

# Single Phase Induction Motors

## 9.1 INTRODUCTION

The characteristics of single phase induction motors are identical to 3-phase induction motors except that single phase induction motor has no inherent starting torque and some special arrangements have to be made for making it self starting. It follows that during starting period the single phase induction motor must be converted to a type which is not a single phase induction motor in the sense in which the term is ordinarily used and it becomes a true single phase induction motor when it is running and after the speed and torque have been raised to a point beyond which the additional device may be dispensed with. For these reasons, it is necessary to distinguish clearly between the starting period when the motor is not a single phase induction motor and the normal running condition when it is a single phase induction motor. The starting device adds to the cost of the motor and also requires more space. For the same output a 1-phase motor is about 30% larger than a corresponding 3-phase motor.

The single phase induction motor in its simplest form is structurally the same as a poly-phase induction motor having a squirrel cage rotor, the only difference is that the single phase induction motor has single winding on the stator which produces mmf stationary in space but alternating in time, a polyphase stator winding carrying balanced currents produces mmf rotating in space around the air gap and constant in time with respect to an observer moving with the mmf. The stator winding of the single phase motor is disposed in slots around the inner periphery of a laminated ring similar to the 3-phase motor.

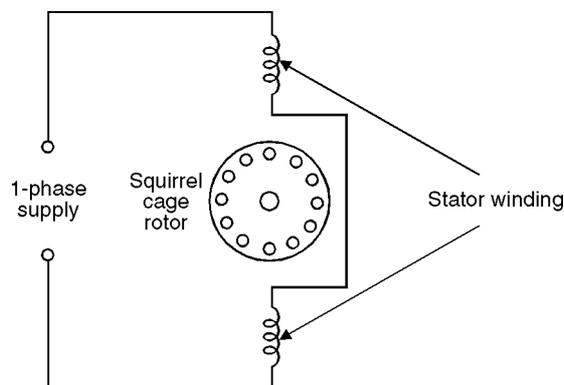


Fig. 9.1. Elementary single phase induction motor.

An induction motor with a cage rotor and single phase stator winding is shown schematically in Fig. 9.1. The actual stator winding as mentioned earlier is distributed in slots so as to produce an approximately sinusoidal space distribution of mmf.

## 9.2 PRINCIPLE OF OPERATION

Suppose the rotor is at rest and 1-phase supply is given to stator winding. The current flowing in the stator winding gives rise to an mmf whose axis is along the winding and it is a pulsating mmf, stationary in space and varying in magnitude, as a function of time, varying from positive maximum to zero to negative maximum and this pulsating mmf induces currents in the short-circuited rotor of the motor which gives rise to an mmf. The currents in the rotor are induced due to transformer action and the direction of the currents is such that the mmf so developed opposes the stator mmf. The axis of the rotor mmf is same as that of the stator mmf. Since the torque developed is proportional to sine of the angle between the two mmf and since the angle is zero, the net torque acting on the rotor is zero and hence the rotor remains stationary.

For analytical purposes a pulsating field can be resolved into two revolving fields of constant magnitude and rotating in opposite directions as shown in Fig. 9.2 and each field has a magnitude equal to half the maximum length of the original pulsating phasor.

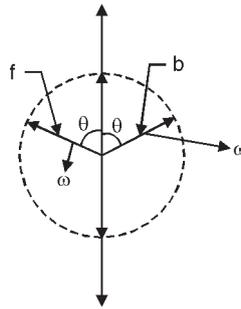
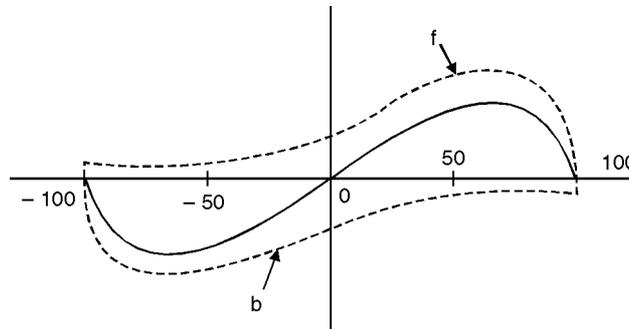


Fig. 9.2. Representation of the pulsating field by space phasors.

These component waves rotate in opposite direction at synchronous speed. The forward (anticlockwise) and backward-rotating (clockwise) mmf waves  $f$  and  $b$  are shown in Fig. 9.2. In case of 3-phase induction motor there is only one forward rotating magnetic field and hence torque is developed and the motor is self-starting. However, in single phase induction motor each of these component mmf waves produces induction motor action but the corresponding torques are in opposite direction. With the rotor at rest the forward and backward field produce equal torques but opposite in direction and hence no net torque is developed on the motor and the motor remains stationary. If the forward and backward air gap fields remained equal when the rotor is revolving, each of the component fields would produce a torque-speed characteristic similar to that of a polyphase induction motor with negligible leakage impedance as shown by the dashed curves  $f$  and  $b$  in Fig. 9.3.

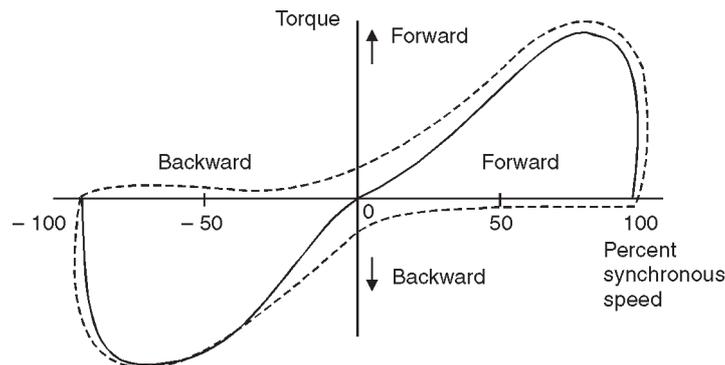
The resultant torque-speed characteristic which is the algebraic sum of the two component curves shows that if the motor were started by auxiliary means it would produce torque in whatever direction it was started.



**Fig. 9.3.** Torque-speed characteristic of a 1-phase induction motor based on constant forward and backward flux waves.

In reality the two fields, forward and backward do not remain constant in the air gap and also the effect of stator leakage impedance can't be ignored. In the above qualitative analysis the effects of induced rotor currents have not been properly accounted for.

When single phase supply is connected to the stator and the rotor is given a push along the forward rotating field, the relative speed between the rotor and the forward rotating magnetic field goes on decreasing and hence the magnitude of induced currents also decreases and hence the mmf due to the induced current in the rotor decreases and its opposing effect to the forward rotating field decreases which means the forward rotating field becomes stronger as the rotor speeds up. However for the backward rotating field the relative speed between the rotor and the backward field increases as the rotor rotates and hence the rotor emf increases and hence the mmf due to this component of current increases and its opposing effect to the backward rotating field increases and the net backward rotating field weakens as the rotor rotates along the forward rotating field. However, the sum of the two fields remains constant since it must induce the stator counter emf which is approximately constant if the stator leakage impedance drop is negligible. Hence, with the rotor in motion the torque of the forward field is greater and that of the backward field is less than what is shown in Fig. 9.3. The true situation being as is shown in Fig. 9.4.



**Fig. 9.4.** Torque-speed characteristic of a 1-phase induction motor taking into account changes in the flux waves.

In the normal running region at a few per cent slip the forward field is several times stronger than the backward field and the flux wave does not differ materially from the constant

amplitude revolving field in the air gap of a balanced polyphase motor. Therefore, in the normal running range of the motor, the torque-speed characteristic of a single phase motor is not very much different from that of a polyphase motor having the same rotor and operating with the same maximum air gap flux density.

In addition to the torque shown in Fig. 9.4, double-stator frequency torque pulsation are produced by the interaction of the oppositely rotating flux and mmf waves which move past each other at twice synchronous speed. These double frequency torques produce no average torque as these pulsations are sinusoidal and over the complete cycle the average torque is zero. However, sometimes these are additive to the main torque and for another half a cycle these are subtractive and therefore a variable torque acts on the shaft of the motor which makes the motor noisier as compared to a polyphase induction motor where the total torque is constant. Such torque pulsations are unavoidable in single phase circuits. Mathematically

$$T \propto I^2 \quad \dots(9.1)$$

Let

$$I = I_m \sin \omega t$$

$$T = K I_m^2 \sin^2 \omega t$$

$$= KI_m^2 \frac{(1 - \cos \omega t)}{2} \quad \dots(9.2)$$

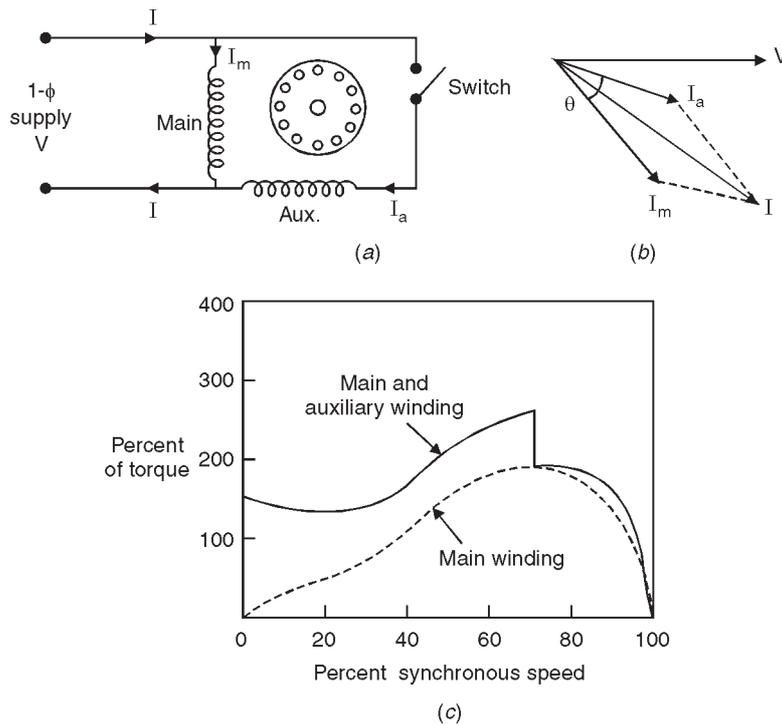
So the expression for torque contains a constant term superimposed over by a pulsating torque with pulsation frequency twice the supply frequency.

### 9.3 STARTING OF SINGLE PHASE INDUCTION MOTORS

The single phase induction motors are classified based on the method of starting method and in fact are known by the same name descriptive of the method. Appropriate selection of these motors depends upon the starting and running torque requirements of the load, the duty cycle and limitations on starting and running current drawn from the supply by these motors. The cost of single phase induction motor increases with the size of the motor and with the performance such as starting torque to current ratio (higher ratio is desirable), hence, the user will like to go in for a smaller size (hp) motor with minimum cost, of course, meeting all the operational requirements. However, if a very large no. of fractional horsepower motors are required, a specific design can always be worked out which might give minimum cost for a given performance requirements. Following are the starting methods.

(a) **Split-phase induction motor.** The stator of a split phase induction motor has two windings, the main winding and the auxiliary winding. These windings are displaced in space by 90 electrical degrees as shown in Fig. 9.5 (a). The auxiliary winding is made of thin wire (super enamel copper wire) so that it has a high  $R/X$  ratio as compared to the main winding which has thick super enamel copper wire. Since the two windings are connected across the supply the current  $I_m$  and  $I_a$  in the main winding and auxiliary winding lag behind the supply voltage  $V$ ,  $I_a$  leading the current  $I_m$  Fig. 9.5(b). This means the current through auxiliary winding reaches maximum value first and the mmf or flux due to  $I_a$  lies along the axis of the auxiliary winding and after some time ( $t = \theta/\omega$ ) the current  $I_m$  reaches maximum value and the mmf or flux due to  $I_m$  lies along the main winding axis. Thus the motor becomes a 2-phase unbalanced motor. It is unbalanced since the two currents are not exactly 90 degrees apart. Because of these two fields a starting

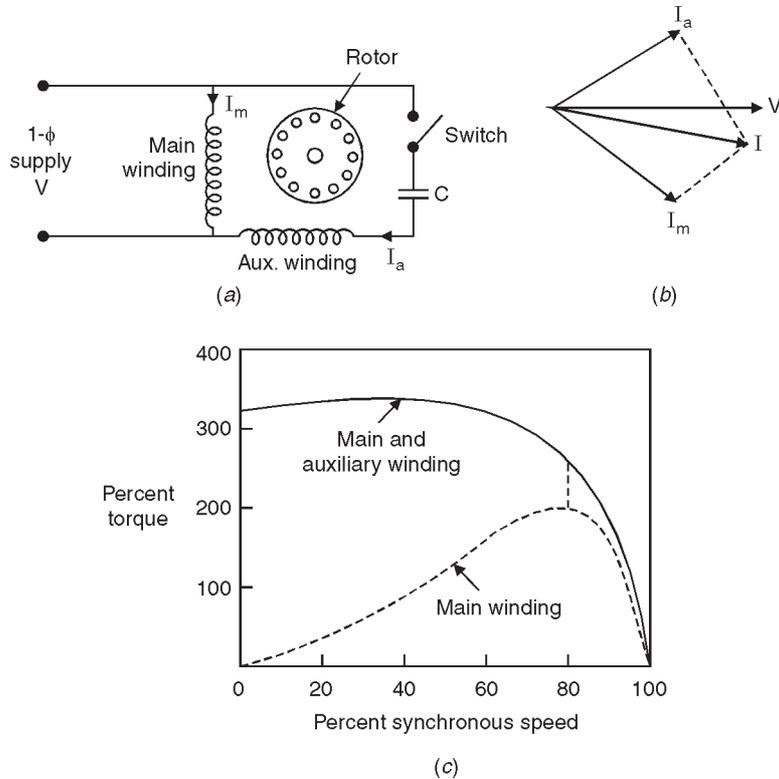
torque is developed and the motor becomes a self-starting motor. After the motor starts, the auxiliary winding is disconnected usually by means of centrifugal switch that operates at about 75 per cent of synchronous speed. Finally the motor runs because of the main winding. Since this being single phase some level of humming noise is always associated with the motor during running. A typical torque speed characteristic is shown in Fig. 9.5 (c). It is to be noted that the direction of rotation of the motor can be reversed by reversing the connection to either the main winding or the auxiliary windings.



**Fig. 9.5.** Split phase induction motor (a) Connection (b) Phasor diagram at starting (c) Typical torque-speed characteristic.

(b) **Capacitor start induction motor.** Capacitors are used to improve the starting and running performance of the single phase inductions motors.

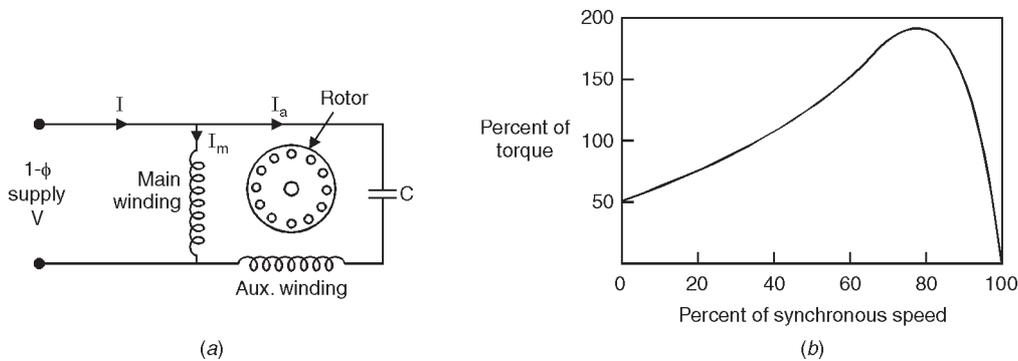
The capacitor start induction motor is also a split phase motor. The capacitor of suitable value is connected in series with the auxiliary coil through a switch such that  $I_a$  the current in the auxiliary coil leads the current  $I_m$  in the main coil by 90 electrical degrees in time phase so that the starting torque is maximum for certain values of  $I_a$  and  $I_m$ . This becomes a balanced 2-phase motor if the magnitude of  $I_a$  and  $I_m$  are equal and are displaced in time phase by 90° electrical degrees. Since the two windings are displaced in space by 90 electrical degrees as shown in Fig. 9.6 maximum torque is developed at start. However, the auxiliary winding and capacitor are disconnected after the motor has picked up 75 per cent of the synchronous speed. The motor will start without any humming noise. However, after the auxiliary winding is disconnected, there will be some humming noise.



**Fig. 9.6.** Capacitor start motor (a) Connection (b) Phasor diagram at start (c) Speed torque curve.

Since the auxiliary winding and capacitor are to be used intermittently, these can be designed for minimum cost. However, it is found that the best compromise among the factors of starting torque, starting current and costs results with a phase angle somewhat less than  $90^\circ$  between  $I_m$  and  $I_a$ . A typical torque-speed characteristic is shown in Fig. 9.6 (c) high starting torque being an outstanding feature.

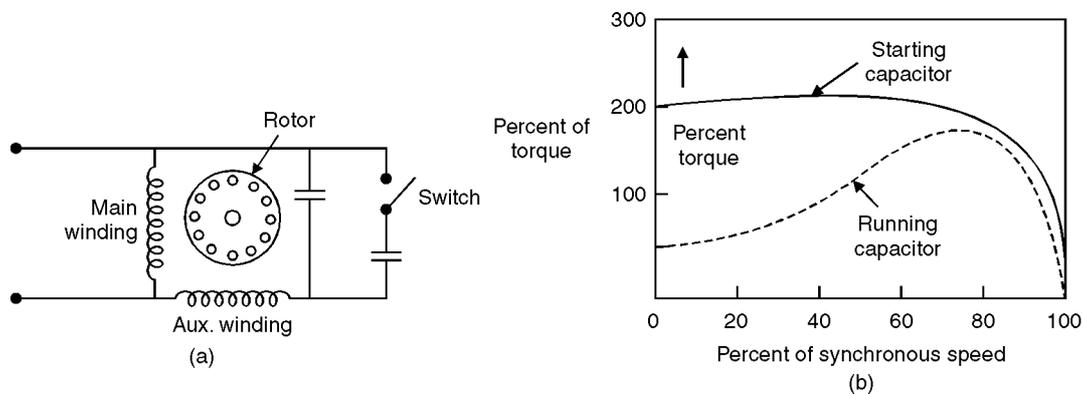
(c) **Permanent-split capacitor motor.** In this motor the auxiliary winding and capacitor are not disconnected from the motor after starting, thus the construction is simplified by the omission of the switch as shown in Fig. 9.7 (a).



**Fig. 9.7.** Permanent split capacitor motor (a) Connection (b) Torque-speed characteristic.

Here the auxiliary winding and capacitor could be so designed that the motor works as a perfect 2-phase motor at anyone desired load. With this the backward rotating magnetic field would be completely eliminated. The double stator frequency torque pulsations would also be eliminated, thereby the motor starts and runs as a noise free motor. With this there is improvement in p.f. and efficiency of the motor. However, the starting torque must be sacrificed as the capacitance is necessarily a compromise between the best starting and running characteristics. The torque-speed characteristic of the motor is shown in Fig. 9.7 (b).

(d) **Capacitor start capacitor run motor.** If two capacitors are used with the auxiliary winding as shown in Fig. 9.8 (a), one for starting and other during the start and run, theoretically optimum starting and running performance can both be achieved.



**Fig. 9.8.** (a) Capacitor start capacitor run motor (b) Torque-speed characteristic.

The small value capacitor required for optimum running conditions is permanently connected in series with the auxiliary winding and the much larger value required for starting is obtained by a capacitor connected in parallel with the running capacitor. The starting capacitor is disconnected after the motor starts.

The value of the capacitor for a capacitor start motor is about  $300 \mu\text{F}$  for  $\frac{1}{2}$  hp motor. Since this capacitor must carry current for a short starting period, the capacitor is a special compact ac electrolytic type made for motor starting duty. However, the capacitor permanently connected has a typical rating of  $40 \mu\text{F}$ ; since it is connected permanently, the capacitor is an ac paper, foil and oil type. The cost of the motor is related to the performance; the permanent capacitor motor is the lowest cost, the capacitor start motor next and the capacitor start capacitor run has the highest cost.

(e) **Shaded pole induction motor.** Fig. 9.9 (a) shows schematic diagram of shaded pole induction motor. The stator has salient poles with one portion of each pole surrounded by a short-circuited turn of copper called a shading coil. Induced currents in the shading coil (acts as an inductor) cause the flux in the shaded portion of the pole to lag the flux in the other portion. Hence the flux under the unshaded pole leads the flux under the shaded pole which results in a rotating field moving in the direction from unshaded to the shaded portion of the pole and a low starting torque is produced which rotates the rotor in the direction from unshaded to the shaded pole. A typical torque speed characteristic is shown in Fig. 9.9 (b). The efficiency is low. These motors are

the least expensive type of fractional horse power motor and are built upto about  $\frac{1}{20}$  hp. Since the rotation of the motor is in the direction from unshaded towards the shaded part of the pole, a shaded pole motor can be reversed only by providing two sets of shading coils which may be opened and closed or it may be reversed permanently by inverting the core.

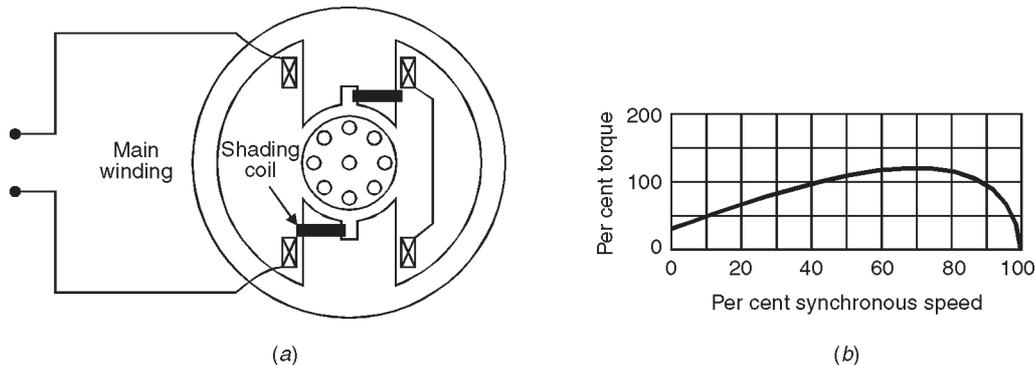


Fig. 9.9. Shaded-pole motor and typical torque-speed characteristic.

## 9.4 APPLICATION

The split phase induction motors are used for fans, blowers, centrifugal pumps and office equipments. Typical ratings are  $\frac{1}{20}$  to  $\frac{1}{2}$  hp; in this range they are the lowest cost motors available. The capacitor start motors are used for compressors, pumps, refrigeration and air-conditioning equipments and other hard to start-loads.

The capacitor start capacitor run motors are manufactured in a number of sizes from  $\frac{1}{8}$  to  $\frac{3}{4}$  hp and are used in compressors, conveyors, pumps and other high torque loads. The permanent split capacitor motors are manufactured in the range of  $\frac{1}{20}$  hp to  $\frac{3}{4}$  hp and are used for direct connected fans, blowers, centrifugal pumps and loads requiring low starting torque.

The shaded pole motors are used in toys, hair driers, deskfans etc.

## 9.5 UNIVERSAL MOTOR

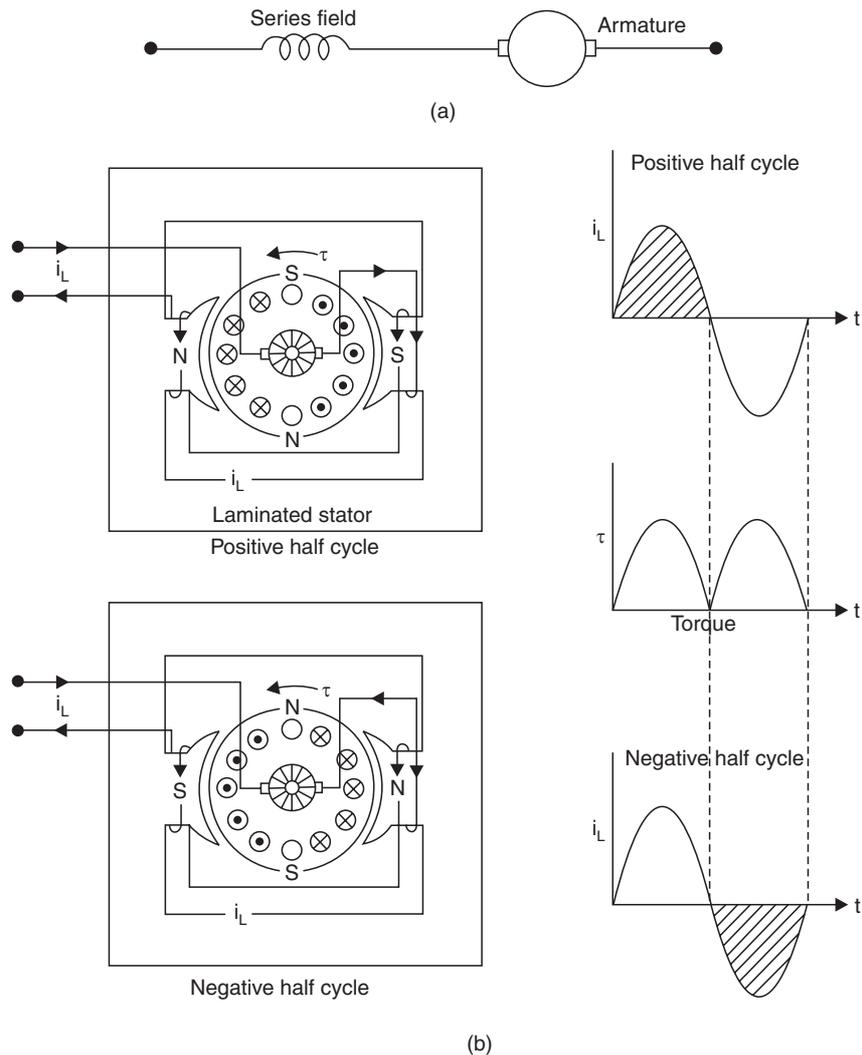
We know that single phase motors are not self starting. We have to provide additional features to make it self starting.

The other solution to the single phase problem is to design a d.c. motor so that it will run on a.c. as well. The direction of rotation of a d.c. machine depends upon the polarities of the armature circuit and the field circuit. If a d.c. machine is designed so that (i) when line current reverses direction the field and armature currents reverse simultaneously and (ii) the core loss with alternating flux is relatively low, then a successful single phase machine results.

The first criterion is met by connecting armature and field windings in series. The second is achieved by using a laminated core. A d.c. shunt motor on the other hand can not be used on

a.c. because of high inductance of the field winding as compared to armature winding which causes the field pole reversals to be out of phase with the current reversals in the armature and the result is that the torque is backward during part of each half cycle lowering average torque and reducing the efficiency.

A d.c. series motor designed to operate also on a.c. is called a universal motor as it will run efficiently on any frequency from d.c. upto its design frequency. Fig. 9.10 shows the principle of operation of the motor.



**Fig. 9.10** The universal motor. (a) Circuit diagram. (b) Principle of operation.

Universal motors are designed for voltages ranging from 32 to 250 volts, frequencies zero to 60Hz and ratings upto 3/4 hp. The average speed is high in the range of 7000 rpm at normal load. The torque/speed characteristic of the motor is shown in Fig. 9.11 No load speed is quite high often in the range of 20,000 rpm. It is limited by windage and friction. Having high speed capability, universal motor of a given horse power rating is significantly smaller than other

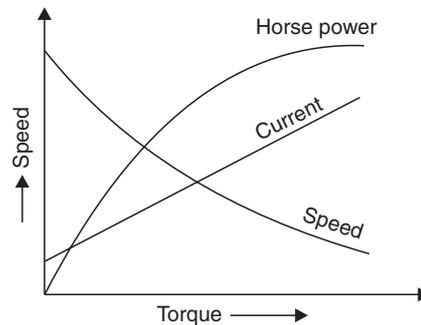


Fig. 9.11 Characteristics of universal motors.

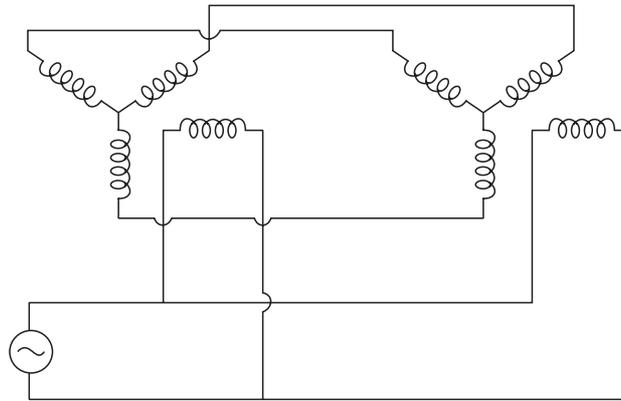
kinds of a.c. motors operating at the same frequency. Their starting torque is relatively high. These characteristics make universal motors ideal for devices such as hand drills, hand grinders, food mixers, vacuum cleaners and the like which require compact motors operating at speeds greater than 3000/3600 rpm. Universal motors must be designed with weak magnetic fields to minimise commutation difficulties. High resistance carbon brushes are used to limit the circulating current due to the transformer voltage in the short circuited coils.

## 9.6 SYNCHROS

The terms synchros and Selsyn (abbreviation of self synchronisation) are both used to refer to a special wound rotor induction motors which are used in pairs to provide shaft position control and/or synchronism of two remote machines. Applications vary from controlling valves to indicating the position of some remote devices. Usually the primary winding is a single phase winding located on the rotor whereas the stator has a three phase winding which acts as the secondary whereas usual standard wound rotor induction motors could be used for the purpose, synchros usually have low inertia and low friction bearings to reduce error and mechanical dampers to improve dynamic performance. Fig. 9.12 shows application of synchros for low torque requirements. Here both the rotors are supplied from the same a.c. source. An unbalanced set of three single phase voltage (in time with the single phase rotor voltage) will be induced in the stator phase windings of both the machines. These voltages will be equal if and only if the two rotors are exactly in the same position. Assuming one machine is the transmitter, its rotor position will be fixed by the controlling mechanical input. If the rotor of the other machine is considered as receiver and if it is not at the same position, unequal phase voltages will exist. This will result in stator current, thus mmf and the torque seeking to align the receiver's rotor position with that of the transmitter.

Equilibrium is reached when the output torque decreases to equal the torque required by the transmitter's load. Therefore, it is necessary that the load torque be small and that friction be minimised in the synchros.

Synchros are also constructed with three phase rotor windings. For low torque applications, it is common to supply both transmitter and receiver stator windings from the same three



**Fig. 9.12.** Low-torque synchros system.

phase source. The rotor windings are then connected in parallel. Again by Faraday's law, flux distribution must be the same in both the machines. Equilibrium will exist in the rotor circuit only when the rotors are synchronised at the same relative positions. Otherwise, a torque will be produced which tends to align the two rotors.

## 9.7 DC TACHOMETER

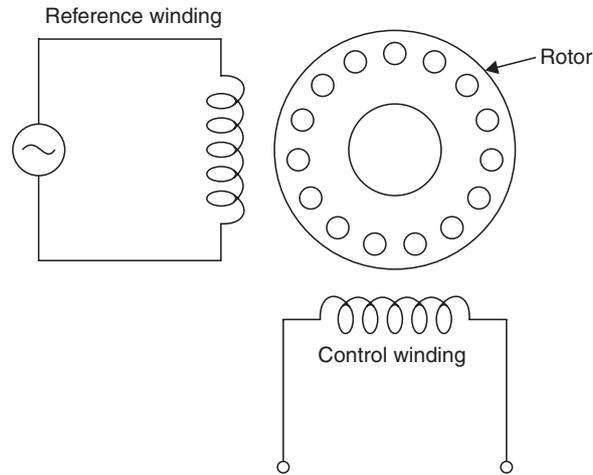
It is sometimes necessary in control systems to feed back a voltage proportional to the speed of the shaft. In a d.c. servomechanism this can be achieved by using a d.c. tachometer which is a permanent magnet d.c. generator. The field is due to permanent magnet which ensures that the voltage output will be directly proportional to the speed.

A d.c. tachometer can be used on a.c. servomechanism by converting the d.c. output voltage to an a.c. voltage by using an inverter circuit.

## 9.8 AC TACHOMETER

An a.c. tachometer is used in feedback control system to feedback an a.c. voltage proportional to the speed of the shaft. This is basically a two-phase induction motor as shown in Fig. 9.13. One of the stator windings is used as the reference winding and the other the control winding. The reference winding is fed a suitable a.c. voltage of constant frequency and magnitude. Therefore, a voltage of the same frequency is induced in the control winding. This output voltage is fed to the high input impedance circuit of an amplifier so that the control winding can be considered as open circuited. It is essential that the voltage induced in the control winding is directly proportional to the shaft speed and phase of this voltage be fixed with respect to voltage supplied to the reference winding.

The principle of operation of an a.c. tachometer can be explained using double revolving field theory. With reference to reference winding the tachometer can be considered equivalent to a single phase induction motor. At standstill, the forward and backward fields are equal and hence voltage induced in the control winding is zero.



**Fig. 9.13.** AC tachometer.

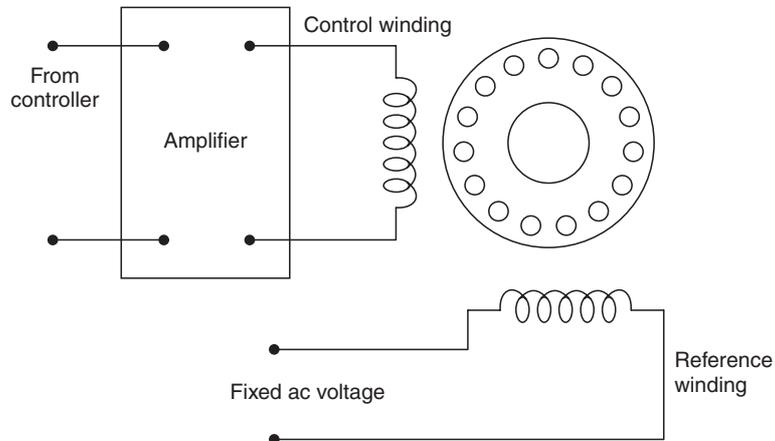
When the rotor is revolving, the rotor current due to forward rotating field decreases since its effective impedance increases whereas for the backward rotating field the impedance decreases, the difference between them being function of speed. Therefore, the voltage developed across control winding is a function of speed. Reversal of direction of rotation reverses the phase of output voltage.

For a constant phase angle of output voltage and linear relationship between output voltage and speed, a suitable value of ratio of rotor reactance to rotor resistance should be chosen. If it is low, the sensitivity *i.e.* volts per revolution per minute is sacrificed but linear speed range is wide. However, if it is high the speed range is limited to a fairly small fraction of synchronous speed to meet the condition of linearity of voltage and consistency of phase angle. An a.c. tachometer should have low inertia when rapid speed variations are encountered as in automatic control system.

## 9.9 TWO PHASE SERVOMOTOR

A two-phase servomotor is commonly used in feed back control system to drive the loads and as sensors to measure speed and position of the controlled element. It is basically a two-phase induction motor with squirrel cage rotor. The rotor has high resistance so that a negative slope (increase in torque results decrease in speed and vice versa) for the torque speed characteristics over the entire operating range is obtained. The negative slope characteristic provides stable operation and positive damping. The ratio of rotor diameter to its length is small so that its moment of inertia is small and hence it gives good acceleration characteristic. The motor is quite rugged and reliable and is used in different range from a fraction of a watt to about hundred watts.

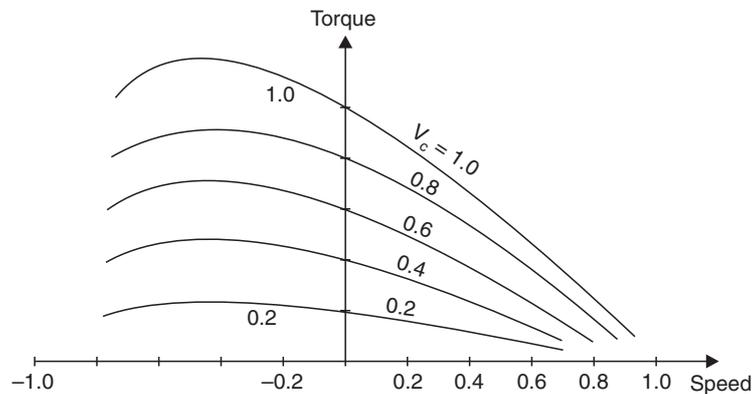
Fig 9.14 shows schematic diagram of a 2-phase servomotor. One of the stator windings is known as a reference winding and is excited by a fixed a.c. voltage  $V_r$ , whereas the second winding known as control winding is excited by the control voltage  $V_c$ . For production of torque it is necessary that the two voltages should be in synchronism. Hence the two voltages must be derived from the same source. The control voltage is fed to the motor through an amplifier. Also the two voltages must have a phase difference of  $90^\circ$  (balance 2-phase operation where the torque is maximum).



**Fig 9.14** Two-phase servomotor.

This phase shift can be obtained either by using a phase shifting network in the amplifier or by adding a capacitor in series with the reference winding. When the control voltage leads the reference voltage, rotation in one direction is obtained and when control voltage lags the reference voltage, rotation in the opposite direction is obtained. Since for constant phase angle say  $90^\circ$  between  $V_c$  and  $V_r$ , the torque is a function of  $V_c$  and  $V_r$ , changing the magnitude of  $V_c$ , the torque developed changes.

Fig. 9.15 shows the torque-speed characteristics of a two-phase servo motor for different values of control voltages and unity reference voltage. The slope of the characteristic is negative for stable operation. The torque is high at zero speed. The maximum torque is developed at a source speed of one-half the synchronous speed which means the rotor will run stably near its zero speed.



**Fig. 9.15.** Torque-speed curve of two-phase servomotor.

## PROBLEMS

- 9.1. Explain why 3-phase induction motor is self-starting and 1-phase is not.
- 9.2. Explain with the help of schematic diagram and phasor diagram the principle of operation of 1-phase split phase induction motor.

- 9.3. Describe how to reverse the following single phase induction motors (a) Resistance split phase (b) Capacitor start (c) Permanent slip capacitor (d) Two value capacitor (e) Shaded pole motor.
- 9.4. A single phase induction motor has poor performance as compared to a 3-phase induction motor. Discuss the reasons.
- 9.5. Discuss the differences between capacitor start, capacitor start capacitor run and permanent split capacitor motors.
- 9.6. What is a universal motor ? Explain with neat diagram construction, principle of operation and application of the motor.
- 9.7. What is a two-phase servomotor ? Give its application. Draw the connection diagram and its speed torque characteristic.
- 9.8. Explain what you mean by stable operation of a two-phase servomotor and how it is achieved.
- 9.9. What is a synchro ? Explain with neat diagram the working of a synchro transmitter system and give its application.
- 9.10. Discuss the function of an a.c. tacho-generator. Explain with neat diagram the construction and principle of operation.