ELECTRICAL MACHINES - II

UNIT I

ALTERNATOR

Basic Principle

A.C. generators or Alternators (as they are usually called) operate on the same fundamental principles of electro magnetic induction as D.C. generators. They also consist of an armature winding and a magnetic field. But there is one important difference between the two.

Whereas in D.C. generators, the *armature rotates* And the field system is *stationary*, the arrangement in

alternators is just the reverse of it. In their case, standard construction consists of armature winding mounted on a stationary element called *stator* and field windings on a rotating element called rotor. The details of construction had shown in fig. 1.1

1.1 CONSTRUCTIONAL DETAILS:



Fig. 1.1

The stator consists of a cast-iron frame, which supports the armature core, having slots on its inner periphery for housing the armature conductors. The rotor is like a flywheel having alternate N and S poles fixed to its outer rim. The magnetic poles are excited (or magnetized) from direct current supplied by a D.C. source at 125 to 600 volts.

In most cases, necessary exciting (or magnetizing) current is obtained from a small D.C. shunt generator which is belted or mounted on the shaft of the alternator itself.

Because the field magnets are rotating, this current is supplied through two slip rings. As the exciting voltage is relatively small, the slip-rings and brush gear are of light construction. Recently, brushless excitation systems have been developed in which a 3-phase A.C. exciter and a group of rectifiers supply D.C. to the alternator. Hence, brushes, slip-rings and commutator are eliminated.

When the rotor rotates, the stator conductors (being stationary) are cut by the magnetic flux, hence they have induced E.M.F. produced in them. Because the magnetic poles are alternately N and S, they induce an E.M.F. and hence current in armature conductors, which first flows in one direction and then in the other. Hence, an alternating E.M.F. is produced in the stator conductors (*i*) whose frequency depends



on the number of N and S poles moving past a conductor in one second and (*ii*) whose direction is given by Fleming's Right-hand rule.

1. Stator Frame

In D.C. machines, the outer frame (or yoke) serves to carry the magnetic flux but in alternators, it is not meant for that purpose. Here, it is used for holding the armature stampings and windings in position. Low speed large-diameter alternators have frames which because of ease of manufacture, are cast in sections. Ventilation is maintained with the help of holes cast in the frame itself.

The provision of radial ventilating Spaces in the stampings assists in cooling the machine. But, these days, instead of using castings, frames are generally fabricated from mild steel plates welded together in such a way as to form a frame having a box type section. In Fig. 1.2 is shown the section through the top of a typical stator.



Fig. 1.2

2. Stator Core

The armature core is supported by the stator frame and is built up of laminations of special magnetic iron or steel alloy. The core is laminated to minimize loss due to eddy current. The laminations are stamped out in complete rings (for smaller machine) or in segments (for larger machines). The laminations are insulated from each other and have spaces between them for allowing the cooling air to pass through. The slots for housing the armature conductors lie along the inner periphery of the core and are stamped out at the same time when laminations are formed. Different shapes of the armature slots are shown in Fig. 1.3.

The wide-open type slot (also used In D.C. machines) has the advantage of Permitting easy installation of form-wound Coils and their easy removal in case of repair But it has the disadvantage of distributing the air-gap flux into bunches or tufts, that Produce ripples in the wave of the generated E.M.F. The semi-closed type slots are better in this respect, but do not allow the use of Form-wound coils. The wholly-closed type Slots or tunnels do not disturb the air-gap flux



but (*i*) they tend to increase the inductance of the windings (*ii*) the armature conductors have to be threaded through, thereby increasing initial lab our and cost of winding and (*iii*) they present a complicated problem of end connections. Hence, they are rarely used.

1.2 <u>TYPES OF ROTORS:</u>

Two types of rotors are used in alternators *(i)* salient-pole type and

(*ii*) smooth-cylindrical type.

(*i*) Salient (or projecting) Pole Type

It is used in low-and medium-speed (engine driven) alternators. It has a large number of projecting (salient) poles, having their cores bolted or dovetailed onto a heavy magnetic wheel of cast -iron, or steel of good magnetic quality (Fig. 1.4). Such generators are characterized by their large diameters and short axial lengths. The poles and pole-shoes (which cover 2/3 of pole-pitch) are laminated to minimize heating due to eddy currents. In large machines, field windings consist of rectangular copper strip wound on edge. *(ii)* **Smooth Cylindrical Type**

It is used for steam turbine-driven alternators turbo alternators, which run at very high speeds. The rotor consists of a smooth solid forged steel cylinder , having a number of slots milled out at intervals along the outer periphery (and parallel to the shaft)





along the outer periphery (and parallel to the shaft)Fig. 1.4for accommodating field coils. Such rotors are designed mostly for 2-pole (or 4-pole)turbo-generators running at 3600 r.p.m. (or 1800 r.p.m.). Two (or four) regionscorresponding to the central polar areas are left unspotted, as shown in Fig. 1.5 (a)and(b).

The central polar areas are surrounded by the field windings placed in slots. The field coils are so arranged around these polar areas that flux density is maximum on the polar central line and gradually falls away on either side. It should be noted that in this case, poles are non-salient *i.e.* they do not project out from the surface of the rotor. To avoid excessive peripheral velocity, such rotors have very small diameters (about 1 metre or so). Hence, turbo-generators are characterised by small diameters and very long axial (or rotor) length. The cylindrical construction of the rotor gives better balance and quieter-operation and also less windage losses.



Fig. 1.5

1.2.1 SPEED AND FREQUENCY:

In an alternator, there exists a definite relationship between the rotational speed (N) of the rotor, the frequency (f) of the generated e.m.f. and the number of poles P.

Consider the armature conductor marked *X* in Fig. 1.6 situated at the centre of a *N*-pole rotating in clockwise direction. The conductor being situated at the place of maximum flux density will have maximum e.m.f. induced in it. The direction of the induced e.m.f. is given by Fleming's right hand rule. But while applying this rule, one should be careful to note that the thumb indicates the direction of the motion of the conductor relative to the field. To an observer stationed on the clockwise revolving poles, the conductor would seem to be rotating anti-clockwise. Hence, thumb



would seem to be rotating anti-clockwise. Hence, thumb should point to the left. The direction of the induced e.m.f. is downwards, in a direction at right angles to the plane of the paper.

When the conductor is in the interpolar gap, as at A in Fig. 1.6, it has minimum e.m.f. induced in it, because flux density is minimum there. Again, when it is at the centre of a S-pole, it has maximum e.m.f. induced in it, because flux density at B is maximum. But the direction of the e.m.f. when conductor is over a N-pole is opposite to that when it is over a S-pole. Obviously, one cycle of e.m.f. is induced in a conductor when one pair of poles passes over it. In other words, the e.m.f. in an armature conductor goes through one cycle in angular distance equal to twice the pole-pitch, as shown in Fig. 1.6.

Let

P = total number of magnetic poles

N = rotative speed of the rotor in r.p.m.

f = frequency of generated e.m.f. in Hz.

Since one cycle of e.m.f. is produced when a pair of poles passes past a conductor, the number of cycles of e.m.f. produced in one revolution of the rotor is equal to the number of pair of poles.

No. of cycles/revolution = P/2 and No. of revolutions/second = N/60

frequency
$$= \frac{P}{2} \times \frac{N}{60} = \frac{PN}{120}$$
 Hz
 $f = \frac{PN}{120}$ Hz

N is known as the synchronous speed, because it is the speed at which an alternator must run, in order to generate an e.m.f. of the required frequency. In fact, for a given frequency and given number of poles, the speed is fixed. For producing a frequency of 60 Hz, the alternator will have to run at the following speeds :

No. of poles	2	4	6	12	24	36
Speed (r.p.m.)	3600	1800	1200	600	300	200

1.3 **EMF EQUATION**:

Let

 $Z = N_0$. of conductors or coil sides in series/phase

 2T where T is the No. of coils or turns per phase (remember one turn or coil has two sides)

- P = No. of poles
- f' = frequency of induced e m.f. in Hz
- $\Phi =$ flux/pole in webers

$$k_d$$
 = distribution factor = $\frac{\sin m \beta/2}{m \sin \beta/2}$

$$k_c$$
 or $k_p = \text{pitch or coil span factor} = \cos \alpha/2$
 $k_f = \text{from factor} = 1.11$ —if e.m.f. is assumed sinuspidal
 $N = \text{rotor 1.p.m.}$

In one revolution of the rotor (*i.e.* in 60./N second) each stator conductor is cut by a flux of ΦP webers.

÷.,

$$d\Phi = \Phi P$$
 and $dt = 60/N$ second

:. Average e.m.f. induced per conductor $= \frac{d \Phi}{dt} = \frac{\Phi P}{60/N} = \frac{\Phi NP}{50}$ Now, we know that f = PN/120 or N = 120 f/P Substituting this value of Nabove, we get

Average e.m.f. per conductor $= \frac{\Phi P}{60} \times \frac{120 f}{P} = 2f \Phi$ volt

If there are Z conductors in series/phase, then Average c.m.f./phase = $2f \Phi Z \text{ volt} = 4f \Phi T \text{ volt}$

R.M.S. value of e m.f/phase = $1.11 \times 4f \Phi T = 4.44f \Phi T$ volt*.

This would have been the actual value of the induced voltage if all the coils in a phase were (*i*) full-pitched and (*ii*) concentrated or bunched in one slot (instead of being distributed in several slots underpoles). But this not being so, the actually available voltage is reduced in the ratio of these two factors.

:. Actually available voltage/phase = $4.44 k_c k_d f \Phi T = 4 k_c k_d f \Phi T$ volt.

If the alternator is star-connected (as is usually the case) then the line voltage is $\sqrt{3}$ times the phase voltage (as found from the above formula)

1.4 ARMATURE REACTION:

As in d.c. generators, armature reaction is the effect of armature flux on the main field flux. *In the case of alternators, the power factor of the load has a considerable effect on the armature reaction.*

We will consider three cases: (*i*) when load of p.f. is unity (*ii*) when p.f. is zero lagging and (*iii*) when p.f. is zero leading.

Before discussing this, it should be noted that in a 3-phase machine the combined ampere-turn wave (or m.m.f. wave) is sinusoidal which moves synchronously. This ampturn or m.m.f. wave is fixed relative to the poles, its amplitude is proportional to the load current, but its position depends on the p.f. of the load.

Consider a 3-phase, 2-pole alternator having a single-layer winding, as shown in Fig. 1.7 (*a*). For the sake of simplicity, assume that winding of each phase is concentrated (instead of being distributed) and that the number of turns per phase is N. Further suppose that the alternator is loaded with a resistive load of unity power factor, so that phase currents Ia, Ib and Ic are in phase with their respective phase voltages. Maximum current Ia will flow when the poles are in position shown in Fig. 1.7 (*a*) or at a time t1 in Fig. 1.7 (*c*). When Ia has a maximum value, Ib and Ic have one-half their maximum values (the arrows attached to Ia, Ib and Ic are only polarity marks and are not meant to give the instantaneous directions of these currents at time t1). The instantaneous directions of currents are shown in Fig. 1.7 (*a*), the m.m.f. (= NIm) produced by phase a-a' is horizontal, whereas that produced by other two phases is (Im/2) N each at 60° to the horizontal. The total armature m.m.f. is equal to the vector sum of these three m.m.fs.

:. Armature m.m.f. = $NI_m + 2.(1/2 NI_m) \cos 60^\circ = 1.5 NI_m$

As seen, at this instant t1, the m.m.f. of the main field is upwards and the armature m.m.f. is behind it by 90 electrical degrees.

Next, let us investigate the armature m.m.f. at instant t^2 . At this instant, the poles are in the horizontal position. Also Ia = 0, but Ib and Ic are each equal to 0.866 of their

maximum values. Since Ic has not changed in direction during the interval t1 to t2, the direction of its m.m.f. vector remains unchanged. But Ib has changed direction, hence, its m.m.f. vector will now be in the position shown in Fig. 1.7 (*d*). Total armature m.m.f. is again the vector sum of these two m.m.fs.

$$\therefore \text{ Armature m.m.f.} = 2 \times (0.866 \, NI_m) \times \cos 30^\circ = 1.5 \, NI_m.$$

If further investigations are made, it will be found that.

1. armature m.m.f. remains constant with time

2. it is 90 space degrees behind the main field m.m.f., so that it is only distortional in nature.

3. it rotates synchronously round the armature *i.e.* stator.



For a lagging load of zero power factors, all currents would be delayed in time 90° and armature m.m.f. would be shifted 90° with respect to the poles as shown in Fig. 1.7 (*e*). Obviously, armature m.m.f. would demagnetize the poles and cause a reduction in the induced E.M.F. and hence the terminal voltage. For leading loads of zero power factors, the armature m.m.f. is advanced 90° with respect to the position shown in Fig. 1.7 (*d*). As shown in Fig. 1.7 (*f*), the armature m.m.f. strengthens the main m.m.f. In this case, armature reaction is wholly magnetizing and causes an increase in the terminal voltage. The above facts have been summarized briefly in the following paragraphs where the matter is discussed in terms of 'flux' rather than m.m.f. waves.

1. Unity Power Factor

In this case [Fig. 1.8 (a)] the armature flux is cross-magnetizing. The result is that the flux at the leading tips of the poles is reduced while it is increased at the trailing tips. However, these two effects nearly offset each other leaving the average field strength constant. In other words, armature reaction for unity p.f. is distortional.

2. Zero P.F. lagging

As seen from Fig. 1.8 (*b*), here the armature flux (whose wave has moved backward by 90°) is in direct opposition to the Hence, the main flux is decreased. Therefore, it is found that armature reaction, in this case, is wholly *demagnetising*, with the result, that due to weakening of the main flux, less e.m.f. is generated. To keep the value of generated e.m.f. the same, field excitation will have to be increased to compensate for this weakening.

3. Zero P.F. leading

In this case, shown in Fig. 1.8 (c) Armature flux wave has moved forward by 90^c so that it is in phase with the main flux wave. This results in added main flux. Hence, in this case, armature reaction is wholly *magnetising*, which results in greater induced e.m.f. to keep the value of generated e.m.f. the same, field excitation will have to be reduced somewhat.



<u>4. For intermediate power factor</u> [Fig. 1.8 (d)], the effect is partly distortional and partly demagnetizing (because p.f. is lagging).

1.5 SYNCHRONOUS REACTANCE:

From the above discussion, it is clear that for the same field excitation, terminal voltage is decreased from its no-load value E0 to V (for a lagging power factor). This is because of

1. drop due to armature resistance, *IRa*

2. drop due to leakage reactance, IXL

3. drop due to armature reaction.

The drop in voltage due to armature reaction may be accounted for by assumiung the presence of a fictitious reactance Xa in the armature winding. The value of Xa is such that IXa represents the voltage drop due to armature reaction. The laskage reactance XI (or XP) and the armature

The leakage reactance XL (or XP) and the armature reactance Xa may be combined to give synchronous reactance XS.

Hence XS = XL + Xa



Fig. 1.9

Therefore, total voltage drop in an alternator under load is = IRa + jIXS = I(Ra + jXS) = IZS where ZS is known as synchronous impedance of the armature, the word 'synchronous' being used merely as an indication that it refers to the working conditions. Hence, we learn that the vector difference between no-load voltage E0 and terminal voltage V is equal to IZS, as shown in Fig. 1.9.

1.6 VOLTAGE REGULATION

It is clear that with change in load, there is a change in terminal voltage of an alternator. The magnitude of this change depends *not only on the load but also on the load power factor*.

The voltage regulation of an alternator is defined as "the rise in voltage when fullload is removed (field excitation and speed remaining the same) divided by the rated terminal voltage."

$$\therefore$$
 % regulation 'up' = $\frac{E_0 - V}{V} \times 100$

1.7 EMF, MMF and ZPF METHODS:

In the case of large machines, the cost of finding the regulation by direct loading becomes prohibitive. Hence, other indirect methods are used as discussed below. It will be found that all these methods differ chiefly in the way the no-load voltage E0 is found in each case.

1.7.1 Synchronous Impedance or E.M.F. Method. It is due to Behn Eschenberg. **1.7.2.** The Ampere-turn or M.M.F. Method. This method is due to Rothert.

1.7.3. Zero Power Factor or Potier Method. As the name indicates, it is due to Potier.

All these methods require—

1. Armature (or stator) resistance Ra

2. Open-circuit/No-load characteristic.

3. Short-circuit characteristic (but zero power factor lagging characteristic for Potier method).

Now, let us take up each of these methods one by one.

(i) Value of Ra

Armature resistance Ra per phase can be measured directly by voltmeter and ammeter method or by using Wheatstone bridge. However, under working conditions, the effective value of Ra is increased due to 'skin effect'. The value of Ra so obtained is increased by 60% or so to allow for this effect. Generally, a value 1.6 times the D.C. value is taken.

(ii) O.C. Characteristic

As in d.c. machines, this is plotted by running the machine on no-load and by noting the values of induced voltage and field excitation current. It is just like the B-H curve.

(iii) S.C. Characteristic

It is obtained by short-circuiting the armature (*i.e.* stator) windings through a low-resistance ammeter. The excitation is so adjusted as to give 1.5 to 2 times the value of full-load current. During this test, the speed which is not necessarily synchronous is kept constant.

1.7.1 Synchronous Impedance or E.M.F. Method

Following procedural steps are involved in this method:

1. O.C.C is plotted from the given data as shown in Fig. 1.10 (*a*).

2. Similarly, S.C.C. is drawn from the data given by the short-circuit test. It is a straight line passing through the origin. Both these curves are drawn on a common field-current base.

Consider a field current *If*. The O.C. voltage corresponding to this field current is E1. When winding is short-circuited, the terminal voltage is zero. Hence, it may be assumed that the whole of this voltage E1 is being used to circulate the armature short-circuit current I1 against the synchronous impedance ZS.

$$E_1 = I_1 Z_s$$
 $\therefore Z_s = \frac{E_1 \text{ (open-circuit)}}{I_1 \text{ (short-circuit)}}$

3. Since R_a can be found as discussed earlier, $X_s = \sqrt{(Z_s^2 - R_a^2)}$

1

4. Knowing *Ra* and *XS*, vector diagram as shown in Fig. 1.10 (*b*) can be drawn for any load and any power factor.



Here
$$OD = E_0 \quad \therefore \quad E_0 = \sqrt{(OB^2 + BD^2)}$$

or $E_0 = \sqrt{[(V \cos \phi + IR_a)^2 + (V \sin \phi + IX_s)^2]}$
 $\therefore \qquad \% \text{ regn. 'up'} = \frac{E_0 - V}{V} \times 100$

1.7.2 Ampere Turn or M.M.F. Method

This method also utilizes O.C. and S.C. data, but is the converse of the E.M.F. method in the sense *that armature leakage reactance is treated as an additional armature reaction*. In other words, it is assumed that the change in terminal p.d. on load is due entirely to armature reaction (and due to the ohmic ressistance drop which, in most cases, is negligible). This fact is shown in Fig. 1.11. Now, field A.T. required to produce a voltage of V on full-load is the vector sum of the following:

(i) Field A.T. required to produce $V(\text{or if } R_a \text{ is to be taken into account, then } V + IR_a \cos \varphi)$ on noload. This can be found from O.C.C. and

(ii) Field A.T. required to overcome the demagnetizing effect of armature reaction on full-load. This value is found from short-circuit test. The field A.T. required producing full-load current on short-circuit balances the armature reaction and the *impedance drop*.

The impedance drop can be neglected because *Ra* is usually very small and *XS* is also small under short-circuit conditions. Hence, p.f. on short-circuit is almost zero lagging and the field A.T. are used entirely to overcome the armature



Fig. 1.11

reaction which is wholly demagnetizing. In other words, the demagnetizing armature A.T. on full-load are equal and opposite to the field A.T. required to produce full-load current on short-circuit.



(*ii*) the field A.T. necessary to neutralize the armature reaction AB1. The total field A.T. are represented by OB1 in Fig. 1.12 (*a*) and equals the vector sum of OA and AB1 If the p.f. is zero leading, the armature reaction is *wholly magnetizing*. Hence, in that case, the field A.T. required is OB2 which is less than OA by the field A.T. = AB2 required to produce full-load current on short-circuit [Fig. 1.12 (*b*)]

If p.f. is unity, the armature reaction is *cross-magnetizing i.e.* its effect is distortional only. Hence, field A.T. required is *OB3 i.e.* vector sum of *OA* and *AB3* which is drawn at right angles to *OA* as in Fig. 1.12 (*c*).

1.7.3 Potier or Z.P.F. Method

This method is based on the separation of armature-leakage reactance drop and the armature reaction effects. Hence, it gives more accurate results. It makes use of the first two methods to some extent. The experimental data required is (i) no-load curve and (ii) full-load zero power factor curve (not the short-circuit characteristic) also called wattless load characteristic. It is the curve of terminal volts against excitation when armature is delivering F.L. current at zero p.f.

The reduction in voltage due to armature reaction is found from above and (*ii*) voltage drop due to armature leakage reactance XL (also called Potier reactance) is found from both. By combining these two, E0 can be calculated. It should be noted that if we vectorially add to V the drop due to resistance and leakage reactance XL, we get E. If to E is further added the drop due to armature reaction (assuming lagging p.f.), then we get E0 The zero p.f. lagging curve can be obtained.

(*a*) If a similar machine is available which may be driven at no-load as a synchronous motor at practically zero p.f. or

(b) By loading the alternator with pure reactors

(c) By connecting the alternator to a 3-Ph line with ammeters and wattmeter's connected for measuring current and power and by so adjusting the field current that we get full-load armature current with zero wattmeter reading.

Point *B* (Fig. 1.13) was obtained in this manner when wattmeter was reading zero. Point *A* is obtained from a short-circuit test with Full-load armature current. Hence, *OA* represents field current whic



is equal and opposite to the demagnetizing armature reaction and for balancing leakage reactance drop at full-load (please refer to A.T. method). Knowing these two points, full-load zero p.f. curve *AB* can be drawn as under.

From *B*, *BH* is drawn equal to and parallel to *OA*. From *H*,

HD is drawn parallel to initial straight part of N-L curve *i.e.* parallel to OC, which is tangential to N-L curve. Hence, we get point D on no-load curve, which corresponds to point B on full-load zero p.f. curve. The triangle BHD is known as Potier triangle. This triangle is constant for a given armature current and hence can be transferred to give us other points like M, L etc. Draw DE perpendicular to BH. The length DE represents the drop in voltage due to armature leakage reactance XL *i.e.* I.XL. BE gives field current necessary to overcome demagnetizing effect of armature reaction at full load and EH for balancing the armature leakage reactance drop DE.

Let V be the terminal voltage on full-load, then if we add to it vector ally the voltage drop due to armature leakage reactance alone (neglecting Ra), then we get voltage E = DF (and not E0). Obviously, field excitation corresponding to E is given by OF. NA (= BE) represents the field current needed to overcome armature reaction. Hence, if we add NA vectorially to OF (as in Rothert's A.T. method) we get excitation for E0 whose value can be read from N-L curve. In Fig. 1.13, FG (= NA) is drawn at an angle of (90° +) for a lagging p.f. (or it is drawn at an angle of 90°- Φ for a leading p.f.). The voltage corresponding to this excitation is JK = E0

 $\therefore \quad \% \text{ regn.} = \frac{E_0 - V}{V} \times 100$

1.7.3.1 Procedural Steps for Potier Method

- 1. Suppose we are given V-the terminal voltage/phase.
- We will be given or else we can calculate armature leakage reactance X_L and hence can calculate LX_L.
- 3. Adding IX₁ (and IR_a if given) vectorially to V, we get voltage E.
- 4. We will next find from N-L curve, field excitation for voltage E. Let it be in.
- 5. Further, field current t_{f2} necessary for balancing armature reaction is found from Potier triangle.
- 6. Combine in and in vertorially (as in A.T. method) to get if
- Read from N-L curve, the e.m.f. corresponding to i_f. This gives us E₀. Hence, regulation can be found.

1.8 SYNCHRONIZING AND PARALLEL OPERATION OF ALTERNATOR

1.8.1 <u>Parallel Operation of Alternators</u>:

The operation of connecting an alternator in parallel with another alternator or with common bus-bars is known as *synchronizing*. Generally, alternators are used in a power system where they are in parallel with many other alternators. It means that the alternator is connected to a live system of constant voltage and constant frequency. Often the electrical system, to which the alternator is connected, has already so many alternators and loads connected to it that no matter what power is delivered by the

incoming alternator, the voltage and frequency of the system remain the same. In that case, the alternator is said to be connected to *infinite* bus-bars.

It is never advisable to connect a stationary alternator to live bus-bars, because, stator induced e.m.f. being zero, a short-circuit will result. For proper synchronization of alternators, the following three conditions must be satisfied :

1. The terminal voltage (effective) of the incoming alternator must be the same as bus-bar voltage.

2. The speed of the incoming machine must be such that its frequency (= PN/120) equals bus-bar frequency.

3. The phase of the alternator voltage must be identical with the phase of the bus-bar voltage. It means that the switch must be closed at (or very near) the instant the two voltages have correct phase relationship.

Condition (1) is indicated by a voltmeter, conditions (2) and (3) are indicated by synchronizing lamps or a synchronoscope.

1.8.2 <u>Synchronizing of Alternators</u>:

(a) Single-phase Alternators

Suppose machine 2 is to be synchronized with or 'put on' the bus-bars to which machine 1 is already connected. This is done with the help of two lamps L1 and L2 (known as synchronizing lamps) connected as shown in Fig1.14. It should be noted that E1 and E2 are in-phase relative to the external circuit but are in direct phase opposition in the local circuit (shown dotted).

If the speed of the incoming machine 2 is not brought up to that of machine 1, then its frequency will also be different, hence there will be a phase-difference between their voltages (even when they are equal in magnitude, which is determined by field excitation). This phase-difference will be continuously changing with the changes in their frequencies. The result is that their resultant voltage will undergo changes similar to the frequency changes of beats produced, when two sound sources of nearly equal frequency are sounded together, as shown in Fig. 1.15.



Sometimes the resultant voltage is maximum and some other times minimum. Hence, the current is alternating maximum and minimum. Due to this changing current through the lamps, a flicker will be produced, the frequency of flicker being (f2 < f1). Lamps wi dark out and glow up alternately. Darkness indicates that the two voltages E1 and E2 are in exact phase opposition relative to the local circuit and hence there is no resultant current through the lamps. Synchronizing is done at the middle of the dark period. That is why, sometimes, it is known as 'lamps dark' synchronizing. Some engineers prefer 'lamps bright' synchronization because of the fact the lamps are much more sensitive to changes in voltage at their



maximum brightness than when they are dark. Hence, a sharper and more accurate synchronization is obtained. In that case, the lamps are connected as shown in Fig. 1.16. Now, the lamps will glow brightest when the two voltages are in phase with the bus-bar voltage because then voltage across them is twice the voltage of each machine.

(b) Three-phase Alternators

In 3- alternators, it is necessary to synchronize one phase only, the other two phases will then be synchronized automatically. However, first it is necessary that the incoming alternator is correctly 'phased out' *i.e.* the phases are connected in the proper order of R, Y, B and not R, B, Y etc.

In this case, three lamps are used. But they are deliberately connected asymmetrically, as shown in Fig. 1.17 and 1.18. This transposition of two lamps, suggested by Siemens and Halske, helps to indicate whether the incoming machine is running too slow. If lamps were connected symmetrically, they would dark out or glow up simultaneously (if the phase rotation is the same as that of the bus-bars). Lamp L1 is connected between R and R, L2 between Y and B (not Y and Y) and L3 between B and Y (and not B and B), as shown in Fig. 1.18. Voltage stars of two machines are shown superimpose on each other in Fig. 1.19. Two sets of star vectors will rotate at unequal speeds if the frequencies of the two machines are different. If the incoming alternator is running faster, then voltage star *RYB* will appear to rotate anticlockwise with respect to the bus-bar voltage star RYB at a speed corresponding to the difference between their frequencies. With reference to Fig. 1.19, it is seen that voltage across L1 is RR and is seen to be increasing from zero that across L2 is YB which is decreasing, having just passed through its maximum that across L3 is BY which is increasing and approaching its maximum. Hence, the lamps will light up one after the other in the order 2, 3, 1; 2, 3, 1 or 1, 2, 3.



Now, suppose that the incoming machine is slightly slower. Then the star R Y B will appear to be rotating clockwise relative to voltage star RYB (Fig. 37.80). Here, we find that voltage across L3 i.e. YB is decreasing having just passed through its maximum, that across L2 i.e. YB is increasing and approaching its maximum, that across L1 is decreasing having passed through its maximum earlier. Hence, the lamps will light up one after the other in the order 3, 2, 1; 3, 2, 1, etc. which is just the reverse of the first order. Usually, the three lamps are mounted at the three corners of a triangle and the apparent direction of rotation of light indicates whether the incoming alternator is running too fast or too slow (Fig. 1.21). Synchronization is done at the moment the uncrossed lamp L1 is in the middle of the dark period. When the alternator voltage is too high for the lamps to be used directly, then usually step-down transformers are used and the synchronizing lamps are connected to the secondary. It will be noted that when the uncrossed lamp L1 is dark, the other two 'crossed' lamps L2 and L3 are dimly but equally bright. Hence, this method of synchronizing is also sometimes known as 'two bright and one dark' method.

It should be noted that synchronization by lamps is not quite accurate, because to a large extent, it depends on the sense of correct judgment of the operator. Hence, to eliminate the element of personal judgment in routine operation of alternators, the machines are synchronized by a more accurate device called synchronoscope. It consists of 3 stationary coils and a rotating iron vane which is attached to a pointer. Out of three coils, a pair is connected to one phase of the line and the other to the corresponding machine terminals, potential transformer being usually used. The pointer moves to one side or the other from its vertical position depending on whether the incoming machine is too fast or too slow. For correct speed, the pointer points vertically up.



1.9 CHANGE OF EXCITATION AND MECHANICAL INPUT:

Consider a star-connected alternator connected to infinite bus bars as shown in Fig. (1.23). Note that infinite bus bars means that bus bars voltage will remain constant and no frequency change will occur regardless of changes made in power input or field excitation of the alternator connected to it.



1.9.1 Effect of change of field excitation

Suppose the alternator connected to infinite bus bars is operating at unity p.f. It is then said to be normally excited. Suppose that excitation of the alternator is increased (overexcited) while the power input to the prime mover is unchanged.

The active power output (W or kW) of the alternator will thus remain unchanged i.e., active component of current is unaltered. The overexcited alternator will supply lagging current (and hence lagging reactive power) to the infinite bus bars. This action can be explained by the m.m.f. of armature reaction. When the alternator is overexcited, it must deliver lagging current since lagging current produces an opposing m.m.f. to reduce the over-excitation. Thus an overexcited alternator supplies lagging current in addition to the constant active component of current. Therefore, an overexcited alternator will operate at lagging power factor. Note that excitation does not control the active power but it controls power factor of the current supplied by the alternator to the infinite bus bars. Fig. (1.25) shows the phasor diagram of an overexcited alternator connected to infinite bus bars. The angle between E and V is called power angle.



Now suppose that excitation of the alternator is decreased below normal excitation (under-excitation) while the power input to the prime mover is unchanged. Therefore, the active power output (W or kW) of the alternator will remain unchanged L e., active component of current is unaltered. The under excited alternator supplies leading current (and hence leading reactive power) to the infinite bus bars. It is because when an alternator is under excited, it must deliver leading current since leading current produces an aiding m.m.f. to increase the under excitation. Thus an under excited alternator supplies leading current in addition to the constant active component of current. Therefore, an under excited alternator will operate at leading power factor. Fig. (1.26) shows the phasor diagram of an under excited alternator connected to infinite bus bars.

Conclusion. An overexcited alternator operates at lagging power factor and supplies lagging reactive power to infinite bus bars. On the other hand, an under excited alternator operates at leading power factor and supplies leading reactive power to the infinite bus bars.

1.10.2 Effect of change in mechanical input

Suppose the alternator is delivering power to infinite bus bars under stable conditions so that a certain power angle δ exists between V and E and E leads V. The phasor diagram for this situation is depicted in Fig. (1.27). Now, suppose that excitation of the alternator is kept constant and power input to its prime mover is increased. The increase in power input would tend to accelerate the rotor and £ would move further ahead of V i.e., angle δ increases. Increasing δ results in larger Ia (= E V/Xs) and lower ϕ as shown in Fig. (1.28). Therefore, the alternator will deliver more active power to the infinite bus bars. The angle assumes such a value that current Ia has an active power component corresponding to the input: Equilibrium will be re-established at the speed corresponding to the frequency of the infinite bus bars with a larger δ . Fig. (1.28) is drawn for the same D.C. field excitation and, therefore, the same E as Fig. (1.27) but the active power output (= VIc $\cos \phi$) is greater than for the condition of Fig. (1.27) and increase in 6 has caused the alternator to deliver additional active power to the bus bars. Note that mechanical input to the prime mover cannot change the speed of the alternator because it is fixed by system frequency. Increasing mechanical input increases the speed of the alternator temporarily till such time the power angle δ increases to a value required for stable operation. Once this condition is reached, the alternator continues to run at synchronous speed.



Conclusion. Increasing the mechanical input power to the prime mover will not change the speed ultimately but will increase the power angle . As a result, the change of driving torque controls the output kW and not the KVAR. When this change takes place, the power factor of the machine is practically not affected.

1.11 **Blondel's Theory (Operation of a Salient Pole Synchronous Machine):**

A multipolar machine with cylindrical rotor has a uniform air-gap, because of which its reactance remains the same, irrespective of the spatial position of the rotor. However, a synchronous machine with salient or projecting poles has non-uniform airgap due to which its reactance varies with the rotor position. Consequently, a cylindrical rotor machine possesses one axis of symmetry (pole axis or direct axis) whereas salientpole machine possesses two axes of geometric symmetry (i) field poles axis, called direct axis or d-axis and (*ii*) axis passing through the centre of the inter polar space, called the quadrature axis or q-axis, as shown in Fig. 1.29.

Obviously, two mmfs act on the *d*-axis of a salient-pole synchronous machine *i.e.* field m.m.f. and armature m.m.f. whereas only one m.m.f., *i.e.* armature mmf acts on the *q*-axis, because field mmf has no component in the *q*-axis. The magnetic reluctance is low along the poles and high between the poles. The above facts form the basis of the two-reaction theory proposed by Blondel, according to which





- (i) armature current I_a can be resolved into two components i.e. I_d perpendicular to E₀ and I_g along E₀ as shown in Fig. 37.71 (b).
- (ii) armature reactance has two components *i.e.* q-axis armature reactance X_{ad} associated with I_d and d-axis armature reactance X_{aa} linked with I_a.

If we include the armature leakage reactance X₁ which is the same on both axes, we get

$$X_d = X_{ad} + X_i$$
 and $X_a = X_{aa} + X_i$

Since reluctance on the q-axis is higher, owing to the larger air-gap, hence,

$$X_{aq} \leq X_{ad}$$
 or $X_q \leq X_d$ or $X_d \geq X_q$

1.11.1 Phasor Diagram for a salient pole synchronous machine:

The equivalent circuit of a salient-pole synchronous generator is shown in Fig. 1.30 (*a*). The component currents Id and Iq provide component voltage drops jId Xd and j Iq Xq as shown in Fig. 1.30 (*b*) for a lagging load power factor.

The armature current Ia has been resolved into its rectangular components with respect to the axis for excitation voltage E0. The angle between E0 and Ia is known as the internal power factor angle. The vector for the armature resistance drop Ia Ra is drawn parallel to Ia. Vector for the drop Id Xd is drawn perpendicular to Id whereas that for $Iq \times Xq$ is drawn perpendicular to Iq. The angle between E0 and V is called the power angle. Following phasor relationships are obvious from Fig. 1.30 (*b*)

E0 = V + IaRa + jId Xd + jIq Xq and Ia = Id + Iq

If *Ra* is neglected the phasor diagram becomes as shown in Fig. 1.30 (*a*). In this case, E0 = V + jId Xd + jIq Xq



Incidentally, we may also draw the phasor diagram with terminal voltage V lying in the horizontal direction as shown in Fig. 1.30 (b). Here, again drop Ia Ra is || Ia and Id Xd is ∞ to Id and drop Iq Xq is ∞ to Iq as usual.

UNIT II

SYNCHRONOUS MOTOR



Synchronous Motor—General

A synchronous motor (Fig. 2.1) is electrically identical with an alternator or a.c. generator. In fact, a given synchronous machine may be used, at least theoretically, as an alternator, when driven mechanically or as a motor, when driven electrically, just as in the case of d.c. machines. Most synchronous motors are rated between 150 kW and 15 MW and run at speeds ranging from 150 to 1800 r.p.m. Some characteristic features of a synchronous motor are worth noting :

1. It runs either at synchronous speed or not at all *i.e.* while running it maintains a constant speed. The only way to change its speed is to vary the supply frequency (because $Ns = 120_f / P$).

2. It is not inherently self-starting. It has to be run upto synchronous (or near synchronous) speed by some means, before it can be synchronized to the supply.

3. It is capable of being operated under a wide range of power factors, both lagging and leading. Hence, it can be used for power correction purposes, in addition to supplying torque to drive loads.

2.1 PRINCIPLE OF OPERATION:

When a 3- winding is fed by a 3magnitude but *rotating* at synchronous speed is produced. Consider a two-pole stator of Fig. 2.2, in which are shown two stator poles (marked NS and SS) rotating at synchronous speed, say, in clockwise direction. With the rotor position as shown, suppose the stator poles are at that instant situated at points A and B. The two similar poles, N (of rotor) and NS (of stator) as well as S and SS will repel each other, with the result that the rotor tends to rotate in the anticlockwise direction. supply, then a magnetic flux of constant



Fig.2.1

But half a period later, stator poles, having rotated around, interchange their positions *i.e.* NS is at point B and SS at point A. Under these conditions, NS attracts S and SS attracts N. Hence, rotor tends to rotate clockwise (which is just the reverse of the first direction). Hence, we find that due to continuous and rapid rotation of stator poles, the rotor is subjected to a torque which is rapidly reversing *i.e.*, in quick succession, the rotor is subjected to torque which tends to move it first in one direction and then in the opposite direction. Owing to its large inertia, the rotor cannot instantaneously respond to such quickly-reversing torque, with the result that it remains stationary.



Fig. 2.2



Now, consider the condition shown in Fig. 2.3 (*a*). The stator and rotor poles are attracting each other. Suppose that the rotor is not stationary, but is rotating clockwise, with such a speed that it turns through one pole-pitch by the time the stator poles interchange their position as shown in Fig. 2.3 (*b*). Here, again the stator and rotor poles attract each other. It means that if the rotor poles also shift their positions along with the stator poles, then they will continuously experience a unidirectional torque *i.e.*, clockwise torque, as shown in Fig. 2.3.



2.2 <u>Torque Equation</u>:

Gross torque,
$$T_g = 9.55 \frac{P_m}{N_s}$$
 N - m

where

$$P_m = Gross motor output in watts = E_h I_a \cos(\delta - \phi)$$

N_s - Synchronous speed in r.p.m.

Shaft torque,
$$T_{sh} = 9.55 \frac{P_{out}}{N_s}$$
 N - m

It may be seen that torque is directly proportional to the mechanical power because rotor speed (i.e., N_s) is fixed.

2.2.1 Different Torques of a synchronous Motor:

Various torques associated with a synchronous motor are as follows:

- **1.** starting torque
- 2. running torque
- 3. pull-in torque and
- **4.** pull-out torque

(a) Starting Torque

It is the torque (or turning effort) developed by the motor when full voltage is applied to its stator (armature) winding. It is also sometimes called *breakaway* torque. Its value may be as low as 10% as in the case of centrifugal pumps and as high as 200 to 250% of full-load torque as in the case of loaded reciprocating two-cylinder compressors.

(b) Running Torque

As its name indicates, it is the torque developed by the motor under running conditions. It is determined by the horse-power and speed of the *driven* machine. The peak horsepower determines the maximum torque that would be required by the driven machine. The motor must have a breakdown or a maximum running torque greater than this value in order to avoid stalling.

(c) Pull-in Torque

A synchronous motor is started as induction motor till it runs 2 to 5% below the synchronous speed. Afterwards, excitation is switched on and the rotor pulls into step with the synchronously rotating stator field. The amount of torque at which the motor will pull into step is called the pull-in torque.

(d) Pull-out Torque

The maximum torque which the motor can develop without pulling out of step or synchronism is called the pull-out torque. Normally, when load on the motor is increased, its rotor progressively tends to fall back *in phase* by some angle (called load angle) behind the synchronously-revolving stator magnetic field though it keeps running synchronously. Motor develops maximum torque when its rotor is retarded by an angle of 90° (or in other words, it has shifted backward by a distance equal to half the distance between adjacent poles). Any further increase in load will cause the motor to pull out of step (or synchronism) and stop.

2.3 STARTING METHODS:

The rotor (which is as yet unexcited) is speeded up to synchronous / near synchronous speed by some arrangement and then excited by the d.c. source. The moment this (near) synchronously rotating rotor is excited, it is magnetically locked into position with the stator *i.e.*, the rotor poles are engaged with the stator poles and both run synchronously in the same direction. It is because of this interlocking of stator and rotor poles that the motor has either to run synchronously or not at all. The synchronous speed is given by the usual relation NS = 120 f / P.

However, it is important to understand that the arrangement between the stator and rotor poles is *not an absolutely rigid one*. As the load on the motor is increased, the rotor progressively tends to fall back *in phase* (but *not* in speed as in d.c. motors) by some angle (Fig. 2.4) *but it still continues to run synchronously*. The value of this load angle or coupling angle (as it is called) depends on the amount of load to be met by the motor. In other words, the torque developed by the motor depends on this angle, say, α



The working of a synchronous motor is, in many ways, similar to the transmission of mechanical power by a shaft. In Fig. 2.5 are shown two pulleys P and Q transmitting power from the driver to the load. The two pulleys are assumed to be keyed together (just as stator and rotor poles are interlocked) hence they run at exactly the same (average) speed. When Q is loaded, it slightly falls behind owing to the twist in the shaft (twist angle corresponds to in motor), the angle of twist, in fact, being a measure of the torque transmitted. It is clear that unless Q is so heavily loaded as to break the coupling, both *pulleys must run at exactly the same (average) speed*.

2.3.1 Motor on Load with Constant Excitation:

Before considering as to what goes on inside a synchronous motor, it is worthwhile to refer briefly to the d.c. motors. When a d.c. motor is running on a supply of, say, V volts then, on rotating, a back e.m.f. *Eb* is set up in its armature conductors.

The resultant voltage across the armature is $(V \quad Eb)$ and it causes an armature current Ia = (V - Eb)/Ra to flow where Ra is armature circuit resistance. The value of Eb depends, among other factors, on the speed of the rotating armature. The mechanical power developed in armature depends on Eb Ia (Eb and Ia being in opposition to each other).

Similarly, in a synchronous machine, a back e.m.f. Eb is set up in the armature (stator) by the rotor flux which opposes the applied voltage V. This back e.m.f. depends on rotor excitation only (and not on speed, as in d.c. motors). The net voltage in armature (stator) is the *vector difference* (not arithmetical, as in d.c. motors) of V and Eb. Armature current is obtained by dividing this *vector* difference of voltages by armature impedance (not resistance as in d.c. machines).



Fig. 2.6 shows the condition when the motor (properly synchronized to the supply) is running on *no-load* and has *no losses* and is having field excitation which makes Eb = V. It is seen that vector difference of Eb and V is zero and so is the armature current. Motor intake is zero, as there is neither load nor losses to be met by it. In other words, the motor just floats. If motor is on no-load, but it has losses, then the vector for Eb falls back (vectors are rotating anti-clockwise) by a certain small angle (Fig. 2.7), so that a resultant voltage ER and hence current Ia is brought into existence, which supplies losses. If, now, the motor is loaded, then its rotor will further fall back *in phase* by a greater value of angle called the load angle or coupling angle (corresponding to the twist in the shaft of the pulleys). The resultant voltage ER is increased and motor draws an increased armature current (Fig. 2.8), though at a slightly decreased power factor.

2.4 OPERATION ON INFINITE BUS BAR

In order to simplify the ideas as much as possible the resistance of the generator will be neglected; in practice this assumption is usually reasonable. Figure 1 (a) shows the schematic diagram of a machine connected to an infinite bus bar along with the corresponding phasor diagram.



2.5 VAND INVERTED V CURVES:

The value of excitation for which back e.m.f. Eb is equal (in magnitude) to applied voltage V is known as 100% excitation. We will now discuss what happens when motor

is either over-excited or under-exicted although we have already touched this point in Art. 2-8. Consider a synchronous motor in which the mechanical load is constant (and hence output is also constant if losses are neglected).



Fig. 2.9

Fig. 2.9 (a) shows the case for 100% excitation *i.e.*, when Eb = V. The armature current I lags behind V by a small angle \cdot . Its angle θ with ER is fixed by stator constants *i.e.* tan $\theta = XS / Ra$. In Fig. 2.9 (b)* excitation is less than 100% *i.e.*, Eb < V. Here. ER is advanced clockwise and so is armature current (because it lags behind E_R by fixed angle θ). We note that the magnitude of I is increased but its power factor is decreased (6 has increased). Because input as well as V are constant, hence the power component of $I i.e., I \cos \phi$ remains the same as before, but wattless component I $\sin \phi$ is increased. Hence, as excitation is decreased, I will increase but p.f. will decrease so that power component of I i.e., I cos $\phi = OA$ will remain constant. In fact, the locus of the extremity of current vector would be a straight horizontal line as shown.

Incidentally, it may be noted that when field current is reduced, the motor pull-out torque is also reduced in proportion.

Fig. 2.9 (c) represents the condition for overexcited motor *i.e.* when Eb > V. Here, the resultant voltage vector ER is pulled anticlockwise and so it is *I*. It is seen that now motor is drawing a leading current. It may also happen for some value of excitation, that *I* may be in phase with *V i.e.*, p.f. is unity [Fig. 2.9 (*d*)]. At that time, the current drawn by the motor would be *minimum*. Two important points stand out clearly from the above discussion :

(*i*) The magnitude of armature current varies with excitation. The current has large value both for low and high values of excitation (though it is lagging for low excitation and leading for higher excitation). In between, it has minimum value corresponding to a certain excitation. The variations of I with excitation are shown in Fig. 2.10 (*a*) which are known as 'V' curves because of their shape.

(*ii*) For the same input, armature current varies over a wide range and so causes the power factor also to vary accordingly. When over-excited, motor runs with leading p.f. and with lagging p.f. when under-excited. In between, the p.f. is unity. The variations of p.f. with excitation are shown in Fig. 2.10 (b). The curve for p.f. looks like inverted 'V' curve. It would be noted that *minimum armature current corresponds to unity power factor*.

It is seen (and it was pointed out in Art. 2.1) that an over-excited motor can be run with leading RO. ARM. Current/Phase. / power factor. This property of the motor renders it extremely useful for phase advancing (and so power factor correcting) purposes in the case of industrial (a) loads driven by induction motors (Fig. 2.11) and lighting and heating loads supplied through transformers. Both transformers and induction motors draw lagging currents from the line. Especially on light loads, the power drawn by them has a large reactive component and the power factor 1.0 has a very low value. This reactive component, though essential for operating the electric m a c h i n e r y, entails appreciable loss in many Power Factor (b) ways. By using s y n c h r o n o u s motors in conjunction with induction motors and transformers, the lagging reactive power required by the latter is supplied locally by the leading reactive 0 component taken by the former, thereby relieving the line and generators of much of the reactive component. Hence, they now supply only the active component of the load current. When used in this way, a synchronous motor is called a *synchronous capacitor*, because it draws, like a capacitor, leading current from the line. Most synchronous capacitors are rated between 20 MVAR and 200 MVAR and many are hydrogen-cooled.







Fig. 2.11

2.6 **POWER INPUT AND POWER DEVELOPED EQUATIONS:**

2.6.1 Power Relations:

Consider an under-excited star-connected synchronous motor driving a mechanical load. Fig. (2.12 (i)) shows the equivalent circuit for one phase, while Fig. (2.12 (ii)) shows the phasor diagram.



- (i) Input power/phase, $P_i = V I_a \cos \phi$
- (ii) Mechanical power developed by the motor/phase,

$$\begin{split} P_{m} &= E_{b} \times I_{a} \times \text{cosine of angle between } E_{b} \text{ and } I_{a} \\ &- E_{b} I_{a} \cos(\delta - \phi) \end{split}$$

- (iii) Armature Cu loss/phase $I_a^2 R_a = P_i P_m$
- (iv) Output power/phasor, $P_{out} = P_m Iron$, friction and excitation loss.

2.6.2. Mechanical Power developed by Motor:

(Armature resistance neglected) Fig. (2.13) shows the phasor diagram of an under-excited synchronous motor driving a mechanical load. Since armature resistance Ra i assumed zero. $\tan \theta = X_5/R_a = \infty$ and hence $\theta = 90^{\circ}$.

Input power/phase – V I_a cos
$$\phi$$

Since Ra is assumed zero, stator Cu loss (Ia² Ra) Will be zero. Hence input power is equal to the mechanical power Pm developed by the motor.

Mech. power developed/ phase, Pm = V Ia cos (i) Referring to the phasor diagram in Fig. (2.13), $AB - E_r \cos \phi - I_a X_s \cos \phi$

Also

$$E_{\rm b}\sin\delta = I_{\rm a}X_{\rm a}\cos\phi$$

 $I_a \cos \phi = \frac{E_b \sin \delta}{X_s}$

AB $E_h \sin \delta$

or

Substituting the value of $I_a \cos \phi$ in exp. (i) above,

$$P_{in} = \frac{VE_{b}}{X_{s}} \quad \text{per phase}$$
$$= \frac{VE_{b}}{X_{s}} \quad \text{for 3-phase}$$

It is clear from the above relation that mechanical power increases with torque angle (in electrical degrees) and its maximum value is reached when $d = 90^{\circ}$ (electrical).

$$P_{max} = \frac{VE_b}{X_s}$$
 per phase

Under this condition, the poles of the rotor will be mid-way between N and S poles of the stator.

2.6 POWER/ POWER ANGLE RELATIONS:

The power-angle relationship has been discussed in Section 2.4.3. In this section we shall consider this relation for a lumped parameter lossless transmission line. Consider the **single-machine-infinite-bus** (SMIB) system shown in Fig. 9.1. In this the reactance X includes the reactance of the transmission line and the synchronous reactance or the transient reactance of the generator. The sending end voltage is then the internal emf of the generator. Let the voltages be given by $V_s + \frac{I_s}{I_s} +$

$$t_3 = \frac{V_3 \angle \delta - V_3}{\mathcal{M}} = \frac{V_1 \cos \delta - V_3 + \mathcal{M}_3 \sin \delta}{\mathcal{M}}$$

we then have

$$P_{S} + jQ_{S} = V_{S}I_{S}^{*} = V_{1}(\cos \delta + j\sin \delta)\frac{V_{1}\cos \delta - V_{2} - jV_{1}\sin \delta}{-jX}$$

The sending end real power and reactive power are then given by

$$P_{s} + \mathcal{N}_{s} = \frac{V_{1}V_{1}\sin\mathcal{S} + \mathcal{J}(V_{1}^{2} - V_{1}V_{2}\cos\mathcal{S})}{X}$$

This is simplified to

Since the line is loss less, the real power dispatched from the sending end is equal to the real

$$P_{s} = P_{s} = P_{s} = \frac{V_{1}V_{2}}{X}\sin\delta = P_{\max}\sin\delta$$

power received at the receiving end. We can therefore write

where $P_{max} = V_1 V_2 / X$ is the maximum power that can be transmitted over the transmission line. The power-angle curve is shown in Fig. 9.2. From this figure we can see that for a given power P_0

$$\delta_0 = \sin^{-1} \left(\frac{P_0}{P_{max}} \right)$$

 $\delta_{max} = 18 U^2 - \delta_0$

. There are two possible values of the angle $-_{0}$ and $_{max}$. The angles are given by

2.8 HUNTING

When a synchronous motor is used for driving a varying load, then a condition known as hunting is produced. Hunting may also be caused if supply frequency is pulsating (as in the case of generators driven by reciprocating internal combustion engines). We know that when a synchronous motor is loaded (such as punch presses, shears, compressors and pumps etc.), its rotor falls back in phase by the coupling angle.

As load is progressively increased, this angle also increases so as to produce more torque for coping with the increased load

motor load, the motor is immediately pulled

corresponding to the new Load But in this process, the rotor overshoots and hence is again pulled back In this way, the rotor starts oscillating (like a pendulum) about its new position of equilibrium corresponding to the new load If the time period of these oscillations happens to be equal to the natural time period of the machine (refer Art 37.36) then mechanical resonance is set up. The amplitude of these oscillations is built up





to a large value and may eventually become so great as to throw the machine out of synchronism. To stop the build-up of these oscillations, dampers or damping grids (also known as squirrel-cage winding) are employed

These dampers consist of short circuited Cu bars embedded in the faces of the field poles of the motor. The oscillatory motion of the rotor sets up eddy currents in the dampers which flow in such a way as to suppress these oscillations. But it should be clearly understood that dampers do not completely prevent hunting because their operation depends upon the presence of some oscillatory motion. However, they serve the additional purpose of making the synchronous motor self-starting.

2.9 SYNCHRONOUS CONDENSER

A synchronous motor takes a leading current when over-excited and, therefore, behaves as a capacitor. An over-excited synchronous motor running on no-load is known as synchronous condenser.

When such a machine is connected in parallel with induction motors or other devices that operate at low lagging power factor, the leading kVAR supplied by the synchronous condenser partly neutralizes the lagging reactive kVAR of the loads. Consequently, the power factor of the system is improved. Fig. (11.14) shows the power factor improvement by synchronous condenser method. The 3-Ph load takes current IL at low lagging power factor cos L. The synchronous condenser takes a current Im which leads the voltage by an angle m. The resultant current I is the vector sum of Im and IL and lags behind the voltage by an angle . It is clear that is less than L so

that cos is greater than cos L. Thus the power factor is increased from cos L to cos . Synchronous condensers are generally used at major bulk supply substations for power factor improvement.



Fig.2.15

Advantages

(i) By varying the field excitation, the magnitude of current drawn by the motor can be changed by any amount. This helps in achieving stepless control of power factor.

- (ii) The motor windings have high thermal stability to short circuit currents.
- (iii) The faults can be removed easily.

Disadvantages

- (i) There are considerable losses in the motor.
- (ii) The maintenance cost is high.
- (iii) It produces noise.
- (iv) Except in sizes above 500 RVA, the cost is greater than that of static capacitors of the same rating.
- (v) As a synchronous motor has no self-starting torque, then-fore, an auxiliary equipment has to be provided for this purpose.

2.10 APPLICATIONS:

- (i) Synchronous motors are particularly attractive for low speeds (< 300 r.p.m.) because the power factor can always be adjusted to unity and efficiency is high.
- (ii) Overexcited synchronous motors can be used to improve the power factor of a plant while carrying their rated loads.
- (iii) They are used to improve the voltage regulation of transmission lines.
- (iv) High-power electronic converters generating very low frequencies enable us to run synchronous motors at ultra-low speeds. Thus huge motors in the 10 MW range drive crushers, rotary kilns and variable-speed ball mills.

UNIT III

THREE-PHASE INDUCTION MOTOR

Classification of A.C. Motors:

With the almost universal adoption of A.C. system of distribution of electric energy for light and power, the field of application of A.C. motors has widened considerably during recent years. As a result, motor manufactures have tried, over the last few decades, to perfect various types of A.C. motors suitable for all classes of industrial drives and for both single and three-phase A.C. supply. This has given rise to bewildering multiplicity of types whose proper classification often offers considerable difficulty. Different A.C. motors may, however, be classified and divided into various groups from the following different points of view:

1. AS REGARDS THEIR PRINCIPLE OF OPERATION

(A) Synchronous motors

(i) plain and (ii) super

(B) Asynchronous motors

(a) Induction motors

(*i*) Squirrel cage { single double}

(*ii*) Slip-ring (external resistance)

(b) Commutator motors

- (*i*) Series { single phase, universal
- (*ii*) Compensated { conductively, inductively}
- (*iii*) Shunt { simple, compensated}
- (*iv*) Repulsion { straight, compensated}
- (*v*) Repulsion-start induction
- (vi) Repulsion induction

2. AS REGARDS THE TYPE OF CURRENT

(*i*) single phase (*ii*) three phase

3. AS REGARDS THEIR SPEED

(*i*) Constant speed (*ii*) variable speed (*iii*) adjustable speed

4. AS REGARDS THEIR STRUCTURAL FEATURES

(i) Open (ii) enclosed (iii) semi-enclosed

(*iv*) Ventilated (*v*) pipe-ventilated (*vi*) riverted frame eye etc.

3.1 CONSTRUCTIONAL DETAILS:

An induction motor consists essentially of two main parts : (*a*) a stator and (*b*) a rotor.

(a) Stator:

The stator of an induction motor is, in principle, the same as that of a synchronous motor or generator. It is made up of a number of stampings, which are slotted to receive the windings [Fig.3.1 (*a*)]. The stator carries a 3-phase winding [Fig.3.2 (*b*)] and is fed from a 3-phase supply. It is wound for a definite number of poles, the exact number of poles being determined by the requirements of speed. Greater the number of poles, lesser the speed and *vice versa*. The stator windings, when supplied with 3-phase currents, produce a magnetic flux, which is of constant magnitude but which revolves (or rotates) at synchronous speed (given by Ns = 120 f/P). This revolving magnetic flux induces an e.m.f. in the rotor by mutual induction.



Fig. 3.1 (a)

Fig. 3.1(b)

(b) Rotor

(*i*) *Squirrel-cage rotor:* Motors employing this type of rotor are known as squirrel-cage induction motors.

(*ii*) *Phase-wound or wound rotor:* Motors employing this type of rotor are variously known as 'phase-wound' motors or 'wound' motors or as 'slip-ring' motors.

<u>3.2 TYPES OF ROTOR:</u>

3.2.1 Squirrel Cage Rotor:

Almost 90 per cent of induction motors are squirrel-cage type, because this type of rotor has the simplest and most rugged construction imaginable and is almost indestructible. The rotor consists of a cylindrical laminated core with parallel slots for carrying the rotor conductors which, it should be noted clearly, are not wires but consist of heavy bars of copper, aluminum or alloys.



Fig. 3.2 (a)

Fig. 3.2(b)

One bar is placed in each slot, rather the bars are inserted from the end when semi-closed slots are used. The rotor bars are brazed or electrically welded or bolted to two heavy and stout short-circuiting end-rings, thus giving us, what is so picturesquely called, a squirrel-case construction (Fig. 3.2). It should be noted that the *rotor bars are permanently short-circuited on themselves*, hence it is not possible to add any external resistance in series with the rotor circuit for starting purposes. The rotor slots are usually not quite parallel to the shaft but are purposely given a slight skew (Fig. 3.3). This is useful in two ways :

- *(i)* it helps to make the motor run quietly by reducing the magnetic hum and
- *(ii)* it helps in reducing the locking tendency of the rotor *i.e.* the tendency of the rotor teeth to

remain under the stator teeth due to direct magnetic attraction between the two.

In small motors, another method of construction is used It consists of placing the entire rotor core in a mould and casting all the bars and end-rings in one piece. The metal commonly used is an aluminium alloy.

Another form of rotor consists of a solid cylinder of steel Fig.3.3 without any conductors or slots at all. The motor operation depends upon the production of eddy currents in the steel rotor.

3.2.2 Phase Wound Rotor:

This type of rotor is provided with 3-phase, double-layer, distributed winding consisting of coils as used in alternators. The rotor is wound for as many poles as the number of stator poles and is always wound 3-phase even *when the stator is wound two-*

phase. The three phases are starred internally. The other three winding terminals are brought out and connected to three insulated slip-rings mounted on the shaft with brushes resting on them [Fig. 3.4 (b)]. These three brushes are further externally connected to a 3-phase star-connected rheostat [Fig. 3.4 (c)]. This makes possible the introduction of additional resistance in the rotor circuit during the starting period for increasing the starting torque of the motor, as shown in Fig. 3.5 (a) and for changing its



Fig.3.4 (a)



speed-torque/current characteristics. When running under normal conditions, the *slip-rings are automatically short-circuited* by means of a metal collar, which is pushed along the shaft and connects all the rings together. Next, the brushes are automatically lifted from the slip-rings to reduce the frictional losses and the wear and tear. Hence, it is seen that under normal running conditions, the wound rotor is short-circuited on itself just like the squirrel-cage rotor. Fig. 3.5 (*b*) shows the longitudinal section of a slip-ring motor, whose structural details are as under:



1. Frame. Made of close-grained alloy cast iron.

2. Stator and Rotor Core. Built from high-quality low-loss silicon steel laminations and flash-enameled on both sides.

3. Stator and Rotor Windings. Have moisture proof tropical insulation embodying mica and high quality varnishes. Are carefully spaced for most effective air circulation and are rigidly braced to withstand centrifugal forces and any short-circuit stresses.

4. Air-gap. The stator rabbets and bore are machined carefully to ensure uniformity of air-gap.

5. Shafts and Bearings. Ball and roller bearings are used to suit heavy duty, toruble-free running and for enhanced service life.

6. Fans. Light aluminum fans are used for adequate circulation of cooling air and are securely keyed onto the rotor shaft.

7. Slip-rings and Slip-ring Enclosures. Slip-rings are made of high quality phosphorbronze and are of molded construction.
Fig. 3.5 (c) shows the disassembled view of an induction motor with squirrel-cage rotor. According to the labeled notation (a) represents stator (b) rotor (c) bearing shields (d) fan (e) ventilation grill and (f) terminal box.

Similarly, Fig. 3.5 (d) shows the disassembled view of a slip-ring motor where (a) represents stator (b) rotor (c) bearing shields (d) fan (e) ventilation grill (f) terminal box (g) slip-rings (h) brushes and brush holders.



Fig.3.5 (c)



3.3 PRINCIPLE OF OPERATION:

As a general rule, conversion of electrical power into mechanical power takes place in the *rotating* part of an electric motor. In d.c. motors, the electric power is *conducted* directly to the armature (*i.e.* rotating part) through brushes and commutator (Art. 29.1). Hence, in this sense, a d.c. motor can be called a *conduction* motor. However, in a.c. motors, the rotor does not receive electric power by conduction but by *induction* in exactly the same way as the secondary



Fig.3.6

of a 2-winding transformer receives its power from the primary. That is why such motors are known as *induction* motors. In fact, an induction motor can be treated as a *rotating* transformer *i.e.* one in which primary winding is stationary but the secondary is free to rotate. Of all the a.c. motors, the polyphase induction motor is the one which is extensively used for various kinds of industrial drives. It has the following main advantages and also some dis-advantages:

Advantages:

1. It has very simple and extremely rugged, almost unbreakable construction (especially squirrel cage type).

2. Its cost is low and it is very reliable.

3. It has sufficiently high efficiency. In normal running condition, no brushes are needed, hence frictional losses are reduced. It has a reasonably good power factor.

4. It requires minimum of maintenance.

5. It starts up from rest and needs no extra starting motor and has not to be synchronized. Its starting arrangement is simple especially for squirrel-cage type motor.

Disadvantages:

- 1. Its speed cannot be varied without sacrificing some of its efficiency.
- 2. Just like a d.c. shunt motor, its speed decreases with increase in load.
- **3.** Its starting torque is somewhat inferior to that of a D.C. shunt motor.

3.3.1 Why does the rotor rotate?

The reason why the rotor of an induction motor is set into rotation is as follow:

When the 3-phase stator windings, are fed by a 3-phase supply then, as seen from above, a magnetic flux of constant magnitude, but rotating at synchronous speed, is set up.

The flux passes through the air-gap, sweeps past the rotor surface and so cuts the rotor conductors which, as yet, are stationary. Due to the relative speed between the rotating flux and the stationary conductors, an e.m.f. is induced in the latter, according to Faraday's laws of electro-magnetic induction. *The frequency of the induced e.m.f. is the same as the supply frequency.* Its magnitude is proportional to the relative velocity between the flux and the conductors and its direction is given by Fleming's Right-hand rule. Since the rotor bars or conductors form a closed circuit, rotor current is produced whose direction, as given by Lenz's law, is such as to oppose the very cause producing it. In this case, the cause which produces the rotor current is the relative velocity between the rotating flux of the stator and the stationary rotor conductors. Hence, to reduce the relative speed, the rotor starts running in the *same* direction as that of the flux and tries to catch up with the rotating flux.

The setting up of the torque for rotating the rotor is explained below:

In Fig 3.7 (*a*) is shown the stator field which is assumed to be rotating clockwise. The relative motion of the rotor with respect to the stator is *anticlockwise*. By applying Right-hand rule, the direction of the induced e.m.f. in the rotor is found to be outwards. Hence, the direction of the flux due to rotor current *alone*, is as shown in Fig. 3.7 (*b*). Now, by applying the Left-hand rule, or by the effect of combined field [Fig. 3.7(*c*)] it is clear that the rotor conductors experience a force tending to rotate them in clockwise direction. Hence, the rotor is set into rotation in the same direction as that of the stator flux (or field).



<u>3.4 SLIP:</u>

In practice, the rotor never succeeds in 'catching up' with the stator field. If it really did so, then there would be no relative speed between the two, hence no rotor e.m.f., no rotor current and so no torque to maintain rotation. That is why the rotor runs at a speed which is always less than the speed of the stator field. The difference in speeds depends upon the load on the motor.

The difference between the synchronous speed Ns and the actual speed N of the rotor is known as *slip*. Though it may be expressed in so many revolutions/second, yet it is usual to express it as a percentage of the synchronous speed. Actually, the term '*slip*' is descriptive of the way in which the rotor 'slips back' from synchronism.

% slip
$$s = \frac{N_s - N}{N_s} \times 100$$

Sometimes, Ns - N is called the *slip speed*.

Obviously, rotor (or motor) speed is N = Ns (1 - s).

It may be kept in mind that revolving flux is rotating synchronously, relative to the stator (*i.e.* stationary space) but at slip speed relative to the rotor.

<u>3.4.1 Frequency of Rotor Current:</u>

When the rotor is stationary, the frequency of rotor current is *the same as the supply frequency*. But when the rotor starts revolving, then the frequency depends upon the relative speed or on slip speed. Let at any slip-speed, the frequency of the rotor current be f'. Then

$$N_s - N = \frac{120 f'}{P} \quad \text{Also,} \quad N_s = \frac{120 f}{P}$$

Dividing one by the other, we get, $\frac{f'}{f} = \frac{N_s - N}{N_s} = s$ $\therefore f' - sf$

As seen, rotor currents have a frequency of f' = sf and when flowing through the individual

phases of rotor winding, give rise to rotor magnetic fields. These individual rotor magnetic fields produce a combined rotating magnetic field, whose speed relative to rotor is

$$=\frac{120 f'}{P}=\frac{120 sf}{P}=sN_{s}$$

However, the rotor itself is running at speed N with respect to space. Hence, speed of rotor field in *space* = speed of rotor magnetic field relative to rotor + speed of rotor relative to space

$$= sN_s + N = sN_s + N_s (1-s) = N_s$$

It means that no matter what the value of slip, rotor currents and stator currents each produce a sinusoidal distributed magnetic field of constant magnitude and constant space speed of *Ns*.

3.5 EQUIVALENT CIRCUIT:

As in the case of a transformer, in this case also, the secondary values may be transferred to the primary and *vice versa*. As before, it should be remembered that when shifting impedance or resistance from secondary to primary, it should be *divided* by K2 whereas current should be *multiplied* by K. The equivalent circuit of an induction motor where all values have been referred to primary *i.e.* stator is shown in Fig. 3.8.



As shown in Fig. 3.9, the exciting circuit may be transferred to the left, because inaccuracy involved is negligible but the circuit and hence the calculations are very much simplified. This is known as the *approximate equivalent* circuit of the induction motor. If transformation ratio is assumed unity *i.e.* E2/E1 = 1, then the equivalent circuit is as shown in Fig. 3.10 instead of that in Fig. 3.8.



3.6 TORQUE EQUATIONS:

3.6.1 Starting Torque:

The torque developed by the motor at the instant of starting is called starting torque. In some cases, it is greater than the normal running torque, whereas in some other cases it is somewhat less.

Let
$$E_2 = \operatorname{rotor} e.m.f.$$
 per phase at standstill;
 $R_2 - \operatorname{rotor}$ resistance/phase
 $X_2 = \operatorname{rotor}$ reactance/phase at standstill
 \therefore $Z_2 = \sqrt{(R_2^2 + X_2^2)} = \operatorname{rotor}$ impedance/phase at standstill
Then, $I_2 - \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{(R_2^2 + X_2^2)}};$ $\cos \phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{(R_2^2 + X_2^2)}}$
Standstill or starting torque $T_R = k_1 E_2 I_2 \cos \phi_2$
or $T_R = k_1 E_2 \cdot \frac{E_2}{\sqrt{(R_2^2 + X_2^2)}} \approx \frac{R_2}{\sqrt{(R_2^2 + X_2^2)}} = \frac{k_1 E_2^2 R_2}{R_2^2 + X_2^2}$
If supply voltage V is constant, then the flux Φ and hence, E_2 both are constant.
 \therefore $T_R = k_2 \frac{R_2}{R_2^2 + X_2^2} = k_2 \frac{R_2}{Z_2^2}$ where k_2 is some other constant.
 $3 = \frac{3}{R_2^2 R_2}$

Now,
$$k_1 = \frac{3}{2\pi N_s}$$
, $\therefore T_{st} = \frac{3}{2\pi N_s} \cdot \frac{E_2 R_2}{R_2^2 + X_2^2}$

Where $Ns \rightarrow$ synchronous speed in rps.

3.6.2 Condition for Maximum Torque:

It can be proved that starting torque is maximum when rotor resistance equals rotor reactance.

$$T_{\pi} = \frac{k_2 R_2}{R_2^2 + X_2^2} \qquad \therefore \quad \frac{dT_{st}}{dR_2} = k_2 \left[\frac{1}{R_2^2 + X_2^2} - \frac{R_2 (2R_2)}{(R_2^2 + X_2^2)^2} \right] = 0$$
$$R_2^2 + X_3^2 = 2R_2^2 \qquad \therefore \quad R_2 - X_3$$

0ľ

3.6.3 Torque under Running Conditions:

 $T \ll E.I$, $\cos \phi$, or $T \ll \phi I$, $\cos \phi$, $(\because E, \infty 0)$ $E_r = rotor e.m.f.$ /phase under *running conditions* where I_r - rotor current/phase under running conditions $E_{-} = sE_{-}$ Now $\therefore \qquad I_r = \frac{L_r}{Z_r} = \frac{sL_2}{\sqrt{|R_2^2 + (sX_2)^2|}}$ C $\cos \phi_n = \frac{R_n}{\sqrt{[R_n^2 + (sX_2)^2]}}$ —Fig. 34.20 Z, SX. $\therefore \qquad T \propto \frac{s \Phi F_2 R_2}{R_1^2 + (sX_2)^2} = \frac{k \Phi \cdot s \cdot F_2 R_2}{R_1^2 + (sX_1)^2}$ В R. Also $T = -\frac{k_1 \cdot sE_2^2 R_2}{R_2^2 + (sX_2)^2} \quad (\because E_2 \approx 0)$ Fig. 34.20

where k_1 is another constant. Its value can be proved to be equal to $3/2\pi N_s$ (Art. 34.38). Hence, in that case, expression for lorque becomes

$$T = -\frac{3}{2\pi N_S}, \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2} = \frac{3}{2\pi N_S}, \frac{sE_2^2 R_2}{Zr^2}$$

At standstill when s = 1, obviously

$$T_{st} = \frac{k_1 E_2^2 R_2}{R_2^2 + X_2^2} \left(\text{or} \quad \frac{3}{2\pi N_s} \cdot \frac{E_2^2 R_2}{R_2^2 + X_2^2} \right) \text{ the same as in Art. 34.13.}$$

3.6.4 Torque developed by Induction Motor:

An induction motor develops gross torque T_g due to gross rotor output P_m (Fig 34.38). Its value can be expressed either in terms of rotor input P_2 or rotor gross output P_m as given below.

$$T_g = \frac{P_2}{\omega_s} = \frac{P_2}{2\pi N_s}$$
 ... in terms of rotor input

$$T_g = \frac{P_m}{\omega} = \frac{P_m}{2\pi N}$$
 ... in terms of rotor output

The shaft torque T_{in} is due to output power P_{out} which is less than P_{in} because of rotor friction and windage losses.

$$T_{\rm sh} = P_{\rm out}/\omega = P_{\rm out}/2\pi N$$

The difference between T_g and T_{sh} equals the torque lost due to friction and windage loss in the motor.

In the above expressions, N and N_a are in r.p.s. However, if they are in r.p.m., the above expressions for motor torque become

$$T_{g} = \frac{P_{2}}{2 \pi N_{s} / 60} = \frac{60}{2\pi} \cdot \frac{P_{2}}{N_{s}} = 9.55 \frac{P_{2}}{N_{s}} \text{ N-m}$$
$$= \frac{P_{m}}{2 \pi N / 60} = \frac{60}{2\pi} \cdot \frac{P_{m}}{N} = 9.55 \frac{P_{m}}{N} \text{ N-m}$$
$$T_{sh} = \frac{P_{oul}}{2\pi N / 60} = \frac{60}{2\pi} \cdot \frac{P_{oul}}{N} = 9.55 \frac{P_{out}}{N} \text{ N-m}$$

3.6.5 Torque, Mechanical Power and Rotor Output:

Stator input P1 = stator output + stator losses The stator output is transferred entirely inductively to the rotor circuit. Obviously, rotor input P2 = stator output Rotor gross output, Pm = rotor input P2 — rotor Cu losses

This rotor output is converted into mechanical energy and gives rise to gross torque Tg. Out of this gross torque developed, some is lost due to windage and friction losses in the rotor and the rest appears as the useful or shaft torque T_{sh} . Let N raps. be the actual speed of the rotor and if Tg is in N-m, then

$$T_g \times 2 \pi N$$
 = rotor gross output in watts, P_m
 $\therefore T_g = \frac{\text{rotor gross output in watts, } P_m}{2\pi N} \text{N-m}^{\pm}$...(1)

If there were no Cu losses in the rotor, then rotor output will equal rotor input and the rotor will run at synchronous speed.

$$T_{g} = \frac{\text{rotor input } P_2}{2\pi N_g} \qquad \dots (2)$$

1/rom (1) and (2), we get,

.

Rotor gross output
$$P_m = T_g \omega - T_g \times 2 \pi N$$

Rotor input $P_2 = T_g \omega_s = T_g \times 2 \pi N_s$...(3)

The difference of two equals rotor Cu loss.

$$\therefore \text{ rotor Culoss} \qquad -P_2 - P_m - T_g \times 2\pi (N_g - N) \qquad ...(4)$$

3.6.6 Induction Motor Torque Equation:

The gross torque T_g developed by an induction motor is given by

 $T_{g} = P_{2} / 2 \pi N_{s} \qquad N_{s} \text{ in r.p.s.} \\ = 60 P_{2} / 2\pi N_{s} = 9.55 P_{2} / N_{s} \qquad -N_{s} \text{ in r.p.m.} \\ P_{2} = \text{rotor Cu loss/s} - 3I_{2}^{-2} R_{2} / s \\ s E_{s} \qquad s K E_{s}$

Now.

or

As seen from Art. 34.19,
$$I_2 = \frac{sE_2}{\sqrt{R_2^2 + (s|X_2|)^2}} = \frac{sKE_1}{\sqrt{R_2^2 + (s|X_2|)^2}}$$

where *K* is rotor/stater turn ratio per phase

where K is rotor/stator turn ratio per phase.

$$P_2 = 3 \times \frac{s^2 E_2^2 R_2}{R_2^2 + (s X_2)^2} \times \frac{1}{s} = \frac{3 s E_2^2 R_2}{R_2^2 + (s X_2)^2}$$

Also,

$$P_{2} = -3 \times \frac{s^{2}K^{2}E_{1}^{2}R_{2}}{R_{2}^{2} + (s X_{2})^{2}} \times \frac{1}{s} = \frac{3 s K^{2}E_{1}^{2}R_{2}}{R_{2}^{2} + (s X_{2})^{2}}$$

$$T_{g} = \frac{P_{2}}{2\pi N_{s}} = \frac{3}{2\pi N_{s}} \times \frac{s E_{s} R_{s}}{R_{2}^{2} + (s X_{2})^{2}} - \text{in terms of } E_{2}$$

$$= \frac{3}{2\pi N_s} \times \frac{s K^2 E_1^2 R_2}{R_2^2 + (sX_2)^2} - \text{in terms of } E_1$$

Here, E_1, E_2, R_2 and X_2 represent phase values.

In fact, $3K^2/2\pi N_s = k$ is called the constant of the given machine. Hence, the above torque equation may be simplified to

$$T_g = k \frac{s K_1^2 R_2}{R_2^2 + (s X_2)^2}$$
 — in terms of E_1

3.7 SLIP-TOROUE CHARACTERISTICS:

A family of torque/slip curves is shown in Fig. 3.11 for a range of s = 0 to s = 1 with *R*2 as the parameter.

$$T = \frac{k \Phi s E_2 R_2}{R_2^2 + (s X_2)^2}$$

It is clear that when s = 0, T = 0, hence the curve starts from point *O*. At normal speeds, close to synchronism, the term (*s X2*) is small and hence negligible *w.r.t. R2*.

$$T \propto \frac{s}{R_2}$$

or $T \propto s$ if R_2 is constant.





Hence, for low values of slip, the torque/slip curve is approximately a straight line. As slip increases (for increasing load on the motor), the torque also increases and becomes maximum when s = R2/X2. This torque is known as '*pull-out*' or '*breakdown*' torque *Tb* or stalling torque. As the slip further increases (*i.e.* motor speed falls) with further increase in motor load, then *R*2 becomes negligible as compared to (*sX*2.). Therefore, for large values of slip

$$T \propto \frac{s}{\left(sX_2\right)^2} \propto \frac{1}{s}$$

Hence, the torque/slip curve is a rectangular hyperbola. So, we see that beyond the point of maximum torque, any further increase in motor load results in decrease of torque developed by the motor. The result is that the motor slows down and eventually stops. The circuit-breakers will be tripped open if the circuit has been so protected. In fact, the stable operation of the motor lies between the values of s = 0 and that corresponding to maximum torque. The operating range is shown shaded in Fig. 3.11.

It is seen that although maximum torque does not depend on R2, yet the *exact location* of T max is dependent on it. Greater the R2, greater is the value of slip at which the maximum torque occurs.

<u> 3.9 LOAD TEST – NO LOAD TEST AND BLOCKED ROTOR TESTS:</u>

3.9.1 No Load Test:

In practice, it is neither necessary nor feasible to run the induction motor synchronously for getting G0 and B0. Instead, the motor is run without any external mechanical load on it. The speed of the rotor would not be synchronous, but very much near to it; so that, for all practical purposes, the speed may be assumed synchronous. The no load test is carried out with different values of applied voltage, below and above the value of normal voltage. The power input is measured by two wattmeters,



I0 by an ammeter and V by a voltmeter, which are included in the circuit of Fig. 3.12. As motor is running on light load, the p.f. would be low *i.e.* less than 0.5, hence total power input will be the difference of the two wattmeter readings W1 and W2. The readings of the total power input W0, I0 and voltage V are plotted as in Fig. 3.13. If we extend the curve for W0, it cuts the vertical axis at point A.

OA represents losses due to friction and windage. If we subtract loss corresponding to OA from W0, then we get the no-load electrical and magnetic losses in the machine, because the no-load input W0 to the motor consists of

small stator Cu loss $3 I_0^2 R1$ (*ii*) *(i)*

stator core loss $W_{CL} = 3G_0 V^2$ (iii)

loss due to friction and windage.

The losses (ii) and (iii) are collectively known as fixed losses, because they are independent of load. OB represents normal voltage. Hence, losses at normal voltage can be found by drawing a vertical line from *B*.

BD = loss due to friction and windage DE = stator Cu loss EF = core lossHence, knowing the core loss WCL, G0 and B0 can be found,

Additionally. 0 can also be found from the relation $W0 = 3 VL I0 \cos 0$

$$\therefore \qquad \cos \phi_0 = \frac{W_0}{\sqrt{3} v_T I_0} \qquad \text{where } V_L = \text{line voltage and } W_0 \text{ is no-load stator input.}$$

3.9.2 Blocked Rotor Test:

It is also known as locked-rotor or short-circuit test. This test is used to find:

1. short-circuit current with *normal* voltage applied to stator

2. power factor on short-circuit. Both the values are used in the construction of circle diagram

3. total leakage reactance X01 of the motor as referred to primary (*i.e.* stator)

4. total resistance of the motor *R*01 as referred to primary. In this test, the rotor is locked (or allowed very slow rotation) and the rotor windings are short-circuited at slip-rings, if the motor has a wound rotor.

Just as in the case of a short-circuit test on a transformer, a reduced voltage (up to 15 or 20 per cent of normal value) is applied to the stator terminals and is so adjusted that full-load current flows in the stator. As in this case s = 1, the equivalent circuit of the motor is exactly like a transformer, having a short-circuited secondary. The values of current, voltage and power input on short-circuit are measured by the ammeter, voltmeter and wattmeter connected in the circuits as before. Curves connecting the above quantities may also be drawn by taking two or three additional sets of readings at progressively reduced voltages of the stator.

(a) It is found that relation between the short-circuit current and voltage is approximately a straight line. Hence, if V is normal stator voltage, Vs the short-circuit voltage (a fraction of V), then short-circuit or standstill rotor current, if normal voltage were applied to stator, is found from the relation

where
$$I_{SN} - I_s \times V/V_s$$

 $I_{SN} = \text{short-circuit current obtainable with normal voltage}$
 $I_s = \text{short-circuit current with voltage } V_s$
(b) Power factor on short-circuit is found from

	$W_{\rm S} = \sqrt{3} V_{SL} I_{SL} \cos \phi_{\rm S}; \qquad \therefore \cos \phi_{\rm S} = W_{\rm S} / (\sqrt{3} V_{SL} I_{SL})$				
where	W_{s} = total power input on short-circuit				
	V_{st} = line voltage on short-circuit				
	I_{NL} line current on short-circuit.				
(c) Now, the motor	r input on short-circuit consists of				

(*i*) mainly stator and rotor Cu losses

(*ii*) core-loss, which is small due to the fact that applied voltage is only a small percentage of the normal voltage. This core-loss (if found appreciable) can be calculated from the curves of Fig. 3.13.

:. Total Cu loss =
$$W_s - W_{CL}$$

 $3 I_s^2 R_{01} = W_s - W_{CL}$: $R_{01} = (W_s - W_{CL})/3 I_s^2$

(*d*) With reference to the approximate equivalent circuit of an induction motor, motor leakage reactance per phase X01 as referred to the stator may be calculated as follows :

$$Z_{01} = V_S / I_S \qquad X_{01} = \sqrt{(Z_{01}^2 - R_{01}^2)}$$

Usually, X_1 is assumed equal to X_2' where X_1 and X_2 are stator and rotor reactances per phase respectively as referred to stator $X_1 - X_2' - X_{01}/2$

If the motor has a wound rotor, then stator and rotor resistances are separated by dividing R_{01} in the ratio of the d.c. resistances of stator and rotor windings.

In the case of squirrel-cage rotor, R_1 is determined as usual and after allowing for 'skin effect' is subtracted from R_{01} to give R_2' – the effective rotor resistance as referred to stator.

 $\therefore \qquad \qquad R_2' = R_0 - R_1$

3.10 CIRCLE DIAGRAM:

3.10.1 Construction:

Circle diagram of an induction motor can be drawn by using the data obtained from (1) **no-load (2) short-circuit test** and (3) **stator resistance test**, as shown below.

<u>Step No. 1</u>

From no-load test, I0 and 0 can be calculated. Hence, as shown in Fig. 3.14, vector for I0 can be laid off lagging 0 behind the applied voltage V.



<u>Step No. 2</u>

Next, from blocked rotor test or short-circuit test, short circuit current ISN corresponding to normal voltage and S are found. The vector OA represents ISN =

(ISV/VS) in magnitude and phase. Vector O A represents rotor current I2 as referred to stator.

Clearly, the two points O and A lie on the required circle. For finding the centre C of this circle, chord O A is bisected at right angles–its bisector giving point C. The diameter O D is drawn perpendicular to the voltage vector.

As a matter of practical contingency, it is recommended that the scale of current vectors should be so chosen that the diameter is more than 25 cm, in order that the performance data of the motor may be read with reasonable accuracy from the circle diagram. With centre C and radius = CO, the circle can be drawn. The line O A is known as **out-put line**.

It should be noted that as the voltage vector is drawn vertically, all vertical distances represent the active or power or energy components of the currents. For example, the vertical component O P of no-load current OO represents the no-load input, which supplies core loss, friction and windage loss and a negligibly small amount of stator I2R loss. Similarly, the vertical component AG of short-circuit current OA is proportional to the motor input on shortcircuit or if measured to a proper scale, may be said to equal power input.

Step No. 3

Torque line. This is the line which separates the stator and the rotor copper losses. When the rotor is locked, then all the power supplied to the motor goes to meet core losses and Cu losses in the stator and rotor windings. The power input is proportional to AG. Out of this, FG (= OP) represents fixed losses *i.e.* stator core loss and friction and windage losses. AF is proportional to the sum of the stator and rotor Cu losses. The point E is such that

$$\frac{AE}{EF} = \frac{\text{rotor Cu loss}}{\text{stator Cu loss}}$$

As said earlier, line O'E is known as torque line. How to locate point E?

(i) Squirrel-cage Rotor. Stator resistance/phase *i.e.* R_1 is found from stator-resistance test. Now, the short-circuit motor input W_3 is approximately equal to motor Cu losses (neglecting iron losses).

Stator Cu loss =
$$3I_S^2 R_1$$
 \therefore rotor Cu loss = $W_S - 3I_S^2 R_1$ \therefore $\frac{AE}{EF} = \frac{W_S - 3I_S^2 R_1}{3I_S^2 R_1}$

(ii) Wound Rotor. In this case, rotor and stator resistances per phase r_2 and r_1 can be easily computed. For any values of stator and rotor currents I_1 and I_2 respectively, we can write

$$\frac{AE}{EF} = \frac{I_2^2 r_2}{I_1^2 r_1} = \frac{r_2}{r_1} \left(\frac{I_2}{I_1}\right)^2; \quad \text{Now,} \quad \frac{I_1}{I_2} = K = \text{transformation ratio}$$
$$\frac{AE}{EF} = \frac{r_2}{r_1} \times \frac{1}{K^2} = \frac{r_2/K^2}{r_1} = \frac{r_2'}{r_1} = \frac{e\text{quivalent rotor resistance per phase}}{\text{stator resistance per phase}}$$

Value of K may be found from short-circuit test itself by using two ammeters, both in stator and rotor circuits.

Let us assume that the motor is running and taking a current OL (Fig. 35.9). Then, the perpendicular JK represents fixed losses, JN is stator Cu loss, NL is the rotor input, NM is rotor Cu loss, ML is rotor output and LK is the total motor input.

From our knowledge of the relations between the above-given various quantities, we can write :

	$\sqrt{3}$. $V_L LK$	=	motor input	$\sqrt{3} V_L$	JK = fixed losses	
	$\sqrt{3}$, V_L , JN	=	stator copper loss	$\sqrt{3}$. V_L .	MN = rotor copper loss	
	$\sqrt{3} V_L . MK$	=	total loss	$\sqrt{3}$. V_{I} .	ML = mechanical output	
	$\sqrt{3}$. V_L . NL	=	rotor input ∝ torque			
1,	ML/LK	=	output/input = efficiency			
2.	MN/NL	=	(rotor Cu loss)/(rotor input) = slip, s.			
3.	$\frac{ML}{NL}$	=	$\frac{\text{rotor output}}{\text{rotor input}} = 1 - $	$s = \frac{N}{N_S} =$	actual speed synchronous speed	
4.	$\frac{LK}{OL}$	=	power factor			

Hence, it is seen that, at least, theoretically, it is possible to obtain all the characteristics of an induction motor from its circle diagram. As said earlier, for drawing the circle diagram, we need (a) stator-resistance test for separating stator and rotor Cu losses and (b) the data obtained from (i) no-load test and (ii) short-circuit test.

3.10.2 Maximum Quantities:

It will now be shown from the circle diagram (Fig. 3.15) that the maximum values occur at the positions stated below :

(*i*) Maximum Output

It occurs at point M where the tangent is parallel to output line O'A. Point M may be located by drawing a line CM from point C such that it is perpendicular to the output line OA.



Maximum output is represented by the vertical MP.

(ii) Maximum Torque or Rotor Input

It occurs at point N where the tangent is parallel to torque line O E. Again, point N may be found by drawing CN perpendicular to the torque line. Its value is represented by NQ. Maximum torque is also known as stalling or pull-out torque.

(iii) Maximum Input Power

It occurs at the highest point of the circle *i.e.* at point R where the tangent to the circle is horizontal. It is proportional to RS. As the point R is beyond the point of maximum torque, the induction motor will be unstable here. However, the maximum input is a measure of the size of the circle and is an indication of the ability of the motor to carry shorttime over-loads. Generally, RS is twice or thrice the motor input at rated load.

3.11 SEPARATION OF NO LOAD LOSSES

The no load losses are the constant losses which include core loss and friction and windage loss. The separation between the two can be carried out by the no load test conducted from variable voltage, rated frequency supply. When the voltage is decreased below the rated value, the core loss reduces as nearly square of voltage. The slip does not increase significantly the friction and windage loss almost remains constant.

The voltage is continuously decreased, till the machine slip suddenly begins to increase and the motor tends to stall. At no load this takes place at a sufficiently reduced voltage. The graph showing no load losses versus voltage is extrapolated to V = 0 which gives friction and windage loss as iron or core loss is zero at zero voltage

3.12 CRAWLING AND COGGING

3.12.1 Crawling:

It has been found that induction motors, particularly the squirrel-cage type, sometimes exhibit a tendency to run stably at speeds as low as one-seventh of their synchronous speed *Ns*. This phenomenon is known as crawling of an induction motor.

This action is due to the fact that the A.C. winding of the stator produces a flux wave, which is not a pure sine wave. It is a complex wave consisting of a fundamental wave, which revolves synchronously and odd harmonics like 3rd, 5th, and 7th etc. which rotate either in the forward or backward direction at Ns / 3, Ns / 5 and Ns / 7 speeds respectively. As a result, in addition to the fundamental torque, harmonic torques are also developed, whose synchronous speeds are 1/nth of the speed for the fundamental torque *i.e.* Ns / n, where n is the order of the harmonic torque. Since 3rd harmonic currents are absent in a balanced 3-phase system, they produce no rotating field and, therefore, no torque. Hence, total motor torque has three components :

(*i*) the fundamental torque, rotating with the synchronous speed Ns

- (*ii*) 5th harmonic torque rotating at Ns / 5 speed and
- (*iii*) 7th harmonic torque, having a speed of Ns / 7.

Now, the 5th harmonic currents have a phase difference of $5 \times 120^\circ = 600^\circ = -120^\circ$ in three stator windings. The revolving field, set up by them, rotates in the *reverse* direction at Ns / 5. The forward speed of the rotor corresponds to a slip greater than 100%. The small amount of 5th harmonic reverse torque produces a braking action and may be neglected. The 7th harmonic currents in the three stator windings have a phase difference of $7 \cdot 120^\circ = 2 \cdot 360^\circ + 120^\circ = 120^\circ$. They set up a forward rotating field, with a synchronous speed equal to 1/7th of the synchronous speed of the fundamental torque. If we neglect all higher harmonics, the resultant torque can be taken as equal to the sum of the fundamental torque and the 7th harmonic torque, as shown in Fig. 3.15. It is seen that the 7th harmonic torque reaches its maximum



positive value just before 1/7th synchronous speed *Ns*, beyond which it becomes negative in value. Consequently, the resultant torque characteristic shows a dip which may become very pronounced with certain slot combinations. If the mechanical load on the shaft involves a constant load torque, it is possible that the torque developed by the motor may fall below this load torque. When this happens, the motor will not accelerate up to its normal speed but will remain running at a speed, which is nearly 1/7th of its full-speed. This is referred to as crawling of the motor.

3.12.2 Cogging or Magnetic Locking:



Fig. 3.16

Fig.3.17

The rotor of a squirrel-cage motor sometimes refuses to start at all, particularly when the voltage is low. This happens when the number of stator teeth *S*1 is equal to the number of

rotor teeth S2 and is due to the magnetic locking between the stator and rotor teeth. That is why this phenomenon is sometimes referred to as teeth-locking.

It is found that the reluctance of the magnetic path is minimum when the stator and rotor teeth face each other rather than when the teeth of one element are opposite to the slots on the other. It is in such positions of minimum reluctance that the rotor tends to remain fixed and thus cause serious trouble during starting. Cogging of squirrel cage motors can be easily overcome by making the number of rotor slots prime to the number of stator slots.

3.13 DOUBLE CAGE ROTOR

The main disadvantage of a squirrel-cage motor is its poor starting torque, because of its low rotor resistance. The starting torque could be increased by having a cage of high resistance, but then the motor will have poor efficiency under normal running conditions (because there will be more rotor Cu losses). The difficulty with a cage motor is that its cage is permanently short-circuited, so no external resistance can be introduced temporarily in its rotor circuit during starting period. Many efforts have been made to build a squirrel-cage motor which should have a high starting torque without sacrificing its electrical efficiency, under normal running conditions.

The result is a motor, due to Boucheort, which has two independent cages on the same rotor, one inside the other. A punching for such a double cage rotor is shown in Fig. 3.16.

The *outer* cage consists of bars of a *high-resistance* metal, whereas the inner cage has low-resistance copper bars. Hence, outer cage has high resistance and low ratio of reactance-to-resistance, whereas the inner cage has low resistance but, being situated deep in the rotor, has a large ratio of reactance-to-resistance.

Hence, the outer cage develops maximum torque at starting, while the inner cage does so at about 15% slip. As said earlier, at starting and at large slip values, frequency of induced e.m.f in the rotor is high. So the reactance of the inner



Fig. 3.18

cage (= 2 f L) and therefore, its impedance are both high. Hence, very little current flows in it. Most of the starting current is confined to outer cage, despite its high resistance. Hence, the motor develops a high starting torque due to high-resistance outer cage. Double squirrel-cage motor is shown in Fig. 3.17. As the speed increases, the frequency of the rotor e.m.f. decreases, so that the reactance and hence the impedance of inner cage decreases and becomes very small, under normal running conditions. Most of the current then flows through it and hence it develops the greater part of the motor torque. In fact, when speed is normal, frequency of rotor e.m.f. is so small that the reactance of both cages is practically negligible. The current is carried by two cages in parallel, giving a low combined resistance. Hence, it has been made possible to construct a single machine, which has a good starting torque with reasonable starting current and which maintains high efficiency and good speed regulation, under normal operating conditions. The torque-speed characteristic of a double cage motor may be approximately taken to be the sum of two motors, one having a high-resistance rotor and the other a low-resistance one (Fig. 3.18). Such motors are particularly useful where frequent starting under heavy loads is required.

3.14 INDUCTION GENERATOR

When run faster than its synchronous speed, an induction motor runs as a generator called a **Induction generator**. It converts the mechanical energy it receives into electrical energy and this energy is released by the stator (Fig. 3.20). Fig. 3.19 shows an ordinary squirrel-cage motor which is driven by a petrol engine and is connected to a 3-phase line. As soon as motor speed exceeds its synchronous speed, it starts delivering **active** power P to the 3-phase line. However, for creating its own magnetic field, it absorbs reactive power Q from the line to which it is connected. As seen, Q flows in the **opposite** direction to P.



The active power *is directly proportional to the slip* above the synchronous speed. The reactive power required by the machine can also be supplied by a group of capacitors connected across its terminals (Fig. 3.21). This arrangement can be used to supply a 3-phase load without using an external source. The frequency generated is slightly less than that corresponding to the speed of rotation.



Fig. 3.21

The terminal voltage increases with capacitance. If capacitance is insufficient, the generator voltage will not build up. Hence, capacitor bank must be large enough to supply the reactive power normally drawn by the motor.

UNIT-IV

STARTING AND SPEED CONTROL OF THREE PHASE INDUCTION MOTOR

Need for Starting

At starting when the rotor is at standstill, the squirrel cage rotor is just like a short circuited secondary. Therefore the current in the rotor circuit will be high and consequently the stator also will draw a high current from the supply lines if full line voltage were applied at start.

A 3-phase induction motor is theoretically self starting. The stator of an induction motor consists of 3-phase windings, which when connected to a 3-phase supply creates a rotating magnetic field. This will link and cut the rotor conductors which in turn will induce a current in the rotor conductors and create a rotor magnetic field. The magnetic field created by the rotor will interact with the rotating magnetic field in the stator and produce rotation.

Therefore, 3-phase induction motors employ a starting method not to provide a starting torque at the rotor, but because of the following reasons;

1) Reduce heavy starting currents and prevent motor from overheating.

2) Provide overload and no-voltage protection.

Types of Starters

- 1. Auto Transformer Starter
- 2. Stator resistance
- 3. Rotor resistance
- 4. DOL Starter
- 5. Star Delta

Auto – Transformer Starter

A three phase auto transformer can be used to reduce the voltage applied to the stator. The advantage of this method is that the voltage is reduced by transformation and not by dropping the excess in resistor and hence the input current and power from the supply are also reduced compared to stator resistor starting.

Auto – Transformer Starter

The ratio of starting torque (Tst) to full

load torque (Tf):

Ist = starting current and Ist = full load current

X = Transformer tapping as p.u. of rated voltage

Sf = Full load slip



Star-Delta Starter

This method applicable for motors designed to run normally with delta connected stator windings - At starting, the stator windings connected in star - After the motor has reached nearly the steady state speed, the windings are connected in delta – over load and single phasing protection are provided.



- At starting the stator phase voltage reduced by 1/ 3 times the voltage.
- Phase current reduced by 1/3 times the current with the direct online starting.
- Line current reduce by 3 times.

Rotor Resistance Starter

Applicable to slip ring induction motors - Rated voltage applied to the stator - balanced three phase resistors connected in series with the rotor through slip rings – Resistance kept at maximum at starting – starting current reduced – starting torque increased – after starting resistance can be cut out .

Stator resistance



DOLStarter



Speed Control of Induction Motors

Synchronous speed of the rotating magnetic field produced by the stator, Ns = 120 f / P

• By changing the frequency.

The available AC voltage (50 Hz) is rectified and then inverted back to AC

of variable frequency/ Variable voltage using inverters. Inverter can be Voltage source or current source inverter.

• By changing the number of poles.

The stator winding is designed for operation for two different pole numbers: 4/6,4/8,6/8 etc. This can be applied only to squirrel cage induction motors. In this method a single stator winding is divided into few coil groups. The terminals of all these groups are brought out. The number of poles can be changed with only simple changes in coil connections. In practice, the stator winding is divided only in two coil groups. The number of poles can be changed in the ratio of 2:1.



Stator phase connections for 4 poles



Series connection



Parallel connection

• Stator voltage control.

The stator voltage is varied – slip and operating speed varies.

The torque developed by an induction motor is proportional to the square of the applied voltage. The variation of speed torque curves with respect to the applied voltage. These curves show that the slip at maximum torque s_m remains same, while the value of stall torque comes down with decrease in applied voltage.

Further, we also note that the starting torque is also lower at lower voltages. Thus, even if a given voltage level is sufficient for achieving the running torque, the machine may not start. This method of trying to control the speed is best suited for loads that require very little starting torque, but their torque

Rotor resistance control

This method is applied to slip ring induction motor – rotor is connected to variable resistance through slip rings – resistance varied – slip and hence the operating speed varies - this method results in power loss in the resistor





In wound rotor induction motor, it is possible to change the shape of the torque – speed curve by inserting extra resistance into rotor circuit of the machine. The resulting torque – speed characteristic curves are shown in fig.

This method of speed control is very simple. It is possible to have a large starting torque and low starting current at small value of slip.

The major disadvantage of this method is that the efficiency is low due to additional losses in resistors connected in the rotor circuit. Because of convenience and simplicity, it is often employed when speed is to be reduced for a short period only (cranes).



Speed Control of Induction Motors

 Using cascade connection – Three phase voltage applied to the stator of a slip ring induction motor(P1 – poles) – slip ring voltage applied to the stator of squirrel cage induction motor (P2 – poles)– two rotors are coupled.

$$Ns = 120 f / (P1 \pm P2)$$

Slip Power Recovery Scheme

This scheme applied to slip ring induction motor:- Rated voltage applied to the stator - the rotor voltage is rectified using a diode bridge rectifier – the resulting DC voltage is inverted using line commutated inverter and the AC voltage is fed back to the supply through appropriate transformer – slip power is thus recovered from the motor and the speed reduced

UNIT V

SINGLE PHASE INDUCTION MOTORS AND SPECIAL MACHINES

5.1 CONSTRUCTIONAL DETAILS

Construction ally, this motor is, more or less, similar to a polyphase induction motor, except that (*i*) its stator is provided with a single-phase winding and (*ii*) a centrifugal switch is used in some types of motors, in order to cut out a winding, used only for starting purposes. It has distributed stator winding and a squirrel-cage rotor. When fed from a single-phase supply, its stator winding produces a flux (or field) which is only *alternating i.e.* one which alternates along one space axis only. It is not a synchronously revolving (or rotating) flux, as in the case of a two- or a three-phase stator winding, fed from a 2-or 3-phase supply. Now, alternating or pulsating flux acting on a *stationary* squirrel-cage rotor cannot produce rotation (only a revolving flux can). That is

why a single-phase motor is *not self starting*. However, if the rotor of such a machine is given an initial start by hand (or small motor) or otherwise, *in either* direction, then immediately a torque arises and the motor accelerates to its final speed (unless the applied torque is too high).

This peculiar behaviour of the motor has been explained in two ways : (*i*) by two -field or doublefield

Fig. 5.1

revolving theory and (*ii*) by cross-field theory. Only the first theory will be discussed briefly.

5.2 DOUBLE REVOLVING FIELD THEORY

This theory makes use of the idea that an alternating uni-axial quantity can be represented by two oppositely-rotating vectors of half magnitude. Accordingly, an *alternating* sinusoidal flux can be represented by two *revolving* fluxes, each equal to half the value of the alternating flux and each rotating synchronously (Ns = 120f/P) in opposite direction.

As shown in Fig.5.2 (*a*), let the alternating flux have a maximum value of m. Its component fluxes A and B will each be equal to m/2 revolving in anticlockwise and clockwise directions respectively



After some time, when A and B would have rotated through angle + and - , as in Fig. 5.2 (b), the resultant flux would be

$$= 2 \times \frac{\Phi_m}{2} \cos \frac{2\theta}{2} = \Phi_m \cos \theta$$

After a quarter cycle of rotation, fluxes A and B will be oppositelydirected as shown in Fig. 36.1 (*c*) so that the resultant flux would be zero.

After half a cycle, fluxes A and B will have a resultant of $-2 \times$

m/2 = -m. After three-quarters of a cycle, again the resultant is zero, as shown in Fig. 5.2 (e) and so on. If we plot the values





of resultant flux against between limits $= 0^{\circ}$ to $= 360^{\circ}$, then a curve similar to the one shown in Fig. 5.3 is obtained. That is why an alternating flux can be looked upon as composed of two revolving fluxes, each of half the value and revolving synchronously in opposite directions. It may be noted that if the slip of the rotor is s with respect to the forward rotating flux (*i.e.* one which rotates in the same direction as rotor) then its slip with respect to the backward rotating flux is (2 - s).

Each of the two component fluxes, while revolving round the stator, cuts the rotor, induces an e.m.f. and this produces its own torque. Obviously, the two torques (called forward and backward torques) are oppositely-directed, so that the net or resultant torques is equal to their difference as shown in Fig. 5.4.

Now, power developed by a rotor is $P_g = \left(\frac{1-s}{s}\right) I_2^2 R_2$

If N is the rotor r.p.s., then torque is given by

Now, $N = N_{\varepsilon} (1-s)$

 $T_{g} = \frac{1}{2\pi N} \cdot \left(\frac{1-s}{s}\right) I_{2}^{2} R_{2}$ $\therefore \quad T_{g} = \frac{1}{2\pi N_{s}} \cdot \frac{I_{2}^{2} R_{2}}{s} = k \cdot \frac{I_{2}^{2} R_{2}}{s}$

Hence, the forward and backward torques are given by

$$T_f = K \frac{I_2^2 R_2}{s} \quad \text{and} \quad T_b = -K \cdot \frac{I_2^2 R_2}{(2-s)}$$
$$T_f = \frac{I_2^2 R_2}{s} \text{ synch watt} \quad \text{and} \quad T_b = -\frac{I_2^2 R_2}{(2-s)} \text{ synch watt}$$
$$T = T_f + T_b$$

or

Total torque



Fig. 5.4 shows both torques and the resultant torque for slips between zero and +2. At standstill, s = 1 and (2 - s) = 1. Hence, Tf and Tb are numerically equal but, being oppositely directed, produce no resultant torque. That explains why there is no **starting** torque in a single-phase induction motor. However, if the rotor is started somehow, say, in the clockwise direction, the clockwise torque starts increasing and, at the same time, the anticlockwise torque starts decreasing. Hence, there is a certain amount of net torque in the clockwise direction which accelerates the motor to full speed.

5.3 EQUIVALENT CIRCUIT

5.3.1 Without Core Loss:

A single-phase motor may be looked upon as consisting of two motors, having a common stator winding, but with their respective rotors revolving in opposite directions. The equivalent circuit of such a motor based on double-field revolving theory is shown in Fig. 5.5. Here, the singlephase motor has been imagined to be made-up of (i) one stator

winding and (*ii*) two imaginary rotors. The stator impedance impedance of each rotor is (r2 + jx2)

where r2 and x2 represent half the actual rotor values in stator terms (*i.e.* x2 stands for half the standstill reactance of the rotor, as referred to stator). Since iron loss has been neglected, the exciting branch is shown consisting of exciting reactance only. Each rotor has been assigned half the magnetizing reactance* (*i.e* xm represents half the actual reactance). The impedance of 'forward running' rotor is

$$Z_{f} = \frac{j x_{m} \left(\frac{r_{2}}{s} + j x_{2}\right)}{\frac{r_{2}}{s} + j (x_{m} + x_{2})}$$

and it runs with a slip of s. The impedance of 'backward' running rotor is

$$Z_{b} = \frac{j x_{m} \left(\frac{r_{2}}{2-s} + j x_{2}\right)}{\frac{r_{2}}{2-s} + j (x_{m} + x_{2})}$$

and it runs with a slip of (2 - s). Under standstill conditions, Vf = Vb, but under running conditions Vf is almost 90 to 95% of the applied voltage.

The forward torque in synchronous watts is $Tf = I_3^2 r_2 / s$. Similarly, backward torque is $Tb = I_5^2 r_2 / (2 - s)$ The total torque is T = Tf - Tb.

5.3.2 With Core Loss:

The core loss can be represented by an equivalent resistance which may be connected either in parallel or in series with the magnetizing reactance as shown in Fig. 5.6. Since under running conditions Vf is very high (and Vb is correspondingly, low) most of the iron loss takes place in the 'forward motor' consisting of the common stator and forward-running rotor.

Core-loss current Iw = core loss / Vf. Hence, half value of core-loss equivalent resistance is rc = Vf / Iw. As shown in Fig. 36.15 (*a*), *rc* has been connected in parallel with xm in each rotor.





5.4 STARTING METHODS

5.4.1 Making Single Phase Induction Motor Self Starting:

As discussed above, a single-phase induction motor is not self-starting. To overcome this drawback and make the motor self-starting, it is temporarily converted into a two-phase motor during starting period. For this purpose, the stator of a single-phase

motor is provided with an extra winding, known as *starting* (or auxiliary) winding, in addition to the *main* or *running winding*. The two windings are spaced 90° electrically apart and are connected in *parallel* across the single-phase supply as shown in Fig. 5.6. It is so arranged that the phase-difference between the currents in the two stator windings is very large (ideal value being 90°). Hence, the motor behaves like a two phase motor. These two currents produce a revolving flux and hence make the motor self-starting. There are many methods by which the necessary phase-difference between the two currents can be created.





(i) In *split*-phase machine, shown in Fig. 5.7 (*a*), the main winding has low resistance but high reactance whereas the starting winding has a high resistance, but low reactance. The resistance of the starting winding may be increased either by connecting a high resistance R in series with it or by choosing a high-resistance fine copper wire for winding purposes. Hence, as shown in Fig. 5.7 (*b*), the current *Is* drawn by the starting winding lags behind the applied voltage *V* by a small angle whereas current *Im* taken by the main winding lags behind V by a very large angle. Phase angle between *Is* and *Im* is made as large as possible because the starting torque of a split-phase motor is proportional to sin .

A centrifugal switch *S* is connected in series with the starting winding and is located inside the motor. Its function is to automatically disconnect the starting winding from the supply when the motor has reached 70 to 80 per cent of its full-load speed. In the case of split-phase motors that are hermetically sealed in refrigeration units, instead of internally-mounted centrifugal switch, an electromagnetic type of relay is used. As shown in Fig. 5.8, the relay coil is connected in series with main winding and the pair of contacts which are normally open, is included in the starting winding.



During starting period, when *Im* is large, relay contacts close thereby allowing *Is* to flow and the motor starts as usual. After motor speeds up to 75 per cent of full-load speed, *Im* drops to a value that is low enough to cause the contacts to open.

A typical torque/speed characteristic of such a motor is shown in Fig. 5.9. As seen, the starting torque is 150 to 200 per cent of the full-load torque with a starting current of 6 to 8 times the full-load current. These motors are often used in preference to the costlier capacitor-start motors. Typical applications are: fans and blowers, centrifugal pumps and separators, washing machines, small machine tools, duplicating machines and domestic refrigerators and oil burners etc. Commonly available sizes range from 1/20 to 1/3 h.p. (40 to 250 W) with speeds ranging from 3,450 to 865 r.p.m. As shown in Fig. 5.10, the direction of rotation of such motors can be reversed by reversing the connections of one of the two stator windings (not both). For this purpose, the four leads are brought outside the frame. As seen from Fig. 5.11, the connections of the starting winding have been reversed.



The speed regulation of standard split-phase motors is nearly the same as of the 3-phase motors. Their speed varies about 2 to 5% between no load and full-load. For this reason such motors are usually regarded as practically constant-speed motors.



5.4.2 Capacitor-start Induction-run motors.

In these motors, the necessary phase difference between Is and Im is produced by connecting a capacitor in series with the starting winding as shown in Fig. 5.12. The capacitor is generally of the electrolytic type and is usually mounted on the outside of the motor as a separate unit (Fig. 5.13). The capacitor is designed for extremely short-duty service and is guaranteed for not more than 20 periods of operation per hour, each period not to exceed 3 seconds. When the motor reaches about 75 per cent of full speed, the centrifugal switch S opens and cuts out both the starting winding and the capacitor from the supply, thus leaving only the running winding across the lines. As shown in Fig. 5.14, current Im drawn by the main winding lags the supply voltage V by a large angle whereas Is leads V by a certain angle. The two currents are out of phase with each other by about

80° (for a 200-W 50-Hz motor) as compared to nearly 30° for a split-phase motor. Their resultant current *I* is small and is almost in phase with *V* as shown in Fig 5.14. Since the torque developed by a split-phase motor is proportional to the sine of the angle between *Is* and *Im*, it is obvious that the increase in the angle (from 30° to 80°) alone increases the starting Fig. 5.15 torque to nearly twice the value developed by a split phase induction motor. Other improvements in motor design have made it possible to increase the starting torque to a value as high as 350 to 450 per cent. Typical performance curve of such a motor is shown in Fig. 5.15.





5.4.3. Capacitor Start-and-Run Motor

This motor is similar to the capacitor-start motor except that the starting winding and capacitor are connected in the circuit at *all times*. The advantages of leaving the capacitor permanently in circuit are (*i*) improvement of over-load capacity of the motor (*ii*) a higher power factor (*iii*) higher efficiency and (*iv*) quieter running of the motor

which is so much desirable for small power drives in offices and laboratories. Some of these motors which start and run with one value of capacitance in the circuit are called *single-value* capacitor-run motors. Other which start with high value of capacitance but run with a low value of capacitance are known as *two-value* capacitor-run motors.

(i) <u>Single-value capacitor-Run Motor</u>

It has one running winding and one starting winding in series with a capacitor as shown in Fig. 5.16. Since capacitor remains in the circuit permanently, this motor is often referred to as permanent-split capacitor-run motor and behaves practically like an unbalanced 2-phase motor.



Obviously, there is no need to use a centrifugal switch which was necessary in the case of capacitor-start motors. Since the same capacitor is used for starting and running, it is obvious that neither optimum starts nor optimum running performance can be obtained because value of capacitance used must be a compromise between the best value for starting and that for running. Generally, capacitors of 2 to 20 μ F capacitance are employed and are more expensive oil or pyranol-insulated foil-paper capacitors because of continuous-duty rating. The low value of the capacitor results in small starting torque which is about 50 to 100 per cent of the rated torque (Fig. 5.17). Consequently, these motors are used where the required starting torque is low such as air - moving equipment *i.e.* fans, blowers and voltage regulators and also oil burners where quiet operation is particularly desirable.

One unique feature of this type of motor is that it can be easily reversed by an external switch provided its *running and starting windings are identical*. One serves as the running winding and the other as a starting winding for one direction of rotation. For reverse rotation, the one that previously served as a running winding becomes the starting winding while the former starting winding serves as the running winding. As seen from Fig.5.18. When the switch is in the forward position, winding *B* serves as running winding and *A* as starting winding. When switch is in 'reverse' position, winding *A* becomes the running winding and *B* the starting winding.

(ii) <u>Two-value capacitor-Run Motor</u>

This motor starts with a high capacitor in series with the starting winding so that the starting torque is high. For running, a lower capacitor is substituted by the centrifugal switch. Both the running and starting windings remain in circuit.

The two values of capacitance can be obtained as follows:

1. by using two capacitors in parallel at the start and then switching out one for low-value run. (Fig. 5.19) or

2. by using a step-up auto-transformer in conjunction with one capacitor so that effective capacitance value is increased for starting purposes.

In Fig. 5.19, B is an electrolytic capacitor of high capacity (short duty) and A is an oil

capacitor of low value (continuous duty). Generally, starting capacitor *B* is 10 to 15 times the running Capacitor *A*. At the start, when the centrifugal switch is closed, the two capacitors are put in parallel, so that their combined capacitance is the sum of their individual capacitances. After the motor has reached 75 percent full-load speed, the switch opens and only capacitor *A* remains in the starting



winding circuit. In this way, both optimum Fig. 5.19 Fig. 5.20 starting and running performance is achieved in such motors. If properly designed, such motors have operating characteristics very closely resembling those displayed by two-phase motors. Their performance is characterized by

- **1.** ability to start heavy loads
- 2. extremely quiet operation
- **3.** higher efficiency and power factor
- 4. ability to develop 25 per cent overload capacity

Hence, such motors are ideally suited where load requirements are severe as in the case of compressors and fire strokers etc. The use of an auto-transformer and single oil-type capacitor is illustrated in Fig.5.20. The transformer and capacitor are sealed in a rectangular iron box and mounted on top of the motor. The idea behind using this combination is that a capacitor of value *C* connected to the secondary of a step-up transformer, appears to the primary as though it had a value of K2C where *K* is voltage transformation ratio. For example, if actual value of C = 4 F and K = 6, then low-voltage primary acts as if it had a 144 μ F(=62 · 4) capacitor connected across its terminals. Obviously, effective value of capacitance has increased 36 times. In the 'start' position of the switch, the connection is made to the mid-tap of the auto-transformer so that K = 2. Hence, effective value of capacitance at start is 4 times the running value and is sufficient to give a high starting torque. As the motor speeds up, the centrifugal switch shifts the capacitor from one voltage tap to another so that the voltage transformation ratio changes from higher value at starting to a lower value for running. The capacitor
which is actually of the paper-tinfoil construction is immersed in high grade insulation like wax or mineral oil.

5.5 TYPES AND APPLICATIONS

Such motors, which are designed to operate from a single-phase supply, are manufactured in a large number of types to perform a wide variety of useful services in home, offices, factories, workshops and in business establishments etc. Small motors, particularly in the fractional kilo watt sizes are better known than any other. In fact, most of the new products of the manufacturers of space vehicles, aircrafts,





business machines and power tools etc. have been possible due to the advances made in the design of fractional-kilowatt motors. Since the performance requirements of the various applications differ so widely, the motor-manufacturing industry has developed many different types of such motors, each being designed to meet specific demands. Single-phase motors may be classified as under, depending on their construction and method of starting :

Induction Motors (split-phase, capacitor and shaded-pole etc.)
Repulsion Motors (sometime called Inductive-Series Motors)
A.C. Series Motor
Un-excited Synchronous Motors

5.6 WORKING PRINCIPLES OF SHADED POLE INDUCTION MOTOR, RELUCTANCE MOTOR, REPULSION MOTOR, HYSTERESIS MOTOR, STEPPER MOTOR AND UNIVERSAL MOTOR

5.6.1 Shaded Pole Induction Motor:

In such motors, the necessary phase-splitting is produced by induction. These motors have salient poles on the stator and a squirrel-cage type rotor Fig. 5.22 shows a four-pole motor with the field poles connected in series for alternate polarity. One pole of such a motor is shown separately in Fig. 5.23. The laminated pole has a slot cut across the laminations approximately one-third distance from one edge. Around the small part of the pole is placed a shortcircuited Cu coil known as *shading coil*. This part of the pole is known as *shaded* part and the other as *unshaded* part. When an alternating current is passed through the exciting (or field) winding surrounding the whole pole, the axis of the pole shifts from the unshaded part a to the shaded part *b*. This shifting of the magnetic axis is, in effect, equivalent to the actual physical movement of the pole. Hence, the rotor starts rotating in the direction of this shift *i.e.* from unshaped part to the shaded part.



Let us now discuss why shifting of the magnetic axis takes place. It is helpful to remember that the shading coil is highly inductive. When the alternating current through exciting coil tends to increase, it induces a current in the shading coil by transformer action in such a direction as to oppose its growth. Hence, flux density decreases in the shaded part when exciting current increases. However, flux density increases in the shaded part when exciting current starts decreasing (it being assumed that exciting current is sinusoidal). In Fig. 5.24 (a) exciting current is rapidly increasing along OA (shown by dots). This will produce an e.m.f. in the shading coil. As shading coil is of low resistance, a large current will be set up in such a direction (according to Lenz's law) as to oppose the rise of exciting current (which is responsible for its production). Hence, the flux mostly shifts to the unshaded part and the magnetic axis lies along the middle of this part *i.e.* along NC. Next, consider the moment when exciting current is near its peak value *i.e.* from point A to B [Fig. 5.24 (b)]. Here, the change in exciting current is very slow. Hence, practically no voltage and, therefore, no current is induced in the shading coil. The flux produced by exciting current is at its maximum value and is uniformly distributed over the pole face. So the magnetic axis shifts to the centre of the pole *i.e.* along positions ND.

Fig. 5.24 (c) represents the condition when the exciting current is rapidly decreasing from B to C. This again sets up induced current in the shading coil by transformer action. This current will flow in such a direction as to oppose this decrease in exciting current, with the result that the flux is strengthened in the shaded part of the pole. Consequently, the magnetic axis shifts to the middle part of the shaded pole *i.e.* along *NE*.



From the above discussion we find that during the positive half-cycle of the exciting current, a *N*-pole shifts along the pole from the unshaded to the shaded part. During the next negative half cycle of the exciting current, a *S*-pole trails along. The effect is as if a number of real poles were actually sweeping across the space from left to right.

Shaded pole motors are built Commercially in very small sizes, varying approximately from 1/250 h.p. (3W) to 1/6 h.p. (125 W). Although such motors are simple in construction, extremely rugged, reliable and cheap, they suffer from the disadvantages of (*i*) low starting torque (*ii*) very little overload capacity and (iii) low efficiency. Efficiencies vary from 5% (for tiny sizes) to 35 (for higher ratings). Because of its low starting torque, the shaded-pole motor is generally used for small fans, toys, instruments, hair dryers, ventilators, circulators and electric clocks. It is



Fig. 5.25

also frequently used for such devices as churns, phonograph turntables and advertising displays etc. The direction of rotation of this motor cannot be changed, because it is fixed by the position of copper rings. A typical torque / speed curve for such a motor is shown in Fig. 5.25.

5.6.2 Repulsion Motor:

Principle:

To understand how torque is developed by the repulsion principle, consider Fig. 5.26 which shows a 2-pole salient pole motor with the magnetic axis vertical. For easy understanding, the stator winding has been shown with concentrated salient-pole construction (actually it is of distributed non-salient type). The basic functioning of the machine will be the same with either type of construction.

As mentioned before, the armature is of standard D.C. construction with commutator and brushes (which are short-circuited with a low-resistance jumper). Suppose that the direction of flow of the alternating current in the exciting or field (stator) winding is such that it creates a N-pole at the top and a S-pole at the bottom. The alternating flux produced by the stator winding will induce e.m.f. in the armature conductors by transformer action. The direction of the induced e.m.f. can be found by using Lenz's law and is as shown in Fig. 5.26 (*a*). However, the direction of the *induced* currents in the armature conductors will depend on the *positions of the short-circuited* brushes. If brush axis is colinear with magnetic axis of the main poles, the directions of

the induced currents (shown by dots and arrows) will be as indicated in Fig. 5.26 (a). As

a result, the armature will become an Electromagnet with a *N*-pole on its top, directly under the main *N*-pole and with a *S*-pole at the bottom, directly over the main *S*-pole. Because of this face-to face positioning of the main and induced magnetic poles, no torque will be developed. The two forces of repulsion on top and bottom act along *Y Y* in direct opposition to each other. If brushes are shifted through 90° to the position shown in Fig. 5.26 (*b*) so that the brush axis is at

at any time in the respective armature conductors are exactly the same as they were for the brush position of Fig. 5.26(a). However, with brush positions of Fig. 5.26(b), the voltages induced in the armature conductors in each path between the brush terminals will neutralize each other, hence there will be no net voltage across brushes to produce armature current. If there is no armature current, obviously, no torque will be developed. If the brushes are set in position shown in Fig. 5.27 (a) so that the brush axis is neither in line with nor 90° from the magnetic axis Y Yof t main poles, a net voltage will be induced between the brush terminals which will produce armature current.

The armature will again act as an electromagnet and develop its own *N*-and *S*-poles

which, in this case, will not directly face the respective main poles. As shown in Fig. 5.27 (a), the armature poles lie along AA making an angle of with YY.

Hence, *rotor* N-pole will be repelled by the main N-pole and the rotor S-pole will, similarly, be repelled by the *main* S-pole. Consequently, the rotor will rotate in clockwise direction [Fig.5.27 (*b*)]. Since the forces are those of *repulsion*, it is appropriate to call the motor as repulsion motor.

In the field of repulsion motor, this type is becoming very popular, because of its good all-round characteristics which are comparable to those of a compound d.c. motor. It is particularly suitable for those applications where the load can be removed entirely by de-clutching or by a loose pulley. This motor is a combination of the repulsion and induction types and is sometimes referred to as *squirrel-cage repulsion motor*. It possesses the desirable characteristics of a repulsion motor and the constant-speed characteristics of an induction motor.





right angles to the magnetic axis of the main poles, the directions of the induced voltages





It has the usual stator winding as in all repulsion motors. But there are two separate and independent windings in the rotor (Fig. 5.28).

- (*i*) a squirrel-cage winding and
- (*ii*) commutated winding similar to that of a d.c. armature.

Both these windings function during the *entire period* of operation of the motor. The commutated winding lies in the outer slots while squirrel-cage winding is located in the inner slots. At start, the commutated winding supplies most of the torque, the squirrel-cage winding being practically inactive because of its high reactance. When the rotor accelerates, the squirrel-cage winding takes up a larger portion of the load. The brushes are short-circuited and ride on the commutator continuously. One of the advantages of this motor is that it requires no centrifugal short circuiting mechanism. Sometimes such motors are also made with compensating winding for improving the power factor. As shown in Fig. 5.29, its starting torque is high, being in excess of 300 per cent. Moreover, it has a fairly constant speed regulation. Its field of application includes house-hold refrigerators, garage air pumps, petrol pumps, compressors, machine tools, mixing machines, lifts and hoists etc. These motors can be reversed by the usual brush-shifting arrangement



5.6.3 Reluctance Motor:

It has either the conventional split-phase stator and a centrifugal switch for cutting out the auxiliary winding (splitphase type reluctance motor) or a stator similar to that of a permanent-split capacitor-run motor (capacitor-type reluctance motor). The stator produces the revolving field. The squirrel-cage rotor is of unsymmetrical magnetic construction. This type of unsymmetrical construction can be achieved by removing some of the teeth of a symmetrical



Fig. 5.30

squirrel-cage rotor punching. For example, in a 48-teeth, four-pole rotor following teeth may be cut away :

1, 2, 3, 4, 5, 6–13, 14, 15, 16, 17, 18–25, 26, 27, 28, 29, 30–37, 38, 39, 40, 41, 42. This would leave four projecting or salient poles (Fig. 36.55) consisting of the following sets of teeth : 7–12; 19–24; 31–36 and 43–48. In this way, the rotor offers variable magnetic reluctance to the stator flux, the reluctance varying with the position of the rotor.

<u>Working</u>

For understanding the working of such a motor one basic fact must be kept in mind. And it is that when a piece of magnetic material is located in a magnetic field, a force acts on the material, tending to bring it into the most dense portion of the field. The force tends to align the specimen of material in such a way that the reluctance of the magnetic path that lies through the material will be minimum.

When the stator winding is energised, the revolving magnetic field exerts reluctance torque on the unsymmetrical rotor tending to align the salient pole axis of the rotor with the axis of the revolving magnetic field (because in this position, the reluctance of the magnetic path is minimum). If the reluctance torque is sufficient to start the motor and its load, the rotor will pull into step with the revolving field and continue to run at the speed of the revolving field. However, even though the rotor revolves synchronously, its poles lag behind the stator poles by a certain angle known as torque angle, (something similar to that in a synchronous motor). The reluctance torque increases with increase in torque angle, attaining maximum value when $\alpha = 45^{\circ}$. If α increases beyond 45°, the rotor falls out of synchronism. The average value of the reluctance torque is given by T =where K is a motor constant. It may be noted that the amount of load $K (V/f) 2 \sin 2$ which a reluctance motor could carry at its *constant speed* would only be a fraction of the load that the motor could normally carry when functioning as an induction motor. If the load is increased beyond a value under which the reluctance torque cannot maintain synchronous speed, the rotor drops out of step with the field. The speed, then, drops to some value at which the slip is sufficient to develop necessary torque to drive the load by induction-motor action. The constant-speed characteristic of a reluctance motor makes it very suitable for such applications as signalling devices, recording instruments, many kinds of timers and phonographs etc.

5.6.4 Hysteresis Motor:

The operation of this motor depends on the presence of a *continuously-revolving* magnetic flux. Hence, for the split-phase operation, its stator has two windings which remain connected to the single-phase supply continuously both at starting as well as during the running of the motor. Usually, shaded-pole principle is employed for this purpose giving shaded-pole hysteresis motor. Alternatively, stator winding of the type used in capacitor-type motor may be used giving capacitor- type shaded-pole motor. Obviously, in either type, no centrifugal device is used.

The rotor is a smooth chrome-steel cylinder having high retentivity so that the hysteresis loss is high. It has no winding. Because of high retentivity of the rotor material,

it is very difficult to change the magnetic polarities once they are induced in the rotor by the revolving flux. The rotor revolves synchronously because the rotor poles magnetically lock up with the revolving stator poles of opposite polarity. However, the rotor poles always lag behind the stator poles by an angle α . Mechanical power developed by rotor is given by Pm = Ph (1 - s/ s) where Ph is hysteres loss in rotor. Also Th = 9.55 Pm /Ns. It is seen that hysteresis torque depends solely on the area of rotor's hysteresis loop.

The fact that the rotor has no teeth or winding of any sort, results in making the motor extremely quiet in operation and free from mechanical and magnetic vibrations. This makes the motor particularly useful for driving tape-decks, tape-decks, turn-tables and other precision audio equipment. Since, commercial motors usually have two poles, they run at 3,000 r.p.m. at 50-Hz single-phase supply. In order to adopt such a motor for driving an electric clock and other indicating devices, gear train is connected to the motor shaft for reducing the load speed. The unit accelerates rapidly, changing from rest to full speed almost instantaneously. It must



Fig. 5.31

do so because it cannot accelerate gradually as an ordinary motor it is either operating at synchronous speed or not at all.

Some unique features of a hysteresis motor are as under :

- *(i)* since its hysteresis torque remains practically constant from locked rotor to synchronous speed, a hysteresis motor is able to synchronise any load it can accelerate–something no other motor does.
- *(ii)* due to its smooth rotor, the motor operates quietly and does not suffer from magnetic pulsations caused by slots/salient-poles that are present in the rotors of other motors.

In Fig. 5.31. is shown a two-pole shaded-pole type hysteresis motor used for driving ordinary household electric clocks. The rotor is a thin metal cylinder and the shaft drives a gear train.

5.6.5 Universal Motor:

A universal motor is defined as a motor which may be operated either on direct or single-phase a.c. supply at approximately the same speed and output. Being a serieswound motor, it has high starting torque and a variable speed characteristic. It runs at dangerously high speed on no-load. That is why such motors are usually built into the device they drive.

Generally, universal motors are manufactured in two types:

concentrated-pole, non-compensated type (low power rating)
distributed-field compensated type (high power rating)

The non-compensated motor has two salient poles and is just like a 2-pole series d.c. motor except that whole of its magnetic path is laminated (Fig. 5.32). The laminated

stator is necessary because the flux is alternating when motor is operated from a.c. supply. The armature is of wound type and similar to that of a small d.c. motor. It consists essentially of a laminated core having either straight or skewed slots and a commutator to which the leads of the armature winding are connected. The distributed field compensated type motor has a stator core similar to that of a split-phase motor and a wound armature similar to that of a small d.c. motor. The compensating winding is used to reduce the reactance voltage present in the armature when motor runs on a.c. supply.



Fig. 5.32

In a 2-pole non-compensated motor, the voltage induced by transformer action in a coil during its commutation period is not sufficient to cause any serious commutation trouble. Moreover, high-resistance brushes are used to aid commutation.



(a) Operation.

As explained in Art. 36.16, such motors develop unidirectional torque, regardless of whether they operate on d.c. or a.c. supply. The production of unidirectional torque, when the motor runs on a.c. supply can be easily understood from Fig. 5.33. The motor works on the same principle as a d.c. motor *i.e.* force between the main pole flux and the current-carrying armature conductors. This is true regardless of whether the current is alternating or direct (Fig. 5.34).

(b) Speed/Load Characteristic.

The speed of a universal motor varies just like that of a d.c. series motor *i.e.* low at full-load and high on no-load (about 20,000 r.p.m. in some cases). In fact, on no-load the speed is limited only by its own friction and windage load. Fig. 5.35 shows typical torque characteristics of a universal motor both for d.c. and a.c. supply. Usually, gear trains are used to reduce the actual load speeds to proper values.

(c) Applications:

Universal motors are used in vacuum cleaners where actual motor speed is the load speed. Other applications where motor speed is reduced by a gear train are : drink and food mixers, portable drills and domestic sewing machine etc.

(d) Reversal of Rotation.

The concentrated-pole (or salient-pole) type universal motor may be reversed by reversing the flow of current through either the armature or field windings. The usual method is to interchange the leads on the brush holders (Fig.5.36). The distributed-field compensated type universal motor may be reversed by interchanging either the armature or field leads and shifting the brushes against the direction in which the motor will rotate. The extent of brush shift usually amounts to several commutator bars.



5.6.6 Stepper Motor:

These motors are also called stepping motors or step motors. The name stepper is used because this motor rotates through a fixed angular step in response to each input current pulse received by its controller. In recent years, there has been widespread demand of stepping motors because of the explosive growth of the computer industry. Their popularity is due to the fact that they can be controlled directly by computers, microprocessors and



programmable controllers. As we know, industrial motors are used to convert electric energy into mechanical energy but they cannot be used for precision positioning of an

object or precision control of speed without using closed-loop feedback. Stepping motors are ideally suited for situations where either precise positioning or precise speed control or both are required in automation systems.

Apart from stepping motors, other devices used for the above purposes are synchros and resolvers as well as dc/ac servomotors (discussed later).

The unique feature of a stepper motor is that its output shaft rotates in a series of discrete angular intervals or steps, one step being taken each time a command pulse is received. When a definite number of pulses are supplied, the shaft turns through a definite known angle. This fact makes the motor well-suited for open-loop position control because no feedback need be taken from the output shaft.

Such motors develop torques ranging from 1N-m (in a tiny wrist watch motor of 3 mm diameter) upto 40 N-m in a motor of 15 cm diameter suitable for machine tool applications. Their power output ranges from about 1 W to a maximum of 2500 W. The only moving part in a stepping motor is its rotor which has no windings, commutator or brushes. This feature makes the motor quite robust and reliable.

Step Angle

The angle through which the motor shaft rotates for each command pulse is called the step angle α . Smaller the step angle, greater the number of steps per revolution and higher the resolution or accuracy of positioning obtained. The step angles can be as small as 0.72° or as large as 90°. But the most common step sizes are 1.8°, 2.5°, 7.5° and 15°.

The value of step angle can be expressed either in terms of the rotor and stator poles (teeth) Nr and Ns respectively or in terms of the number of stator phases (m) and the number of rotor teeth.

$$\beta = \frac{(N_s - N_r)}{N_s \cdot N_r} \times 360^{\circ}$$

or
$$\beta = \frac{360^{\circ}}{mN_r} = \frac{360^{\circ}}{\text{No. of stator phases } \times \text{No. of rotor teeth}}$$

For example, if $N_s = 8$ and $N_p = 6$, $\beta = (8 - 6) \times 360 / 8 \times 6 = 15^{\circ}$

Resolution is given by the number of steps needed to complete one revolution of the rotor shaft. Higher the resolution, greater the accuracy of positioning of objects by the motor

∴ Resolution = No. of steps / revolution = 360° / β

A stepping motor has the extraordinary ability to operate at very high stepping rates (upto 20,000 steps per second in some motors) and yet to remain fully in synchronism with the command pulses. When the pulse rate is high, the shaft rotation seems continuous. Operation at high speeds is called 'slewing'. When in the slewing range, the motor generally emits an audible whine having a fundamental frequency equal to the stepping rate. If f is the stepping frequency (or pulse rate) in pulses per second (pps) and α is the step angle, then motor shaft speed is given by

 $n = \beta \times f/360$ rps = pulse frequency resolution

If the stepping rate is increased too quickly, the motor loses synchronism and stops. Same thing happens if when the motor is slewing, command pulses are suddenly stopped instead of being progressively slowed. Stepping motors are designed to operate for long periods with the rotor held in a fixed position and with rated current flowing in the stator windings. It means that stalling is no problem for such motors whereas for most of the other motors, stalling results in the collapse of back emf (*Eb*) and a very high current which can lead to a quick burn-out.

Applications :

Such motors are used for operation control in computer peripherals, textile industry, IC fabrications and robotics etc. Applications requiring incremental motion are typewriters, line printers, tape drives, floppy disk drives, numerically-controlled machine tools, process control systems and *X*-*Y* plotters.

Usually, position information can be obtained simply by keeping count of the pulses sent to the motor thereby eliminating the need for expensive position sensors and feedback controls. Stepper motors also perform countless tasks outside the computer industry. It includes commercial, military and medical applications where these motors perform such functions as mixing, cutting, striking, metering, blending and purging. They also take part in the manufacture of packed food stuffs, commercial endproducts and even the production of science fiction movies.