Electrical, Computer & Energy Engineering
UNIVERSITY OF COLORADO BOULDER

ECEN 5053-003 Homework Assignment

Course Name: Embedding Sensors and Actuators
Corresponding Module: C2M1
Week Number: 5
Module Name: AC Motor Designs
Student Name: Rushi James Macwan

Note: Correct answer is in Blue Font

Homework is worth 100 points.

Part 1: Each question is worth 8 points.

A. An AC induction motor is rated with 4.5% slip and 3600 RPM synchronous speed N_s. What is the rotor speed N_r in RPM

Sol. **3438 RPM**

To solve this problem, the motor slip formula can be used:

$S (\%) = (N_s – N_r) / N_r$

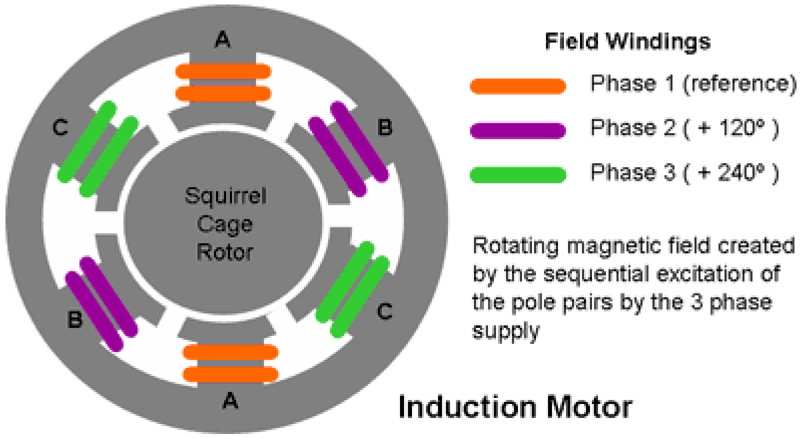
Solving this equation for N_r which stands for the rotor speed in RPM, we can reduce the above equation to the below given form:

$N_r = (1 – S (\%)) \times N_s = (1 – (4.5/100)) \times 3600 = 0.955 \times 3600 =$ **3438 RPM**

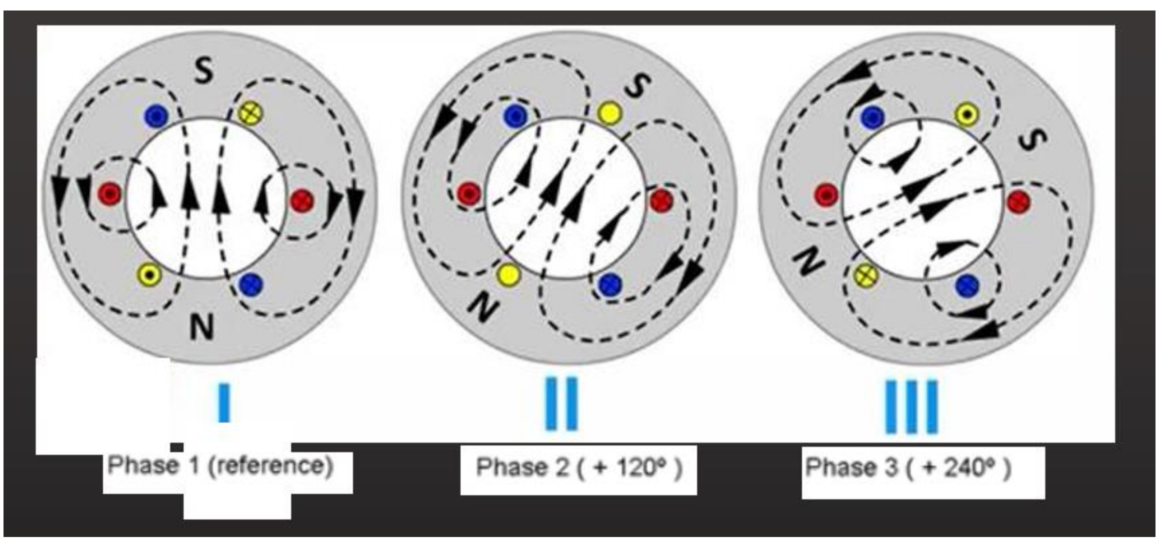
B. How is the magnetic flux wave set up around the stator of an AC induction motor?

Sol.

In an AC motor, there's a ring of electromagnets arranged around the outside (making up the stator), which are designed to produce a rotating magnetic field. Inside the stator, there's a solid metal axle, a loop of wire, a coil, a squirrel cage made of metal bars and interconnections (like the rotating cages people sometimes get to amuse pet mice), or some other freely rotating metal part that can conduct electricity. Unlike in a DC motor, where you send power to the inner rotor, in an AC motor you send power to the outer coils that make up the stator. The coils are energized in pairs, in sequence, producing a magnetic field that rotates around the outside of the motor.



Rotating magnetic fields are created by polyphase excitation of the stator windings. In the example below of a 3 phase motor, as the current applied to the winding of pole pair A (phase 1) passes its peak and begins to fall, the flux associated with the winding also begins to weaken, but at the same time the current in the winding of the next pole pair B (phase 2) and its associated flux is rising. Simultaneously the current through the winding of the previous pole pair C (phase 3) and its associated flux will be negative and rising (towards positive).



The net effect is that a magnetic flux wave is set up as the flux created by the stator poles rotates from one pole to the next, about the axis of the machine, at the frequency of the applied voltage. In other words, the rotating flux field appears to the stator as the north and south poles of a magnet rotating about the stator.

The magnitude of the rotating flux wave is proportional applied MMF. Ignoring the effect of the back EMF set up by the induced currents in the rotor windings, the flux density **B** will be proportional to the applied voltage.

Thus, the magnetic flux wave sets up around the stator of an AC induction motor.

Courtesy: Links to references: [1] [2]

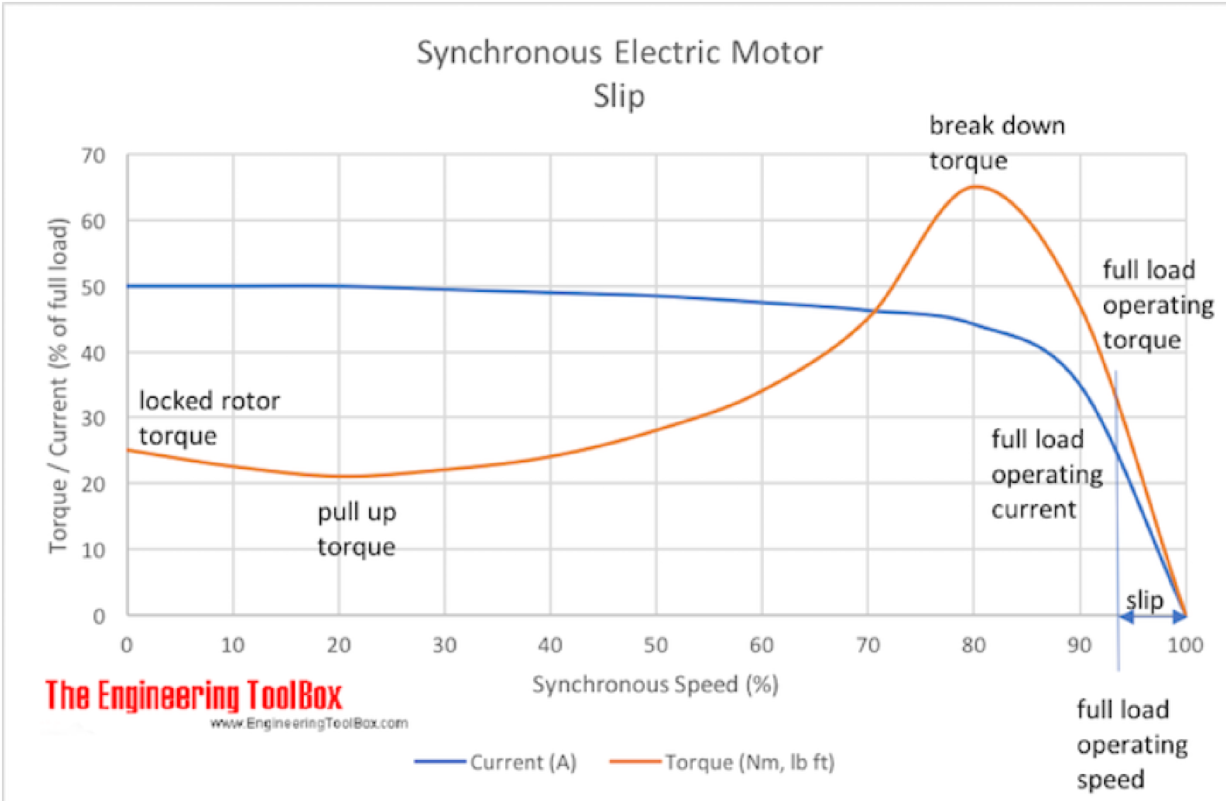
C. What is the difference between locked rotor torque and breakdown torque in an AC motor?

Sol.

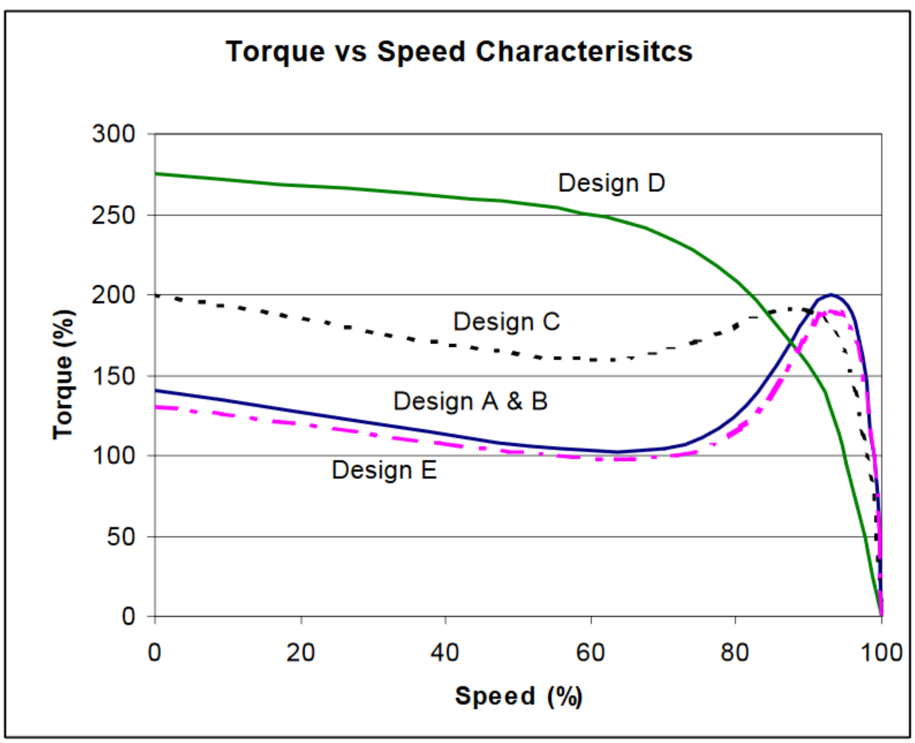
The locked rotor torque is developed by the motor at standstill. This is sometimes also referred to as starting torque. In other terms, The **Locked Rotor Torque** or **Starting Torque** is the torque an electrical motor develops when starting at zero speed. A high Starting Torque is more important for application or machines hard to start - like positive displacement pumps, cranes etc. A lower Starting Torque can be accepted for centrifugal fans or pumps where the start load is low or close to zero.

On the opposite side, the breakdown torque is the maximum torque that the motor is capable of developing. In the case of a Design D motor, this may be the same as LRT. To conclude, The **Break-down Torque** is the highest torque available before the torque decreases when the machine continues to accelerate to working conditions.

The below given diagram shows the consistent differences between the two considering the Torque / Current (% of full load) vs Synchronous Speed (%) values against each other for different values of both the constraints.



Furthermore, for type A, B, C, D and E motors, the following relation can be established pertaining to the Torque vs Speed relation based on the concepts developed from LRT and BDT.



Relative torque characteristics of NEMA Design A,B,C,D and E motors.

Courtesy: Links to references: [1] [2]

D. Why is the torque in an AC motor proportional to the slip?

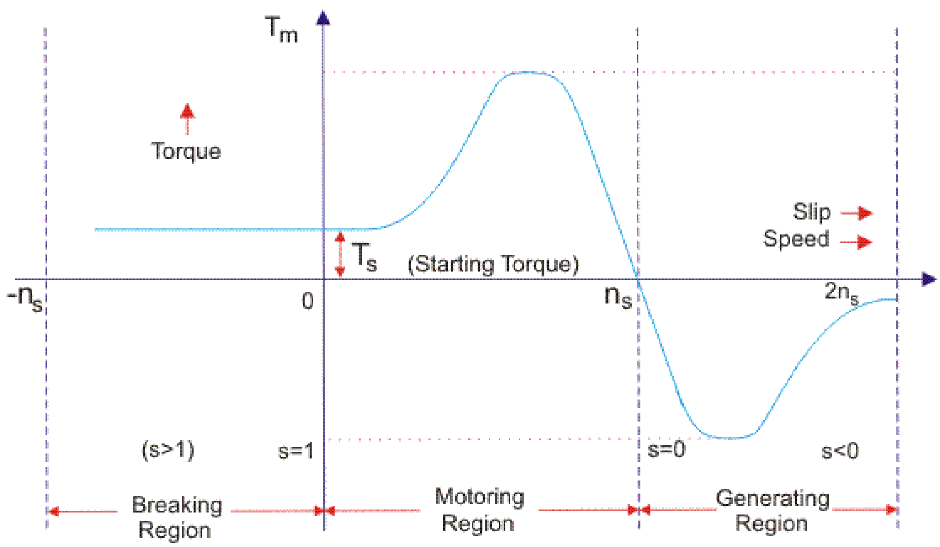
Sol.

An AC induction motor consists of two assemblies, stator and rotor. The interaction of currents flowing in the rotor bars and the stators' rotating magnetic field generate torque. In actual operation, rotor speed always lags the magnetic field's speed, allowing the rotor bars to cut magnetic lines of force and produce useful torque. This speed difference is called slip speed. Slip also increases with load and is necessary for torque production.

The torque slip curve for an induction motor gives us the information about the variation of torque with the slip. The slip is defined as the ratio of difference of synchronous speed and actual rotor speed to the synchronous speed of the machine. The variation of slip can be obtained with the variation of speed that is when speed varies the slip will also vary and the torque corresponding to that speed will also vary.

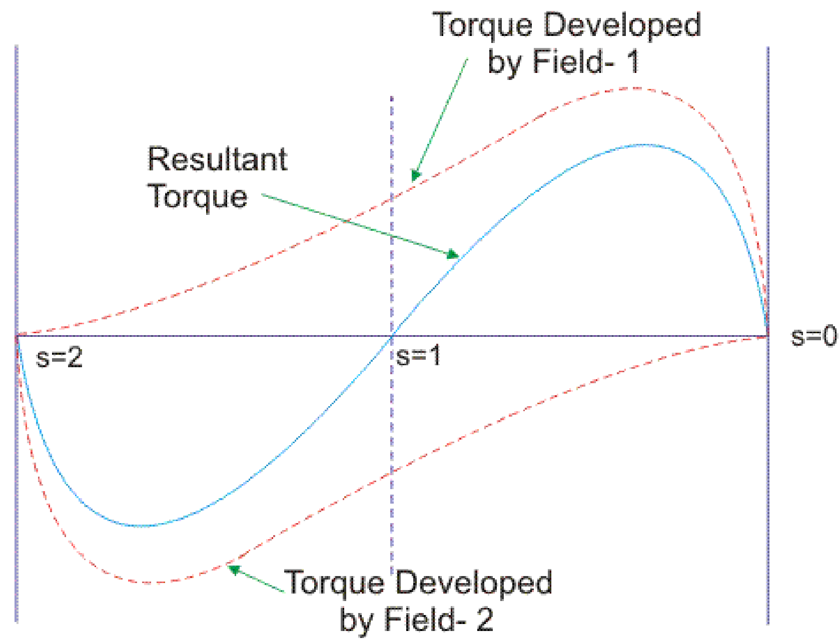
At low values, slip is directly proportional to the rotor resistance, stator voltage frequency and load torque, and inversely proportional to the second power of supply voltage.

The curve can be described in three modes of operation for a three phase induction motor -



Torque Slip Curve for Three Phase Induction Motor

The curve for a single phase induction motor can be given as:



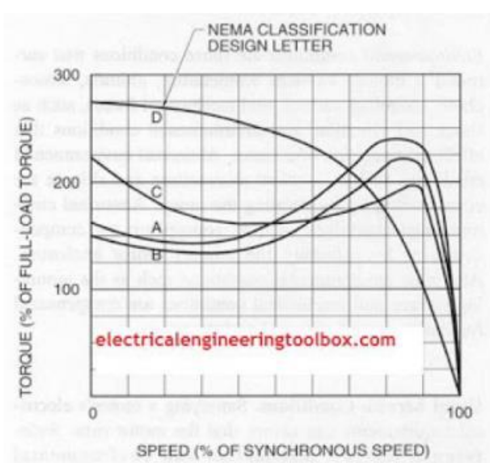
Torque Slip Characteristics of Single Phase Induction Motor

To summarize:

- The motor speed depends on the motor load, per a phenomenon called slip where slip S (%) is the relative angular motion between the rotating magnetic field and the moving rotor assembly.
- Given the information in the class slides, it is established that the rotor current is proportional to the flux density B in the air gap between stator and rotor, the slip, and the rotor resistance.
- Lastly, torque is proportional to rotor current and since the rotor current is proportional to slip, torque is also proportional to slip.

Courtesy: Links to references: [1] [2] [3] [4] [5] [6]

E. Refer to this NEMA curve below for types A, B, C, and D motors.



E.1 Which of the types of motors has the highest locked rotor torque?

Sol. $\boxed{\textbf{Type D Motor}}$

The type D motor has the highest locked rotor torque. This is because LRT is defined as the torque when the motor is at standstill or at zero speed interval. Given this concept, at standstill, type D motor has the highest torque available at full-load based on the graph that is provided for the problem on NEMA curves.

E.2 Other than for type D, which of these motors has the lowest breakdown torque?

Sol. $\boxed{\textbf{Type C Motor}}$

Based on the NEMA curve provided in the problem, the type C motor has the least of all maximum torques available except for type D. Since, BDT is defined as the maximum torque that can be developed by the motor, type C motor generates the lowest BDT as compared to type A and type B motors and therefore type C motor is the solution.

E.3 Other than for type D, which of these motors has the highest pullup torque?

Sol. $\boxed{\textbf{Type C Motor}}$

Pull-Up Torque (PUT) is the minimum torque developed by the motor as it accelerates from standstill to the speed at which breakdown torque occurs. Based on the same definition and the NEMA curve that is provided in the problem, the type C motor has the highest PUT other than for type D since both type A and type B motors have lower PUT than type C motor PUT.

E.4 Which one of these motors would you use if you needed to accelerate an enormous load from zero speed to a high speed in as short a time as possible?

Ans. $\boxed{\textbf{Type D Motor}}$

The type D motor should be used in case if there is a need to accelerate an enormous load from zero speed to a high speed in as short a time as possible. This is because, at full load and at zero speed or standstill point, based on the NEMA curve that is provided, the type D motor provides the highest torque and therefore it would be better to use a type D motor to immediately provide enormous torque and therefore enormous acceleration to a full load at zero speed to let it reach high speed in the as short as possible amount of time.

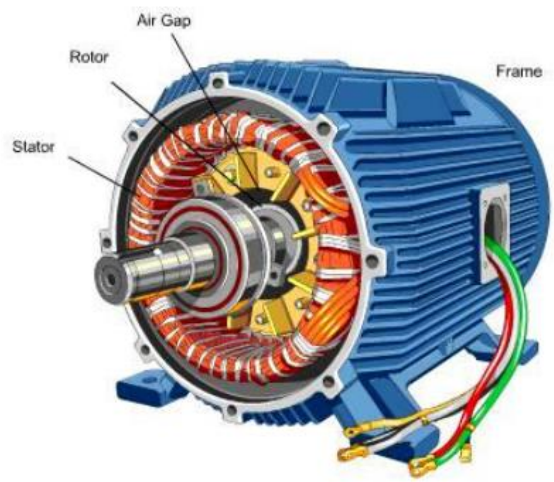
E.5 What would happen to the torque-speed curve for all of these motors if you purposely powered them with AC current at a voltage well under the rated voltage for the motors.

Sol.

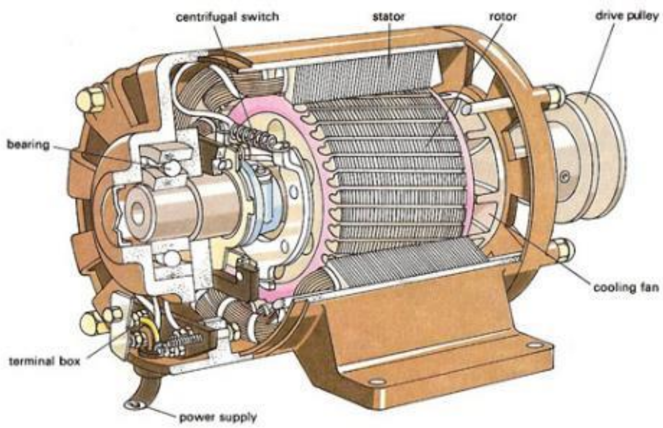
If the motors are purposely powered with an AC supply voltage well under the rated voltage value then the breakdown torque that is available to every motor will scale down proportional to the reduction in the AC voltage supply. Moreover, this will also reduce the speed of the motor (slip) since torque is proportional to slip for the motors and thus at full load, the motors will deliver lesser torque and thus lesser speed. Also, with these conditions, the motors can be less efficient and would provide less response to applications that require heavy startup torque or otherwise a high amount of locked rotor torque. Since applications like crushing waste material for recycling or using crane services for lifting heavy objects or use of heavy elevators that carry tens of passengers demand a pretty high amount of startup torque (LRT), the reduction in the AC voltage supply to the proposed motors will render the motors meaningless since they would not be able to provide the required speed and torque.

Courtesy (for problem E): Links to references: [1] [2] [3] [4]

F. Refer to these diagrams below of a 3-phase AC motor.



Partially Assembled Motor



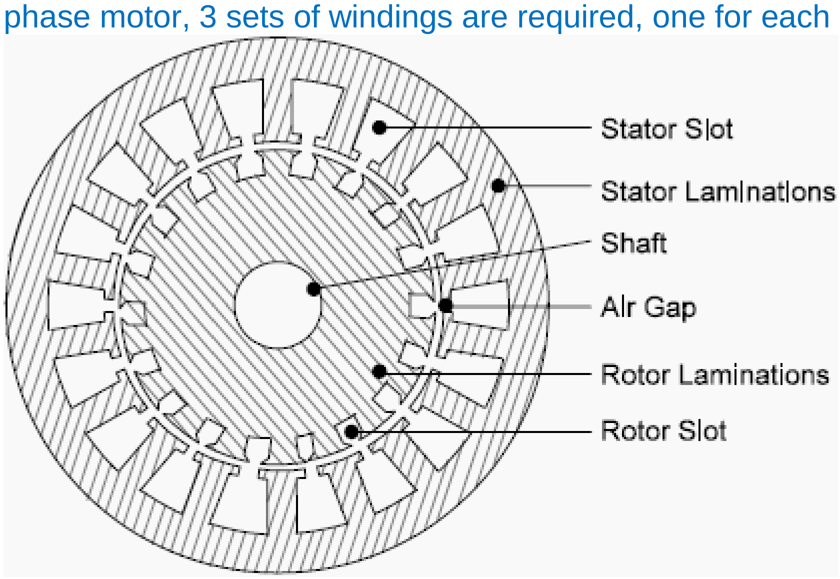
F.1 What is the function of the stator? Describe its construction.

Sol.

Stator:

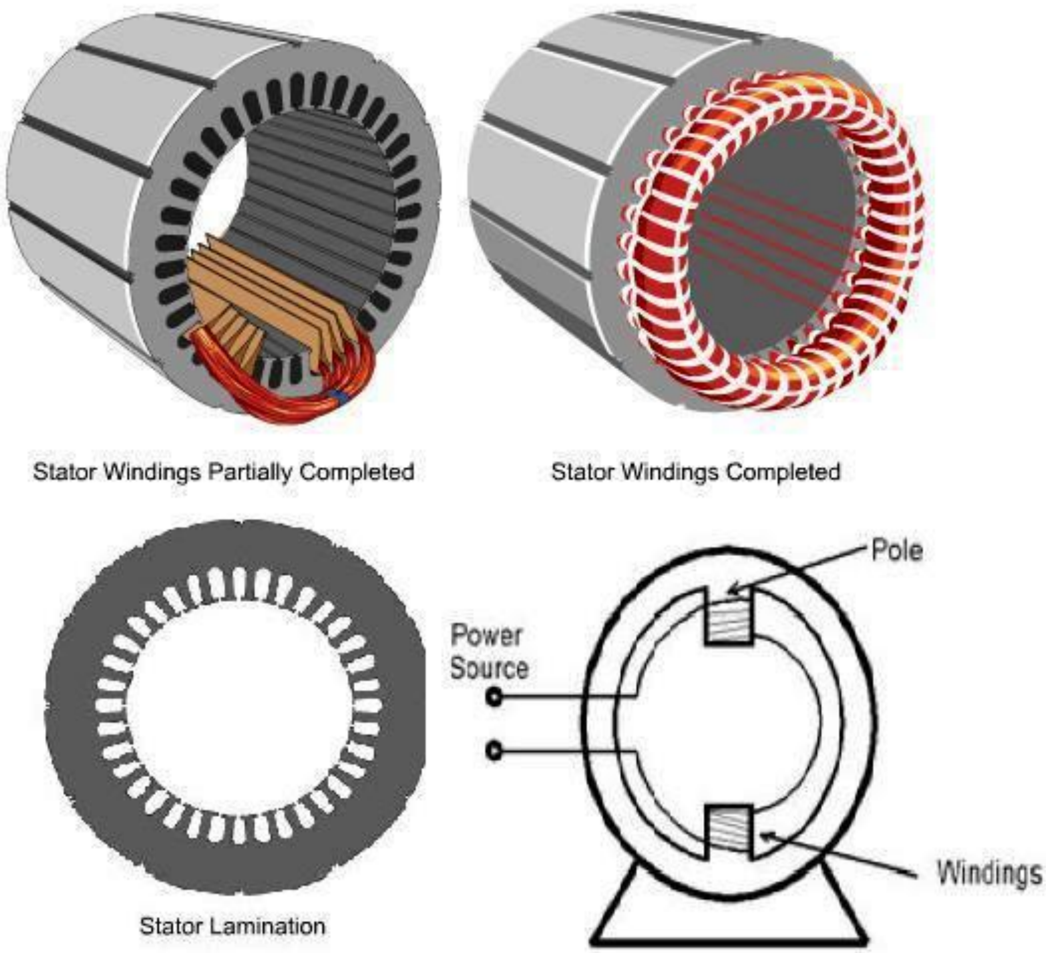
The stator is the outer stationary part of the motor, which consists of:

- **The outer cylindrical frame of the motor**, which is made either of welded sheet steel, cast iron or cast aluminum alloy. This may include feet or a flange for mounting.
- **The magnetic path**, which comprises a set of slotted steel laminations pressed into the cylindrical space inside the outer frame. The magnetic path is laminated to reduce eddy currents, lower losses and lower heating.
- **A set of insulated electrical windings**, which are placed inside the slots of the laminated magnetic path. The cross-sectional area of these windings must be large enough for the power rating of the motor. For a 3-phase motor, 3 sets of windings are required, one for each phase.



As its name indicates stator is a stationary part of induction motor. A stator winding is placed in the stator of induction motor and the three phase supply is given to it. The stator is the stationary part of the motor's electromagnetic circuit. The stator is electrical circuit that performs as electromagnet. The stator core is made up of many thin metal sheets, called laminations. Laminations are used to reduce energy losses that would result if a solid core were used.

The stator structure is composed of steel laminations shaped to form poles. Copper wire coils are wound around these poles. These primary windings are connected to a voltage source to produce a rotating magnetic field. Three-phase motors with windings spaced 120 electrical degrees apart are standard for industrial, commercial and residential use.



Stator Windings Partially Completed

Stator Windings Completed

Stator Lamination

Stator laminations are stacked together forming a hollow cylinder. Coils of insulated wire are inserted into slots of the stator core.

When the assembled motor is in operation, the stator windings are connected directly to the power source. Each grouping of coils, together with the steel core it surrounds, becomes an electromagnet when current is applied. Electromagnetism is the basic principle behind motor operation.

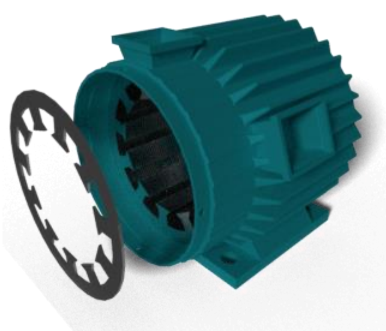
The stator of the three-phase induction motor consists of three main parts:

1. Stator frame,
2. Stator core,
3. Stator winding or field winding.

Stator Frame

It is the outer part of the **three phase induction motor**. Its main function is to support the stator core and the field winding. It acts as a covering, and it provides protection and mechanical strength to all the inner parts of the induction motor. The frame is either made up of die-cast or fabricated steel. The frame of three phase induction motor should be strong and rigid as the air gap length of three phase induction motor is very small. Otherwise, the rotor will not remain concentric with the stator, which will give rise to an unbalanced magnetic pull.

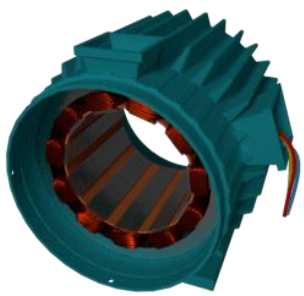
Stator Core



The main function of the stator core is to carry the alternating flux. In order to reduce the eddy current loss, the stator core is laminated. These laminated types of structure are made up of stamping which is about 0.4 to 0.5 mm thick. All the stamping are stamped together to form stator core, which is then housed in stator frame. The stamping is made up of silicon steel, which helps to reduce the hysteresis loss occurring in the motor.

Stator Winding or Field Winding

The slots on the periphery of the stator core of the three-phase induction motor carry three phase windings. We apply three phase ac supply to this three-phase winding. The three phases of the winding are connected either in star or delta depending upon which type of starting method we use. We start the squirrel cage motor mostly with star-delta stater and hence the stator of squirrel cage motor is delta connected. We start the slip ring three-phase induction motor by inserting resistances so, the stator winding of slip ring induction motor can be connected either in star or delta. The winding wound on the stator of three phase induction motor is also called field winding, and when this winding is excited by three phase ac supply, it produces a rotating magnetic field.



For a better, brief and concise construction details of the stator, the reference can be reached by clicking here.

Stator Construction Details

The stator core is built of laminated, electrical-grade steel, and the coils are mounted in slots distributed around the circumference of the stator. The stator winding of the three-phase induction motor is very similar to the armature winding of a three-phase synchronous machine.

The frame has cast iron and has cooling fins and mounting feet cast as part of the frame. The National Electrical Manufacturers' Association (NEMA) defines standard frame sizes so that motors will be interchangeable from one manufacturer to another. One coil of wire occupies two slots in the stator (one slot for each side of the coil). Only the portion of the coil in the slots contributes to the magnetic field. The coil sides are connected together by the end turns. In fact, the winding for a phase of the motor is typically composed of several coils of different sizes that occupy a number of slots around the stator. There will be a set of windings for each of the three phases times the number of pole pairs in the machine. So a two-pole motor would have three-phase coils. While a four-pole motor would have six phase coils. Copper wire is used in the stator coils. The size of the wire is a function of the motor's expected full-load current, insulation type, and rated operating temperature.

Courtesy: Links to references: [1] [2] [3] [4]

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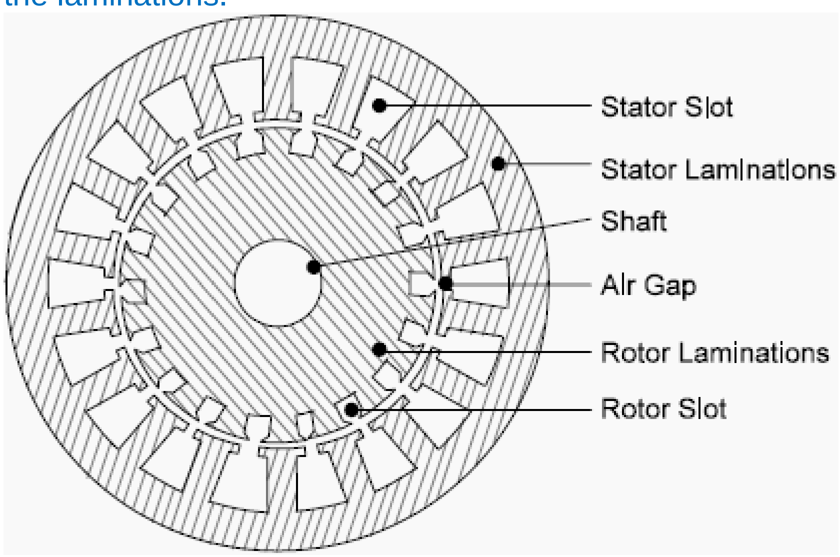
F.2 What is the function of the rotor? Describe its construction.

Sol.

Rotor:

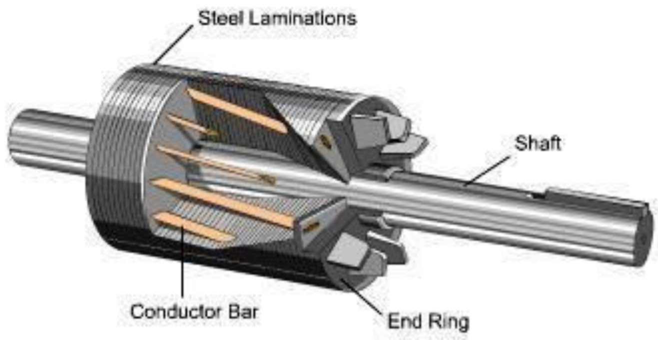
This is the rotating part of the motor. As with the stator above, the rotor consists of a set of slotted steel laminations pressed together in the form of a cylindrical magnetic path and the electrical circuit. The electrical circuit of the rotor can be either:

- **Wound rotor type**, which comprises 3 sets of insulated windings with connections brought out to 3 sliprings mounted on the shaft. The external connections to the rotating part are made via brushes onto the sliprings. Consequently, this type of motor is often referred to as a slipring motor.
- **Squirrel cage rotor type**, which comprises a set of copper or aluminum bars installed into the slots, which are connected to an end-ring at each end of the rotor. The construction of these rotor windings resembles a 'squirrel cage'. Aluminum rotor bars are usually die-cast into the rotor slots, which results in a very rugged construction. Even though the aluminum rotor bars are in direct contact with the steel laminations, practically all the rotor current flows through the aluminum bars and not in the laminations.



The rotor is the rotating part of the motor's electromagnetic circuit. Magnetic field from the stator induces an opposing magnetic field onto the rotor causing the rotor to "push" away from the stator field.

The rotor is another assembly made of laminations over a steel shaft core. Radial slots around the laminations' periphery house rotor bars, cast-aluminium or copper conductors shorted at the ends and positioned parallel to the shaft. Arrangement of the rotor bars resembles a squirrel cage; hence, the term squirrel-cage induction motor. The name "induction motor" comes from the AC "induced" into the rotor via the rotating magnetic flux produced in the stator.



Cutaway View of Rotor

Rotor Lamination

For a better, brief and concise construction details of the rotor, the reference can be reached by clicking here.

Rotor Construction Details

Two types of rotors are used in induction machines: wound and squirrel cage. The wound rotor has a winding that is virtually a mirror image of the stator winding. Connections to it are made via slip rings on the shaft. The wound-rotor machine is used for special purposes, usually involving speed control.

The squirrel-cage induction motor is by far the most common type of induction motor. The rotor is built of a stack of steel laminations. The laminations are aligned and heat-shrunk onto the shaft, and then the molten aluminum is forced into the slots to form the squirrel-cage winding.

It is essential that no air pockets be allowed to form as the squirrel cage is cast; otherwise, the resistance of the bar would increase, causing excessive heating. The bars are shorted together at the ends by shorting rings, which are formed at the same time as bars. The rotor winding thus appears like a squirrel or hamster cage.

In case of aluminum squirrel-cage rotor, the rotor steel is selectively etched away which shows the aluminum bars. One of the shorting rings is visible at the left end of the squirrel cage. Larger rotors usually have fins cast onto them to provide additional cooling surface and to stir the air inside the motor.

The rotor of the machine must fit inside of the stator and be supported so that it can turn. This is done with bearings. The bearing assemblies are at the top and bottom of the rotor body. The bearings are ball bearings, which have less friction than cheaper sleeve bearings. Virtually all motors larger than one horsepower, and many smaller ones use ball bearings.

Courtesy: Links to references: [1] [2] [3] [4]

F.3 Why is the air gap between the stator and rotor made so small, roughly .020” (0.5 mm)?

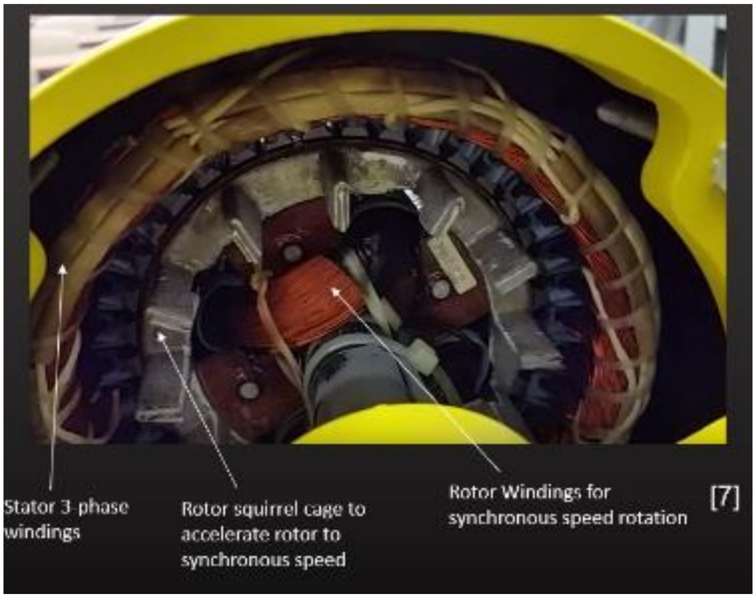
Sol.

The larger air gap thickness between the stator and rotor of the motor results is in a high eddy current loss, especially in the stator. The influence of air gap thickness on the performance of the motor is analysed and studied, which is of great significance for the further improvement of the motor performance and the improvement of the material. During the study, the rotor output power was kept constant, and the air gap thickness was increased from 0.4 mm to 1.0 mm. The air gap loss increases with the thickness of the shielding sleeve.

In order to obtain the required output power, the stator phase current of the motor increases correspondingly, and the copper loss of the stator increases, which makes the efficiency of shielding motor far lower than ordinary permanent magnet synchronous motor. The study also shows that, although the air gap thickness increases, the air gap loss increases gradually, but the flowing rate of working fluid through the air gap increases and the cooling performance improves. It can be found that when the air gap thickness is less than 0.5 mm, the maximum temperature inside the stator reaches 200°C, which seriously affects the reliability and life of the motor. Therefore, considering the efficiency and reliability of the motor, the optimum value of the air gap thickness is 0.6 mm. At this point, the motor efficiency can still reach 90%.

Courtesy: Links to references: [1] [2]

G. Refer to this diagram below for a synchronous AC motor.



G.1 At what speed does the synchronous AC motor rotate and how do you calculate this speed?

Sol.

AC motors are unique because they are built to run at specific speeds regardless of their design or manufacturer. The speed of an AC motor is dependent on the number of poles it has and the line frequency of the power supply, not on its voltage. Common AC motor units are constructed with either two or four poles. A magnetic field is created in the stator poles that induces resulting magnetic fields in the rotor which follow the frequency of the changing magnetic field in the stator. Two pole AC motors operating at 60 Hz will always run at approximately 3600 rpm, and four pole AC motors will have speeds around 1800 rpm.

Speed = 120 x frequency (Hz) / poles of the motor

Example 120 x 60 hertz / 4 poles = 1,800 rpm.

The speed of an AC motor will not run at these exact numbers—and will be slightly lower—because there is a certain amount of slip that must be present for the motor to produce torque. The rotor will always rotate slower than the magnetic field of the stator and is playing a constant game of catch up. This produces the torque to get an AC motor running. The difference between the synchronous speeds of the stator (3600 and 1800 rpm) and the actual operating speed is called slip.)

The speed of a synchronous motor is determined by the following formula:

ns = 120 * f / p

where,

ns = synchronous speed (rpm)
f = frequency of AC supply (Hz)
p = number of magnetic poles

Courtesy: Links to references: [1] [2] [3]

G.2 What are two reasons you would use an AC synchronous motor in an application?

Sol.

The initial cost of a synchronous motor is more than that of a conventional AC induction motor due to the expense of the wound rotor and synchronizing circuitry. However, these initial costs are often off-set by:

- Precise speed regulation makes the synchronous motor an ideal choice for certain industrial processes and as a prime mover for generators.
- Synchronous motors have speed / torque characteristics which are ideally suited for direct drive of large horsepower, low-rpm loads such as reciprocating compressors.
- Synchronous motors operate at an improved power factor, thereby improving overall system power factor and eliminating or reducing utility power factor penalties. An improved power factor also reduces the system voltage drop and the voltage drop at the motor terminals.
- Because of the higher efficiency compared to induction motors they can be employed for loads which require constant speeds. Some of the typical applications of high speed synchronous motors are such drives as fans, blowers, dc generators, line shafts, centrifugal pumps, compressors, reciprocating pumps, rubber and paper mills.
- Synchronous motors are used to regulate the voltage at the end of transmission lines.
- In textile and paper industries synchronous motors are employed to attain wide range of speeds with variable frequency drive system.

Courtesy: Links to references: [1] [2] [3] [4] [5]

H. Refer to this cut-away photo of a single phase AC motor.

H.1 How do the stator coils create a fluctuating magnetic field?

Sol.

Single phase induction motors generally have a construction similar to that of a three phase motor: an ac windings is placed on the stator, short-circuited conductors are placed in a cylindrical rotor. The significant difference is, of-course, that there is only a single phase supply to the stator.

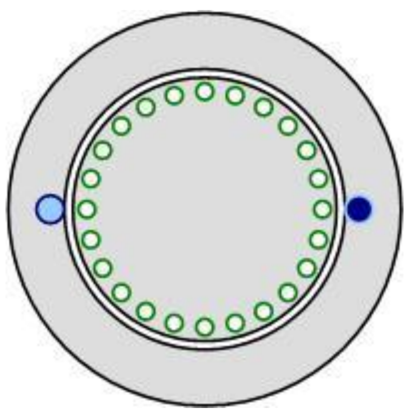


Fig. 1. Illustration of a single phase inducion motor cross section

Consider the motor schematic shown in Fig. 1. If an ac supply is connected to the stator winding, a pulsating flux density will be produced, which will link the rotor circuits. The voltage induced in the rotor circuits will cause a current to flow, producing a flux density to oppose change in the stator flux linking the circuit. In the diagram above, both the stator and rotor flux densities will act in the y-direction. i.e. the cross product of flux densities will be zero, the motor produces no torque. **This simple qualitative analysis indicates a problem, single phase supplies produce pulsating fields, not rotating fields and pulsating fields do not produce torque. However, single phase motors can be made, so there seems to be a contradiction in what we know works, vs. the analysis.**

There are a number of different types of single phase induction machine, which have slightly different approaches to creating a rotating field at starting.

<u>Process of creating a fluctuating magnetic field:</u>

The majority of single phase indcution machines work by applying two phase currents to the motor (two windings connected to the same supply voltage, with different impedences to create different phase angles for the currents).

FIG. 4. ANIMATION OF TWO PHASES, CAPABLE OF PRODUCING A ROTATING FIELD

In the illustration in Fig. 4, there are two phases supplying the motor. **If the phase supplies are balanced (the same per-unit mmf), with a 90° electrical phase angle between the currents and a 90° electrical space angle between the coils, then the result is a purely rotational field with no pulsations. If the supplies are unbalanced, or the phase**

angle is not exactly 90°, there will be a combination of a pulsating and rotating effect.

Courtesy: Links to references: [1] [2] [3]

H.2 Why does a single phase AC motor need a mechanism to create a net torque on the rotor during startup?

Sol.

When the motor is connected to a single-phase power supply,

1. the main winding carries an alternating current.
2. This current produces a pulsating magnetic field.
3. Due to induction, the rotor is energized.
4. As the main magnetic field is pulsating, the torque necessary for the motor rotation is not generated.
5. This will cause the rotor to vibrate, but not to rotate. Hence, the single single phase induction motor is required to have a starting mechanism that can provide the starting kick for the motor to rotate.

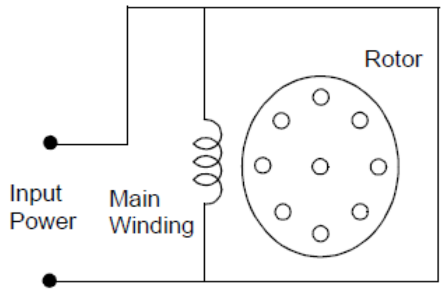
Since the above mentioned details point out that a single phase AC motor is not self-starting, it needs a mechanism to create a net torque on the rotor during the startup to ensure that the motor starts producing required torque from the standstill condition.

Courtesy: Links to references: [1]

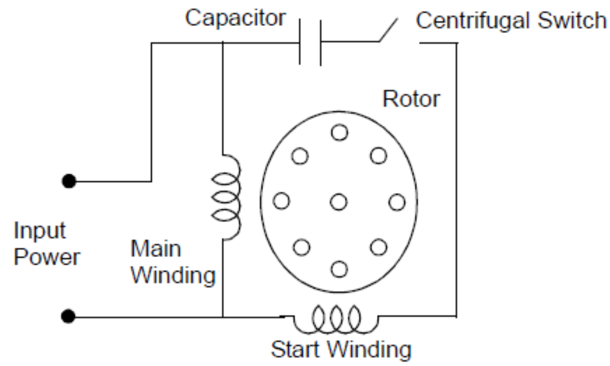
H.3 How is the net torque created in a single phase AC motor?

Sol.

The net torque is primarily created in a single phase AC motor with the help of an additional stator winding (called start/auxiliary winding) as per the figure below:



Single-Phase AC Induction Motor without Start Mechanism



Single-Phase AC Induction Motor with Start Mechanism

As per the figure, the start winding can have a series capacitor and/or a centrifugal switch to connect/disconnect the additional winding as and when required. The further steps to establish the net torque are as under:

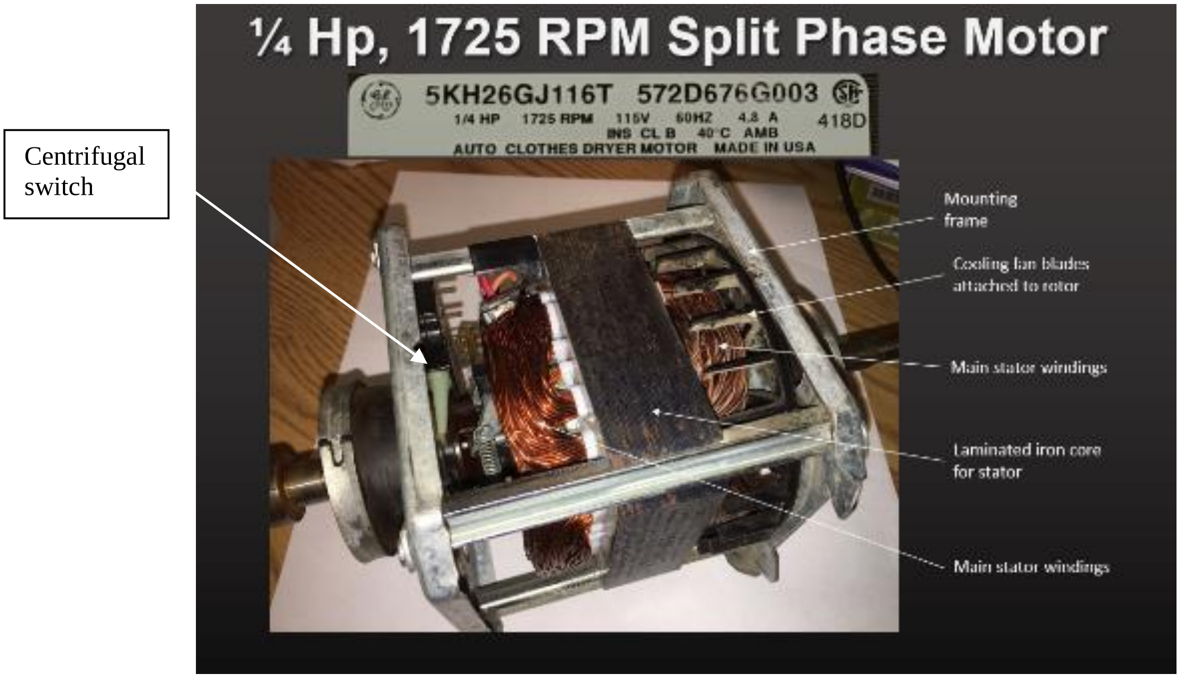
The start winding can have a series capacitor and/or a centrifugal switch.

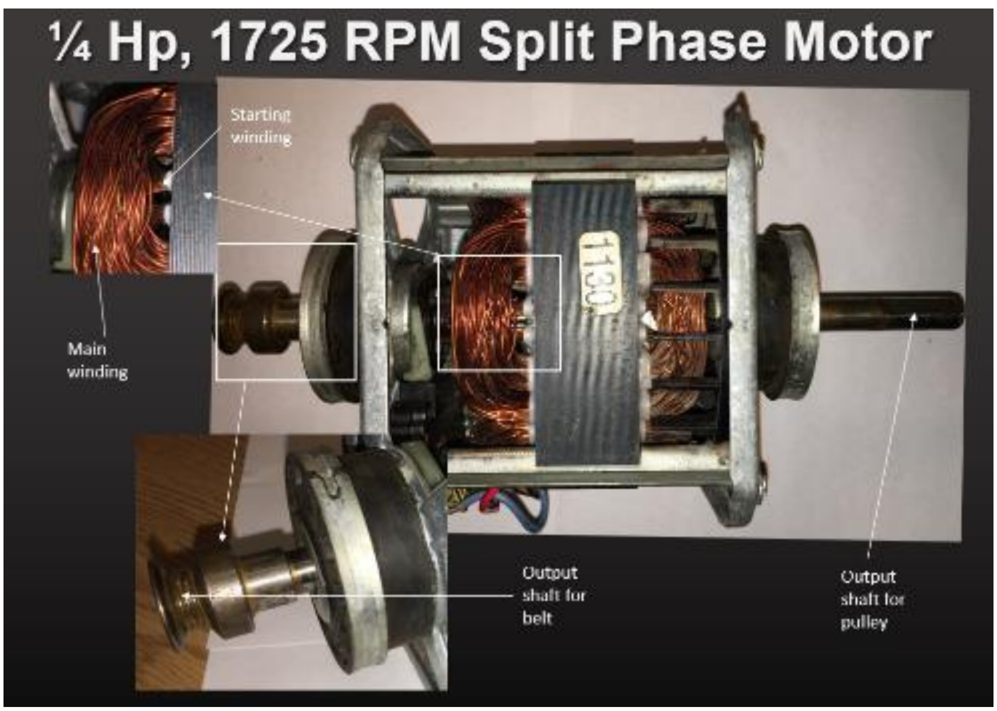
- When the supply voltage is applied, current in the main winding lags the supply voltage due to the main winding impedance.
- At the same time, current in the start winding leads/lags the supply voltage depending on the starting mechanism impedance.
- Interaction between magnetic fields generated by the main winding and the starting mechanism generates a resultant magnetic field rotating in one direction.
- The motor starts rotating in the direction of the resultant magnetic field.
- Once the motor reaches about 75% of its rated speed, a centrifugal switch disconnects the start winding.

From this point on, the single-phase motor can maintain sufficient torque to operate on its own.

Courtesy: Links to references: [1]

I. Refer to these diagrams below of a split phase motor used in a clothing dryer.

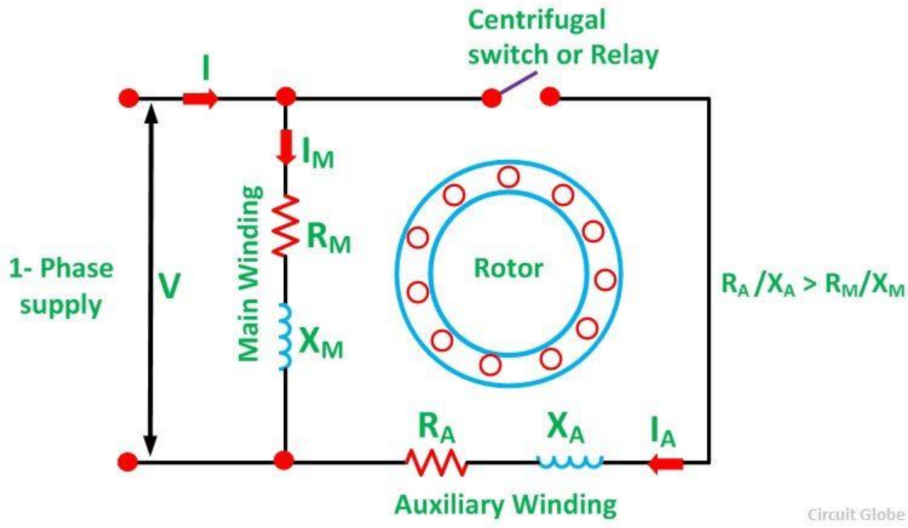




I.1 Describe the differences in dimensional and electrical properties between the main and starting windings. Why are these windings different?

Sol.

The **Split Phase Motor** has two windings known as main winding and starting winding. Both the windings are displaced 90 degrees in space. The main winding has very low resistance and a high inductive reactance whereas the starting winding has high resistance and low inductive reactance. The Connection Diagram of the motor is shown below.

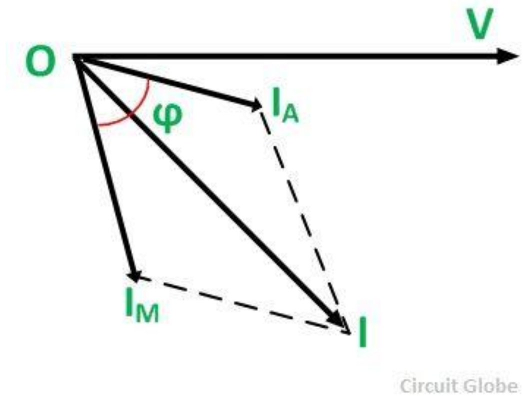


A resistor is connected in series with the auxiliary winding. The current in the two windings is not equal as a result the rotating field is not uniform. Hence, the starting torque is small, of the order of 1.5 to 2 times of the started running torque. At the starting of the motor both the windings are connected in parallel.

As soon as the motor reaches the speed of about 70 to 80 % of the synchronous speed the starting winding is disconnected automatically from the supply mains. If the motors are rated about 100 Watt or more, a centrifugal switch is used to disconnect the starting winding and for the smaller rating motors relay is used for the disconnecting of the winding.

A relay is connected in series with the main winding. At the starting, the heavy current flows in the circuit, and the contact of the relay gets closed. Thus, the starting winding is in the circuit, and as the motor attains the predetermined speed, the current in the relay starts decreasing. Therefore, the relay opens and disconnects the auxiliary winding from the supply, making the motor runs on the main winding only.

The phasor diagram of the Split Phase Induction Motor is shown below.



The current in the main winding (I_M) lag behind the supply voltage V almost by the 90-degree angle. The current in the auxiliary winding I_A is approximately in phase with the line voltage. Thus, there exists the time difference between the currents of the two windings. **The time phase difference ϕ is not 90 degrees, but of the order of 30 degrees. This phase difference is enough to produce a rotating magnetic field.**

REASON FOR THE WINDINGS TO BE DIFFERENT

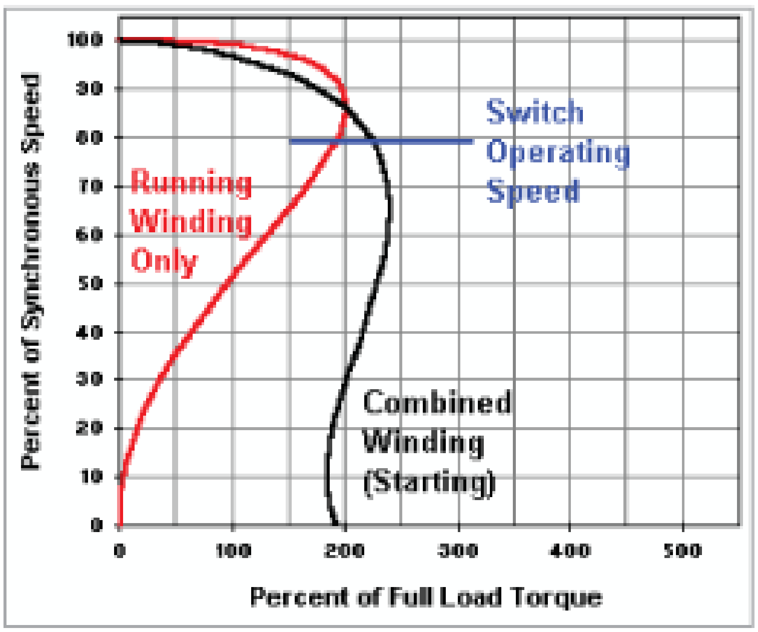
1. When power is first applied, both the running winding and starting winding are energized. Because of their different electrical characteristics, the running winding current lags behind the starting winding current in time. ***This produces a phase difference between the two windings and a rotating magnetic field is developed because the two windings are out of phase. This causes the rotor to rotate with the rotating magnetic fields.***

- The start winding is made with smaller gauge wire and fewer turns, relative to the main winding to create more resistance, thus putting the start winding's field at a different angle than that of the main winding which causes the motor to start rotating.
- The main winding, which is of a heavier wire, keeps the motor running the rest of the time.

Current is induced in the rotor as the run winding establishes a stronger magnetic field. The interaction of the induced-current in the rotor and the magnetic field causes the rotor to start to turn. ***The current induced in the rotor perpetuates its motion as speed increases, and the starting winding is NO longer needed***. At about 75% of operating-speed, the centrifugal switch opens disconnecting current to the starting winding. The motor will have starting problems if the centrifugal switch sticks open or closed which can be relatively common in dirty environments. ***Thus, the two windings are different so that they provide desirable start up torque (Locked Rotor Torque) so that the motor can handle different values of load. In short, the single phase AC motor can maintain sufficient torque to operate on its own once when the additional winding helps produce some net torque in the non self-starting single phase AC motor. This is the primary reason for two different windings.***

Characteristics

The split phase type motor is most widely used for single voltage ratings, 1 HP or less, and for applications where starting torque requirements are 200% or less of full load. The split phase motor has a start and run winding. Both windings are energized when the motor is started. When the motor reaches about 75% of its rated full load speed, the start winding is disconnected from the circuit by an automatic switch.



Applications

Common applications of split phase motors include: fans, blowers, pumps, office machines and tools, such as small saws or drill presses where the load is applied after the motor has obtained its operating speed.

Courtesy: Links to references: [1] [2] [3] [4] [5]

I.2 What is the function of the laminated iron core?

Sol.

The laminated iron core is designed to provide a path for the magnetic field to flow around, which is necessary for induction of voltages between the two windings. Moreover, besides providing a low reluctance path for the magnetic field, the core is designed to prevent circulating electric currents within the iron core itself. Circulating currents, called “eddy currents”, cause heating and energy losses within the core decreasing the transformers efficiency.

These losses are due mainly to voltages induced in the iron circuit, which is constantly being subjected to the alternating magnetic fields setup by the external sinusoidal supply voltage. One way to reduce these unwanted power losses is to construct the transformer core from thin steel laminations.

The central iron core is constructed from of a highly permeable material made from thin silicon steel laminations. These thin laminations are assembled together to provide the required magnetic path with the minimum of magnetic losses. The resistivity of the steel sheet itself is high, thus reducing any eddy current loss by making the laminations very thin.

These steel laminations vary in thickness between 0.25mm to 0.5mm and as steel is a conductor, the laminations and any fixing studs, rivets or bolts are electrically insulated from each other by a very thin coating of insulating varnish or by the use of an oxide layer on the surface.

Courtesy: Links to references: [1]

I.3 What is the function of the centrifugal switch?

Sol.

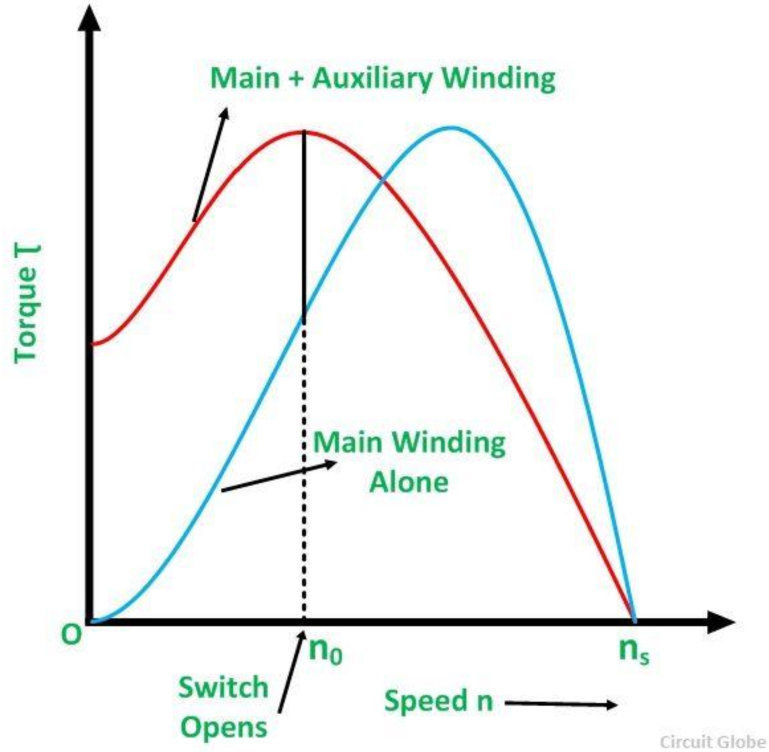
Current is induced in the rotor as the run winding establishes a stronger magnetic field. The interaction of the induced-current in the rotor and the magnetic field causes the rotor to start to turn. ***The current induced in the rotor perpetuates its motion as speed increases, and the starting winding is NO longer needed***. Thus, at about 75% of operating-speed, a centrifugal switch is connected in series with the starting winding. ***The purpose of this switch is to disconnect the auxiliary winding from the main circuit when the motor attains a speed up to 75 to 80% of the synchronous speed.*** Moreover, the centrifugal switch is used to disconnect the starting winding and for the smaller rating motors relay is used for the disconnecting of the winding.

Courtesy: Links to references: [1] [2] [3]

I.4 How does the centrifugal switch work?

Sol.

The **Torque Speed Characteristic** of the Split Phase motor is shown below.



Here, n_0 is the point at which the centrifugal switch operates. The starting torque of the resistance start motor is about 1.5 times of the full load torque. The maximum torque is about 2.5 times of the full load torque at about 75% of the synchronous speed. The starting current of the motor is high about 7 to 8 times of the full load value.

When the motor reaches about 75% of synchronous speed, the centrifugal switch opens the circuit of the starting winding. The motor then operates as a single-phase induction motor and continues to accelerate till it reaches the normal speed. The normal speed of the motor is below the synchronous speed and depends upon the load on the motor.

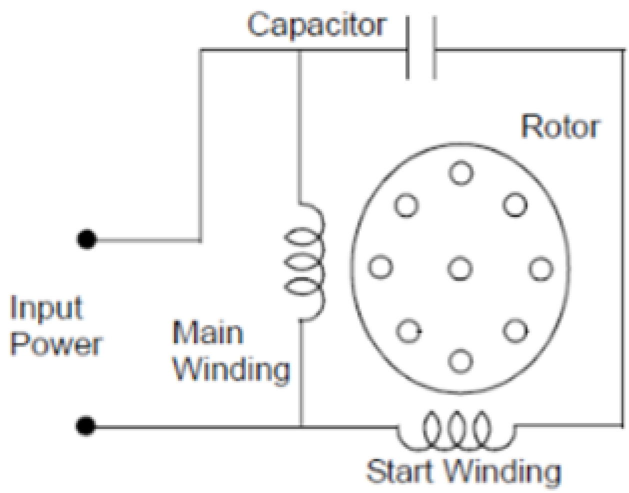
Mechanical Operation (Based on Class Slides):

- At rest, levers press a nonconductive plate against a set of electrical contacts are mounted to the motor housing.
- This closes the contacts and connects the starting winding to its power source.
- When the motor approaches 1725 RPM centrifugal force overcomes the spring force and the levers push the plate to the right.

- The contacts open and the starting winding is disconnected from the circuit.

Courtesy: Links to references: [1] [2]

J. Refer to this circuit diagram below of a permanent split capacitor (PSC) motor.



J.1 What are the four advantages of using a permanent split capacitor (PSC) motor?

Sol.

The four advantages of using a permanent split capacitor (PSC) motor are as under:

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

Courtesy: Links to references: [1]

J.2 What is the major disadvantage of using a permanent split capacitor motor?

Sol.

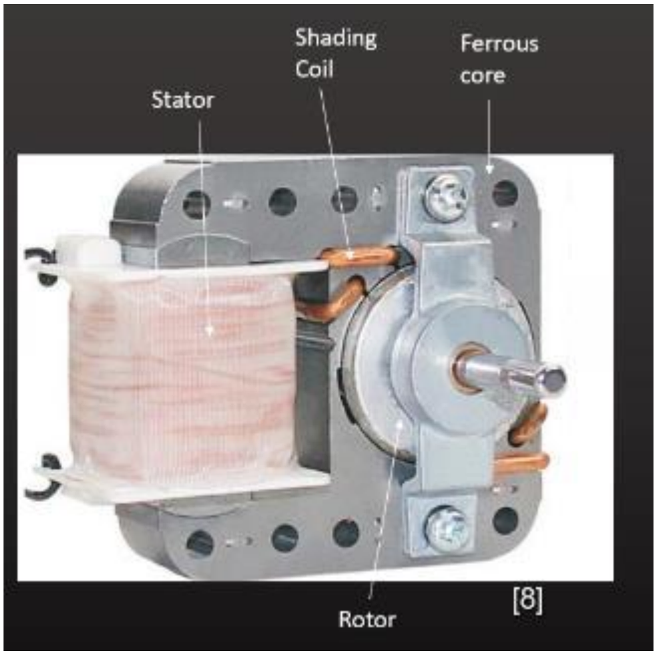
The two major disadvantages of using a permanent capacitor motor are as under:

- The paper capacitor is used in the motor as an Electrolytic capacitor cannot be used for continuous running. The cost of the paper capacitor is higher, and size is also large as compared to the electrolytic capacitor of the same ratings.

- It has low starting torque, less than full load torque.

Courtesy: Links to references: [1]

K. Refer to this photo below of a shaded pole motor.



K.1 What are the three advantages of using a shaded pole motor?

Sol.

The three advantages of using a shaded pole motor are as under:

1. Electrically simple construction, easy to construct and suitable for small devices
2. Very cheap, low cost and reliable
3. Fit for low startup torque applications

K.2 What are the three disadvantages of using a shaded pole motor?

Sol.

The three disadvantages of using a shaded pole motor are as under:

1. It has the lowest starting torque compared to any other type of AC motor
2. It has a considerably high slip
3. Low energy efficiency

Courtesy: References include class slides and links: [1]

L. What are the applications for a universal motor, and why is this type of motor well suited for these applications?

Sol.

[1]

Universal motors can operate with both AC and DC power and that is because they are commutated series-wound motors where field coils are connected with the rotor windings through a commutator. This makes them unique and advantageous for many applications. These motors have a high starting torque that will run at high speeds and are lightweight. The quick, high intensity makes them ideal for items like hair dryers or dremels. Often times these motors are able to work in reverse as well. In addition, they are rather easy to control electronically. Applications of these motors are vast. Many of the applications can are found in smaller equipment. Some of the products that use them are vacuum cleaners, blenders, power tools, weed trimmers and fans just to name a few of a very long list of potential equipment that operates efficiently because of these motors.

When these motors are used in commercial appliances such as electric shavers, sewing machines, office machines, and small hand hair dryers or vacuum cleaners, they are always directly loaded with little danger of motor runaway.

[2]

The use of these motors in alternating current is very widespread due to the higher starting torque with respect to that of the induction motors and due to its high rotation speed, which allows to reduce its size and its price. The universal motor is undoubtedly the most used motor in the household appliance industry.

It is generally used in portable machine tools of all kinds, small appliances such as electric saws, drills, kitchen utensils, fans, blowers, blenders and other applications where high turning speed is required with weak loads or small resistant forces. These motors for alternating current and continuous, including the universal ones, are distinguished by their winding commutator and the brushes.

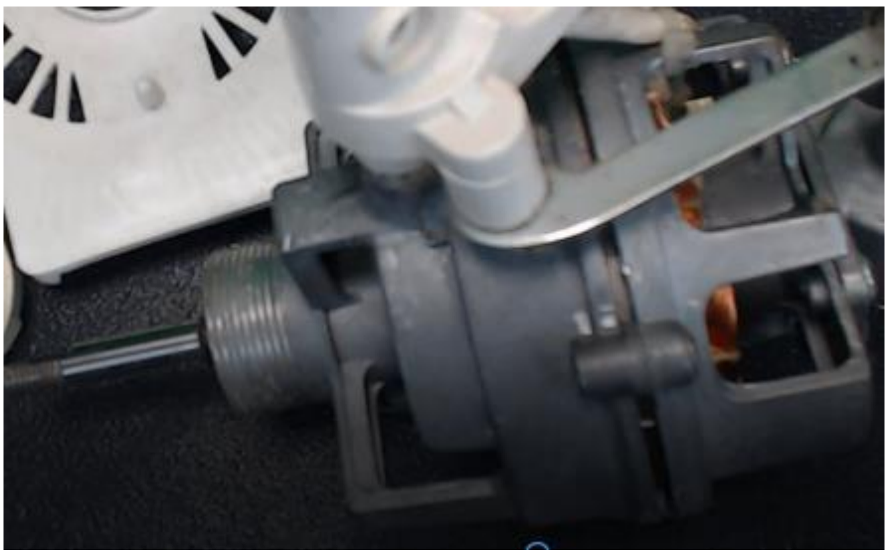
[3]

Furthermore, universal motors in general have the following applications:

- Universal motors have high starting torque and are lightweight and compact.
- Popular in portable drills and saws, vacuum cleaners, food processors, and portable fans.
- The commutator makes the universal noisy: acoustically and electromagnetically.
- Not for continuous use - commutator brushes wear off very quickly.

Courtesy: The references used to frame this answer are provided above.

M. Refer to this screen shot of a universal motor from our video on Universal and gear motors (C1M1V8.mp4 stored in Canvas Pages section)

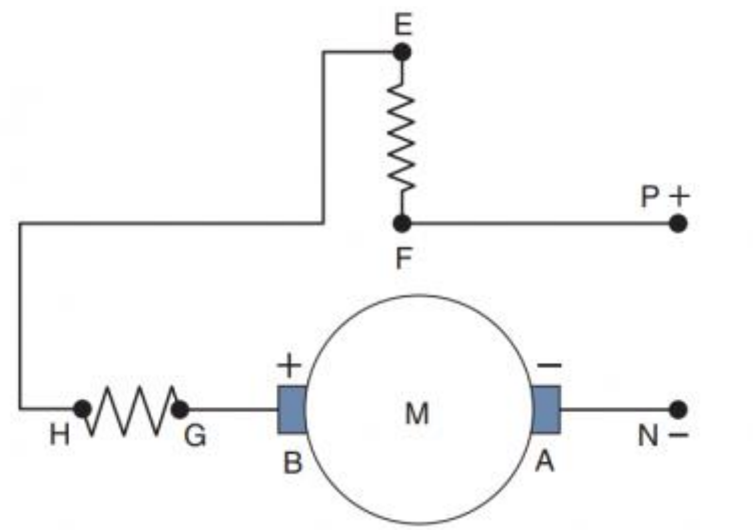


M.1 Describe the construction of the stator. Provide a screen shot of the stator and document its components.

Sol.

Constitution and operating principle of the universal motor

The universal motor is a type of single-phase motor that can work both in direct current and in alternating current. Its constitution is essentially that of the direct current series motor and its operating characteristics are analogous. Next we represent this engine schematically:



The direct current series motor is characterized by having a strong starting torque and its speed is in inverse function to the load. In this way it is easy to reach very high speeds when running in a vacuum. At the moment in which the universal motor works in alternating current, this inconvenience is reduced because its application is usually in small power motors and the losses due to friction, bearings, etc., are high with respect to the total, so that they present the danger of accelerating so much, although if they reach speeds of up to 20,000 revolutions per minute (rpm). For this reason they are quite suitable for small appliances.

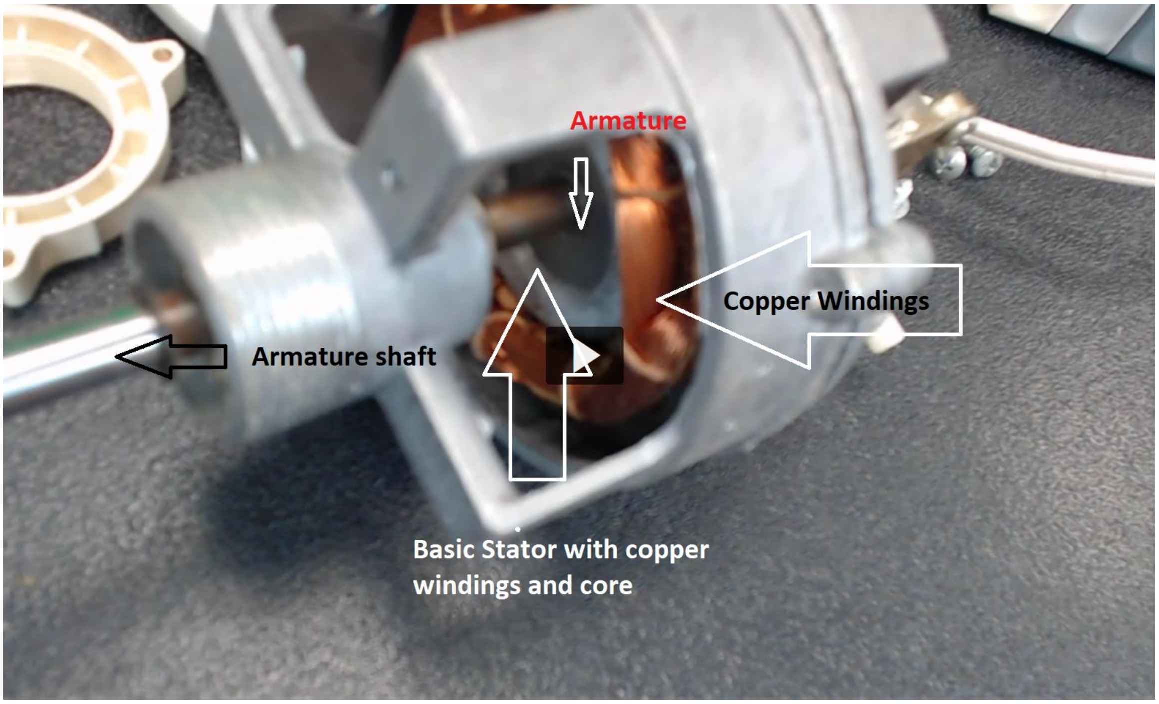
The Stator:

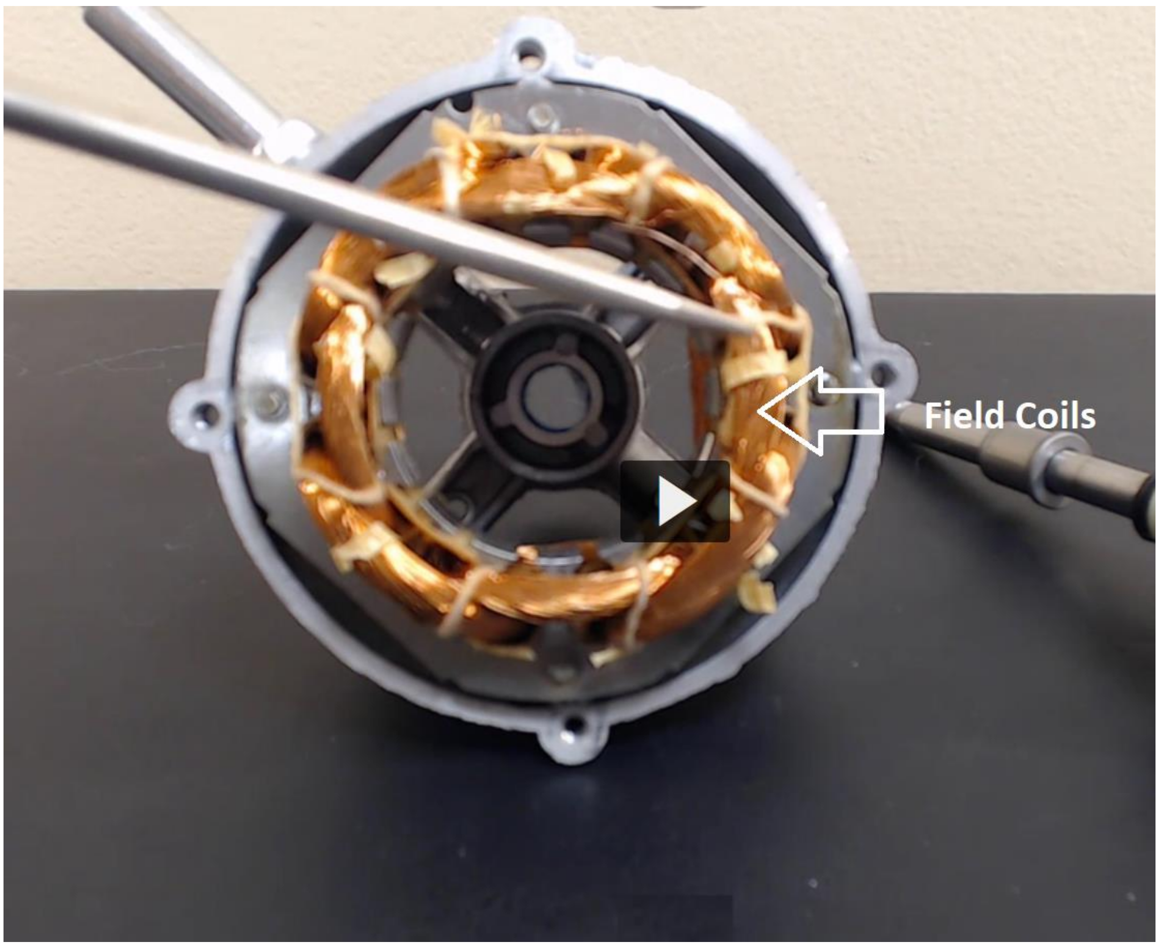
The stator is the fixed part of an electric machine. By electric machine we refer to both electric motors and electric generators.

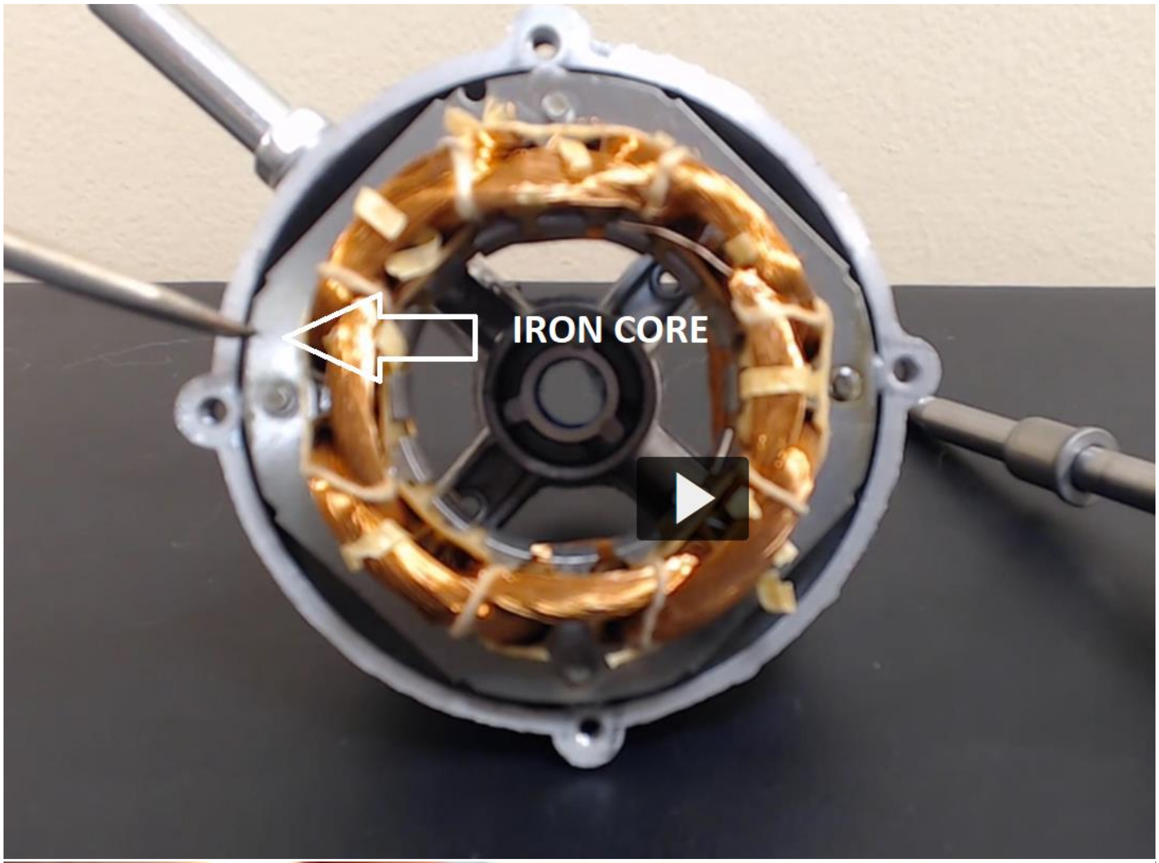
In AC machines the stator is generally in the form of a cylindrical tube, with a certain wall thickness. A based on stacked crowns of magnetic sheet with a toothed on its inner circle are formed the slots where the coils are housed. In the continuous current machines the stator is formed by a solid steel cylindrical frame. This frame has polar poles or pieces with corresponding coils attached to it.

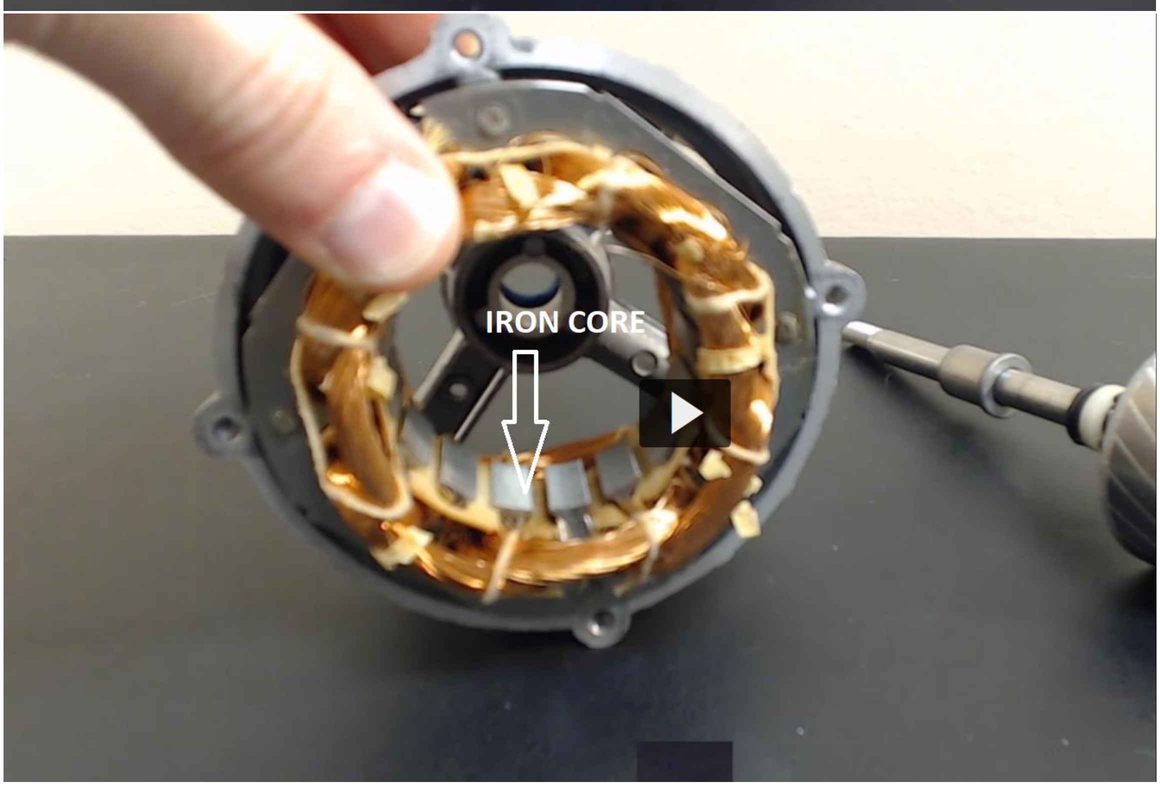
Depending on the configuration of a rotating electric force device, this stator can act as a magnet (through the electromagnet effect), reacting with the armature to produce movement. In addition, the stator can also act as an armature by accepting inductors of a moving field coil located in a rotor.

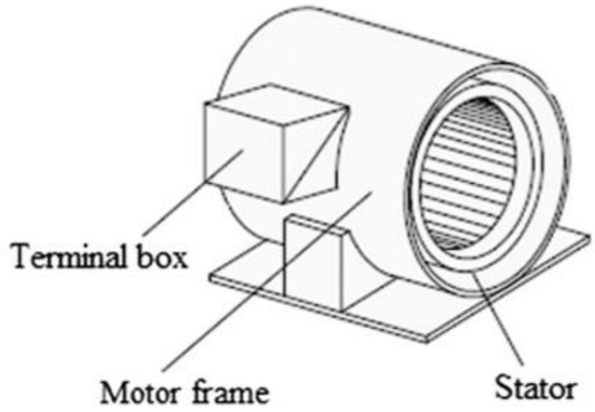
The stator for this type of device can be composed of permanent or electromagnetic magnets. If the stator is an electromagnet, the coil that drives it is known as a field coil. An alternator is also capable of generating power through multiple multiplication coil generators that have high power amplifiers. These amplifiers are connected in parallel without the need for a converter.


Armature
Copper Windings
Armature shaft
Basic Stator with copper
windings and core


Field Coils


IRON CORE


IRON CORE



Stator of an induction motor

Courtesy: Links for references: [1] [2]

M.2 What would happen to the speed of the fan if the armature were to touch the iron core of the stator during rotation?

Sol.

If the armature of the motor were to touch the iron core of the stator during rotation then there would be a rise of friction between the armature and the iron core which would eventually provide wear and tear to the bearings. This situation would lead to an obstruction to the free movement of the armature commutator and the brush connections. Also, as the gap between the stator and rotor would be negligible since the armature touches the iron core, based on the reference provided in this problem, it can be found that when the air gap thickness is less than 0.5 mm, the maximum temperature inside the stator reaches 200°C, which seriously affects the reliability and life of the motor. Thus, the fan speed would reduce as well as the temperature inside the motor box would also rise to a very unstable value which can result in a fatal accident.

Courtesy: Links to references: [1] [2] [3]