$$I_m = \sqrt{I_{NL}^2 - I_w^2}$$

$$X_m = 2\frac{|E_{1F}|}{I_m}$$

4.3 **Methods of Starting**

It is clear from previous discussion that a single phase induction motor when having only one winding and it is not self-starting. To make it a self-starting anyone of the following can be adopted.

(1) Split phase starting.

(2) Repulsion starting.

(3) Shaded pole starting.

4.3.1 PRINCIPLE OF SPLIT PHASE INDUCTION MOTOR

The basic principle of operation of a split phase induction motor is similar to that of a polyphase induction motor. The main difference is that the single phase motor does not produce a rotating magnetic field but produces only a pulsating filed.

Hence, to produce the rotating magnetic field for self-starting, phase splitting is to be done to make the motor to work as a two phase motor for starting.

4.3.1 ***Working of Split Phase Motor***

In split phase motor two windings named as main winding and starting winding are provided. At the time of starting, both the main and starting windings should be connected across the supply to produce the rotating magnetic field.

The rotor is of a squirrel cage type and the revolving magnetic field sweeps part the stationary rotor, inducing emf in the rotor. As the rotor bars are short-circuited, a current flows through them producing a magnetic field.

This magnetic field opposes the revolving magnetic field and will combine with the main filed to produce a revolving filed. By this action, the rotor starts revolving in the same direction of the rotating magnetic field as in the case of a squirrel cage induction motor.

Hence, once the rotor starts rotating, the starting winding can be disconnected from the supply by some mechanical means as the rotor and stator fields from a revolving magnetic field. There are several types of split phase motors.

4.3.2 TYPES OF SPLIT-PHASE INDUCTION MOTORS

1. Resistance-start, induction-run motors
2. Capacitor-start, induction-run motors
3. Capacitor-start, capacitor-run motors
4. Shaded pole motors.

1. RESISTANCE-START, INDUCTION-RUN MOTORS

As the starting torque of this type of motor is relatively small and its starting current is high, these motors are most commonly used for rating up to 0.5 HP where the load could be started easily. The essential parts are shown in Fig: 4.7.

- Main winding or running winding.
- Auxiliary winding or starting winding
- Squirrel cage type rotor.
- Centrifugal switch.

CONSTRUCTION AND WORKING

The starting winding is designed to have a higher resistance and lower reactance than the main winding. This is achieved by using small conductors in the auxiliary winding than in the main winding. The main winding will have higher inductance when surrounded by more iron, which could be made possible by placing it deeper into the stator slots, it is obvious that the current would split as shown in Fig: 4.7(b).

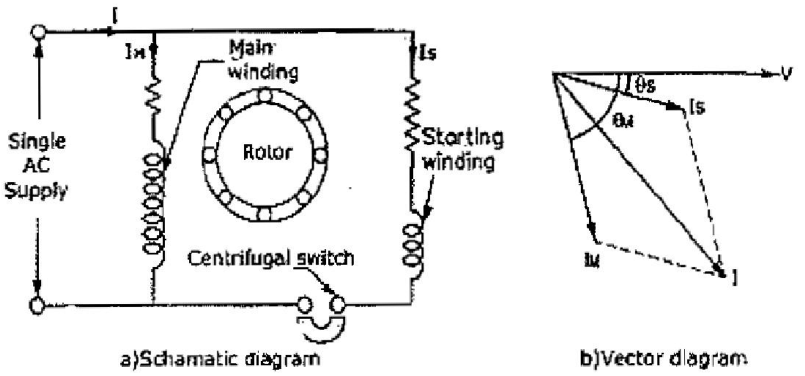


Fig: 4.7

The starting current "I" start will lag the main supply voltage "V" line by 15 degree and the main winding current. "I" main lags the main voltage by about 80 degree. Therefore, these currents will differ in time phase and their magnetic fields will combine to produce a rotating magnetic field.

When the motor has come upto about 75 to 80% of synchronous speed, the starting winding is opened by a centrifugal switch and the motor will continue to operate as a single phase motor.

CHARACTERISTICS

At the point where the starting winding is disconnected, the motor develops nearly as much torque with the main winding alone as with both windings connected. This can be observed from, the typical torque-speed characteristics of this motor, as shown in Fig: 4.8.

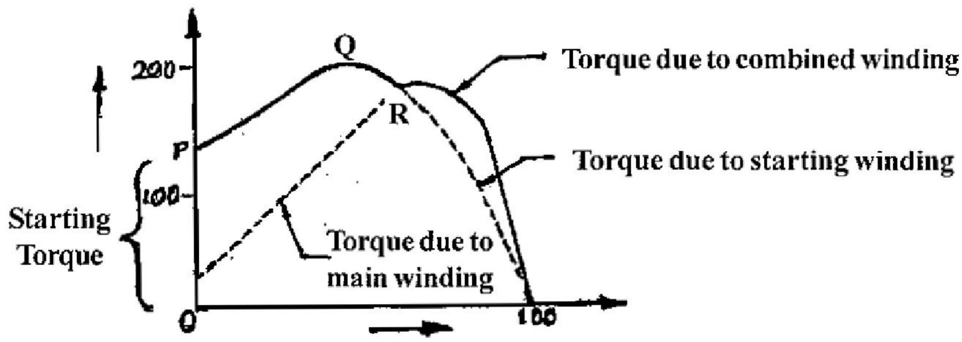


Fig: 4.8

The direction of rotating of a split-phase motor is determined by the way the main and auxiliary windings are connected. Hence, either by changing the main winding terminals or by changing the starting winding terminals, the reversal of direction of rotating could be obtained.

APPLICATIONS

These motors are used for driving fans, grinders, washing machines.

2. CAPACITOR-START, INDUCTION-RUN MOTOR

A drive which requires a large starting torque may be fitted with a capacitor-start, induction-run motor as it has excellence starting torque as compared to the resistance-start, induction-run motor.

CONSTRUCTION AND WORKING

Fig: 4.9(a) shows the schematic diagram of a capacitor-start, induction-run motor. As shown, the main winding is directly connected across the main supply whereas the starting winding is connected across the main supply through a capacitor and centrifugal switch.

Both these windings are placed in a stator slot at 90 degree electrical apart, and a squirrel cage type rotor is used.

As shown in Fig: 4.9(b), at the time of starting the current in the main winding lags the supply voltages by 90 degrees, depending upon its inductance and resistance. On the other hand, the current in the starting winding due to its capacitor will lead the applied voltage, by say 20 degrees.

Hence, the phase difference between the main and starting winding becomes near to 90 degrees. This in turn makes the line current to be more or less in phase with its applied voltage, making the power factor to be high, thereby creating an excellent starting torque.

However, after attaining 75% of the rated speed, the centrifugal switch operates opening the starting winding and the motor then operates as an induction motor, with only the main winding connected to the supply.

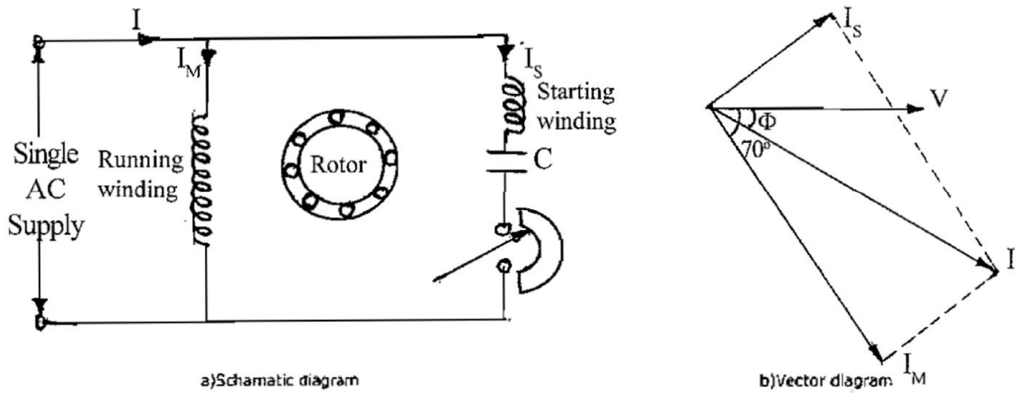


Fig: 4.9

As shown in Fig: 4.9(b), the displacement of current in the main and starting winding is about 80/90 degrees, and the power factor angle between the applied voltage and line current is very small. This results in producing a high power factor and an excellent starting torque, several times higher than the normal running torque as shown in Fig: 4.10.

CHARACTERISTICS

The torque-speed characteristics of this motor is shown in Fig: 4.10.

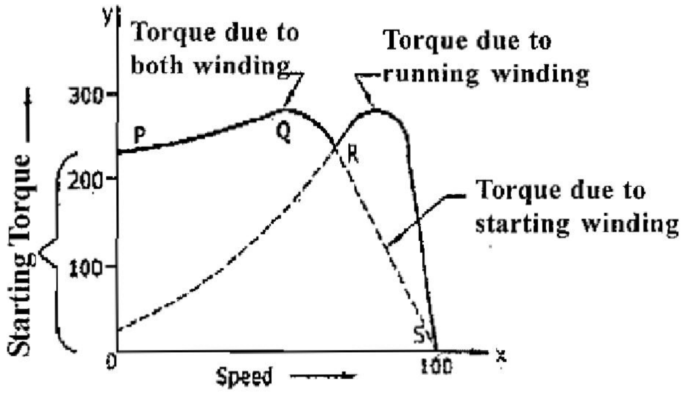


Fig: 4.10

In order to reverse the direction of rotation of the capacitor-start, induction-run motor, either the starting or the main winding terminals should be changed.

This is due to the fact that the direction of rotation depends upon the instantaneous polarities of the main field flux and the flux produced by the starting winding. Therefore, reversing the polarity of one of the field will reverse the torque.

APPLICATIONS

Due to the excellent starting torque and easy direction-reversal characteristics,

- Used in belted fans,
- Used in blowers dryers,
- Used in washing machines,
- Used in pumps and compressors.

3. CAPACITOR-START, CAPACITOR-RUN MOTORS

As discussed earlier, one capacitor-start, induction-run motors have excellent starting torque, say about 300% of the full load torque and their power factor during starting in high.

However, their running torque is not good, and their power factor, while running is low. They also have lesser efficiency and cannot take overloads.

CONSTRUCTION AND WORKING

The aforementioned problems are eliminated by the use of a two valve capacitor motor in which one large capacitor of electrolytic (short duty) type is used for starting whereas a smaller capacitor of oil filled (continuous duty) type is used for running, by connecting them with the starting winding as shown in Fig:4.11. A general view of such a two valve capacitor motor is shown in Fig: 4.11.

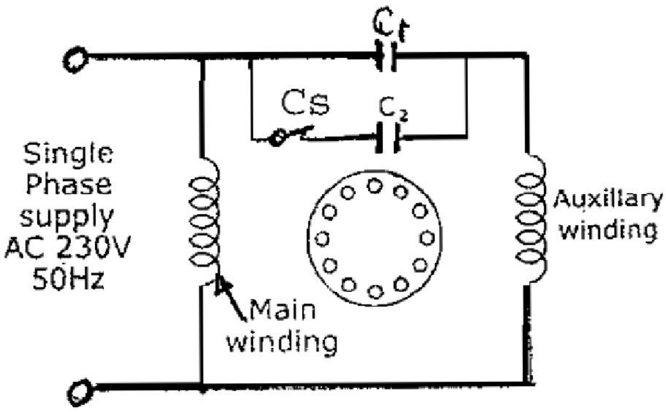


Fig: 4.11

This motor also works in the same way as a capacitor-start, induction-run motor, with exception, that the capacitor C1 is always in the circuit, altering the running performance to a great extent.

The starting capacitor which is of short duty rating will be disconnected from the starting winding with the help of a centrifugal switch, when the starting speed attains about 75% of the rated speed.

CHARACTERISTICS

The torque-speed characteristics of this motor is shown in Fig: 4.12.

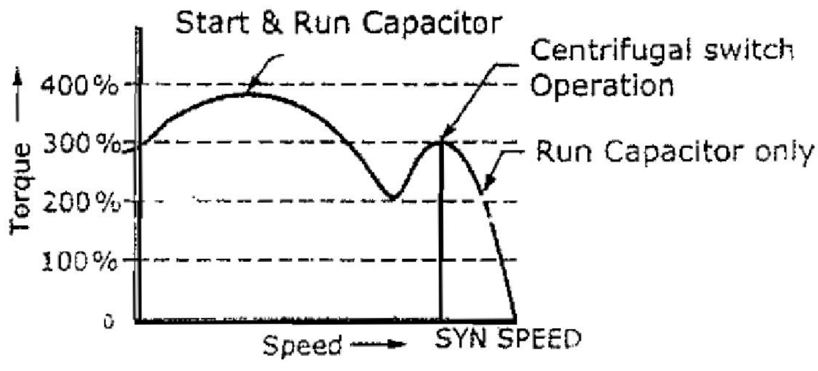


Fig: 4.12

This motor has the following advantages:

- The starting torque is 300% of the full load torque
- The starting current is low, say 2 to 3 times of the running current.
- Starting and running power factor are good.
- Highly efficient running.
- Extremely noiseless operation.
- Can be loaded upto 125% of the full load capacity.

APPLICATIONS

- Used for compressors, refrigerators, air-conditioners, etc.
- Higher starting torque.
- High efficiency, higher power factor and overloading.
- Costlier than the capacitor-start — Induction run motors of the same capacity.

4.3.2 REPULSION STARTING

This type of starting need a wound rotor with brush and commutator arrangement like a dc armature Fig 4.13(a). The starting operation is based on the principle of repulsion and hence the name.

CONSTRUCTION AND WORKING

Repulsion starting, though complicated in construction and higher in cost, are still used in certain industries due to their excellent starting torque, low starting current, ability to withstand long spell of starting currents to drive heavy loads and their easy method of reversal of direction.

Now there is a condition that the rotor north pole will be repelled by the main north pole and the rotor south pole is repelled by the main south pole, so that a torque could be developed in the rotor. Now due to the repulsion action between the stator and the rotor poles, the rotor will start rotating in a clockwise direction. As the motor torque is due to repulsion action, this starting method is named as repulsion starting.

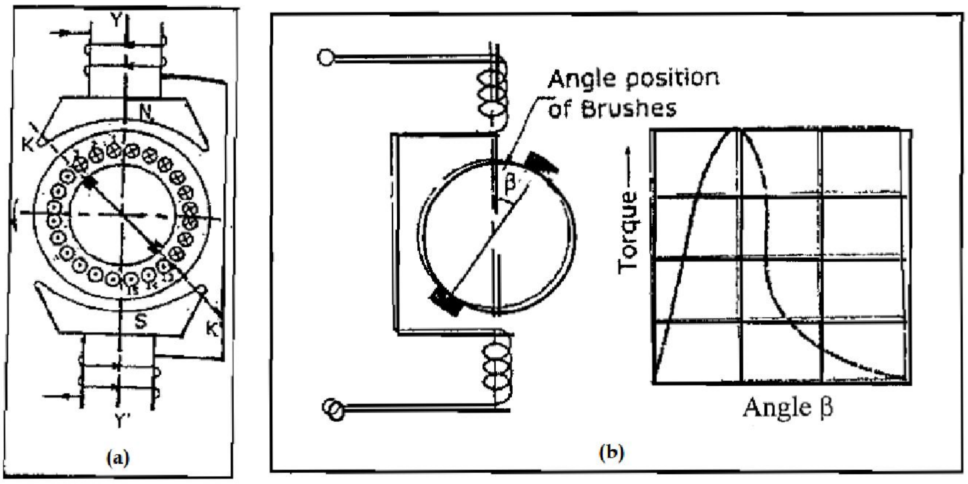


Fig: 4.13

To change the direction of rotation of this motor, the brush axis needs to be shifted from the right side as shown in Fig:4.13(b) to the left side of the main axis in a counter clockwise direction as shown in Fig:4.13(b).

CHARACTERISTICS

The torque developed in a repulsion motor will depend upon the amount of brush shaft as shown in Fig: 4.13 (b), whereas the direction of shift decides the direction of rotation.

Further, the speed depends upon the amount of brush shift and the magnitude of the load also on the relationship between the torque and brush-position angle.

Though the starting torque from 250 to 400% of the full load torque, the speed will be dangerously high during light loads. This is due to the fact that the speed of the repulsion motor start does not depend on frequency or number of poles but depends upon the repulsion principle.

Further, there is a tendency of sparking in the brushes at heavy loads, and the PF will be poor at low speeds. Hence the conventional repulsion motor start is not much popular.

4.3.3 SHAPED POLE STARTING

The motor consists of a yoke to which salient poles are fitted as shown in Fig: 4.14(a) and it has a squirrel cage type rotor.

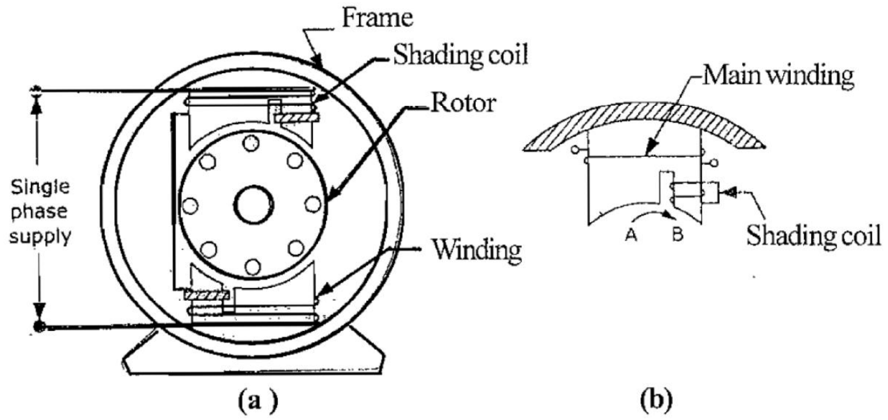


Fig: 4.14

A shaded pole made of laminated sheets has a slot cut across the lamination at about one third the distance from the edge of the pole.

Around the smaller portion of the pole, a short-circuited copper ring is placed which is called the shading coil, and this part of the pole is known as the shaded part of the pole. The remaining part of the pole is called the unshaded part which is clearly shown in Fig: 4.14(b).

Around the poles, exciting coils are placed to which an AC supply is connected. When AC supply is effected to the exciting coil, the magnetic axis shifts from the unshaded part of the pole to the shaded part as will be explained in details in the next paragraph. This shifting of axis is equivalent to the physical movement of the pole.

This magnetic axis, which is moving, cuts the rotor conductors and hence, a rotational torque is developed in the rotor.

By this torque the rotor starts rotating in the direction of the shifting of the magnetic axis that is from the unshaded part to the shaded part.

THE MAGNETIC FLUX SHIFTING

As the shaded coil is of thick copper, it will have very low resistance but as it is embedded in the iron case, it will have high inductance. When the exciting winding is connected to an AC supply, a sine wave current passes through it.

Let us consider the positive half cycle of the AC current as shown in Fig: 4.15.

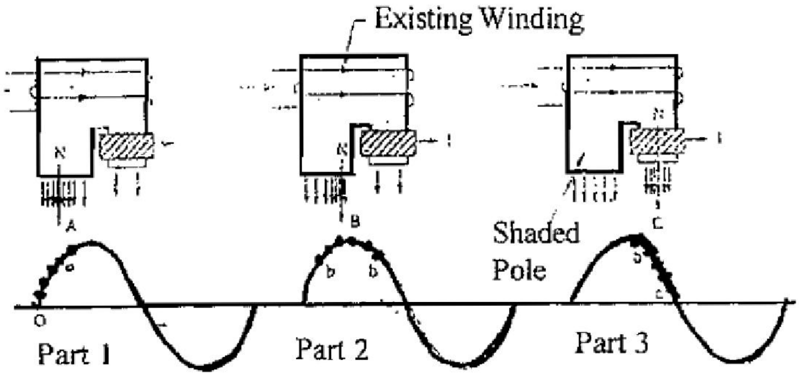


Fig: 4.15 Shifting of magnetic flux

When the current raises from "Zero" Value of point "0" to a point "a" the change in current is very rapid (Fast). Hence, it reduces an emf in the shaded coil on the basis of Faraday's law of electromagnetic induction.

The induced emf in the shaded coil produces a current which, in turn, produces a flux in accordance with Lenz Law. This induced flux opposes the main flux in the shaded portion and reduces the main flux in that area to a minimum value as shown in Fig: 4.15.

This makes the magnetic axis to be in the centre of the unshaded portion as shown by the arrow in part of Fig: 4.15. On the other hand as shown in part 2 of 3 when the current raises from point "a" to point "b" the change in current is slow the induced emf and resulting current in the shading coil is minimum and the main flux is able to pass through the shade portion.

This makes the magnetic axis to be shifted to the centre of the whole pole as shown in by the arrow in part 2 of Fig: 4.15.

In the next instant, as shown in part 3 of Fig: 4.15. When the current falls from "b" to "c" the change in current is fast but the change of current is from maximum to minimum.

Hence a large current is induced in the shading ring which opposes the diminishing main flux, thereby increasing the flux density in the area of the shaded part. This makes the magnetic axis to shift to the right portion of the shaded part as shown by the arrow in part.

From the above explanation it is clear the magnetic axis shifts from the unshaded part to the shaded part which is more or less a physical rotary movement of the poles.

Simple motors of this type cannot be reversed. Specially designed shaded pole motors have been constructed for reversing operations. Two such types:

a. The double set of shading coils method

b. The double set of exciting winding method.

Shaded pole motors are built commercially in very small sizes, varying approximately from 1/250 HP to 1/6 HP. Although such motors are simple in construction and cheap, there are certain disadvantages with these motor as stated below:

- Low starting torque.
- Very little overload capacity.
- Low efficiency.

APPLICATIONS

- Record players
- Fans
- Hair driers.

4.4 Single Phase Series Motor

The single-phase series motor is a commutator-type motor. If the polarity of the line terminals of a dc series motor is reversed, the motor will continue to run in the same direction. Thus, it might be expected that a dc series motor would operate on alternating current also. The direction of the torque developed in a dc series motor is determined by both filed polarity and the direction of current through the armature[$T \propto \phi I_a$].

4.4.1 Operation

Let a dc series motor be connected across a single-phase ac supply. Since the same current flows through the field winding and the armature, it follows that ac reversals from positive to negative, or from negative to positive, will simultaneously affect both the field flux polarity and the current direction through the armature. This means that the direction of the developed torque will remain positive, and rotation will continue in the same direction. Thus, a series motor can run both on dc and ac.

However, a series motor which is specifically designed for dc operation suffers from the following drawbacks when it is used on single-phase ac supply:

1. Its efficiency is low due to hysteresis and eddy-current losses.
2. The power factor is low due to the large reactance of the field and the armature winding.
3. The sparking at the brushes is excessive.

In order to overcome these difficulties, the following modifications are made in a D.C. series motor that is to operate satisfactorily on alternating current:

1. The field core is constructed of a material having low hysteresis loss. It is laminated to reduce eddy-current loss.
2. The field winding is provided with small number of turns. The field-pole areas is increased so that the flux density is reduced. This reduces the iron loss and the reactive voltage drop.
3. The number of armature conductors is increased in order to get the required torque with the low flux.
4. In order to reduce the effect of armature reaction, thereby improving commutation and reducing armature reactance, a compensating winding is used.

The compensating winding is put in the stator slots. The axis of the compensating winding is 90 (electrical) with the main field axis. It may be connected in series with both the armature and field as shown in Fig: 4.16. In such a case the motor is conductively compensated.

The compensating winding may be short circuited on itself, in which case the motor is said to be inductively compensated shown in Fig: 4.17.

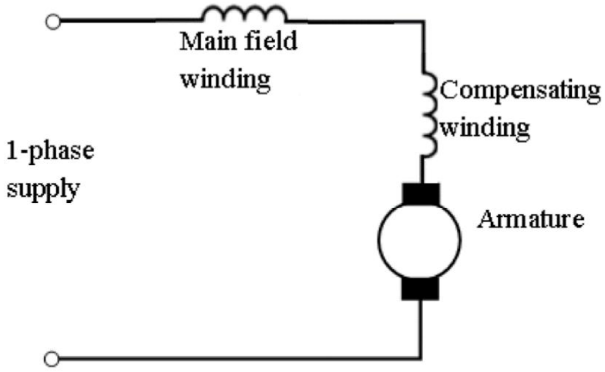


Fig: 4.16

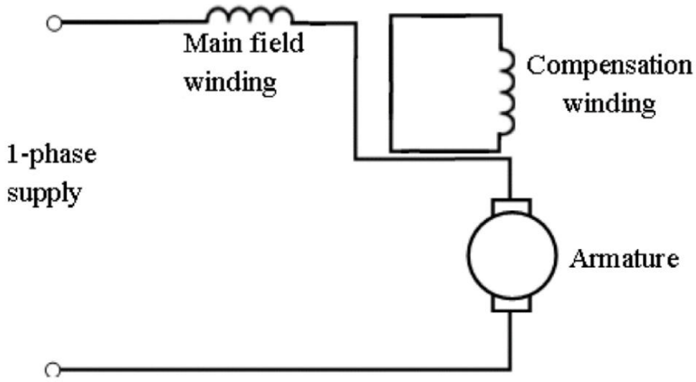


Fig: 4.17

The characteristics of single-phase series motor are very much similar to those of D.C. series motors, but the series motor develops less torque when operating from an a.c. supply than when working from an equivalent D.C. supply [Fig: 4.18]. The direction of rotation can be changed by interchanging connections to the field with respect to the armature as in D.C. series motor.

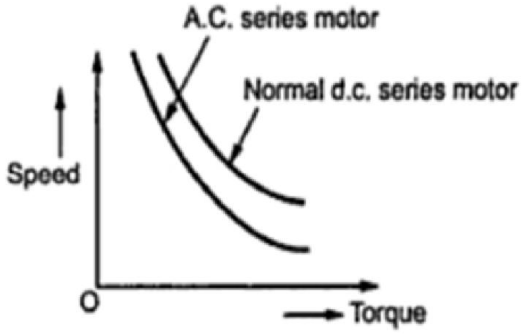


Fig: 4.18

Speed control of universal motors is best obtained by solid-state devices. Since the speed of these is not limited by the supply frequency and may be as high as 20,000 r.p.m. (greater than the maximum synchronous speed of 3000 r.p.m. at 50 Hz), they are most suitable for applications requiring high speeds.

4.4.2 Phasor Diagram of A.C Series Motor

The schematic diagram and phasor diagram for the conductively coupled single-phase ac series motor are shown in Fig: 4.19 and Fig: 4.20 respectively.

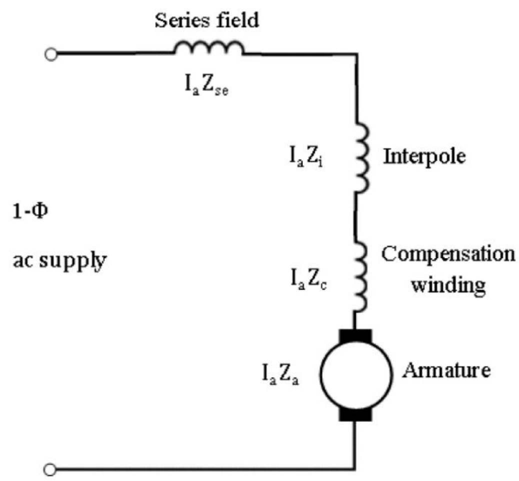


Fig: 4.19

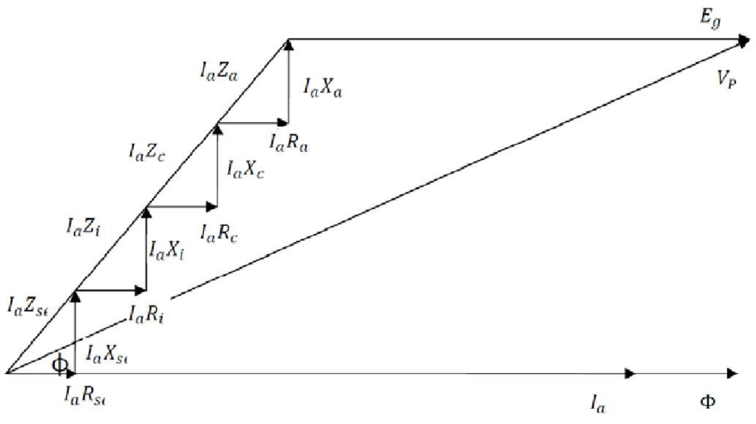


Fig: 4.20

The resistance I_aR_{se}, I_aR_i, I_aR_c and I_aR_a drops are due to resistances of series field, interpole winding, compensating winding and of armature respectively are in phase with armature current I_a. The reactance drops I_aX_{se}, I_aX_i, I_aX_c and I_aX_a are due to reactance of series field, interpole winding, compensating winding and of armature respectively lead current I_a by 90^0. The generated armature counter emf is E_g. The terminal phase voltage V_P is equal to the phasor sum of E_g and all the impedance drops in series.

$$V_p = E_g + I_aZ_{se} + I_aZ_i + I_aZ_c + I_aZ_a$$

The power factor angle between V_P and I_a is .

4.4.3 Applications

There are numerous applications where single-phase ac series motors are used, such as hair dryers, grinders, table-fans, blowers, polishers, kitchen appliances etc. They are also used for many other purposes where speed control and high values of speed are necessary.

4.5 Schrage Motor

Schrage motor is basically an inverted polyphase induction motor, with primary winding on the rotor and secondary winding on the stator. The primary winding on the rotor is fed through three slip rings and brushes at line frequency; secondary winding on the stator has slip frequency voltages induced in it.

The speed and power factor of slip ring induction motor can be controlled by injecting slip frequency voltage in the rotor circuit. If resultant rotor voltage increases, current increases, torque increases and speed increases. Depending on the phase angle of injected voltage, power factor can be improved. In 1911, K. H. Schrage of Sweden combined elegantly a SRIM (WRIM) and a frequency converter into a single unit.

4.5.1 Construction and Operation

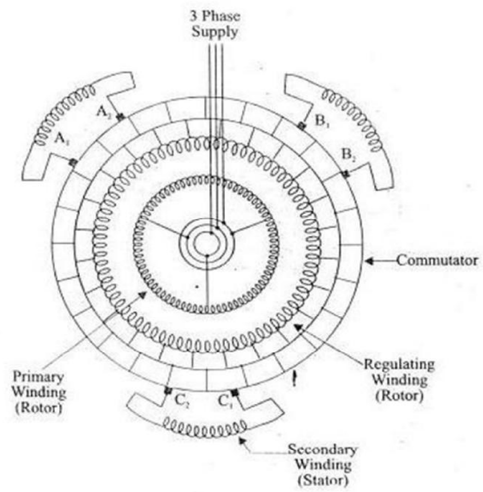


Fig: 4.21

Schrage motor has three windings- Two in Rotor and One in Stator.

Primary winding: Placed on the lower part of the slots of the Rotor. Three phase supply at line frequency is fed through slip rings and brushes which generates working flux in the machine.

Regulating winding: Placed on the upper part of the slots of the Rotor. These are connected to commutator segments in a manner similar to that of D.C. machine. Regulating windings are also known as *tertiary winding / auxiliary winding / commutator winding.*

Secondary winding: Same is phase wound & located on stator. Each winding is connected to a pair of brushes arranged on the commutator. Brushes are mounted on brush rockers. These are designed to move in opposite directions, relative to the centre line of its stator phase.

Brushes A_1, B_1 & C_1 move together and are 120^0 apart.

Brushes A_2, B_2 & C_2 also move together and are 120^0 apart.

Now the primary energized with line frequency voltage. Transformer action occurs between primary and regulating winding. Induction motor action occurs between primary and secondary windings. Commutator acting as a frequency converter converts line frequency voltage of regulating winding to slip frequency voltage and feeds the same to secondary winding on the stator.

Voltage across the brush pairs A_1 - A_2, B_1 - B_2 & C_1 - C_2 increases as brushes are separated.

Magnitude of voltage injected into the secondary winding depends on the angle of separation 'θ' of the brushes A_1 & A_2, B_1 & B_2, C_1 & C_2. ('θ' – Brush separation angle).

When primary is energized synchronously rotating field in clockwise direction is set up in the rotor core. Assume that the brushes are short circuited through commutator segment i.e. the secondary is short circuited. Rotor still at rest, the rotating field cuts the stationary secondary winding, induces an e.m.f. The stator current produce its own field. This stator field reacts with the rotor field thus a clockwise torque produced in the stator. Since the stator cannot rotate, as a reaction, it makes the rotor rotate in the counter clockwise direction.

Suppose that the rotor speed is N_r rpm. Rotor flux is rotating with N_S relative to primary & regulating winding. Thus the rotor flux will rotate at slip speed (N_S - N_r) relative to secondary winding in stator with reference to space.

4.5.2 Speed Control

Speed of Schrage Motor can be obtained above and below Synchronous speed by changing the Brush position i.e. changing "θ" ('θ' – Brush separation angle).

In Fig: 4.22 (a) Brush pair on the same commutator segment.i.e. the secondary winding short circuited. Thus the Injected voltage Ej = 0 and the machine operates as an Inverted Induction Motor so here $N_r < N_S$.

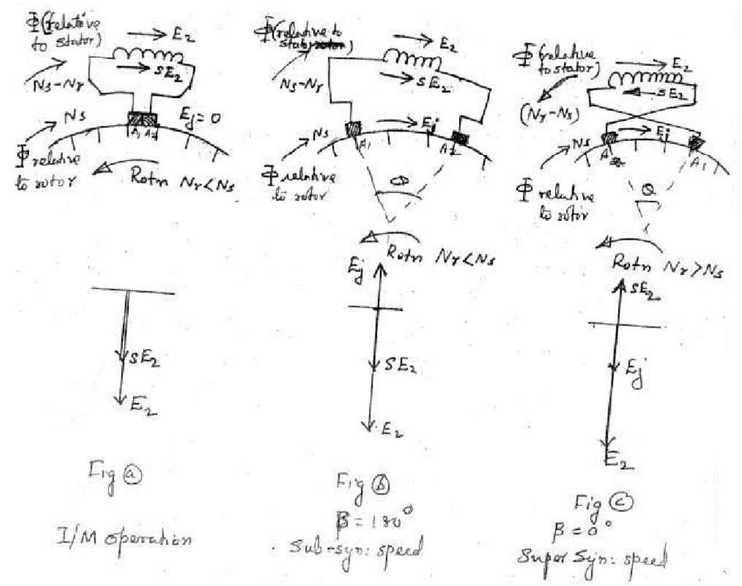


Fig: 4.22 (a) ,(b) & (c)

In Fig: 4.22 (b) Brushes parted in one direction which produces sub-synchronous speed. Injected voltage Ej, is obtained from the section of the regulating winding between them. If the centre line of this group of conductors is coincident with the centre line of the corresponding secondary phase, then E_2 and Ej are in phase opposition.

Neglecting impedance drop, sE_2 must be equal and opposite of Ej.

"β" is the angle between E_2 and Ej. $\beta=180^0$ and so here also $N_r < N_S$.

In Fig: 4.22 (c) Brushes parted in opposite direction which produces super-synchronous speed. Here Ej is reversed relative to E_2 i.e. $\beta=0^0$ & sE_2 must also be reversed.

This is occurring only because 's' becoming negative i.e. The speed is thus above synchronous speed so $N_r > N_S$.

The commutator provides maximum voltage when the brushes are separated by one pole pitch. i.e. 'θ' = 180^0.

4.5.3 Power Factor Improvement

This can be obtained by changing the phase angle of the injected voltage into the secondary winding. In this case one set of brushes is advanced more rapidly than the other set. Now the two centre lines do not coincide, have an angle 'ρ' between them. ("ρ" – Brush shift angle).

In Fig: 4.22 (d) Brush set is moved against the direction of rotation of rotor. In this case Speed decreases and the p.f. is improved.

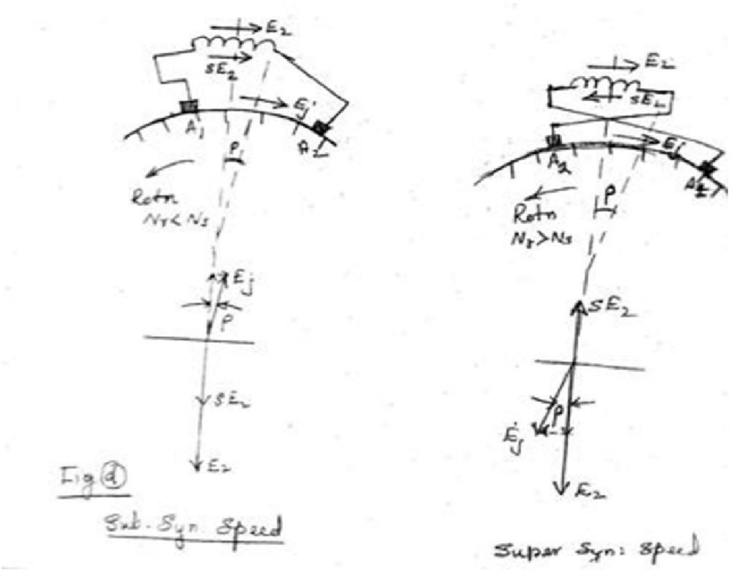


Fig: 4.22 (d) & (e)

In Fig: 4.22 (e) Brush set is moved in the same direction of rotation of rotor. In this case Speed increases, the p.f. is also improved.

Both p.f. and speed can be controlled by varying 'θ' & 'ρ'.

Thus 'Ej Cos ρ' and 'Ej Sin ρ' effect the speed and p.f. respectively. Fig: 4.23 show Variation of no load speed with Brush Separation.

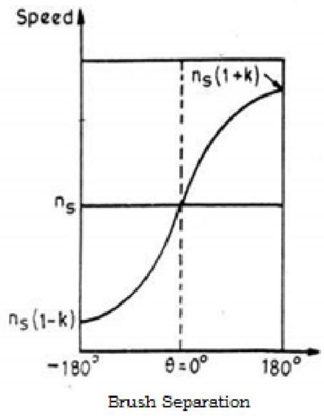


Fig: 4.23

4.5.4 Speed Torque Characteristics

Above discussion reveals that the Schrage Motor is almost a constant speed motor i.e. it has D.C Shunt motor characteristics. Figure 4.23 shows the typical speed-torque characteristics of Schrage motor.

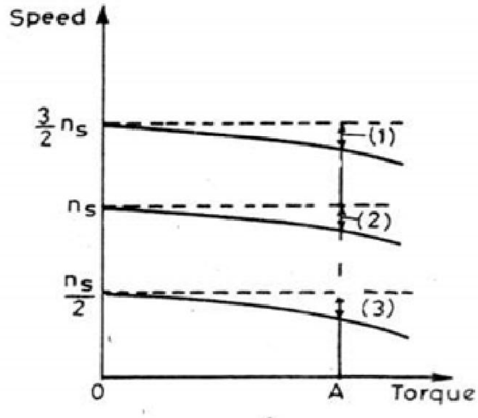


Fig: 4.23

4.5.5 Advantages & Shortcomings

Advantages:

(i) Good Speed Regulation.
(ii) High p.f. for high speed setting.

(iii) High efficiency at all speeds except N_S

Shortcomings:

(i) Operating voltage has to be limited to 700V because the power is to be supplied through slip rings.
(ii) Low p.f. at low speed settings.
(iii) Poor commutation.
(iv) High Cost.

4.5.6 Applications

Can be applied to any individual drive requiring variable speed, especially in knitting & Ring spinning applications, Cranes & Hoists Fans & Centrifugal Pumps, printing Machinery Conveyors, Packing machinery & Paper Mills etc.

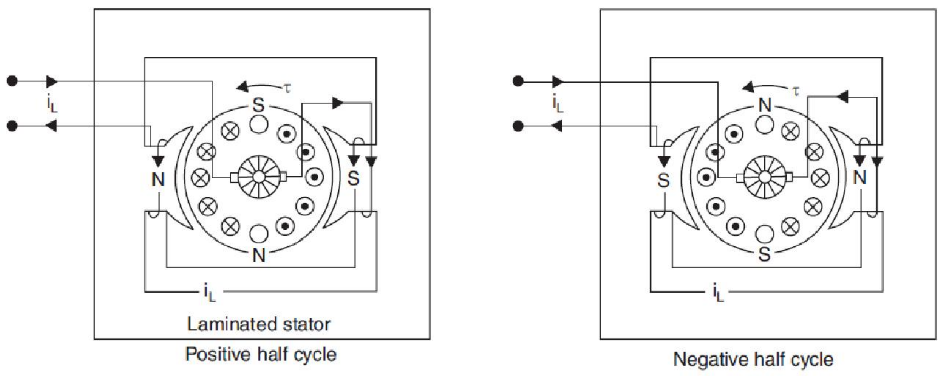
4.6 Universal Motors

It is also commutator type motor. A universal motor is one which operates both on AC and DC supplies. It develops more horsepower per Kg. weight than any other AC motor mainly due to its high speed.

The principle of operation is the same as that of a DC motor. Though a universal motor resembles a DC series motor, it required suitable modification in the construction, winding and brush grade to achieve sparkles commutation and reduced heating when operated on AC supply, due to increased inductance and armature reaction.

A universal motor could therefore be defined as a series or a compensated series motor [Fig: 4.24 & Fig: 4.25 (a), (b)]designed to operate at approximately the same speed and output at either direct current or single phase alternating current of a frequency not greater than 50Hz, and of approximately the same RMS voltage. Universal motor is also named as AC single phase series motor.

Fig: 4.24



(a) (b)

Fig: 4.25

The main parts of a universal motor are an armature, field winding, stator stampings, frame and plates and brushed. The increased sparking at the brush position in AC operation is reduced by the following means:

Providing commutating inter poles in the stator and connecting the interpole winding in series with the armature winding. Providing high contact resistance brushed to reduce sparking at brush positions.

4.6.1 Operation

A universal motor works on the same principles as a DC motor i.e. force is created on the armature conductors due to the interaction between the main field flux and the flux created by the current carrying armature conductors. A universal motor develops unidirectional torque regardless of whether it operated on AC or DC supply.

Fig: 4.25 (a),(b) & Fig: 4.26 shows the operation of a universal motor on AC supply. In AC operation, both field and armature currents change their polarities, at the same time resulting in unidirectional torque.

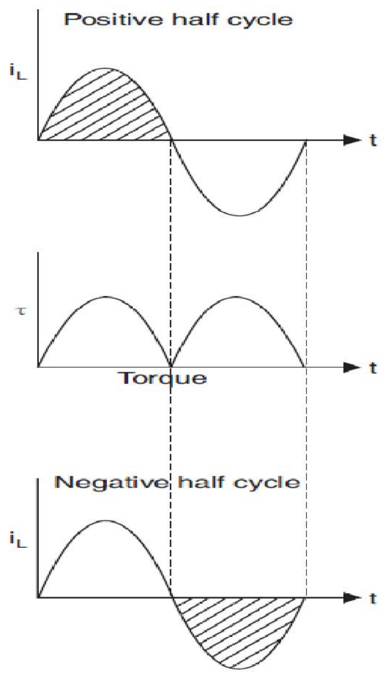


Fig: 4.26

4.6.2 Characteristic

The speed of a universal motor inversely proportional to the load i.e. speed is low at full load and high, on no load.

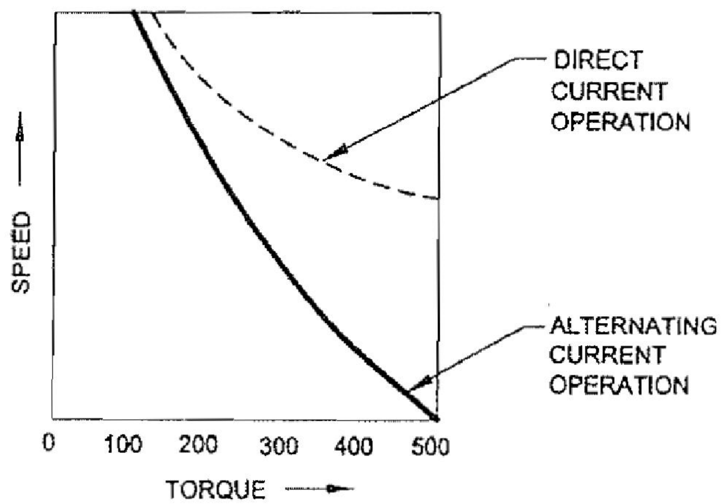


Fig: 4.27

The speed reaches a dangerously high value due to low field flux at no loads in fact the no load speed is limited only by its own friction and windage losses. As such these motors are connected with permanent loads or gear trains to avoid running at no load thereby avoiding high speeds.

Fig: 4.27 shows the typical torque-speed relation of a universal motor, both for AC and DC operations. This motor develops about 450 % of full load torque at starting, as such higher than any other type of single phase motor.

4.6.3 Applications

There are numerous applications where universal motors are used, such as hand drills, hair dryers, grinders, blowers, polishers, and kitchen appliances etc. They are also used for many other purposes where speed control and high values of speed are necessary like in vaccum cleaners, food mixers, portable drills and domestic sewage machines. Universal motors of a given horse power rating are significantly smaller than other kinds of a.c. motors operating at the same frequency.