, current induces in the armature conductors of a dc generator only due to the residual magnetism. The field flux gradually increases as the induced current starts flowing through the field winding.
Self-excited generators can be further classified as –
Series wound dc generator – In this type, field winding is connected in series with the armature winding. Therefore, the field winding carries whole of the load current (armature current). That is why series winding is designed with few turns of thick wire and the resistance is kept very low (about 0.5 Ohm).

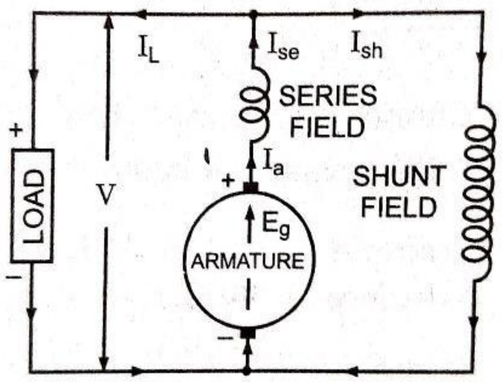




Series Wound DC Generators **Shunt Wound DC Generators**

Shunt wound dc Generator– Here, field winding is connected in parallel with the armature winding. Hence, the full voltage is applied across the field winding. Shunt winding is made with a large number of turns of a wire having cross- sectional area very small (Thin wire). The resistance is kept very high (about 100 Ohm). It takes only small current which is less than 5% of the rated armature current.
Compound wound dc Generator – In this type, there are two sets of field winding. One is connected in series and the other is connected in parallel(Shunt) with the armature. Depending upon connection of shunt or parallel field winding Compound wound generators are further divided as -
Short shunt – field winding is connected in parallel with only the armature circuit.
Long shunt – field winding is connected in parallel with armature as well as series field winding.



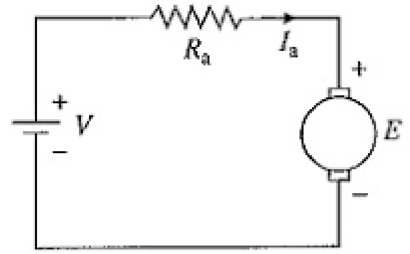
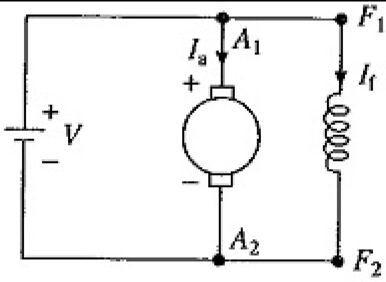
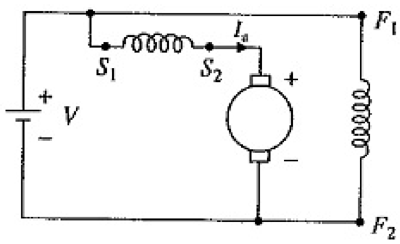


Short Shunt DC Generators **Long Shunt DC Generators**

Types of DC motor

In practical DC motors, the magnetic field is produced by electromagnets rather than permanent magnets. DC motors are then classified based on the connection of field winding in the motor circuit. On this basis, DC motors are classified into the following two types – Separately Excited DC Motor and Self Excited DC motor.

Depending upon the manner in which the field winding is connected with the armature winding, self-excited DC motors are classified in the following three types:

Types	Equivalent Circuit	Applications
Series DC motor		• **Electric trains and locomotives** • **Trolleys and trams** • **Cranes** • **Hoists and elevators** • **Conveyors** • **Large industrial mixers and agitators** • **Automobile starters**
Shunt DC motor		• **Lathes** • **Drills** • **Milling machines** • **Fans and blowers** • **Centrifugal and reciprocating pumps** • **Conveyors**
Compound DC motor		• **Presses and Shears** • **Elevators and Lifts** • **Rolling Mills** • **Heavy Planers and Conveyors**

Summary

1. What is a DC Motor?

Answer. A DC motor is a device that converts DC electrical energy into mechanical energy (rotation). It works based on the principle that a current-carrying conductor experiences a force when placed in a magnetic field. This force creates a torque that causes the motor to rotate.

2. How does a DC Motor work?

Answer. When a DC voltage is applied to the motor's windings (armature), it creates an electromagnetic field. This field interacts with the stationary magnetic field produced by the field windings or permanent magnets, generating a rotational force, or torque. A commutator and brushes reverse the current direction in the armature windings as it rotates, ensuring the torque is always in the same direction, which allows for continuous rotation.

3. What is a DC Generator?

Answer. A DC generator is a device that converts mechanical energy into DC electrical energy. It operates on the principle of electromagnetic induction.

4. How does a DC Generator work?

When the armature (rotor) of the generator is mechanically rotated within a stationary magnetic field, it cuts the magnetic lines of flux, which induces an electromotive force (EMF) and current in the windings. A commutator is used to convert the alternating current (AC) induced in the armature into a direct, pulsating current at the output terminals.

5. What are the main types of DC machines?

Answer. DC machines are categorized based on how their field windings are connected to the armature windings. The primary types are:

- **Separately Excited DC Machine**: The field winding is powered by an independent external DC source.
- **Self-Excited DC Machine**: The field winding is powered by the machine's own output. This type is further divided into:
    - **DC Shunt Machine**: Field windings are connected in parallel (shunt) with the armature.
    - **DC Series Machine**: Field windings are connected in series with the armature.
    - **DC Compound Machine**: Has both series and shunt field windings.

6. What are some applications of DC machines?

Answer.

- **DC Motors:** Widely used in applications requiring variable speed and high starting torque. Examples include electric vehicles, cranes, elevators, and rolling mills. Smaller DC motors are found in toys, power tools, and household appliances.

- **DC Generators:** Used for applications where a DC power source is needed. Examples include battery charging, arc welding, and providing field excitation for synchronous machines.
-

7. What is Back EMF in a DC Motor?
Answer. Back electromotive force (or back EMF) is a voltage generated by a spinning DC motor's armature windings. This voltage opposes the original voltage applied to the motor. It is a fundamental concept in DC motors, as it acts as a self-regulating mechanism. The faster the motor spins, the greater the back EMF, which in turn reduces the net voltage and current flowing through the armature. This helps protect the motor from excessive current and regulates its speed.

8. What is the Commutator and its Function?
Answer. The commutator is a key mechanical component in DC machines. It is a rotating cylindrical device made of insulated copper segments. Its primary function is to reverse the direction of current in the armature windings.

- In a **DC motor**, the commutator ensures that the magnetic force on the armature remains unidirectional, allowing for continuous rotation.
- In a **DC generator**, the commutator converts the alternating voltage induced in the armature windings into a unidirectional (DC) voltage at the output terminals. Brushes, typically made of carbon, ride on the commutator to maintain electrical contact.

9. What is Armature Reaction?
Answer. Armature reaction is a phenomenon in DC machines where the magnetic field produced by the current in the armature windings distorts the main magnetic field of the machine. This distortion can shift the neutral axis and cause sparking at the brushes, reducing efficiency and stability. Armature reaction can be mitigated by using interpoles and compensating windings to counteract the armature's magnetic field.

10. For what type of de machine, wave winding is employed?
Answer. For low current and high voltage rating machine

11. For what type of dc machine lap winding is employed?
Answer. For high current and low voltage rating machine

12. How can the direction of rotation of a de motor be determined?
Answer. By applying Fleming's left hand rule.

13. How can the direction of rotation of a de motor be determined?
Answer. By applying Fleming's left hand rule.

14. How can the direction of rotation of a separately-excited dc motor be reversed?
Answer. Direction of rotation of a separately-excited dc motor can be reversed by reversing the current flow through either the armature winding or the field winding.

15. How can the direction of rotation of a dc series motor be changed?
Answer. By reversing the supply terminals to either armature or series field, not both

Numerical

1. Calculate the emf generated by a 6 pole DC generator having 480 conductors and driven at a speed of 1200 rpm. The flux per pole is 0.012 Wb. Assume the generator to be (a) Lap wound, (b) Wave wound.

Solution:

$$Emf_{total} = \frac{NPZ\Phi}{60\ A}$$

For Lap wound $A = P$

$$Emf_{total} = \frac{1200\ \times 6 \times 480\ \times 0.012}{60\ \times 6}$$

$$Emf_{total} = 115.2\,Volt$$

For wave wound $A = 2$

$$Emf_{total} = \frac{1200\ \times 6 \times 480\ \times 0.012}{60\ \times 2}$$

$$Emf_{total} = 345.6\,Volt\ \text{(Answer)}$$

2. A 4-pole DC motor takes an armature current of 6 A. The armature has 480 lap connected conductors. The flux per pole is 20 mWb. Calculate the gross torque developed by the motor.

Solution:

$$\tau_{total} = Z.\ P.\phi \frac{I_a}{2\pi.A} = 0.159\ Z.\ P.\phi \frac{I_a}{A}$$

$$\tau_{total} = 0.159\ \times 480 \times 4 \times 20\ \times 10^{-3} \times \frac{6}{4}$$

$$\tau_{total} = 9.158\ Nm\ \text{(Answer)}$$

3. A separately excited generator with constant excitation is connected to a constant load. When the speed is 500 rpm, it delivers 120 A at 500 V. At what speed will the current be reduced to 60 A? Armature resistance is 0.1 W, contact drop/ brush is 1 V. Armature reaction may be ignored.

Solution: Given: Speed N = 1500 rpm; Load current I_L = 120 A.

Terminal Voltage V = 500 V;

Armature resistance R_a = 0.1 Ω

Contact drop / brush = 1 V

Brush drop = 2 x 1 = 2 V.

To find: Motor speed N at 60 A.

$E_{g1} = V + I_{a1} R_a + V_{brush} = 500 + (120 \times 0.1) + (2 \times 1) = 514$ V

$E_{g2} = V + I_{a1} R_a + V_{brush} = 500 + (60 \times 0.1) + (2 \times 1) = 508$ V

$$\frac{E_{g1}}{E_{g2}} = \frac{N_1}{N_2}$$

$$N_2 = N_1 \times \frac{E_{g2}}{E_{g1}}$$

$$= 1500 \times \frac{508}{514}$$

$$N_2 = 1482.5\ rpm \quad \text{(Answer).}$$

4. A wave connected armature winding has 19 slots with 54 conductors per slot. If the flux per pole is 0.025 Wb and number of poles is 8, find the speed at which the generator should be run to give 513 V. Also find the speed if the armature is lap connected.

Solution: $N = 1200\ rpm$

5. A 4 pole DC motor takes an armature current of 50 A. The armature has 480 lap connected conductors. The flux per pole is 20 mWb. Calculate the gross torque developed by the motor.

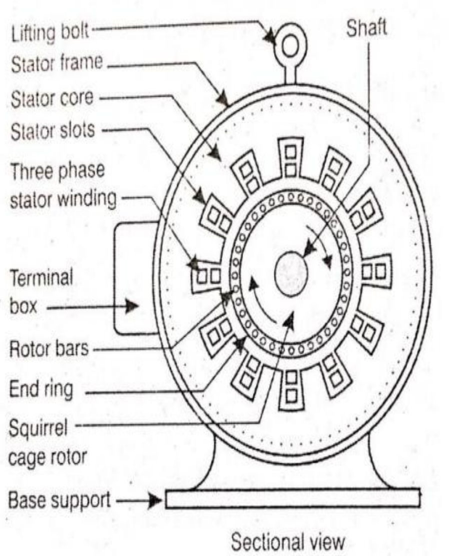
Solution: $\tau_{\text{Gross}} = 76.32\ Nm$

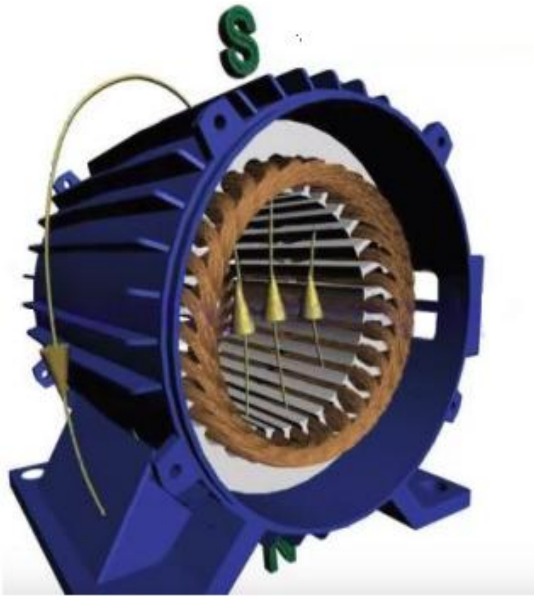
Three-phase Induction Motor

A three-phase **Induction motor** mainly consists of two parts called the **Stator** and the **Rotor**. The stator is the stationary part of the induction motor, and the rotor is the rotating part. The construction of the stator is similar to the three-phase synchronous motor, and the construction of the rotor is different for the different machines. The construction of the induction motor is explained below in detail.

Construction of Stator

- Stator consists of a steel frame which encloses hollow cylindrical stator core constructed from stacked laminations.
- The stampings are slotted in its periphery to carry the stator winding. Silicon steel is used to minimize hysteresis loss and laminations are used to minimize





- The slots in the periphery of the stator core carries a three phase winding, connected either in star or delta. This winding when excited by a three phase supply produces a magnetic rotating field.

The Rotating Magnetic Field (RMF)

- The most important function of the stator is to produce a rotating magnetic field (RMF). When a balanced 3-phase AC power supply is connected to the stator windings, the currents in each phase peak at different times. This phase difference creates a magnetic field that rotates at a constant speed, known as the synchronous speed (Ns). The speed of the RMF is determined by the supply frequency (f) and the number of poles (P) per phase.

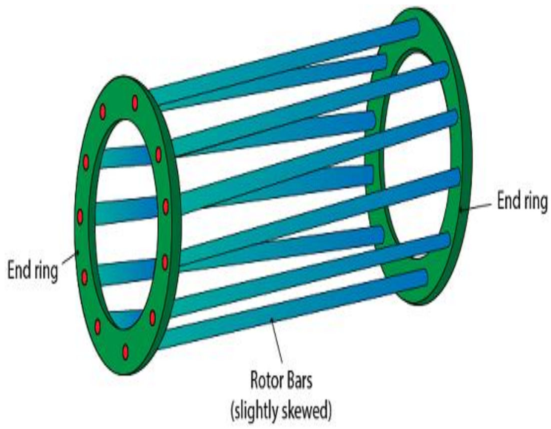
$$Ns = 120*f/p$$

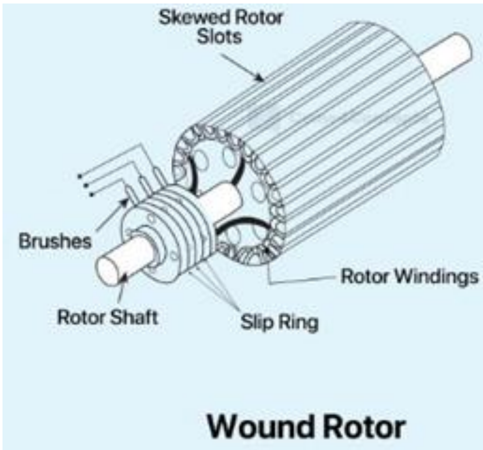
Construction of Rotor:-

The rotor is placed inside the stator. The rotor core is also laminated in construction and uses cast iron. It is cylindrical, with slots on its periphery. The rotor conductors or winding is placed in the rotor slots. There are two types of rotors-
(i). Squirrel Cage Induction Motor,
(ii). Slip-ring or Wound Rotor Induction Motor

Squirrel Cage Induction Rotor

- The construction of this type of rotor is very simple and rugged. A squirrel cage rotor consists of a laminated cylindrical core. The squirrel cage rotor consists of rotor bars instead of the rotor winding.
- The rotor consists of a cylindrical laminated core and has slots on the outer periphery. The circular slots at the outer periphery are semi-closed. Each slot contains aluminum or copper conductor. At the end of the rotor the conductors are short-circuited by a heavy ring of copper or aluminum.
- The slots are not parallel but it is skewed at some angle. It helps to prevent magnetic locking between the stator and rotor teeth. It results in smooth operation and reduces the humming noise. It increases the length of the rotor conductor due to this the rotor resistance is increased.





Wound Rotor or Slip-ring Induction Rotor

- The wound rotor consists of a slotted armature. Insulated conductors are put in the slots and connected to form a three-phase double layer distributed winding similar to the stator winding. The windings of the rotor are connected in star.
- Rotor windings are distributed uniformly and usually connected in the star with here leads brought out of the machine by via slip rings placed on the shaft. The slip rings are tapped using copper carbon brushes.
- Wound rotor construction is generally used for large size machine, where the starting torque requirements are stringent. External resistance can be added in the rotor circuit through slip ring for reducing the starting current and simultaneously the starting torque.

Working Principle of Three phase Induction Motor

- **Production of Rotating Magnetic Field**: - When a three-phase stator winding (either delta connected or star connected) of an induction motor is connected to the three AC supply, current starts flowing in the stator conductors. Due to this current, a rotating magnetic field of constant amplitude and a constant speed is set up in the air gap between stator and rotor air gap.
- **Induced EMF by Faraday law of Electromagnetic Induction**: - The rotor winding is still stationary. So rotating magnetic field cuts the stationary rotor conductors and induces an EMF in the rotor winding. Voltage induced in the rotor gives rise to rotor currents.
- **Rotor current & relative speed**: - The direction of the rotor current is such that it will oppose the cause that produces the current (Lenz's law). And the cause behind producing the rotor current is 'relative speed' between the rotor and rotating magnetic field.
- **Rotor speed at no-load ($N < N_s$ slightly)**: - So the rotor current will flow in such a direction that the rotor will experience a force that accelerates it in the same direction as that of the rotating magnetic field. At the no-load rotor rotates at slightly less speed than Ns.
- **Rotor speed at synchronous speed ($N = N_s$)**: - The speed of the rotor (N) is always less than N_s. Because as soon as $N = N_s$, the relative speed between rotor and rotating magnetic field becomes zero, and motor slows down. This happens every time when N tends to become equal to N_s. Therefore, the rotor in an induction motor cannot rotate at the synchronous speed.
- **Rotor speed at load ($N < N_s$)**: - When we put a load on the motor, its speed(N) decreases to produce the required torque. The reduction in speed of motor (N) will stop as soon as torque produced by the motor is exactly equal to load torque.

Slip of Induction Motor & its significance

In the **induction motor** rotor always rotates speed less than synchronous speed. The difference between synchronous speed and rotor speed is called slip speed i.e. Slip speed = $N_s - N$**. Then the ratio of relative speed to the rotating magnetic flux speed (N_s) is called slip (s)**.

i.e. $s = (N_s - N)/N_s$ & Percentage slip, $\% s = [(N_s - N)/N_s] \times 100$

at N = 0 hence s = 1 (standstill condition)

at $N = N_s$, hence s = 0 (as Synchronous Motor).

The value of **slip in induction motor** at full load varies from about 6% for small motors to about 2% for large motors.

Induced EMF in Rotor

$E_{2r} = sE_2$

Where E_2 = Rotor Induced EMF per phase at standstill.
E_{2r} = Rotor induced EMF per phase in running condition.

At standstill s = 1 hence $E_{2r} = E_2$ whereas at $N = N_s$, s = 0, $E_{2r} = 0$.

Thus rotor induced EMF fluctuates between 0 and E_2 for the rotor speeds between $N = N_s$ and N = 0.

Frequency of Induced EMF in Rotor

The expression for frequency of induced EMF in the rotor is: $\mathbf{f_r = s}f_1$
i.e. rotor EMF frequency = fractional slip x supply frequency

At standstill, induction motor slip s is 1, hence the frequency of induced EMF in the rotor of the induction motor is same as that of supply frequency and reduces with increase in speed (due to the reduction in slip).

Applications of Three phase Induction Motor

Squirrel Cage Induction Motors	Slip Ring Motors/ Wound Rotor
It use where speed control of motors is not needed	It use where high initial torque is needed for heavy load applications.
Applications:- • Pumps and submersible • Pressing machine, Lathe machine • Grinding machine, Conveyor • Flour mills, Compressor	**Applications:-** • Steel mills, Lift • Crane Machine, Hoist • Line shafts
Advantages:- • cheaper, and the construction is robust. • The absence of the brushes reduces the risk of sparking and maintenance is less. • The power factor is higher. • The efficiency of the cage rotor is higher.	**Advantages:-** • High starting torque and low starting current. For controlling the speed of the motor, an external resistance can be added in the circuit. • For the same size, rotor speed is higher.
Disadvantages:- • It draws very high current at starting due to low resistance of rotor. • The starting torque is very low and not suitable for the appliances which demands high starting torque. • During light load condition, the power factor is very less. And it draws more current. So, less efficiency.	**Disadvantages:-** ▪ If speed is to be varied, we have sacrificed some of its efficiency. ▪ Due to high rotor resistance, copper loss increases and having less efficiency as compare to **Squirrel Cage Rotor.** ▪ For the same rating, cost is high.

Summary

1. What is the fundamental principle of a 3-phase induction motor?

Answer. The motor works based on the principle of electromagnetic induction. When a 3-phase AC supply is fed to the stator windings, it produces a rotating magnetic field (RMF). This RMF induces a voltage and a subsequent current in the rotor windings. According to Lenz's Law, the induced current in the rotor creates its own magnetic field, which interacts with the stator's RMF, producing a torque that causes the rotor to rotate in the same direction as the RMF.

2. What are the main components of a 3-phase induction motor?

Answer. The two main components are:

- **Stator**: The stationary part of the motor. It consists of a laminated core with slots that hold the 3-phase windings.
- **Rotor**: The rotating part of the motor. It consists of a laminated core mounted on a shaft. There are two common types of rotors:
    - **Squirrel-cage rotor**: The most common type. It has uninsulated, thick copper or aluminum bars embedded in the core, short-circuited by end rings.
    - **Wound rotor**: The rotor windings are connected to slip rings, allowing for the connection of external resistance to control starting torque and speed.

3. What is the difference between synchronous speed and actual speed?

Answer.

- **Synchronous Speed (Ns):** The speed of the rotating magnetic field. It is determined by the frequency of the AC supply and the number of poles in the motor's stator windings ($N_s=120f/P$).
- **Actual Speed (Nr):** The actual mechanical speed of the rotor. Due to induction, the rotor must always spin slower than the synchronous speed. If it spun at the same speed, there would be no relative motion between the rotor and the RMF, and thus no induced current, no torque, and no rotation.

4. What is slip?

Answer. Slip (s) is the difference between the synchronous speed and the actual rotor speed, expressed as a percentage or a fraction of the synchronous speed. It is a crucial parameter for induction motors.

$s=(N_s-N_r)/N_s$

A motor at rest has a slip of 1 (or 100%). A motor operating at full load typically has a slip of 2-5%.

5. Why are they called "induction motors"?

Answer. They are called induction motors because the current in the rotor is not supplied directly. Instead, it is induced by the rotating magnetic field of the stator, just as a current is induced in a transformer's secondary winding.

3-phase Induction Motor (Numerical)

1. **A three-phase 6 pole, 50 Hz, induction motor is running at 5% slip. What is the speed of the motor?**

Solution:

Given: Three phase supply frequency $f_s = 50$ Hz,

Slip s = 5%

Poles P = 6,

Find: Synchronous speed (N_s) & rotor speed (N_r)

Synchronous speed $N_s = (120 * f_s)/P$

$\Rightarrow N_s = (120 \times 50)/6 = 1000$ rpm

Rotor speed $N_r = N_s (1 - s)$

$\therefore N_r = 1000 (1 - 0.05)$

= **950 rpm (Answer)**

2. **A 3-phase 440 V, 50 Hz induction motor has 4% slip. What will be the the frequency of rotor?**

Solution:

Given: Three phase supply frequency $f_s = 50$ Hz,

Slip s = 4%

Poles P = 6,

Find: Rotor frequency (f_r)

Rotor frequency $f_r = sf_s$

$\Rightarrow f_r = s \times f_s = 0.04 \times 50 =$ **2 Hz (Answer)**

3. **The frequencies of the stator and rotor currents flowing in the three-phase 8-pole induction motor are 40 Hz and 1 Hz, respectively. What will be the motor speed?**

Solution:

Given: Stator frequency $f_s = 40$ Hz, Rotor frequency f_r = 1 Hz

No. of Poles = 8,

Find: slip s , N_s & N_r

$f_r = sf_s$

$\Rightarrow 1 = s \times 40$

$\Rightarrow s = 1/40 = 0.025$

$N_s = (120 * f_s)/P$

$\Rightarrow 600 = (120 \times 40)/8$

$N_r = N_s (1 - s)$

$\therefore N_r = 600 (1 - 0.025)$

= **585 rpm (Answer)**

4. **A three-phase 440V, 6 poles, 50Hz, squirrel cage induction motor is running at a slip of 5%. What is the speed of stator magnetic field to rotor magnetic field and speed of rotor with respect to stator magnetic field respectively?**

Solution:

Given: Stator frequency f_s = 50 Hz,

No. of Poles P = 6,

Slip s = 5%

Find: slip speed, $N_{smf, rmf}$ & $N_{r, smf}$

Synchronous Speed, $N_s = (120 * f_s)/P \Rightarrow N_s = (120 \times 50)/6 = 1000$ rpm

Now rotor speed $N_r = N_s (1 - s) \Rightarrow N_r = 1000 * (1 - 0.05) = 950$ rpm

Speed of stator magnetic field = speed of rotor magnetic field = 1000 rpm

Speed of stator magnetic field w.r.t. rotor magnetic field =

$\Rightarrow N_{smf, rmf}$, = 1000 – 1000 = 0 rpm

Speed of rotor w.r.t. stator magnetic field =

$\Rightarrow N_{r, smf}$, = 950 – 1000 = – 50 rpm

Single Phase Induction Motor

Construction

Like any other electrical motor asynchronous motor also have two main parts namely rotor and stator.

Stator of Single Phase Induction Motor

The stator of the single-phase induction motor has laminated stamping to reduce eddy current losses on its periphery. The slots are provided on its stamping to carry stator or main winding. Stampings are made up of silicon steel to reduce the hysteresis losses. When we apply a single phase AC supply to the stator winding, the magnetic field gets produced, and the motor rotates at

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

Where N speed slightly less than the synchronous speed, N_s Synchronous speed
f = supply voltage frequency, & P = No. of poles of the motor.

The construction of the stator of the single-phase induction motor is similar to that of three phase induction motor except there are two dissimilarities in the winding part of the single phase induction motor.

1. Firstly, the single-phase induction motors are mostly provided with concentric coils. We can easily adjust the number of turns per coil can with the help of concentric coils. The mmf distribution is almost sinusoidal.
2. Except for shaded pole motor, the asynchronous motor has two stator windings namely the main winding and the auxiliary winding. These two windings are placed in space quadrature to each other.

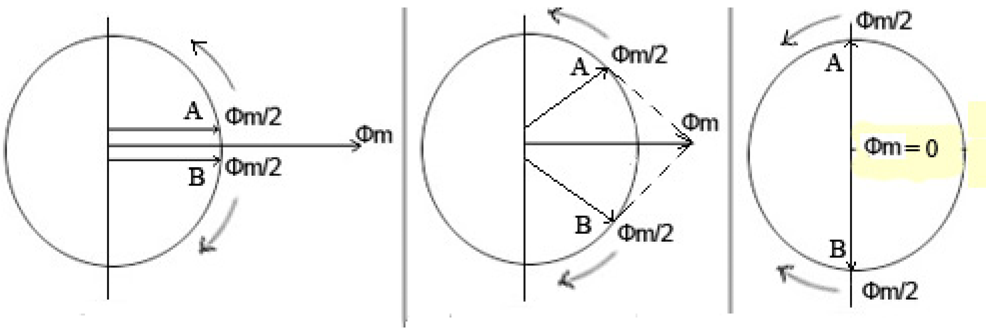
Rotor of Single Phase Induction Motor

- The construction of the rotor of the single-phase induction motor is similar to the squirrel cage three-phase induction motor. The rotor is cylindrical and has slots all over its periphery.
- **The squirrel cage rotor** consists of aluminum, brass or copper bars. These aluminum or copper bars are called rotor conductors and placed in the slots on the periphery of the rotor.
- To provide mechanical strength, these rotor conductors are braced to the end ring and hence form a complete closed circuit resembling a cage and hence got its name as squirrel cage induction motor.
- As end rings permanently short the bars, the rotor electrical resistance is very small and it is not possible to add external resistance as the bars get permanently shorted. The absence of slip ring and brushes make the construction of single phase induction motor very simple and robust.

Why Single Phase Induction Motor is not Self Starting?

- According to double field revolving theory, we can resolve any alternating quantity into two components. Each component has a magnitude equal to the half of the maximum magnitude of the alternating quantity, and both these components rotate in the opposite direction to each other. For example – a flux, φ can be resolved into two components

$$\frac{\phi_m}{2} \ and \ -\frac{\phi_m}{2}$$



- Each of these components rotates in the opposite direction i. e if one $\varphi_m/2$ is rotating in a clockwise direction then the other φ_m / 2 rotates in an anticlockwise direction.
- When we apply a single phase AC supply to the stator winding of single phase induction motor, it produces its flux of magnitude, φ_m. According to the double field revolving theory, this alternating flux, φ_m is divided into two components of magnitude $\varphi_m/2$. Each of these components will rotate in the opposite direction, with the synchronous speed, N_s.
- Let us call these two components of flux as forwarding component of flux, φ_f and the backward component of flux, φ_b. The resultant of these two components of flux at any instant of time gives the value of instantaneous stator flux at that particular instant.

$$i.e.\phi_r = \frac{\phi_m}{2} + \frac{\phi_m}{2} \ or \ \phi_r = \phi_f + \phi_b$$

- Now at starting condition, both the forward and backward components of flux are exactly opposite to each other. Also, both of these components of flux are equal in magnitude. So, they cancel each other and hence the net torque experienced by the rotor at the starting condition is zero. So, the **single phase induction motors** are not self-starting motors.
- The performance of the single phase induction motor is analysed by the two theories. One is known as the **Double Revolving Field Theory**, and the other is **Cross Field Theory**. Both the theories are similar and explain the reason for the production of torque when the rotor is rotating.

Working Principle of Single Phase Induction Motor

- We know that for the working of any electrical motor whether its AC or DC motor, we require two fluxes as the interaction of these two fluxes produced the required torque.
- When we apply a single phase AC supply to the stator winding of single phase induction motor, the alternating current starts flowing through the stator or main winding. This alternating current produces an alternating flux called main flux. This main flux also links with the rotor conductors and hence cut the rotor conductors.
- According to the Faraday's law of electromagnetic induction, emf gets induced in the rotor. As the rotor circuit is closed one so, the current starts flowing in the rotor. This current is called the rotor current. This rotor current produces its flux called rotor flux. Since this flux is produced due to the induction principle so, the motor working on this principle got its name as an induction motor.
- Now there are two fluxes one is main flux, and another is called rotor flux. These two fluxes produce the desired torque which is required by the motor to rotate.

How to make single phase induction motor self starting?

- As explained above, **single phase induction motor is not self-starting**. To make it self-starting, it can be temporarily converted into a two-phase motor while starting. This can be achieved by introducing an additional 'starting winding' also called as auxillary winding.
- Hence, stator of a single phase motor has two windings: (i) Main winding and (ii) Starting winding (auxillary winding). These two windings are connected in parallel across a single phase supply and are spaced 90 electrical degrees apart. Phase difference of 90 degree can be achieved by connecting a capacitor in series with the starting winding.
- Hence the motor behaves like a two-phase motor and the stator produces revolving magnetic field which causes rotor to run.

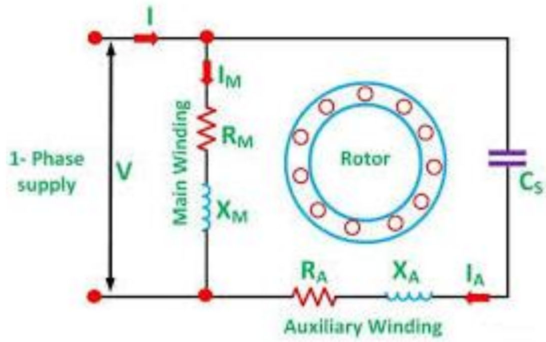
Methods of Starting

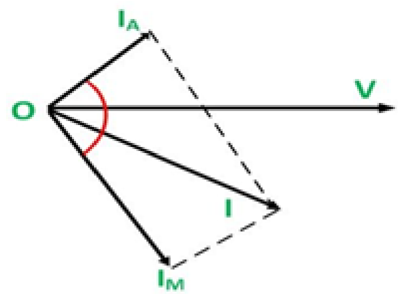
The various Starting methods of a Single Phase Induction motor are as follows:-

- Split Phase Motor
- Capacitor Start Motor
- Permanent Capacitor Motor
- Capacitor Start Capacitor Run Motor
- Shaded Pole Motor.

Permanent Capacitor Induction Motor

The Permanent Capacitor Induction motor also has a cage rotor and the two windings named as main and auxiliary winding. It has a capacitor connected permanently in series with the starting winding both at the starting and the running conditions. The main winding has very low resistance and a high inductive reactance whereas the starting winding has resistance and low inductive reactance with capacitor in series. The Connection & phasor diagram of the motor is shown below. As the capacitor is always in the circuit and thus this type of motor does not contain any starting switch. The auxiliary winding is always there in the circuit.





Therefore, the motor operates as the balanced two-phase motor. The motor produces a uniform torque and has a noise-free operation. The two windings are placed 90 degrees apart. A capacitor CS is connected in series with the starting winding. I_M is the current in the main winding which is lagging the auxiliary current I_A by 90 degrees as shown in the phasor diagram above. Thus, a single phase supply current is split into two phases. The two windings are displaced apart by 90 degrees electrical, and their MMF's are equal in magnitude but 90 degrees apart in time phase.

Advantages of Permanent Split Capacitor Motor

- No centrifugal switch is required.
- Efficiency is high.
- As the capacitor is connected permanently in the circuit, the power factor is high.
- It has a higher pullout torque.

Applications of Permanent Split Capacitor Motor

- Used in fans and blowers in heaters and air conditioners.
- Used in refrigerator compressors.
- Used in office machinery.

Summary

1. What is the main characteristic of a single-phase induction motor?
Answer. The most important characteristic is that it is not self-starting. When a single-phase AC current is applied to the stator winding, it creates a pulsating magnetic field, not a rotating one. This pulsating field can be thought of as two equal and opposite rotating magnetic fields. Since they are equal and opposite, they cancel each other out, resulting in a zero net torque at start-up.

2. How a single-phase induction motor is made self-starting?
Answer. To make it self-starting, a starting mechanism is used to create a temporary rotating magnetic field. This is typically done by adding an auxiliary winding, to the stator, which is placed at a 90-degree angle to the main winding. When the motor starts, the current in this auxiliary winding is made to be out of phase with the main windings current. This creates a rotating magnetic field that provides the initial torque to get the motor spinning.

3. What are the main types of single-phase induction motors?
Answer. Single-phase induction motors are classified based on their starting method:
- **Split-Phase Motor**: Uses a high-resistance starting winding to create a phase shift.
- **Capacitor-Start Motor**: Uses a capacitor in series with the starting winding to create a larger phase shift, which results in a higher starting torque.
- **Capacitor-Start Capacitor-Run Motor**: Uses two capacitors, one for starting and one for running, to optimize both starting torque and running efficiency.
- **Permanent-Split Capacitor (PSC) Motor**: The capacitor is permanently connected in the circuit, which provides good running efficiency and a quiet operation, though with lower starting torque.
- **Shaded-Pole Motor**: Uses a short-circuited copper band (shading coil) on a portion of the poles to create a weak rotating field. This type has very low starting torque.

4. What are some common applications of these motors?
Answer. Due to their simple and robust design, single-phase induction motors are used in a wide range of applications that don't require very high starting torque.
- **Household Appliances**: Refrigerators, air conditioners, washing machines, fans, and mixers.
- **Office Equipment**: Pumps, small blowers, and vacuum cleaners.
- **Small Tools**: Drilling machines and saws.

Previous Years University Exams Questions

1. Describe briefly the different types of DC machines. **(A.K.T.U - 2022-23 Sem-1)**
2. A six-pole, 2-circwave-connected armature of a DC machine has 300 conductors and runs at 1000 rpm. The emf generated on the open circuit is 400 V. Determine the useful flux per pole. **(A.K.T.U - 2022-23 Sem-1)**
3. What is the function of slip rings in 3-phase induction motor? **(A.K.T.U - 2023-24 Sem-1)**
4. Describe the working principle of 3-induction motor. **(A.K.T.U - 2023-24 Sem-1), (A.K.T.U - 2022-23 Sem-1)**
5. Derive the expression of torque for DC motor. A 6 pole lap wound DC shunt motor has 500 conductors in the armature. The resistance of the armature path is 0.05 Ω. The resistance of the shunt field is 25 Ω. Find the speed of the motor when it takes 120 A from DC mains of 100 V. Flux per pole is 0.02 Wb. **(A.K.T.U - 2023-24 Sem-1)**
6. Why 1-phase induction motor is not self-starting? What are the methods of starting? Explain any one of them. **(A.K.T.U - 2023-24 Sem-1)**
7. A 3-phase 440 V, 50 Hz induction motor has a 5% slip. What will be the frequency of the rotor current? **(A.K.T.U - 2023-24 Sem-2)**
8. Define the commutator in D.C. machine. **(A.K.T.U - 2024-25 Sem-1)**
9. A three phase 50Hz, 2 pole induction motor has a full speed of 2860 rpm. What is the (i) synchronous speed (ii)slip of the induction motor and (iii) rotor emf frequency? **(A.K.T.U - 2024-25 Sem-1)**
10. Explain the working principle of DC generator and also Derive the EMF equation of DC generator. **(A.K.T.U - 2024-25 Sem-1), (A.K.T.U - 2022-23 Sem-1)**
11. Calculate the emf generated by a 6 pole DC generator having 480 conductors and driven at a speed of 1200 rpm. The flux per pole is 0.012 Wb. Assume the generator to be (a) Lap wound, (b) Wave wound. **(A.K.T.U - 2024-25 Sem-1)**
12. A 3-phase 440 V, 50 Hz induction motor has a 4% slip. What will be the frequency of the rotor current? **(A.K.T.U - 2024-25 Sem-2)**
13. Derive the torque equation of DC machines. **(A.K.T.U - 2024-25 Sem-2)**
14. A six-pole, wave-connected armature of a DC machine has 300 Conductors and runs at 1000 rpm. The emf generated on the open circuit is 400V. Determine the useful flux per pole. **(A.K.T.U - 2024-25 Sem-2)**

Practice Questions

1. A dc generator has an armature emf of 100V when the useful flux/pole is 20 mWb, and the speed is 800 rpm. Calculate the generated emf:

a) With the same flux and a speed of 1000 rpm.

b) With a flux per pole of 24 mWb and a speed of 900 rpm.

Answer: E_2 = 125V, E_{new} = 135V.

2. The armature of dc separately-excited machine has a resistance of 0.10 and is connected to a 230 V supply. Calculate the generated emf when it is running

a) As a generator giving 80 A.

b) As a motor taking 60 A.

Answer: E_g = 238 V, E_m = 224 V.

3. In a 4 pole, 20 kW, 200 V wave wound DC shunt generator, what will be the current in each parallel path.

Answer: 50 A.

4. a) A DC shunt machine develops an AC emf of 250 V at 1500 rpm. Find the torque developed for an armature current of 50A.

b) At 1200 rpm the induced emf of a DC machine is 200V. What will be the electromagnetic torque produced, for an armature current of 15A.

Answer: 79.6 Nm, 23.87 Nm.

5. A shunt generator delivers 430 A at 240 V and the resistance of the shunt field and armature are 60 2 and 0.02 Ω respectively. Calculate the armature voltage drop.

Answer: 8.68 V.

6. A series motor whose combined resistance of armature and field circuit is 0.1 2 is connected across 230V supply mains. The armature takes 100 A and its speed is 1000 rpm. Find the speed when the armature takes 200 A and flux being increased by 20%.

Answer: N_2 = 795 rpm.

7. A 6 pole DC machine has 400 conductor and capable of 80 A current/conductor. If machine is driven at 1800 rpm and each pole carrying 0.020 Wb. Calculate for lap & wave connected:

a) Total Current

b) Emf

c) Power developed in armature

d) Electromagnetic torque

Answer: (I_a = 480 A, & 160A), (E_g = 240V & 720V), 115.2 kW (both), 611.46 Nm (both).

8. A 4-pole dc shunt generator with lap connected armature has field and armature resistances of 80 2 and 0.1 2 respectively. It supplies power to 50 lamp rated for 100V, 60W each. Calculate the total armature current and generated emf by allowing a contact drop of 1V per brush.

Answer: I_a = 31.25 A, E_g = 105.125 V.

9. A dc shunt machine connected to 230 V supply has resistance of armature 0.115 2 and of field winding as 115 Ω. Find the ratio of the speed as a generator to the speed as a motor with the line current in each case being 100 A. Find the speed of generator if motor speed is 1200 rpm.

Answer: N_g / N_m = 1.1052, N_g = 1326 rpm.

10. A 3-phase, 6 pole, 50 Hz induction motor has a slip of 1% at no load and 3% at full load. Calculate:

a) Synchronous speed
b) No-load speed & full load speed
c) Frequency of rotor current at no load & full load
d) Frequency of rotor current at standstill

Answer: N_s = 1000 rpm, (N_0 = 990 rpm, N_{fl} = 970 rpm), (0.5 Hz & 1.5 Hz), f_o = 50 Hz.

11. A 3-phase, 50 Hz induction motor has 6 poles and operates with a slip of 5% at a certain load, Determine:

a) The speed of rotor w.r.t. stator.
b) The speed of rotor magnetic field w.r.t. stator
c) The speed of rotor magnetic field w.r.t. rotor
d) The speed of rotor magnetic field w.r.t. stator magnetic field
e) The frequency of rotor current.

Answer: N_r = 950 rpm, $N_{rmf,\, s}$ = 1000 rpm, $N_{rmf,\, r}$ = 50 rpm, $N_{rmf,\, smf}$ = 0 rpm, f_r = 2.5 Hz.

12. A 3-phase, 50 Hz induction motor has a full-load speed of 1460 rpm. Calculate slip, no. of poles, and frequency of rotor induced emf.

Answer: s = 2.667 %, P = 4, f_r = 1.333 Hz.

13. A 0.6 kV, 20 poles, 50 Hz, 3-phase induction motor has rotor resistance of 0.12 2 and standstill reactance of 1.12 Ω. The motor has speed of 292.5 rpm at full load. Calculate the slip at maximum torque.

Answer: s_{maxT} = 0.107.

14. A 3-phase, 440V, 50 Hz 4-pole induction motor is running at 1440 rpm and rotor standstill emf per phase of 130V. Calculate slip, frequency of rotor induced emf, the rotor induced emf per phase at running condition, stator to rotor turn ratio for same speed.

Answer: s = 4 %, f_r = 2 Hz, 5.2 V, 44/13.