ENERGY CONVERSION-II

LECTURE NOTE

Based on New syllabus (2018-19) circulated by SCTE&VT, Odisha for 1st and 2nd Semester Diploma Engineering courses approved by AICTE, New Delhi

PREPARED BY

Shibashis Kar

Lecturer (Electrical), Department of Electrical Engg.

Govt. Polytechnic Kalahandi

CHAPTER 1

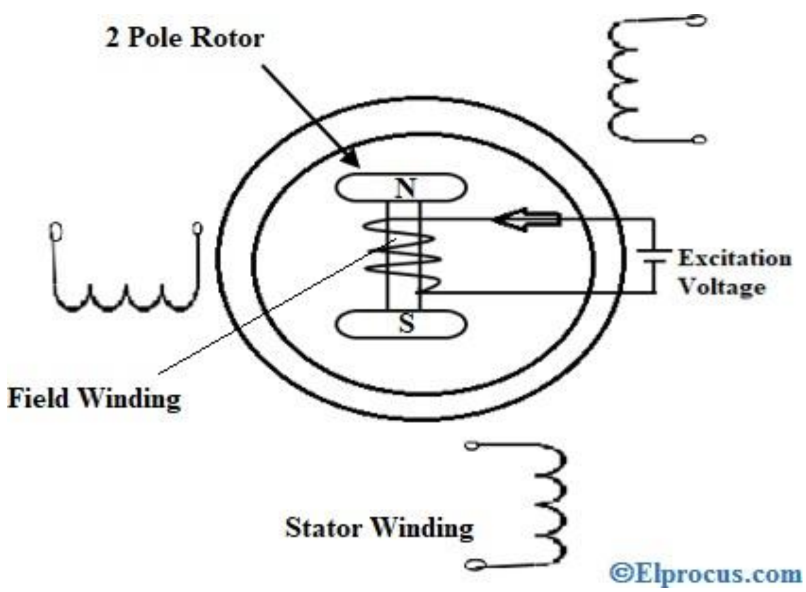
ALTERNATOR:

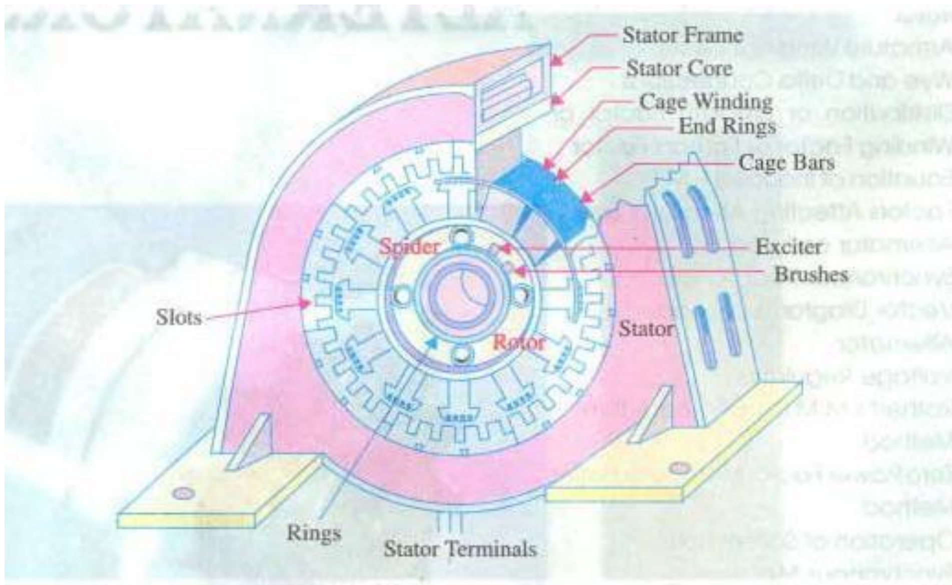
Types of alternator and their constructional features.

An alternator is defined as a machine or generator which produces AC (Alternating Current) supply and it converts mechanical energy into electrical energy, so it is also called an AC generator or synchronous generator.

Construction of an Alternator

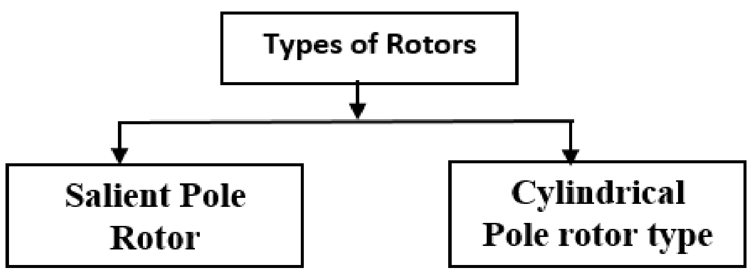
The main components of an alternator or synchronous generator are rotor and stator. The main difference between rotor and stator is, the rotor is a rotating part and stator is not a rotating component means it is a stationary part. The motors are generally run by rotor and stator. The armature conductors are housed on the stator.It consists of field poles placed on the rotating fixture of the machine. Alternator which have armature **stationary** and **rotating** field system differs from DC generator as its field system is **stationary** and armature **rotates**. There are different types of alternators based on applications and design. The Marine type alternator, Automotive type alternator, Diesel-electric locomotive types alternator, Brushless type alternator, and Radio alternators are the types of alternators based on the applications. The Salient Pole type and Cylindrical Rotor type are the types of alternators based on the rotor design.





Stator

The Stationary part of the alternator known as stator is made up of cast iron. It provides housing and support for the rotor. Slots are provided in the inner side of the stator to fix poles or windings. Ventilation inside alternator is maintained with the help of holes.



©Elprocus.com

Salient Pole Rotor

The meaning of the salient is projecting outward, which means the poles of the rotor are projecting outward from the center of the rotor. There is a field winding on the rotor and for this field winding will use DC supply. When we pass the current through this field winding N and S poles are created. The salient rotors are unbalanced so the speeds are restricted. This type of rotor used in hydro stations and diesel power stations. The salient pole rotor used for low-speed machines approximately 120-400rpm.It is characterized by large diameters and low axial length.

Cylindrical Rotor

The cylindrical rotor is also known as a non-salient rotor or round rotor and this rotor is used for high-speed machines approximately 1500-3000 rpm and the example for this is a thermal power plant. This rotor is made up of a steel radial cylinder having the number of slots and in these slots, the field winding is placed and these field windings are always connected in series. The advantages of this are mechanically robust, flux distribution is uniform, operates at high speed and produces low noise It is characterized by short diameters and long axial length

Damper Windings

The damper windings are basically copper bars short-circuited at both ends are placed in the holes made in the pole axis. These windings are helpful in preventing hunting (momentary speed fluctuations). When the alternator is driven at a steady speed, the relative velocity of the damping winding with respect to the main field will be zero. But as soon as it departs from the synchronous speed there will be relative motion between the damper winding and the main field which is always rotating at synchronous speed.

Basic working principle of alternator and the relation between speed and frequency.

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

One cycle of emf is induced in a conductor when one pair of poles passes over it. In other words, the emf in an armature conductor goes through one cycle in angular distance equal to twice the pole pitch.

Let P=total number of magnetic poles

N=rotative speed of the rotor in rpm

f =frequency of generated emf in Hz

Since one cycle of emf is produced when a pair of poles passes past a conductor, the number of cycles of emf produced in one revolution of the rotor is equal to the number of pair of poles. Therefore No. of cycles/revolution=P/2 and No. of revolutions/second=N/60

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

$$\mathbf{f = \frac{PN}{120}\ Hz}$$

where N is known as the synchronous speed, because it is the speed at which an alternator must run, in order to generate an emf of the required frequency.

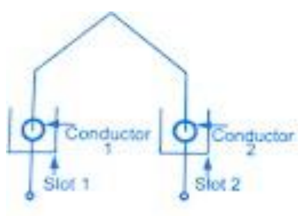
Armature windings

Armature windings of alternators are different from that of d.c machines. Basically, three phase alternators carry three sets of windings arranged in the slots in such a way that there exists a phase difference of 120° between the induced e.m.f.s in them.In a dc machine, winding is closed while in **alternators** winding is open i.e., two ends of each set of the winding are brought out.

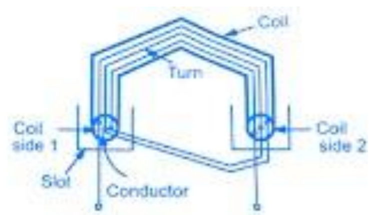
In three phase alternators, the six terminals are brought out which are finally connected in star or delta and then the three terminals are brought out.Each set of windings represents winding per phase and induced emf in each set is called induced emf per phase denoted as Eph.All the coils used for one phase must be connected in such a way that their emf.s help each other. And overall design should be in such a way that the waveform of an induced emf is almost sinusoidal in nature.

1) Conductor: The part of the wire, which is under the influence of the magnetic field and responsible for the induced emf is called active length of the conductor. The conductors are placed in the armature slots.

2) Turn: A conductor in one slot, when connected to a conductor in another slot forms a turn. So two conductors constitute a turn.This is shown in the below figure(a).



(a)Turn



(b)Multiturn coil

3) Coil: As there are a number of turns, for simplicity the number of turns are grouped together to form a coil. Such a coil is called a multi-turn coil. A coil may consist of single turn called single turn coil. Figure(b) shows a multi-turn coil.

4) Coil Side: Coil consists of many turns. Part of the coil in each slot is called coil side of a coil as shown in the above figure(b).

5) Pole Pitch: It is centre to centre distance between the two adjacent poles. 1 pole is responsible for 180° electrical of induced emf.So 180° electrical is also called one pole pitch. Practically the no. of slots under one pole responsible for 180° electrical, are measured to specify the pole pitch.

For example let us consider 2 poles, 18 slots armature of an alternator. Then under 1 pole, there are 18/2 i.e. 9 slots. So pole pitch is 9 slots or 180° electrical. This means 9 slots are responsible for producing a phase difference of 180° between the emfs induced in different conductors.

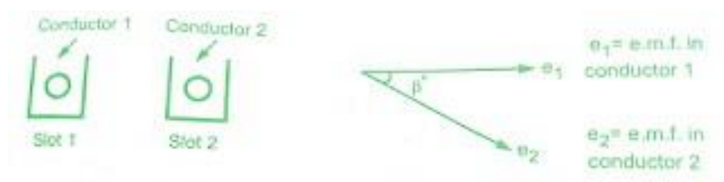
This number of slots/pole is denoted as 'n'.
Pole pitch = 180° electrical = slots per pole (no. of slots/P) = n

6) Slot angle (β): The phase difference contributed by one slot in degrees electrical is called slot angle As slots per pole contributes 180° electrical which is denoted as 'n', we can write,

$$1 \text{ slot angle} = 180°/n \quad ,\beta = 180°/n$$

In the above example, $n = 18/2 = 9$, while $\beta = 180°/n = 20°$

Note: This means that if we consider an induced e.m.f. in the conductors which are placed in the slots which are adjacent to each other, there will exist a phase difference of in between them.While if emf induced in the conductors which are placed in slots which are 'n' slots distance away, there will exist a phase difference of 180° in between them.



(a) Adjacent slots (b) Indication of phase differe

<u>Types of **Armature Windings** in Alternator:</u>

The different types of armature windings in alternators are,
1) Single layer and double layer winding
2) Full pitch and short pitch winding
3) Concentrated and distributed winding

<u>1) Single Layer and Double Layer Winding :</u>

If a slot consists of only one coil side, winding is said to be a single layer. This is shown in figure(a). While there are two coil sides per slot, one, at the bottom and one at the top the winding is called **double layer** as shown in figure(b).A lot of space gets wasted in single layer hence in practice generally **double layer winding** is preferred.

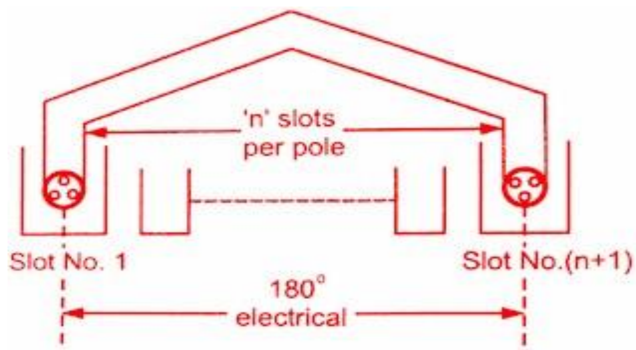
(a) Single layer (b) Double layer

Shibashis Kar

2) Full Pitch and Short Pitch Winding:

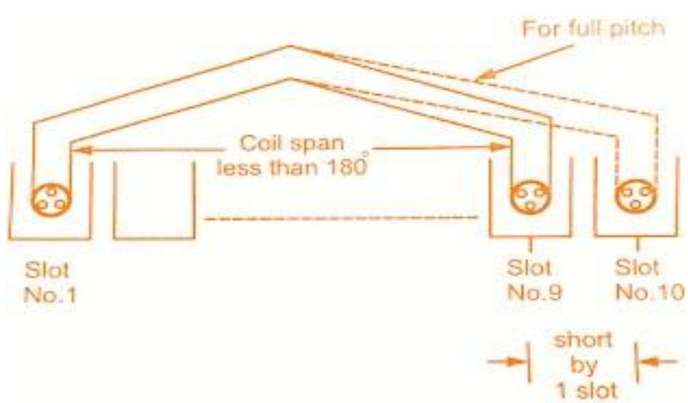
As seen earlier, one pole pitch is 180° electrical. The value of 'n', slots per pole indicates how many slots are contributing 180° electrical phase difference. So if coil side in one slot is connected to a coil side in another slot which is one pole pitch distance away from the first slot, the winding is said to be **full pitch winding** and coil is called full pitch coil. For example, in 2 poles, 18 slots alternator, the pole pitch is n = 18/2 = 9 slots. So if coil side in slot No. 1 is connected to coil side in slot No. 10 such that two slots No. 1 and No. 10 are one pole pitch or n slots or 180° electrical apart, the coil is called full pitch coil. Here we can define one more term related to a coil called coil span.

Coil Span:



It is the distance on the periphery of the armature, between two coil sides of a coil. It is usually expressed in terms of number of slots or degrees electrical. So if coil span is 'n' slots or 180° electrical the coil is called 180° full pitch coil. This is shown in the figure to left. As against this if coils are used in such a way that coil span is slightly less than a pole pitch i.e. less than 180° electrical, the coils are called, **short pitched coils** or fractional pitched coils. Generally, coils are shorted by one or two slots.

So in 18 slots, 2 pole alternator instead of connecting a coil side in slot No 1 to slot No.10, it is connected to a coil side in slot No.9 or slot No. 8, the coil is said to be short pitched coil and winding are called **short pitch winding**. This is shown in the below figure.



Shibashis Kar

Advantages of Short Pitch Coils:

In actual practice, short pitch coils are used as it has following advantages,

1. The length required for the end connections of coils is less i.e. the inactive length of winding is less. So less copper is required. Hence economical.
2. Short pitching eliminates high frequency harmonics which distort the sinusoidal nature of e.m.f. Hence waveform of an induced e.m.f. is more sinusoidal due to short pitching.
3. As high frequency harmonics get eliminated, eddy current and hysteresis losses which depend on frequency also get minimised. This increases the efficiency.

3) Concentrated and distributed winding:

In three phase alternators, we have seen that there are three **different sets of windings**, each for a phase. So depending upon the total number of slots and number of poles, we have certain slots per phase available under each pole. This is denoted as 'm'.

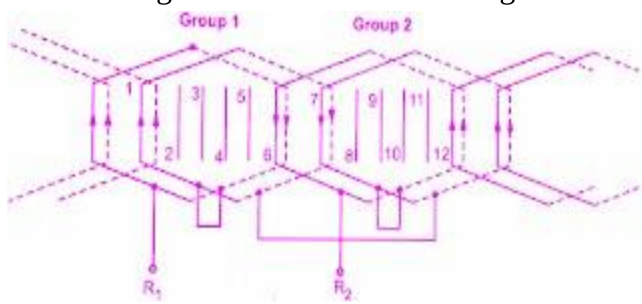
m = Slots per pole per phase = n/number of phases = n/3 (generally no. of phases is 3)
For example in 18 slots, 2 pole alternator we have, n = 18/2 = 9
and m = 9/3

So we have 3 slots per pole per phase available. Now let 'x' number of conductors per phase are to be placed under one pole. And we have 3 slots per pole per phase available. But if all 'x' conductors per phase are placed in one slot keeping remaining 2 slots per pole per phase empty then the winding is called **concentrated winding**. So in a **concentrated winding**, all conductors or coils belonging to a phase are placed in one slot under every pole.

But in practice, an attempt is always made to use all the 'm' slots per pole per phase available for distribution of the winding. So if 'x' conductors per phase are distributed amongst the 3 slots per phase available under every pole, the winding is called **distributed winding**. So in distributed type of winding all the coils belonging to a phase are well distributed over the 'm' slots per phase, under every pole. **Distributed winding** makes the waveform of the induced e.m.f. more sinusoidal in nature. Also in **concentrated winding** due to a large number of conductors per slot, heat dissipation is poor. So in practice, **double layer**, **short pitched** and distributed type of **armature winding** is preferred for the alternators. Full pitch coils are to be used so if phase 1 says R is started in slot 1, it is to be connected to a coil in slot 7. so that coil span will be 6 slots i.e. 'n' slots i.e. 1 pole pitch. As **distributed winding** is to be used, both the slots per pole per phase (m = 2) available are to be used to place the coils. And all coils for one phase are to be connected in series. So from slot No.7 we have to connect it to coil slot No.2 and slot No.2 second end to slot No.8 and so on. After finishing all slots per phase available under the first pair of pole, we will connect the coil to slot No.13 under next pole and winding will be repeated in a similar fashion. The starting end Rs and final end Rf winding for R-phase are taken out finally. Connections for R-phase only are shown in the below figure. Now, we want to have a phase difference of 120° between 'R' and 'Y'. Each slot contributes 30° as β = 30°.So start of 'Y' phase should be 120° apart from the start of 'R' i.e. 4 slots away from the start of R. So start of

'Y' will be in slot 5 and will get connected to slot No.11 to have full pitch coil. Similarly, the start of 'B' will be further 120° apart from 'Y' i.e. 4 slots apart start of 'Y' i.e. will be in slot No.9 and will continue similar to 'R'.

Finally, all six terminals of three sets will be brought out which are connected either in star or delta to get three ends R, Y and B outside to get three phase supply. The entire winding diagram with star connected windings is shown in the below figure.

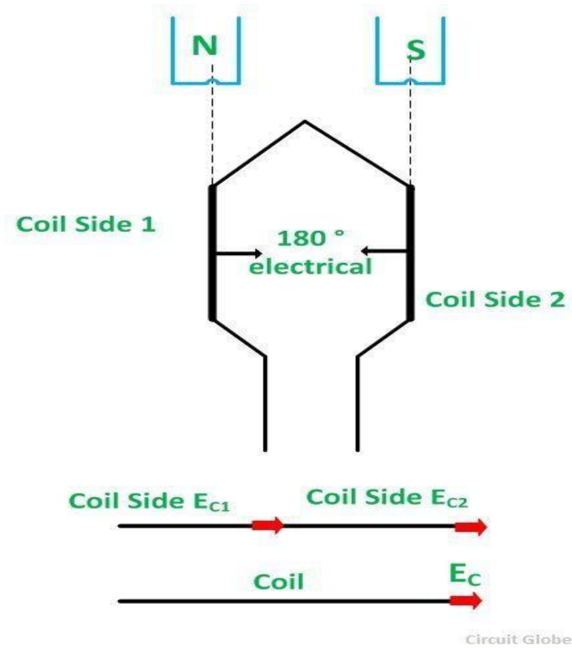


Double layer integral slot winding

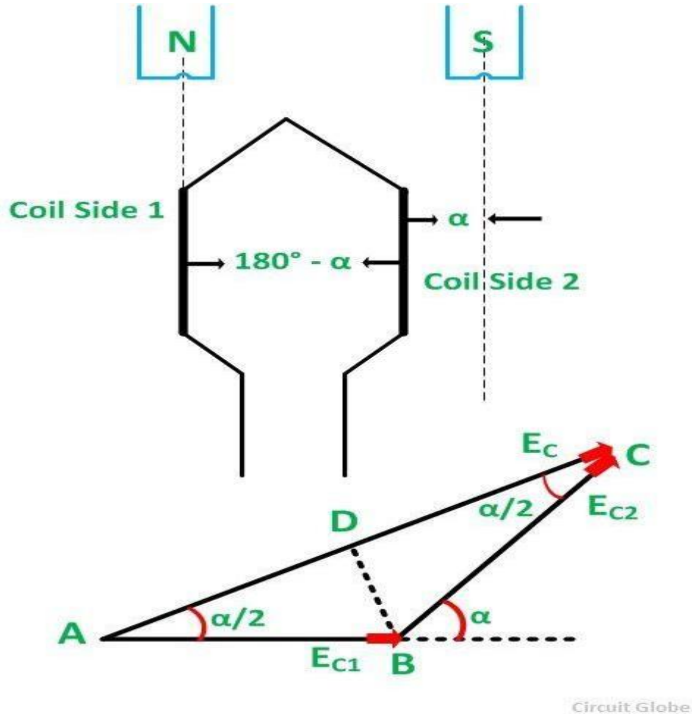
If the short pitch coils are used for **integral slot winding** then in each group of the slots per pole phase, the coil sides of different phases exist.

Pitch Factor

The **Pitch Factor** or **Coil Span Factor** K_C is defined as the ratio of the voltage generated in the short pitch coil to the voltage generated in the full pitch coil. The distance between he two sides of a coil is called the **Coil Span** or **Coil Pitch Factor**. It is also known as **Chording Factor.** The angular distance between the central line of one pole to the central line of the next pole is called **Pole Pitch**. A pole pitch is always 180 electrical degrees, regardless of the number of poles on the machine. A coil having a span equal to 180^0 electrical is called a **full pitch coi**l as shown in the figure below.



A Coil having a span less than 180^0 electrical is called a **short pitch coil** or fractional pitch coil. It is also called a Chorded coil. The short pitch coil factor is shown in the figure below.



A stator winding using fractional pitch coil is called a chorded winding. If the span of the coil is reduced by an angle α electrical degrees, the coil span will be (180 – α) electrical degrees.

In case of a full pitch coil, the distance between the two sides of the coil is exactly equal to the pole pitch of 180^0 electrical. As a result, the voltage in a full pitch coil is such that the voltage of each side of the coil is in phase.

Let E_{C1} and E_{C2} be the voltages generated in the coil sides, and E_C is the resultant coil voltage.

Then the equation is given as shown below.

$$E_C = E_{C1} + E_{C2}$$

$$|E_{C1}| = |E_{C2}| = E_1 \quad \text{(Say)}$$

Since E_{C1} and E_{C2} are in phase, the resultant coil voltage E_C is equal to their arithmetic sum.

Therefore,

$$E_C = E_{C1} + E_{C2} = 2E_1$$

Shibashis Kar

If the coil span of a single coil is less than the pole pitch of 180^0 electrical, the voltages generated on each coil side are not in phase. The resultant coil voltage E_C is equal to the phasor sum of E_{C1} and E_{C2}

If the coil span is reduced by an angle α electrical degrees, the coil span is (180 – α) electrical degrees. The voltage generated E_{C1} and E_{C2} in the two coil sides will be out of phase with respect to each other by an angle α electrical degrees. The phasor sum of E_{C1} and E_{C2} is E_C, which is equal to AC as shown in the phasor diagram above.

The coil span factor is represented as

$$K_C = \frac{\text{Actual Voltage Generated in the Coil}}{\text{Voltage Generated in the coil of span } 180^\circ \text{ electrical}}$$

$$K_C = \frac{\text{Phasor sum of the voltages of two coil sides}}{\text{Arithmetic sum of the voltages of two coil sides}}$$

$$K_C = \frac{AC}{2AB} = \frac{2AD}{2AB} = \cos\frac{\alpha}{2}$$

$$K_C = \cos\frac{\alpha}{2}$$

For full pitch coil, the value of α will be 0^0, cos α/2 = 1 and $\mathbf{K_C = 1}$.

For a short pitch coil $\mathbf{K_C < 1}$.

Distribution Factor

The **Distribution Factor** or the **Breadth Factor** is defined as the ratio of the actual voltage obtained to the possible voltage if all the coils of a polar group were concentrated in a single slot. It is denoted by $\mathbf{K_d}$ and is given by the equation shown below.

$$K_d = \frac{\text{Phasor Sum of the coil volatges per phase}}{\text{Arithmetic sum of coil voltages per phase}} \quad \ldots\ldots\ldots(1)$$

In a concentrated winding, each phase of a coil is concentrated in a single slot. The individual coil voltages induced are in phase with each other. These voltages must be added arithmetically. In order to determine the induced voltage per phase, a given coil voltage is multiplied by the number of series connected coils per phase. In actual practice, in each phase, coils are not concentrated in a single slot. They are distributed in a number of slots in space to form a polar group under each pole.

The voltages induced in coil sides are not in phase, but they differ by an angle β which is known as the angular displacement of the slots. The phasor sum of the individual coil voltages is equal to the total voltage induced in any phase of the coil.

Let,

M = slots per pole per phase

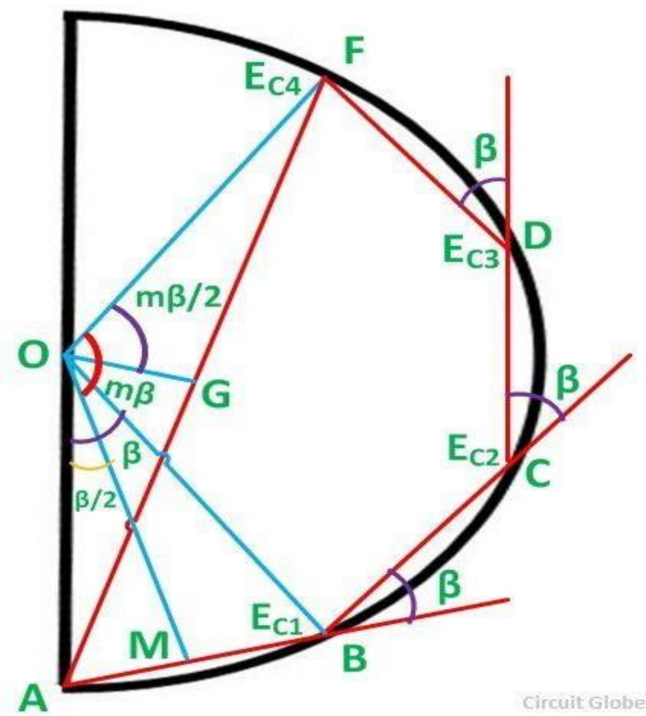
$$m = \frac{\text{slots}}{\text{poles x phases}} \quad \dots \dots (2)$$

β = angular displacement between adjacent slots in electrical degrees

$$\beta = \frac{180°}{\text{slots/pole}} = \frac{180° \text{ x poles}}{\text{slots}} \quad \dots \dots (3)$$

Thus, one phase of the winding consists of coils arranged in m consecutive slots. Voltages E_{C1}, E_{C2}, E_{C3}….. are the individual coil voltages. Each coil voltage E_C will be out of phase with the next coil voltages by the slot pitch β.

The figure below shows the voltage polygon of the induced voltages in the four coils of a group (m = 4)



The voltages E_{C1}, E_{C2}, E_{C3} and E_{C4} are represented by the phasors AB, BC, CD and DF respectively. Each of these phasor is a chord of a circle with the center O and subtends an angle β at the point O. The phasor sum AF, represents the resultant winding voltage, subtends at an angle mβ at the center.

Shibashis Kar

The arithmetic sum of the individual coil voltage is given as

$$mE_C = mAB = m(2AM)$$

$$= 2mOA \text{ Sin } AOM = 2m \text{ OA Sin } \beta/2$$

The phasor sum of the individual coil voltages is given as

$$= AF = 2AG = 2 \text{ OA Sin AOG} = 2 \text{ OA Sin } \frac{m\beta}{2}$$

Therefore, from the equation (1) shown above, we know that,

$$K_d = \frac{\text{Phasor Sum of the coil volatges per phase}}{\text{Arithmetic sum of coil voltages per phase}} = \frac{2 \text{ OA Sin m } \beta/2}{2 \text{ OA m Sin } \beta/2} \quad \text{or}$$

$$K_d = \frac{\text{Sin m } \beta/2}{\text{m Sin } \beta/2} \ldots \ldots (4)$$

The distribution factor Kd for a given number of phases is dependent only on the number of distributed slots under a given pole. It is independent of the type of the winding, lap or wave or the number of turns per coil, etc. the distribution factor decreases as the number of slots per pole increases.

Winding Factor

The winding factor is the method of improving the rms generated voltage in a three phase AC machines so that the torque and the output voltage does not consists any harmonics which reduces the efficiency of the machine**. Winding Factor**(K_w). is defined as the product of Distribution factor (K_d) and the coil span factor (K_c). **K_w=(K_c).x(K_d)**.

Explain harmonics, its causes and impact on winding factor

Harmonics are created by electronic equipment with nonlinear loads drawing in current in abrupt short pulses. The short pulses **cause** distorted current waveforms, which in turn **cause harmonic** currents to flow back into other parts of the power system.

If the flux distribution contains space harmonics, the chording angle for the r^{th} harmonic becomes r times the chording angle for the fundamental component and pitch factor for the r^{th} harmonic is given as,

$$K_{pr} = cos\frac{r\alpha}{2}$$

The slot angular pitch β on the fundamental scale, would become rβ for the r^{th} harmonic component and thus the distribution factor for the r^{th} harmonic would be.

$$K_{dr} = \frac{\sin \frac{rm\beta}{2}}{m \sin \frac{r\beta}{2}}$$

EMF Equation of a Synchronous Generator

The generator which runs at a synchronous speed is known as the synchronous generator. The synchronous generator converts the mechanical power into electrical energy for the grid.The Derivation of **EMF Equation** of a synchronous generator is given below.

Let,

P be the number of poles

ϕ is Flux per pole in Webers

N is the speed in revolution per minute (r.p.m)

f be the frequency in Hertz

Z_{ph} is the number of conductors connected in series per phase

T_{ph} is the number of turns connected in series per phase

K_c is the coil span factor

K_d is the distribution factor

Flux cut by each conductor during one revolution is given as **Pϕ** Weber.

Time taken to complete one revolution is given by **60/N** sec

Average **EMF** induced per conductor will be given by the equation shown below

$$\frac{P\varphi}{60/N} = \frac{P\varphi N}{60} \quad \text{volts}$$

Average **EMF** induced per phase will be given by the equation shown below

$$\frac{P\varphi N}{60} \times Z_{ph} = \frac{P\varphi N}{60} \times 2T_{ph} \quad \text{and}$$

$$T_{ph} = \frac{Z_{ph}}{2}$$

$$\text{Average EMF} = 4 \times \varphi \times T_{ph} \times \frac{PN}{120} = 4\varphi f T_{ph}$$

The average EMF equation is derived with the following assumptions given below.

1. Coils have got the full pitch.
2. All the conductors are concentrated in one stator slot.

Root mean square (R.M.S) value of the EMF induced per phase is given by the equation shown below.

E_{ph} (rms) = Average value x form factor

Therefore,

$$E_{ph} = 4\varphi f T_{ph} \times 1.11 = 4.44\, \varphi\, f\, T_{ph} \text{ volts}$$

If the coil span factor K_c and the distribution factor K_d , are taken into consideration than the Actual **EMF** induced per phase is given as

$$E_{ph} = 4.44\, K_c K_d \varphi\, f\, T_{ph} \text{ volts} \;\ldots\ldots(1)$$

Equation (1) shown above is the EMF equation of the Synchronous Generator.

ALTERNATOR ON LOAD

(a) Armature Resistance

The armature resistance/phase R_a causes a voltage drop/phase of IR_a which is in phase with the armature current I. However, this voltage drop is practically negligible.

(b) Armature Leakage Reactance

When current flows through the armature conductors, fluxes are set up which do not cross the air-gap, but take different paths. Such fluxes are known as *leakage fluxes*. Various types of leakage fluxes are shown in Fig. 37.22.

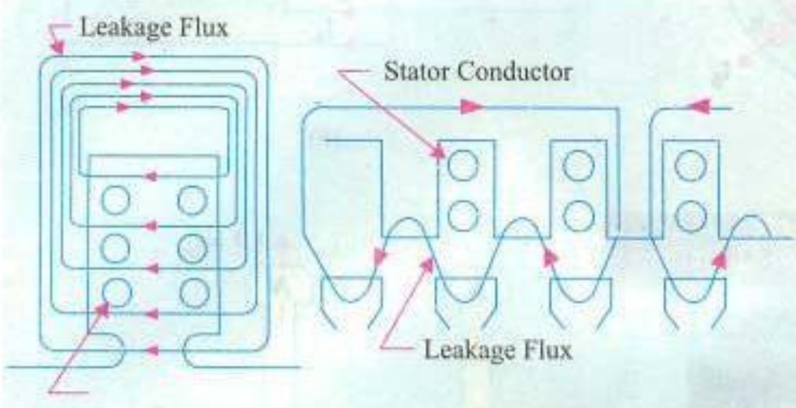


Fig. 37.22

Fig. 37.23

The leakage flux is practically independent of saturation, but is dependent on I and its phase angle with terminal voltage V. This leakage flux sets up an e.m.f. of self-inductance which is known as *reactance e.m.f.* and which is ahead of I by 90°. Hence, armature winding is assumed to possess leakage reactance X_L (also known as Potier rectance X_P) such that voltage drop due to this equals IX_L. A part of the generated e.m.f. is used up in overcoming this reactance e.m.f.

$$\therefore \qquad E = V + I\,(R + jX_L)$$

This fact is illustrated in the vector diagram of Fig. 37.23.

(c) 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 amp-turn 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. 37.24 (*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 I_a, I_b and I_c are in phase with their respective phase voltages. Maximum current I_a will flow when the poles are in position shown in Fig. 37.24 (*a*) or at a time t_1 in Fig. 37.24 (*c*). When I_a has a maximum value, I_b and I_c have one-half their maximum values (the arrows attached to I_a, I_b and I_c are only polarity marks and are not meant to give the instantaneous directions of these currents at time t_1). The instantaneous directions of currents are shown in Fig. 37.24 (*a*). At the instant t_1, I_a flows in conductor α whereas I_b and I_c flow out.

Shibashis Kar

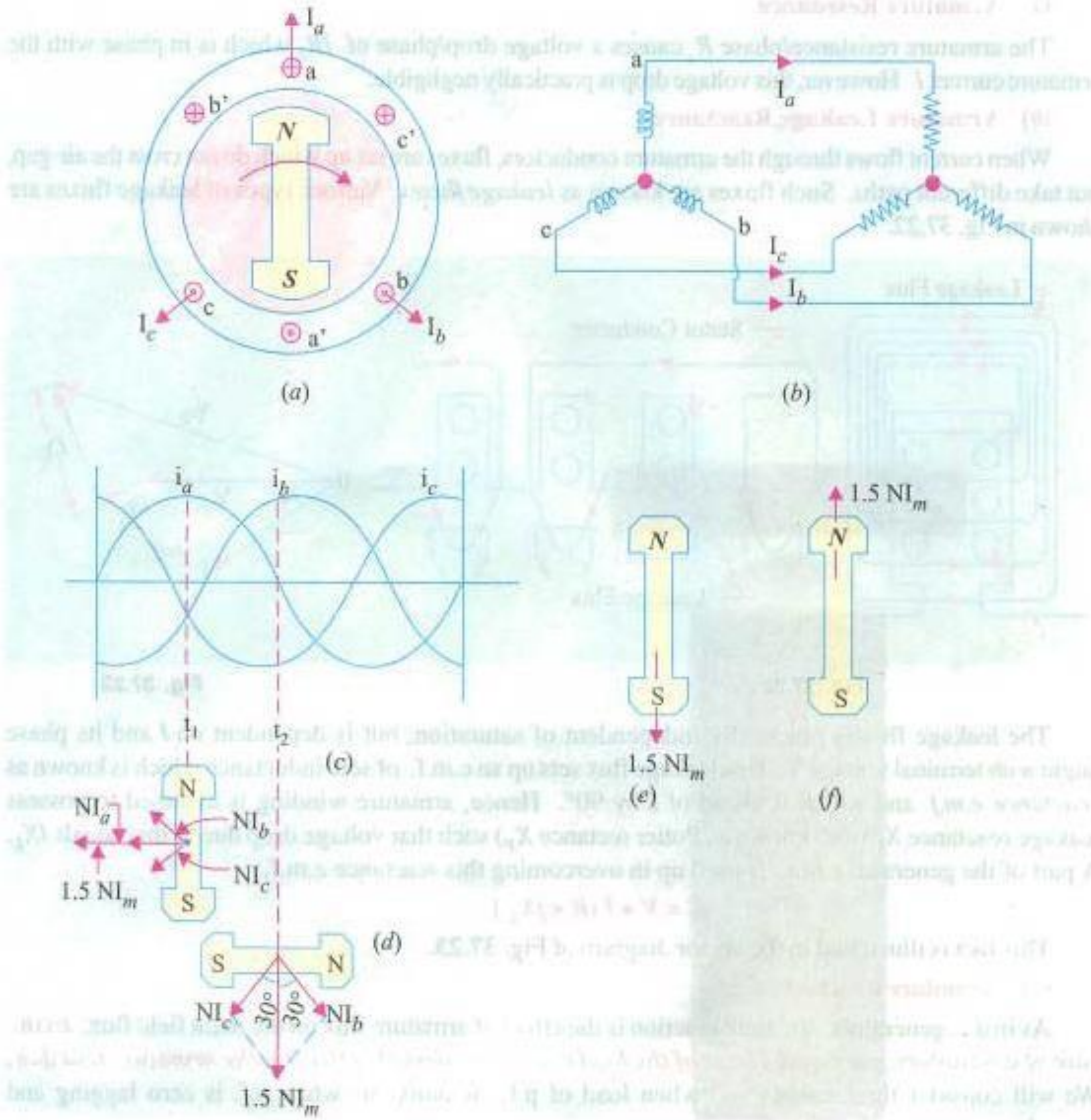


Fig. 37.24

As seen from Fig. 37.24 (*d*), the m.m.f. ($= NI_m$) produced by phase *a-a'* is horizontal, whereas that produced by other two phases is $(I_m/2)$ 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.

$\therefore$ Armature m.m.f. $= NI_m + 2.(1/2\, NI_m) \cos 60° = 1.5\, NI_m$

As seen, at this instant t_1, 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 $I_a = 0$, but I_b and I_c are each equal to 0.866 of their maximum values. Since I_c has not changed in direction during the interval t_1 to t_2, the direction of its m.m.f. vector remains unchanged. But I_b has changed direction, hence, its m.m.f. vector will now be in the position shown in Fig. 37.24 (*d*). Total armature m.m.f. is again the vector sum of these two m.m.fs.

$\therefore$ Armature m.m.f. $= 2 \times (0.866\, NI_m) \times \cos 30° = 1.5\, NI_m$.

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

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

Shibashis Kar

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 factor, 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. 37.24 (*e*). Obviously, armature m.m.f. would demagnetise the poles and cause a reduction in the induced e.m.f. and hence the terminal voltage.

For leading loads of zero power factor, the armature m.m.f. is advanced 90° with respect to the position shown in Fig. 37.24 (*d*). As shown in Fig. 37.24 (*f*), the armature m.m.f. strengthens the main m.m.f. In this case, armature reaction is wholly magnetising 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. 37.25 (*a*)] the armature flux is cross-magnetising. 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. 37.25 (*b*), here the armature flux (whose wave has moved backward by 90°) is in direct opposition to the main flux.

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. 37.25 (*c*) armature flux wave has moved forward by 90° 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.

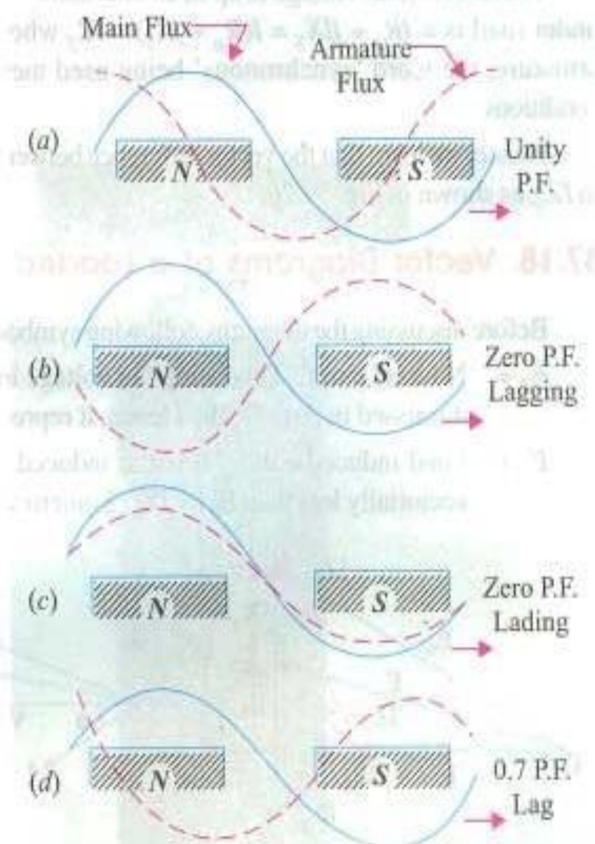


Fig. 37.25

4. For intermediate power factor [Fig. 37.25 (*d*)], the effect is partly distortional and partly demagnetising (because p.f. is lagging).

Shibashis Kar

Thus to summarize, the effect of armature reaction mmf on main field mmf of alternator is tabulated below.

Sr. No.	Loading Condition	Effect of Armature Reaction
1)	No Load	No effect
2)	Unity Power Factor	Cross-magnetizing
3)	Zero Power Factor Lagging	Purely demagnetizing
4)	Zero Power Factor Leading	Purely magnetizing
5)	Lagging Load	Cross-magnetizing and demagnetizing

Vector Diagram Of Loaded Alternator.

From the above discussion, it is clear that for the same field excitation, terminal voltage is decreased from its no-load value E_0 to V (for a lagging power factor). This is because of

1. drop due to armature resistance, IR_a
2. drop due to leakage reactance, IX_L
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 X_a in the armature winding. The value of X_a is such that IX_a represents the voltage drop due to armature reaction.

The leakage reactance X_L (or X_P) and the armature reactance X_a may be combined to give synchronous reactance X_S.

Hence $X_S = X_L + X_a$*

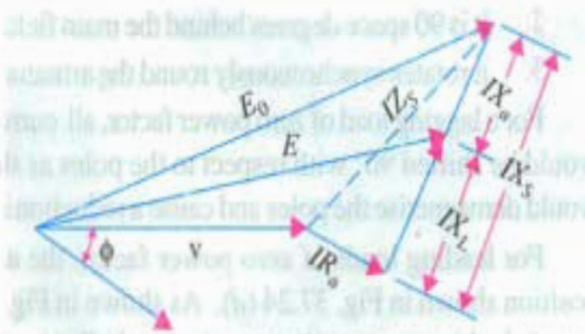


Fig. 37.26

Therefore, total voltage drop in an alternator under load is $= IR_a + jIX_S = I(R_a + jX_S) = IZ_S$ where Z_S 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 E_0 and terminal voltage V is equal to IZ_S, as shown in Fig. 37.26.

Shibashis Kar

Before discussing the diagrams, following symbols should be clearly kept in mind.

E_0 = No-load e.m.f. This being the voltage induced in armature in the absence of three factors discussed in Art. 37.16. Hence, it represents the maximum value of the induced e.m.f.

E = Load induced e.m.f. It is the induced e.m.f. after allowing for armature reaction. E is vectorially less than E_0 by IX_a. Sometimes, it is written as E_a (Ex. 37.16).

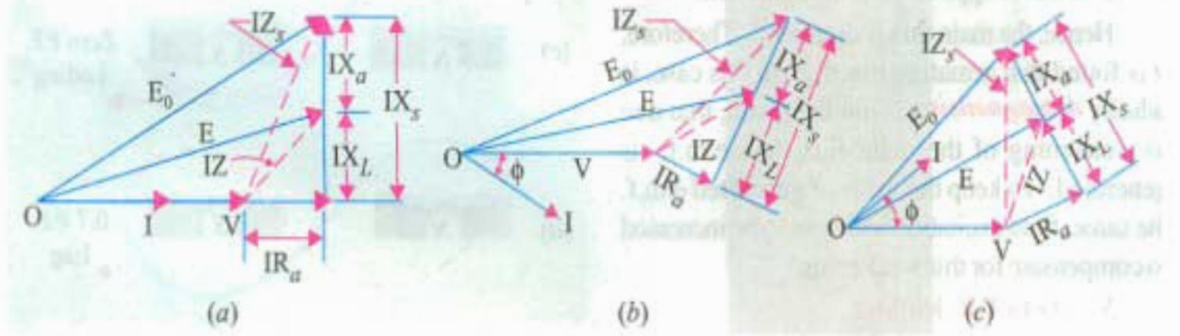


Fig. 37.27

V = Terminal voltage, It is vectorially less than E_0 by IZ_S or it is vectorially less than E by I_Z where

Z = $\sqrt{(R_a^2 + X_L^2)}$. It may also be written as Z_a.

I = armature current/phase and ϕ = load p.f. angle.

In Fig. 37.27 (*a*) is shown the case for unity p.f., in Fig. 37.27 (*b*) for lagging p.f. and in Fig. 37.27 (*c*) for leading p.f. All these diagrams apply to one phase of a 3-phase machine. Diagrams for the other phases can also be drawn similary.

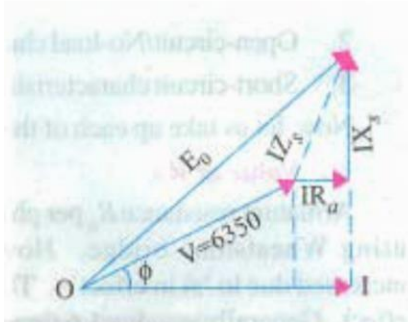


Fig. 37.28

As seen from the vector diagram of Fig. 37.28 where I instead of V has been taken along reference vector,

$$E_0 = \sqrt{(V \cos \phi + IR_a)^2 + (V \sin \phi + IX_S)^2}$$

Shibashis Kar

Voltage Regulation of a Synchronous Generator

The **Voltage Regulation** of a **Synchronous Generator** is the rise in voltage at the terminals when the load is reduced from full load rated value to zero, speed and field current remaining constant. It depends upon the power factor of the load. For unity and lagging power factors, there is always a voltage drop with the increase of load, but for a certain leading power, the full load voltage regulation is zero.

The voltage regulation is given by the equation shown below.

$$\text{Per Unit Voltage Regulation} \triangleq \frac{|E_a| - |V|}{|V|} \quad \ldots\ldots\ldots (1)$$

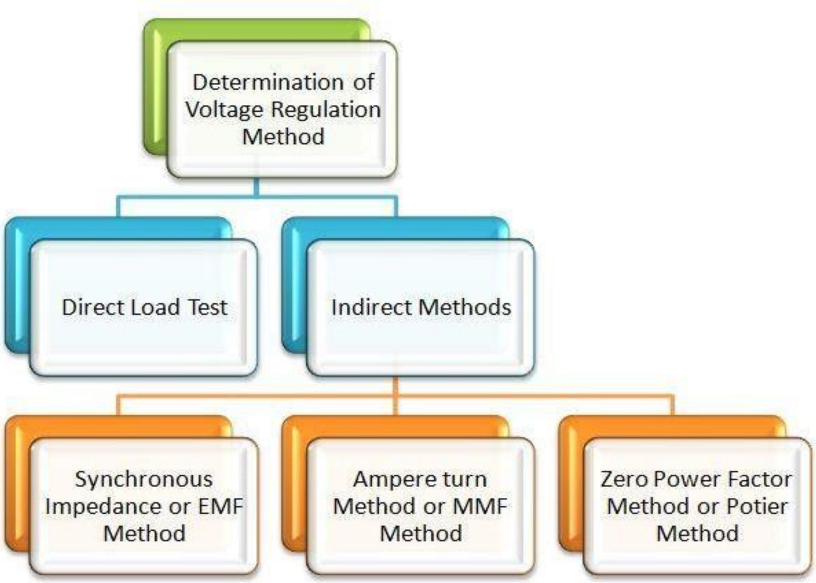
$$\text{Percentage Voltage Regulation} \triangleq \frac{|E_a| - |V|}{|V|} \times 100 \quad ..(2)$$

Where, $|E_a|$ is the magnitude of a generated voltage per phase, $|V|$ is the magnitude of rated terminal voltage per phase.

In this case, the terminal voltage is the same for both full load and no load conditions. At lower leading power factors, the voltage rises with the increase of load, and the regulation is negative.

Determination of Voltage Regulation

There are mainly two methods which are used to determine the regulation of voltage of a smooth cylindrical rotor type alternators. They are named as **direct load test** method and **indirect methods** of voltage regulation. The indirect method is further classified as **Synchronous Impedance** Method, **Ampere-turn** Method and **Zero Power Factor** Method.



Shibashis Kar

Direct Load Test

The alternator runs at synchronous speed, and its terminal voltage is adjusted to its rated value V. The load is varied until the Ammeter and Wattmeter indicate the rated values at the given power factor. The load is removed, and the speed and the field excitation are kept constant. The value of the open circuit and no load voltage is recorded.

It is also found from the percentage voltage regulation and is given by the equation shown below.

$$\% \text{ Voltage Regulation} = \frac{E_a - V}{V} \text{ x } 100\%$$

The method of direct loading is suitable only for small alternators of the power rating less than 5 kVA.

Indirect Methods of Voltage Regulation

For large alternators, the three indirect methods are used to determine the voltage regulation they are as follows.

1. Synchronous Impedance Method or EMF method.
2. Ampere-turn method or MMF method of Voltage Regulation.
3. Zero Power Factor method or Potier Method

Only Synchronous Impedance Method or EMF method is in scope of syllabus.

Synchronous Impedance Method

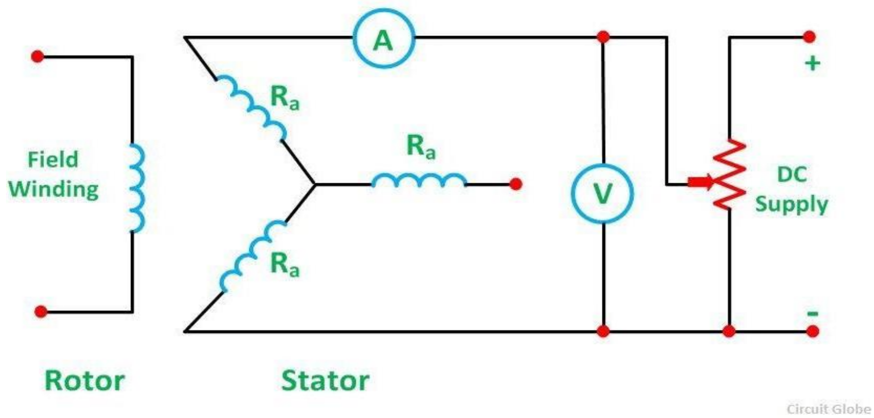
The **Synchronous Impedance Method or Emf Method** is based on the concept of replacing the effect of armature reaction by an imaginary reactance. For calculating the regulation, the synchronous method requires the following data; they are the armature resistance per phase and the open circuit characteristic. The open circuit characteristic is the graph of the circuit voltage and the field current. This method also requires short circuit characteristic which is the graph of the short circuit and the field current.

The measurement of synchronous impedance is done by the following tests. They are known as

1. DC resistance test
2. Open circuit test
3. Short circuit test

DC resistance test

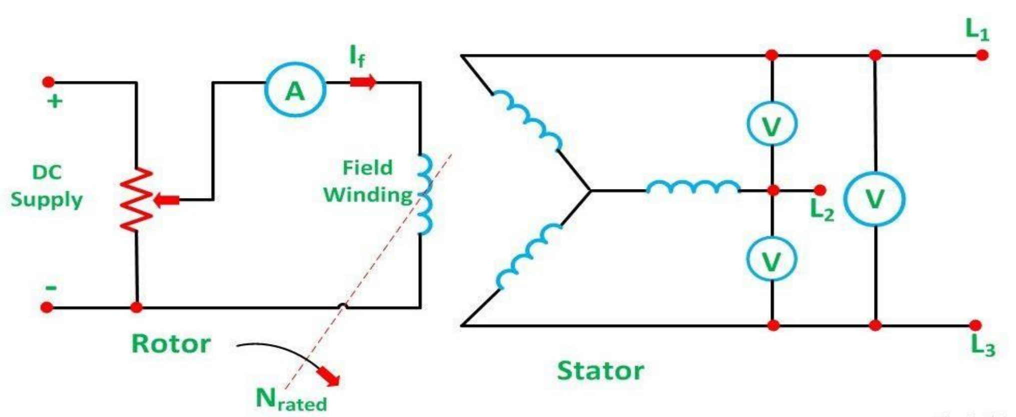
In this test, it is assumed that the alternator is star connected with the DC field winding open as shown in the circuit diagram below.



It measures the DC resistance between each pair of terminals either by using an ammeter – voltmeter method or by using the Wheatstone's bridge. The average of three sets of resistance value R_t is taken. The value of R_t is divided by 2 to obtain a value of DC resistance per phase. Since the effective AC resistance is larger than the DC resistance due to skin effect. Therefore, the effective AC resistance per phase is obtained by multiplying the DC resistance by a factor 1.20 to 1.75 depending on the size of the machine. A typical value to use in the calculation would be 1.25.

Open Circuit Test

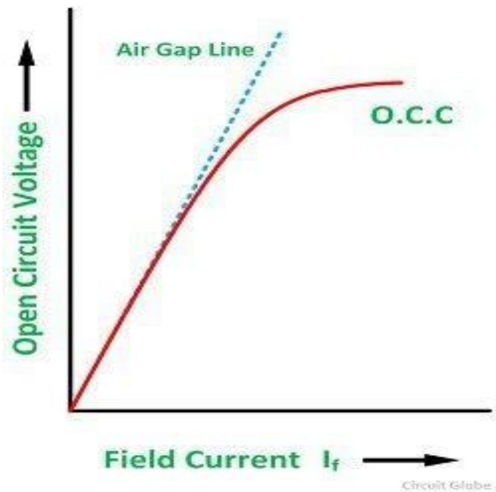
In the **open circuit test** for determining the synchronous impedance, the alternator is running at the rated synchronous speed, and the load terminals are kept open. This means that the loads are disconnected, and the field current is set to zero. The circuit diagram is shown below.



Shibashis Kar

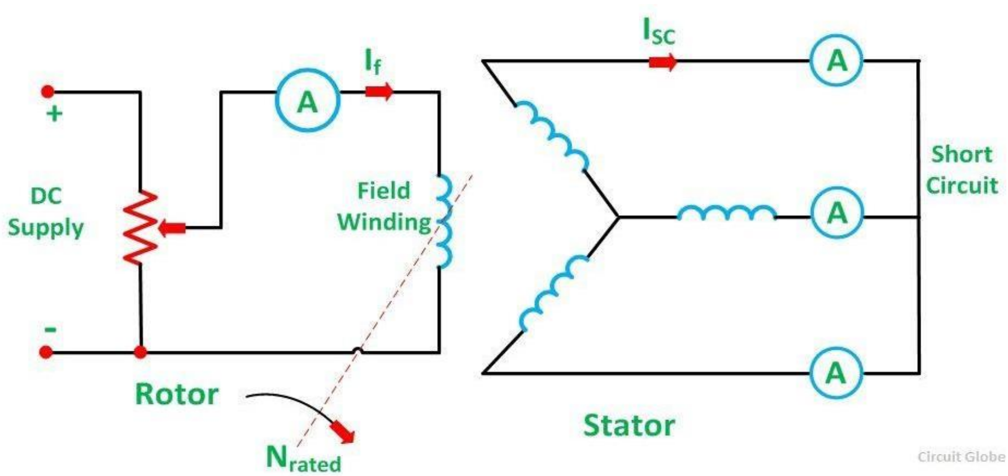
After setting the field current to zero, the field current is gradually increased step by step. The terminal voltage E_t is measured at each step. The excitation current may be increased to get 25% more than the rated voltage. A graph is drawn between the open circuit phase voltage $E_p = E_t/\sqrt{3}$ and the field current I_f. The curve so obtains called Open Circuit Characteristic (O.C.C). The shape is same as normal magnetisation curve. The linear portion of the O.C.C is extended to form an air gap line.

The **Open Circuit Characteristic (O.C.C)** and the air gap line is shown in the figure below.



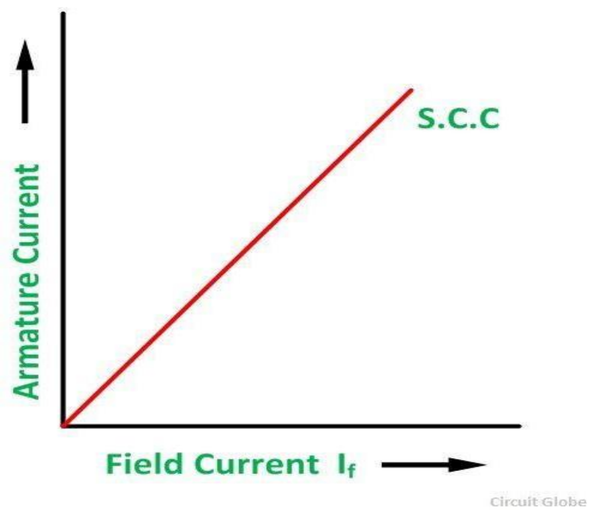
Short Circuit Test

In the **short circuit test**, the armature terminals are shorted through three ammeters as shown in the figure below.



The field current should first be decreased to zero before starting the alternator. Each ammeter should have a range greater than the rated full load value. The alternator is then run at synchronous speed. Same as in an open circuit test that the field current is increased gradually in steps and the armature current is measured at each step. The field current is increased to get armature currents up to 150% of the rated value.

The value of field current If and the average of three ammeter readings at each step is taken. A graph is plotted between the armature current Ia and the field current If. The characteristic so obtained is called **Short Circuit Characteristic (S.C.C)**. This characteristic is a straight line as shown in the figure below.



Calculation of Synchronous Impedance

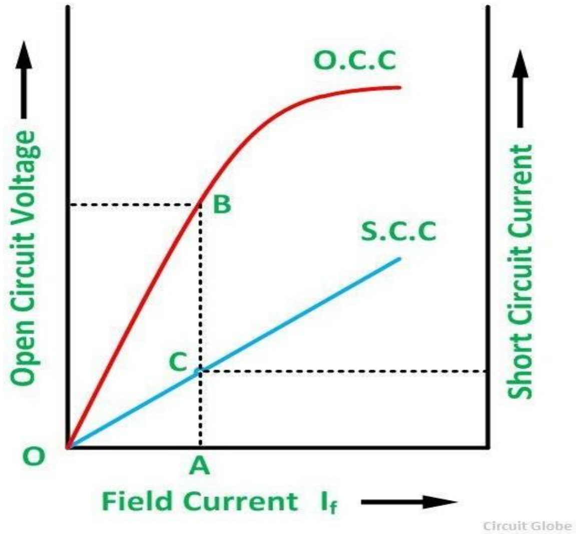
1. The following steps are given below for the calculation of the synchronous impedance.
2. The open circuit characteristics & the short circuit characteristic are drawn on the same curve.
3. Determine the value of short circuit current I_{sc} and gives the rated alternator voltage per phase.
4. The synchronous impedance Z_S will then be equal to the open circuit voltage divided by the short circuit current at that field current which gives the rated EMF per phase.

$$Z_S = \frac{\text{Open circuit voltage per phase}}{\text{Short circuit armature current}} \quad \text{(for the same value of field current)}$$

The synchronous reactance is determined as

$$X_S = \sqrt{Z_S^2 - R_a^2}$$

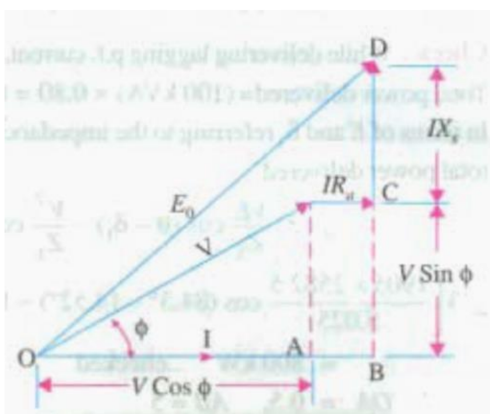
The graph is shown below.



From the above figure consider the field current I_f = OA that produces rated alternator voltage per phase. Corresponding to this field current, the open circuit voltage is AB

Therefore,

$$Z_S = \frac{\text{AB (in volts)}}{\text{AC (in amperes)}}$$



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

or $E_0 = \sqrt{[(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2]}$

$\therefore$ % regn. 'up' $= \dfrac{E_0 - V}{V} \times 100$

Shibashis Kar

Parallel operation of alternator

Parallel operation of alternator is a method of adding an alternator in the existing live system with another alternator. When there is more demand of power to supply the load, there comes the need of additional generator. So, an additional generator is connected to the live system to deliver the required power.

Parallel operation of alternator is needed to satisfy one or many of the following.

- To supply big loads, paralleling of alternator is essential, which cannot be fulfilled by a single alternator.
- During light load condition, instead of operating all the alternators, it is better to operate one alternator and shut down the other alternators.
- If any one of the alternator is shut down because of any problem or maintenance, the other alternator in parallel is operated for continued supply.
- If there is any increase in the demand of power, then it is possible to add another alternator to meet the demand.
- Operating two or more alternators in parallel will reduce the operating cost and the cost of energy generation.

Conditions for Parallel Operation

For proper synchronization of alternators, the following three conditions must be satisfied.

1. The terminal voltage of the incoming alternator must be same as the bus-bar voltage.
2. The speed of the incoming machine must be such that its frequency equals bus-bar frequency.
3. The phase of the alternator voltage must be identical with the phase of the bus-bar voltage. The switch must be closed at the instant the two voltage have correct phase relationships.

Synchronizing of Alternators

(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 L_1 and L_2 (known as synchronizing lamps) connected as shown in Fig. 37.74.

It should be noted that E_1 and E_2 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 continously 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. 37.75.

Sometimes the resultant voltage is maximum and some other times minimum. Hence, the current is alternatingly maximum and minimum. Due to this changing current through the lamps, a flicker will be produced, the frequency of flicker being $(f_2 \sim f_1)$. Lamps will dark out and glow up alternately. Darkness indicates that the two voltages E_1 and E_2 are in exact phase opposition relative to the local circuit and hence

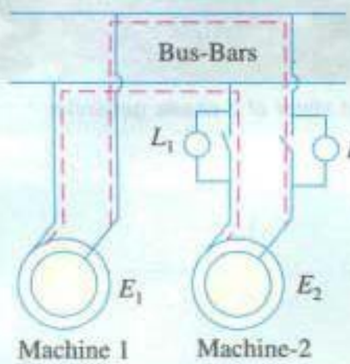


Fig. 37.74

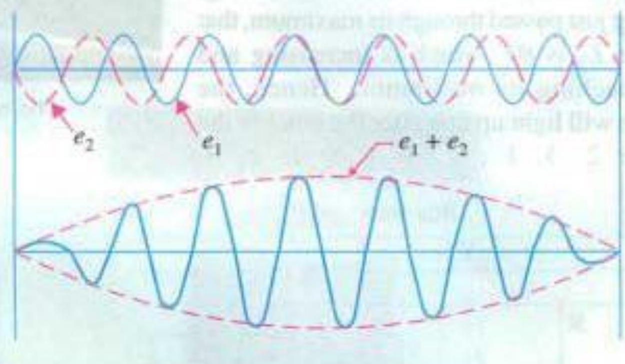


Fig. 37.75

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. 37.76. 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.

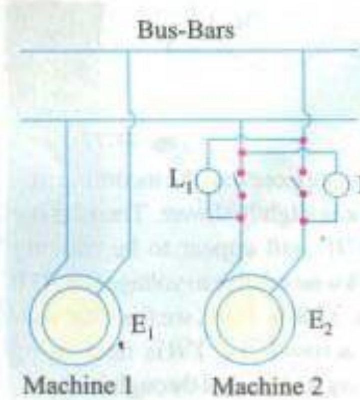


Fig. 37.76

(b) Three-phase Alternators

In 3-ϕ 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. 37.77 and 37.78.

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 L_1 is connected between R and R', L_2 between Y and B' (not Y and Y') and L_3 between B and Y' (and not B and B'), as shown in Fig. 37.78.

Voltage stars of two machines are shown superimposed on each other in Fig. 37.79.

Shibashis Kar

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 $R'Y'B'$ 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. 37.79, it is seen that voltage across L_1 is RR' and is seen to be increasing from zero, that across L_2 is YB' which is decreasing, having just passed through its maximum, that across L_3 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.

The rotor and stator of 3-phase generator

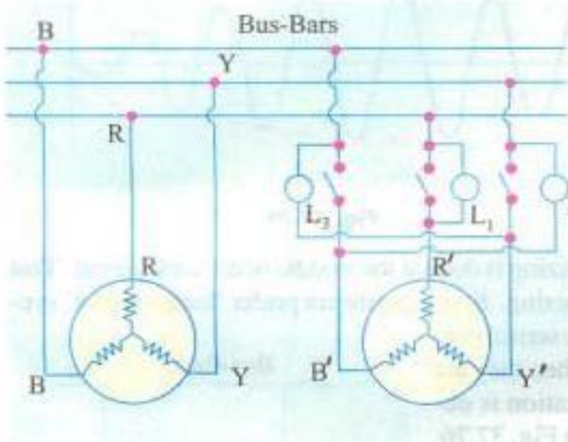


Fig. 37.77

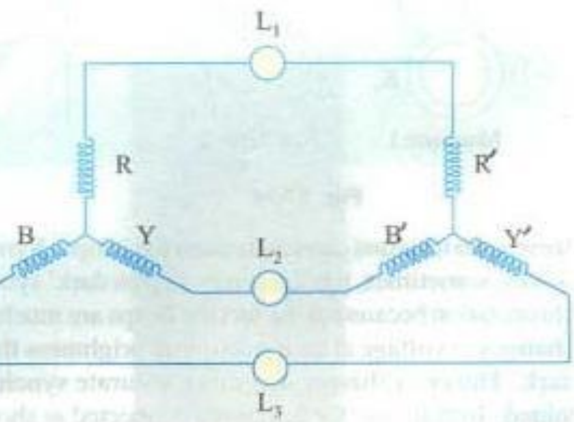


Fig. 37.78

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 L_3 *i.e.* $Y'B$ is decreasing having just passed through its maximum, that across L_2 *i.e.* YB' is increasing and approaching its maximum, that across L_1 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

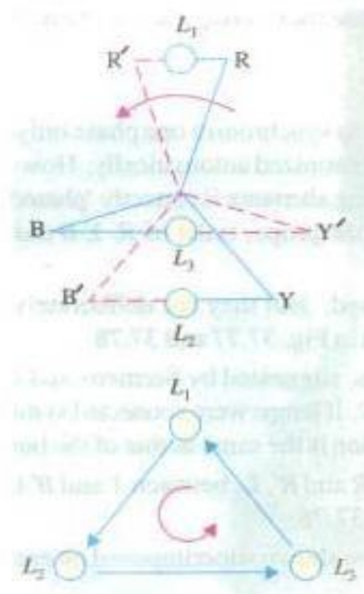


Fig. 37.79

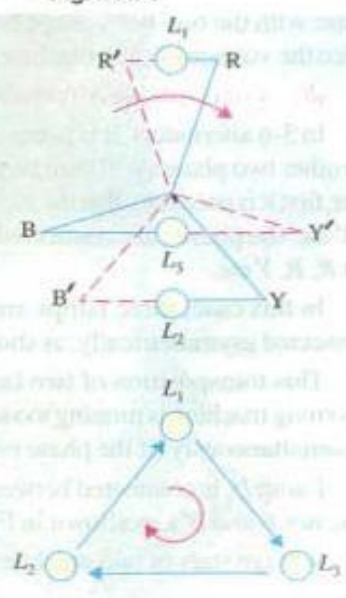


Fig. 37.80

Shibashis Kar

indicates whether the incoming alternator is running too fast or too slow (Fig. 37.81). Synchronization is done at the moment the uncrossed lamp L_1 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 secondaries.

It will be noted that when the uncrossed lamp L_1 is dark, the other two 'crossed' lamps L_2 and L_3 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 judgement 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 a 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.

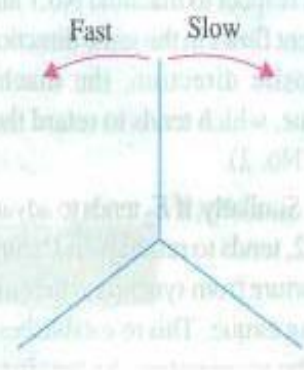


Fig. 37.81

Explain distribution of load by parallel connected alternators.

37.38. Parallel Operation of Two Alternators

Consider two alternators with identical speed/load characteristics connected in parallel as shown in Fig. 37.86. The common terminal voltage **V** is given by

$$\mathbf{V} = \mathbf{E}_1 - \mathbf{I}_1\mathbf{Z}_1 = \mathbf{E}_2 - \mathbf{I}_2\mathbf{Z}_2$$

$$\therefore \quad \mathbf{E}_1 - \mathbf{E}_2 = \mathbf{I}_1\mathbf{Z}_1 - \mathbf{I}_2\mathbf{Z}_2$$

Also $\quad \mathbf{I} = \mathbf{I}_1 + \mathbf{I}_2$ and $\mathbf{V} = \mathbf{IZ}$

$$\therefore \quad \mathbf{E}_1 = \mathbf{I}_1\mathbf{Z}_1 + \mathbf{IZ} = \mathbf{I}_1(\mathbf{Z} + \mathbf{Z}_1) + \mathbf{I}_2\mathbf{Z}$$

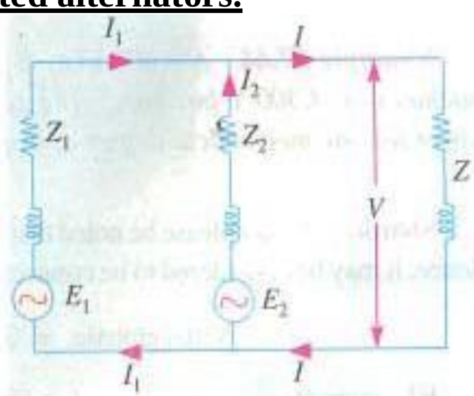


Fig. 37.86

Shibashis Kar

$$E_2 = I_2Z_2 + IZ = I_2(Z + Z_2) + I_1Z$$

$$\therefore \quad I_1 = \frac{(E_1 - E_2)\,Z + E_1Z_2}{Z\,(Z_1 + Z_2) + Z_1Z_2}$$

$$I_2 = \frac{(E_2 - E_1)\,Z + E_2Z_1}{Z\,(Z_1 + Z_2) + Z_1Z_2};$$

$$I = \frac{E_1Z_2 + E_2Z_1}{Z\,(Z_1 + Z_2) + Z_1Z_2}$$

$$V = IZ = \frac{E_1\,Z_2 + E_2Z_1}{Z_1 + Z_2 + (Z_1Z_2/Z)};\, I_1 = \frac{E_1 - V}{Z_1};\, I_2 = \frac{E_2 - V}{Z_2}$$

The circulating current under no-load condition is $I_C = (E_1 - E_2)/(Z_1 + Z_2)$.

Using Admittances

The terminal Voltage may also be expressed in terms of admittances as shown below:

$$V = IZ = (I_1 + I_2)Z \qquad \therefore\; I_1 + I_2 = V/Z = VY \qquad \text{..}(i)$$

Also $\quad I_1 = (E_1 - V)/Z_1 = (E_1 - V)Y_1; \qquad I_2 = (E_2 - V)/Z_2 = (E_2 - V)Y_2$

$$\therefore \quad I_1 + I_2 = (E_1 - V)\,Y_1 + (E_2 - V)Y_2 \qquad \text{...}(ii)$$

From Eq. (*i*) and (*ii*), we get

$$VY = (E_1 - V)Y_1 + (E_2 - V)Y_2 \quad \text{or} \quad V = \frac{E_1\,Y_1 + E_2Y_2}{Y_1 + Y_2 + Y}$$

Using Parallel Generator Theorem

$$V = IZ = (I_1 + I_2)\,Z = \left(\frac{E_1 - V}{Z_1} + \frac{E_2 - V}{Z_2}\right)Z$$

$$= \left(\frac{E_1}{Z_1} + \frac{E_2}{Z_2}\right)Z - V\left(\frac{1}{Z_1} + \frac{1}{Z_2}\right)Z$$

$$\therefore \quad V\left(\frac{1}{Z} + \frac{1}{Z_1} + \frac{1}{Z_2}\right) = \frac{E_1}{Z_1} + \frac{E_2}{Z_2} = I_{SC1} + I_{SC2} = I_{SC}$$

where I_{SC1} and I_{SC2} are the short-circuit currents of the two alternators.

If $$\frac{1}{Z_0} = \left(\frac{1}{Z} + \frac{1}{Z_1} + \frac{1}{Z_2}\right);\ \text{then } V \times \frac{1}{Z_0} = I_{SC} \text{ or } V = Z_0\,I_{SC}$$

****

Shibashis Kar

CHAPTER 2

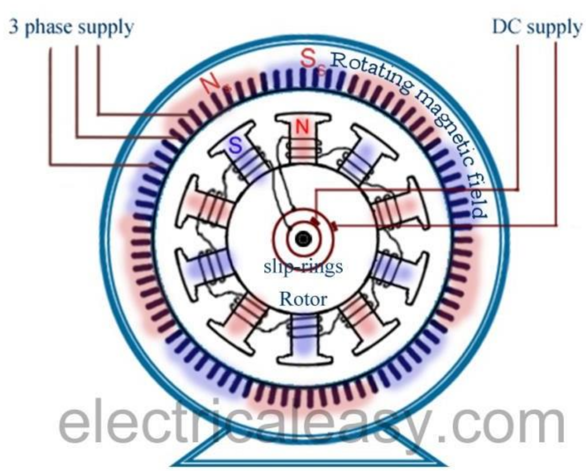
SYNCHRONOUS MOTOR

Definition: The motor which runs at synchronous speed is known as the synchronous motor. The synchronous speed is the constant speed at which motor generates the electromotive force. The synchronous motor is used for converting the electrical energy into mechanical energy.

Main Features of Synchronous Motor

1. Synchronous motor will run either at synchronous speed or will not run at all.
2. The speed of the synchronous motor is independent of the load, i.e., the variation of the load does not affect the speed of the motor.
3. The synchronous motor is not self-starting. The prime mover is used for rotating the motor at their synchronous speed.
4. The synchronous motor operates both for leading and lagging power factor.

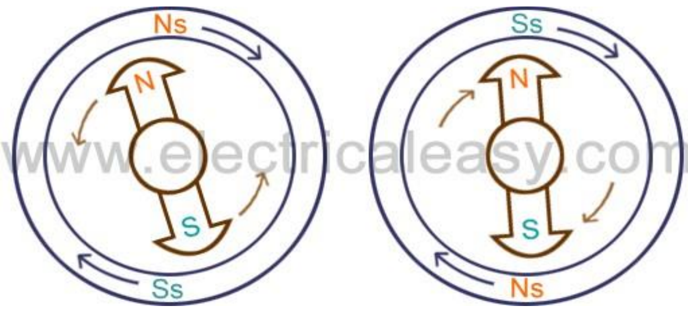
The **construction of a synchronous motor** is similar to the construction of alternator. Synchronous motor construction (with salient pole rotor) is as shown in the figure below. Just like any other motor, it consists of a stator and a rotor. The stator core is constructed with thin silicon lamination and insulated by a surface coating, to minimize the eddy current and hysteresis losses. The stator has axial slots inside, in which three phase stator winding is placed. The stator is wound with a three phase winding for a specific number of poles equal to the rotor poles.



The **rotor in synchronous motors** is mostly of salient pole type. DC supply is given to the rotor winding via slip-rings. The direct current excites the rotor winding and creates electromagnetic poles. In some cases permanent magnets can also be used. The figure above illustrates the **construction of a synchronous motor** very briefly.

Working Of Synchronous Motor

The stator is wound for the similar number of poles as that of rotor, and fed with three phase AC supply. The 3 phase AC supply produces rotating magnetic field in stator. The rotor winding is fed with DC supply which magnetizes the rotor. Consider a two pole **synchronous machine** as shown in figure below.



- Now, the stator poles are revolving with synchronous speed (lets say clockwise). If the rotor position is such that, N pole of the rotor is near the N pole of the stator (as shown in first schematic of above figure), then the poles of the stator and rotor will repel each other, and the *torque produced will be anticlockwise*.
- The stator poles are rotating with synchronous speed, and they rotate around very fast and interchange their position. But at this very soon, rotor cannot rotate with the same angle (due to inertia), and the next position will be likely the second schematic in above figure. In this case, poles of the stator will attract the poles of rotor, and *the torque produced will be clockwise.*
- Hence, the rotor will undergo to a rapidly reversing torque, and the motor will not start(i.e. motor is not self starting).

But, if the rotor is rotated upto the synchronous speed of the stator by means of an external force (in the direction of revolving field of the stator) or *with such a speed that it turns through one pole-pitch by the time the stator poles interchange their positions*, and the rotor field is excited near the synchronous speed, the poles of stator will keep attracting the opposite poles of the rotor (as the rotor is also, now, rotating with it and the position of the poles will be similar throughout the cycle). Now, the rotor will undergo unidirectional torque. The opposite poles of the stator and rotor will get locked with each other, and the rotor will rotate at the synchronous speed.

Method of Starting

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 all. The synchronous speed is given by the usual relation $N_S = 120\, f / P$.

The rotor and the stator parts of motor.

Shibashis Kar

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. 38.4) ***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.

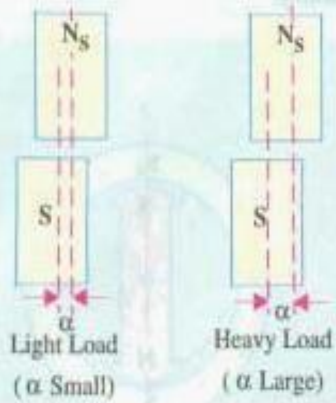


Fig. 38.4

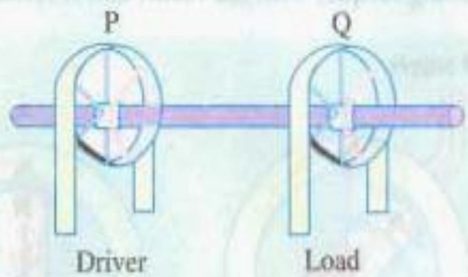


Fig. 38.5

The working of a synchronous motor is, in many ways, similar to the transmission of mechanical power by a shaft. In Fig. 38.5 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 α 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***.

In other words, **load angle** is nothing but an angle different between stator axis and rotor pole axis of the synchronous motor. For ideal motor, the load angle is zero since the rotor poles aligned with stator poles, but in practice, this is not possible. The motor has both mechanical and electrical losses, hence load angle is always present in the synchronous motor.

Significance of load angle:

1. The Torque produced in the synchronous motor is purely depending on the load angle (sin δ). It is measured by the degree in electrical.
2. Increasing in load angle indicate the decreasing magnetic locking between the rotor poles and stator poles.
3. When δ = 90 deg. The motor reaches to the full load torque. If you increase the load further, the motor losses the synchronism. Such a torque is called pull out torque.

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. We have seen (Art. 29.3) that when a d.c. motor is running on a supply of, say, V volts then, on rotating, a back e.m.f. E_b is set up in its armature conductors. The resultant voltage across the armature is $(V - E_b)$ and it causes an armature current $I_a = (V - E_b)/ R_a$ to flow where R_a is armature circuit resistance. The value of E_b depends, among other factors, on the speed of the rotating armature. The mechanical power developed in armature depends on $E_b I_a$ (E_b and I_a being in opposition to each other).

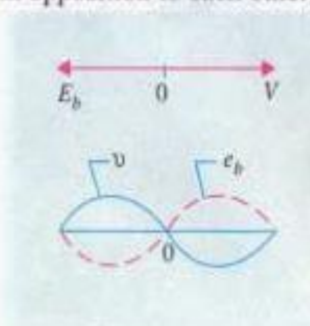


Fig. 38.6

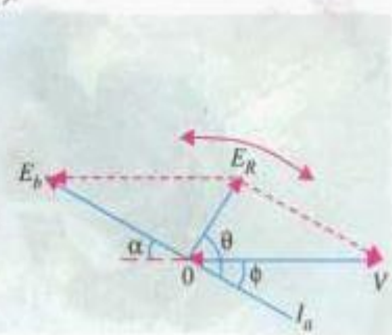


Fig. 38.7

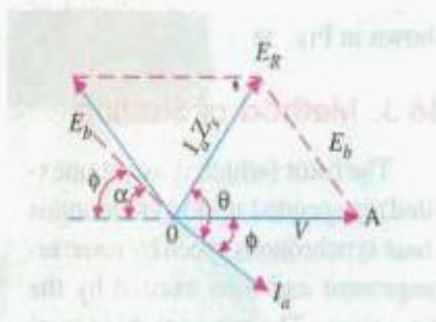
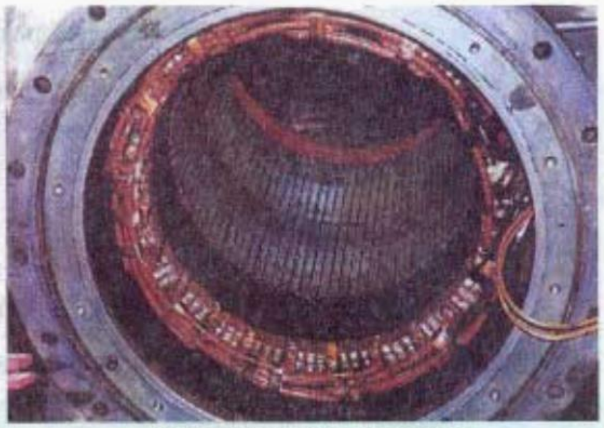


Fig. 38.8

Similarly, in a synchronous machine, a back e.m.f. E_b 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 E_b. Armature current is obtained by dividing this *vector* difference of voltages by armature impedance (not resistance as in d.c. machines).

Shibashis Kar



Stator of synchronous motor

Fig. 38.6 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 $E_b = V$. It is seen that vector difference of E_b 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 E_b falls back (vectors are rotating anti-clockwise) by a certain small angle α (Fig. 38.7), so that a resultant voltage E_R and hence current I_a 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 α – called the load angle or coupling angle (corresponding to the twist in the shaft of the pulleys). The resultant voltage E_R is increased and motor draws an increased armature current (Fig. 38.8), though at a slightly decreased power factor.

38.5. Power Flow within a Synchronous Motor

Let R_a = armature resistance / phase ; X_S = synchronous reactance / phase

then $\mathbf{Z_S} = \mathbf{R}_a + j\,X_S$; $\mathbf{I}_a = \dfrac{\mathbf{E_R}}{\mathbf{Z_S}} = \dfrac{\mathbf{V} - \mathbf{E_b}}{\mathbf{Z_S}}$; Obviously, $\mathbf{V} = \mathbf{E}_b + \mathbf{I}_a\,\mathbf{Z_S}$

The angle θ (known as internal angle) by which I_a lags behind E_R is given by $\tan\theta = X_S / R_a$.

If R_a is negligible, then $\theta = 90°$. Motor input $= V\,I_a \cos\phi$ —per phase

Here, V is applied voltage / phase.

Total input for a star-connected, 3-phase machine is, $P = \sqrt{3}\,V_L \cdot I_L \cos\phi$.

The mechanical power developed in the rotor is

P_m = back e.m.f. × armature current × cosine of the angle between the two *i.e.*, angle between I_a and E_b reversed.

$= E_b\,I_a \cos(\alpha - \phi)$ per phase ...Fig. 38.8

Out of this power developed, some would go to meet iron and friction and excitation losses. Hence, the power available at the shaft would be less than the developed power by this amount.

Out of the input power / phase $V\,I_a \cos\phi$, and amount $I_a^2\,R_a$ is wasted in armature***, the rest $(V.\,I_a \cos\phi - I_a^2\,R_a)$ appears as mechanical power in rotor; out of it, iron, friction and excitation losses are met and the rest is available at the shaft. If power input / phase of the motor is P, then

$$P = P_m + I_a^2\,R_a$$

or mechanical power in rotor $P_m = P - I_a^2\,R_a$ —per phase

For three phases $P_m = \sqrt{3}\,V_L\,I_L \cos\phi - 3\,I_a^2\,R_a$

The per phase power development in a synchronous machine is as under :

Shibashis Kar

Power input/phase in stator

$P = VI_a \cos \phi$

Armature (*i.e.*, stator) Cu loss $= I_a^2 R_a$

Mechanical power in armature $P_m = E_b I_a \cos(\alpha - \phi)$

Iron, excitation & friction losses

Output power P_{out}

Different power stages in a synchronous motor are as under :

38.6. Equivalent Circuit of a Synchronous Motor

Fig. 38.9 (*a*) shows the equivalent circuit model for one armature phase of a cylindrical rotor synchronous motor.

It is seen from Fig. 38.9 (*b*) that the phase applied voltage V is the vector sum of reversed back e.m.f. *i.e.*, $-E_b$ and the impedance drop $I_a Z_S$. In other words, $V = (-E_b + I_a Z_S)$. The angle α* between the phasor for V and E_b is called the load angle or power angle of the synchronous motor.

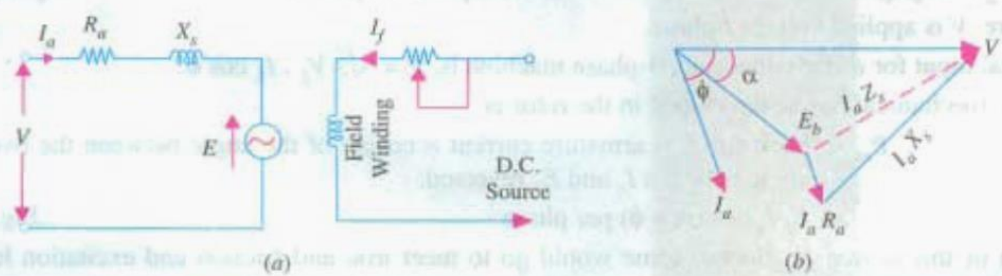


Fig. 38.9

38.7. Power Developed by a Synchronous Motor

Except for very small machines, the armature resistance of a synchronous motor is negligible as compared to its synchronous reactance. Hence, the equivalent circuit for the motor becomes as shown in Fig. 38.10 (*a*). From the phasor diagram of Fig. 38.10 (*b*), it is seen that

$$AB = E_b \sin \alpha = I_a X_S \cos \phi$$

$$\text{or} \quad VI_a \cos \phi = \frac{E_b V}{X_S} \sin \alpha$$

Now, $VI_a \cos \phi =$ motor power input/phase

Shibashis Kar

$$\therefore \quad P_{in} = \frac{E_b V}{X_S} \sin\alpha \qquad \text{...per phase*}$$

$$= 3\frac{E_b V}{X_S} \sin\alpha \qquad \text{... for three phases}$$

Since stator Cu losses have been neglected, P_{in} also represents the gross mechanical power $\{P_m\}$ developed by the motor.

$$\therefore \quad P_m = \frac{3E_b V}{X_S} \sin\alpha$$

The gross torque developed by the motor is $T_g = 9.55\, P_m / N_s$ N–m ...Ns in rpm.

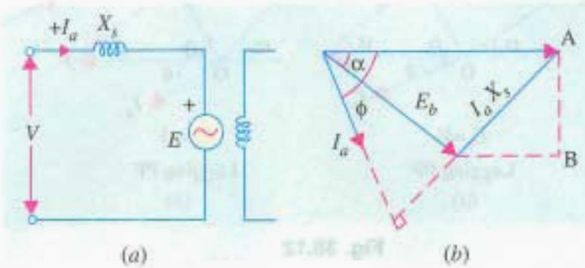


Fig. 38.10

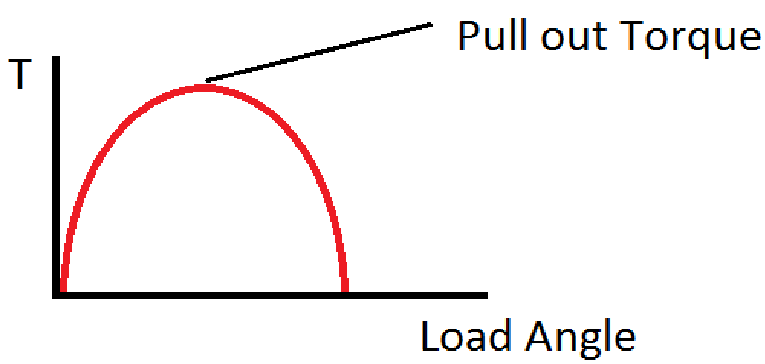
Types of Torque in the Synchronous Motor

Starting Torque: The torque is being developed at the starting time of the motor. It is also called as breakaway torque. The starting torque of the synchronous motor is purely depending on the method of starting the motor.

Running Torque: The full load torque of the motor is called running torque. The running torque is defending on the motor specifications.

Pull-in Torque: Let we assume the synchronous motor is started and the speed is nearer to the synchronous speed, during that time the stator pulls the rotor into synchronism, that torque is called pull-in torque.

Pull out Torque: Let we assume the motor is running at the maximum torque, beyond that slight increase in load causes the motor pulls out the synchronism, that maximum torque is called pull out torque. The pull out torque will be three to four-time of the full load torque of the motor.



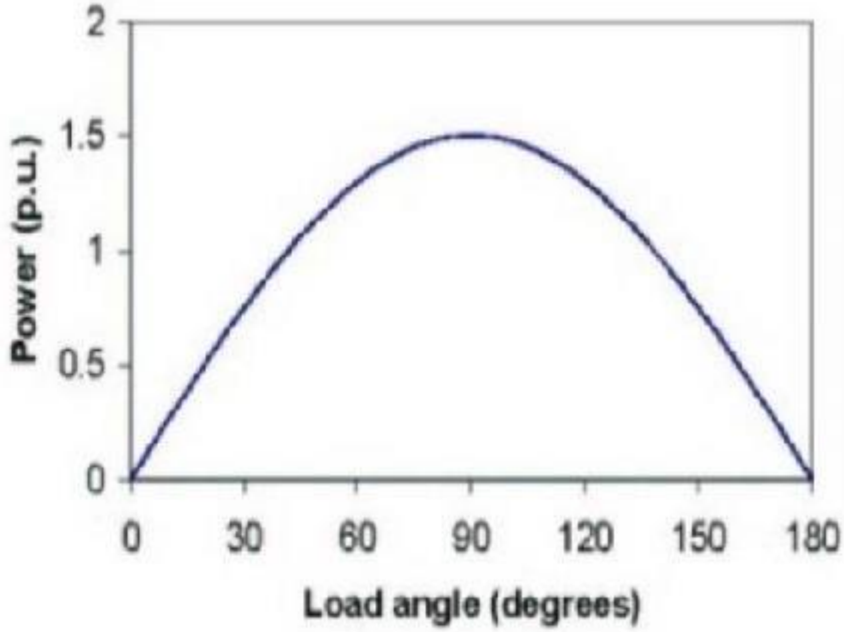
Torque Vs Load Angle

At load angle 90 degree the motor produces the maximum torque. Further increasing the loads, the magnetic locking between the stator and rotor become weak. Then the motor stops. Therefore, the maximum torque is produced by the motor without loss of synchronism is called pull out Torque.

Shibashis Kar

Power angle characteristics of cylindrical rotor motor.

As we know that $P_{in} = \frac{E_b.V}{X_s} \sin\alpha$, then the power angle curve of cylindrical rotor motor is shown as below in which power is maximum for the value of α=90°.



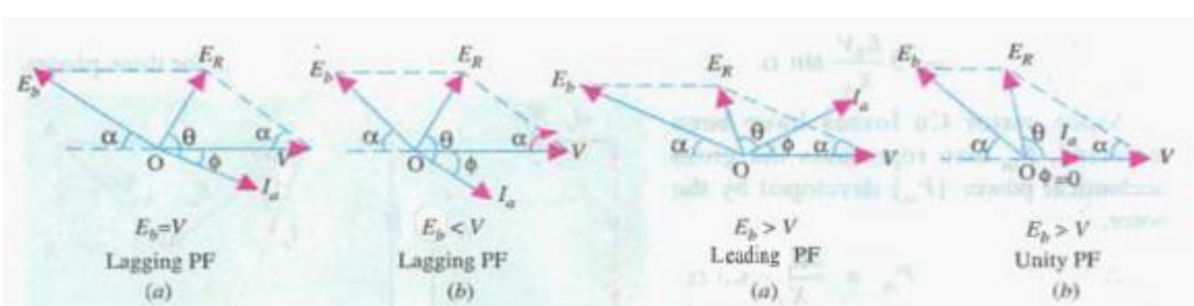


Fig. 38.12 Fig. 38.13

Shibashis Kar

38.9. Effect of Increased Load with Constant Excitation

We will study the effect of increased load on a synchronous motor under conditions of normal, under and over-excitation (ignoring the effects of armature reaction). With normal excitation, $E_b = V$, with under excitation, $E_b < V$ and with over-excitation, $E_b > V$. Whatever the value of excitation, it would be kept *constant* during our discussion. It would also be assumed that R_a is negligible as compared to X_S so that phase angle between E_R and I_a *i.e.*, $\theta = 90°$.

(i) Normal Excitation

Fig. 38.15. (*a*) shows the condition when motor is running with light load so that (*i*) torque angle α_1 is small (*ii*) so E_{R1} is small (*iii*) hence I_{a1} is small and (*iv*) ϕ_1 is small so that cos ϕ_1 is large.

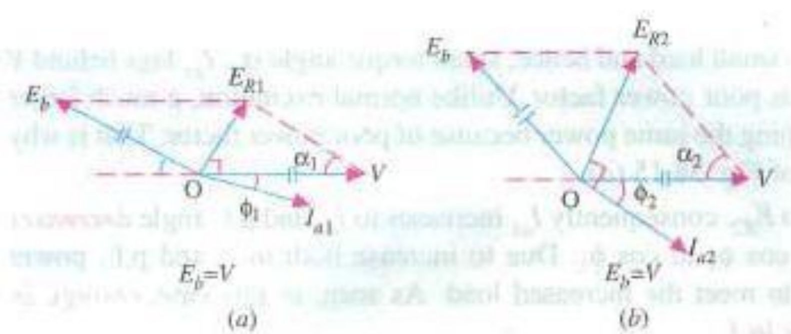
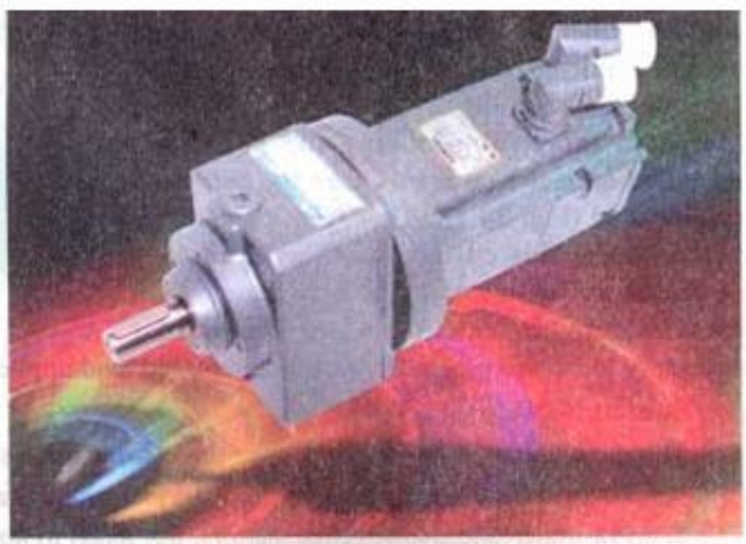


Fig. 38.15

Now, suppose that load on the motor is *increased* as shown in Fig. 38.15 (*b*). For meeting this extra load, motor must develop more torque by drawing more armature current. Unlike a d.c. motor, a synchronous motor cannot increase its I_a by decreasing its speed and hence E_b because both are constant in its case. What actually happens is as under :

1. rotor falls back *in phase i.e.*, load angle increases to α_2 as shown in Fig. 38.15 (*b*).
2. the resultant voltage in armature is increased *considerably* to new value E_{R2}.
3. as a result, I_{a1} increases to I_{a2}, thereby increasing the torque developed by the motor,
4. ϕ_1 increases to ϕ_2, so that power factor *decreases* from cos ϕ_1 to the new value cos ϕ_2.



Geared motor added to synchronous servo motor line offers a wide range of transmission ratios, and drive torques.

Since increase in I_a is much greater than the *slight* decrease in power factor, the torque developed by the motor is *increased* (on the whole) to a new value sufficient to meet the extra load put on the motor. It will be seen that essentially it is by increasing its I_a that the motor is able to carry the extra load put on it.

Shibashis Kar

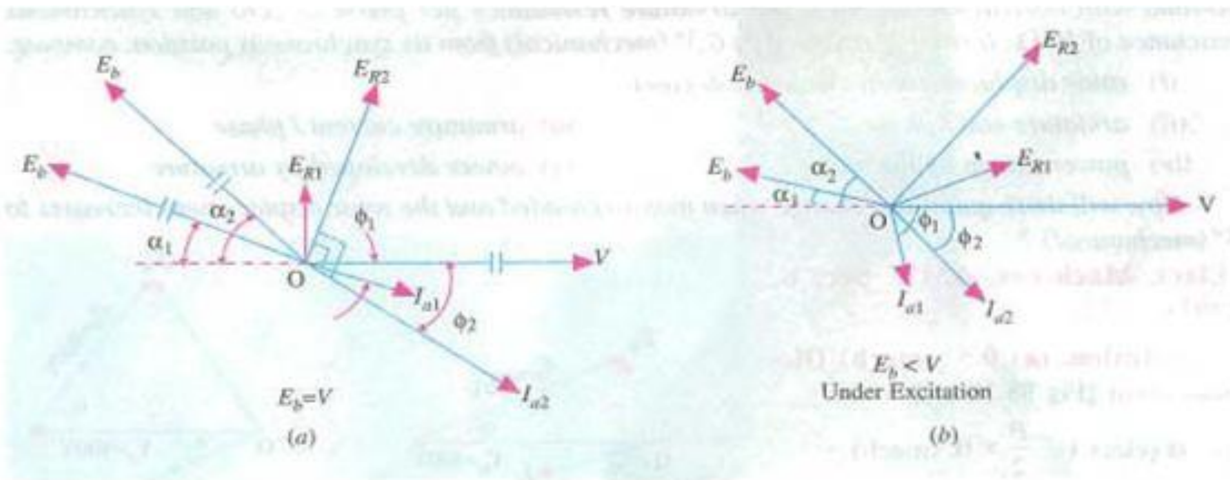


Fig. 38.16

A phase summary of the effect of increased load on a synchronous motor at ***normal excitation*** is shown in Fig. 38.16 (a) It is seen that there is a comparatively much greater ***increase*** in I_a than in ϕ.

(ii) Under-excitation

As shown in Fig. 38.16 (*b*), with a small load and hence, small torque angle α_1, I_{a1} lags behind V by a ***large*** phase angle ϕ_1 which means poor power factor. Unlike normal excitation, a much larger armature current must flow for developing the same power because of poor power factor. That is why I_{a1} of Fig. 38.16 (*b*) is larger than I_{a1} of Fig. 38.15 (*a*).

As load increases, E_{R1} increases to E_{R2}, consequently I_{a1} increases to I_{a2} and p.f. angle ***decreases*** from ϕ_1 to ϕ_2 or p.f. ***increases*** from cos ϕ_1 to cos ϕ_2. Due to increase both in I_a and p.f., power generated by the armature increases to meet the increased load. As seen, in this case, ***change in power factor is more than the change in I_a.***

(iii) Over-excitation

When running on light load, α_1 is small but I_{a1} is comparatively larger and ***leads V*** by a larger angle ϕ_1. Like the under-excited motor, as more load is applied, the power factor improves and ***approaches*** unity. The armature current also increases thereby producing the necessary increased armature power to meet the increased applied load (Fig. 38.17). However, it should be noted that in this case, power factor angle ϕ decreases (or p.f. increases) at a faster rate than the armature current thereby producing the necessary increased power to meet the increased load applied to the motor.

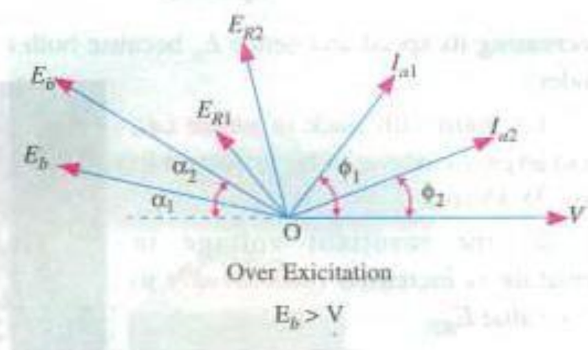


Fig. 38.17

Summary

The main points regarding the above three cases can be summarized as under :

1. As load on the motor increases, I_a ***increases regardless of excitation.***
2. For under-and over-excited motors, p.f. tends to approach unity with increase in load.
3. Both with under-and over-excitation, change in p.f. is greater than in I_a with increase in load.
4. With normal excitation, when load is increased change in I_a is greater than in p.f. which tends to become increasingly lagging.

Shibashis Kar

38.10. Effect of Changing Excitation on Constant Load

As shown in Fig. 38.20 (*a*), suppose a synchronous motor is operating with normal excitation ($E_b = V$) at unity p.f. with a given load. If R_a is negligible as compared to X_S, then I_a lags E_R by 90° and is in phase with V because p.f. is unity. The armature is drawing a power of $V.I_a$ per phase which is enough to meet the mechanical load on the motor. Now, let us discuss the effect of decreasing or increasing the field excitation when the load applied to the motor ***remains constant***.

(*a*) Excitation Decreased

As shown in Fig. 38.20 (*b*), suppose due to decrease in excitation, back e.m.f. is reduced to Eb_1 at the ***same load angle*** α_1. The resultant voltage E_{R1} causes a lagging armature current I_{a1} to flow. Even though I_{a1} is larger than I_a in magnitude it is incapable of producing necessary power VI_a for carrying the ***constant*** load because $I_{a1}\cos\phi_1$ component is less than I_a so that $VI_{a1}\cos\phi_1 < VI_a$.

Hence, it becomes necessary for load angle to ***increase*** from α_1 to α_2. It increases back e.m.f. from E_{b1} to E_{b2} which, in turn, increases resultant voltage from E_{R1} to E_{R2}. Consequently, armature current increases to I_{a2} whose in-phase component produces enough power ($VI_{a2}\cos\phi_2$) to meet the constant load on the motor.

(*b*) Excitation Increased

The effect of increasing field excitation is shown in Fig. 38.20 (*c*) where increased E_{b1} is shown at the original load angle α_1. The resultant voltage E_{R1} causes a ***leading*** current I_{a1} whose in-phase component is larger than I_a. Hence, armature develops more power than the load on the motor. Accordingly, load angle ***decreases*** from α_1 to α_2 which decreases resultant voltage from E_{R1} to E_{R2}. Consequently, armature current decreases from I_{a1} to I_{a2} whose in-phase component $I_{a2}\cos\phi_2 = I_a$. In that case, armature develops power sufficient to carry the constant load on the motor.

Hence, we find that variations in the excitation of a synchronous motor running with a ***given*** load produce variations in its ***load angle only***.

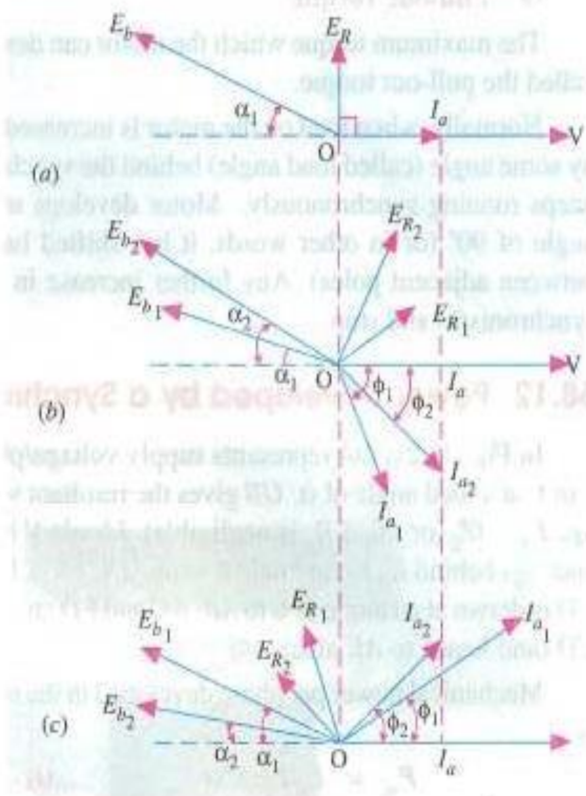


Fig. 38.20

Shibashis Kar

38.17. Effect of Excitation on Armature Current and Power Factor

The value of excitation for which back e.m.f. E_b 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. 38-8.

Consider a synchronous motor in which the mechanical load is constant (and hence output is also constant if losses are neglected).

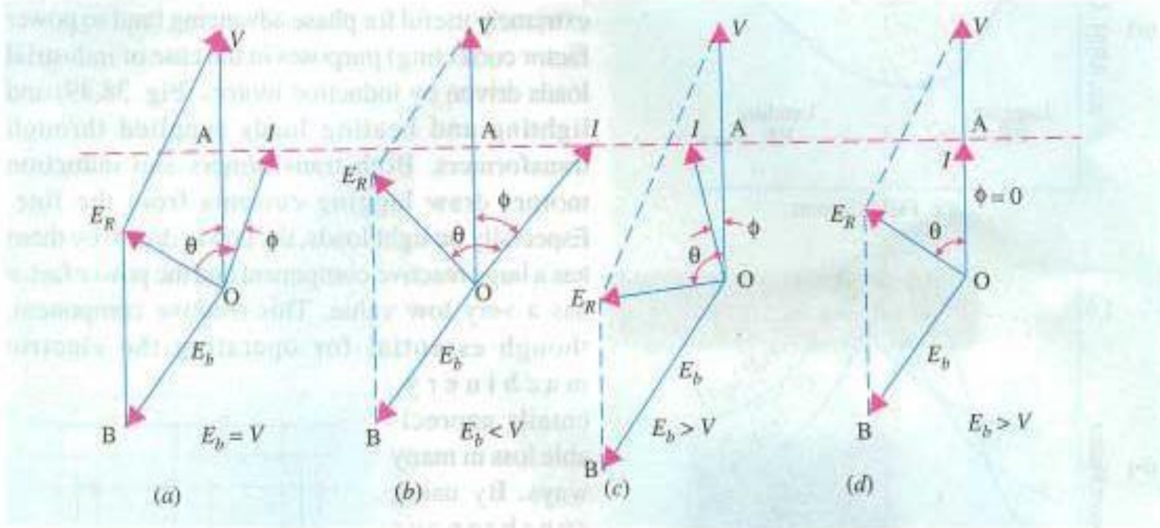


Fig. 38.47

Fig. 38.47 (*a*) shows the case for 100% excitation *i.e.*, when $E_b = V$. The armature current I lags behind V by a small angle ϕ. Its angle θ with E_R is fixed by stator constants *i.e.* $\tan\theta = X_S / R_a$.

In Fig. 38.47 (*b*)* excitation is less than 100% *i.e.*, $E_b < V$. Here, E_R 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 (ϕ 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. 38.47 (*c*) represents the condition for overexcited motor *i.e.* when $E_b > V$. Here, the resultant voltage vector E_R is pulled anticlockwise and so 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. 38.47 (*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. 38.48 (*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

Shibashis Kar

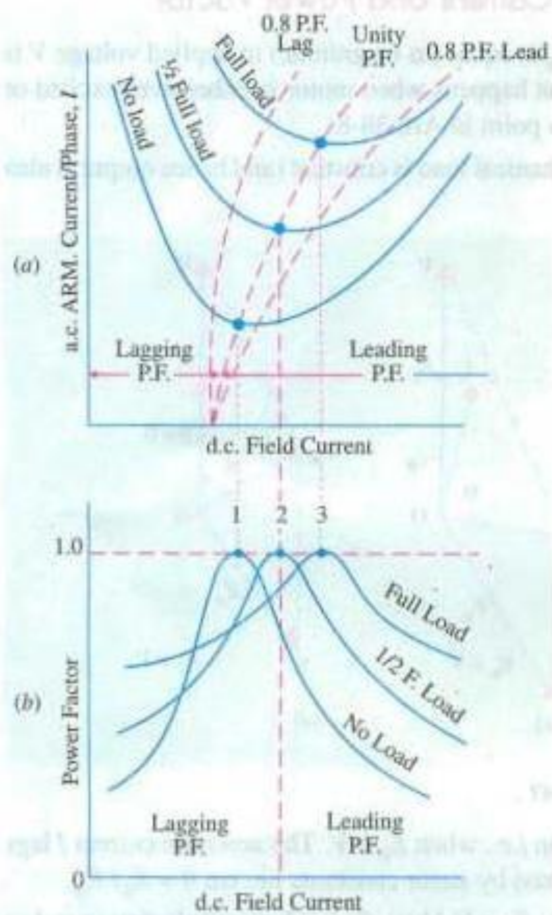


Fig. 38.48

Inductor motor

are shown in Fig. 38.48 (*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. 38.1) that an over-excited motor can be run with leading 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 loads driven by induction motors (Fig. 38.49) 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 has a very low value. This reactive component, though essential for operating the electric machinery, entails appreciable loss in many ways. By using synchronous motors in conjunction with induction motors and transformers, the lagging reactive power required by the latter is supplied locally by the leading reactive 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.

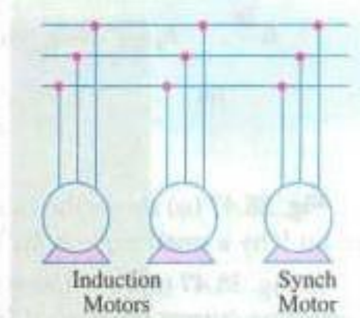


Fig. 38.49

Shibashis Kar

Prepared by: Shibashis Kar, Lecturer, Electrical, G.P.Kalahandi

38.20. Hunting or Surging or Phase Swinging

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 α. As load is progressively increased, this angle also increases so as to produce more torque for coping with the increased load. If now, there is sudden decrease in the motor load, the motor is immediately pulled up or advanced to a new value of α 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 (Fig. 38.57). The oscillatory motion of the rotor sets up eddy currents in the dampers which flow in such a way as to suppress these oscillations.

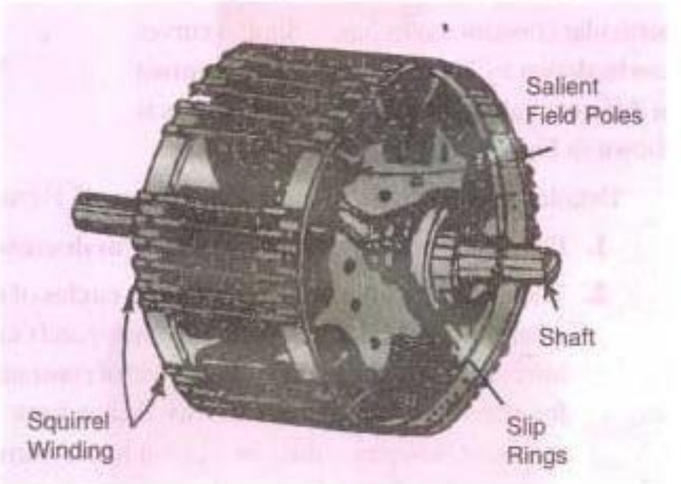


Fig. 38.57

Salient - poled squirrel eage motor

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.

Shibashis Kar

2. When full line voltage is switched on to the armature at rest, a very large current, usuall-
to 7 times the full-load armature current is drawn by the motor. In some case-
be objectionable but where it is, the applied voltage at starting, i-
transformers (Fig. 38.58). However, the voltage should
because the starting torque of an induction mo-
applied voltage. Usually, a value of 5-
Auto-transformer conne-
switches S_1 ar-
clo-

Shibashis Kar

38.22. Procedure for Starting a Synchronous Motor

While starting a modern synchronous motor provided with damper windings, following procedure is adopted.

1. First, main field winding is short-circuited.
2. Reduced voltage with the help of auto-transformers is applied across stator terminals. The motor starts up.
3. When it reaches a steady speed (as judged by its sound), a weak d.c. excitation is applied by removing the short-circuit on the main field winding. If excitation is sufficient, then the machine will be pulled into synchronism.
4. Full supply voltage is applied across stator terminals by cutting out the auto-transformers.
5. The motor may be operated at any desired power factor by changing the d.c. excitation.

38.23. Comparison Between Synchronous and Induction Motors

1. For a given frequency, the synchronous motor runs at a constant average speed whatever the load, while the speed of an induction motor falls somewhat with increase in load.
2. The synchronous motor can be operated over a wide range of power factors, both lagging and leading, but induction motor always runs with a lagging p.f. which may become very low at light loads.
3. A synchronous motor is inherently not self-starting.
4. The changes in applied voltage do not affect synchronous motor torque as much as they affect the induction motor torque. The breakdown torque of a synchronous motor varies approximately as the first power of applied voltage whereas that of an induction motor depends on the square of this voltage.
5. A d.c. excitation is required by synchronous motor but not by induction motor.
6. Synchronous motors are usually more costly and complicated than induction motors, but they are particularly attractive for low-speed drives (below 300 r.p.m.) because their power factor can always be adjusted to 1.0 and their efficiency is high. However, induction motors are excellent for speeds above 600 r.p.m.
7. Synchronous motors can be run at ultra-low speeds by using high power electronic converters which generate very low frequencies. Such motors of 10 MW range are used for driving crushers, rotary kilns and variable-speed ball mills etc.

****

Shibashis Kar

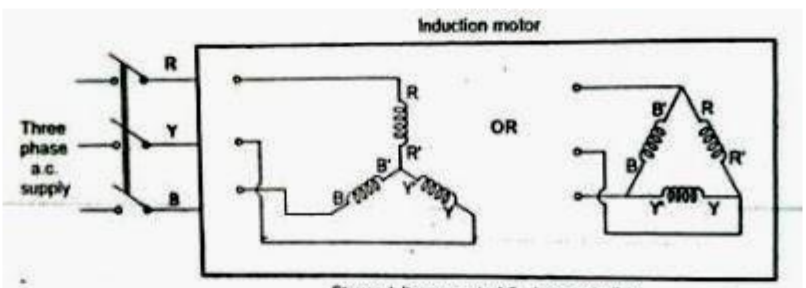
CHAPTER 3

THREE PHASE INDUCTION MOTORS

Production of Rotating Magnetic Field

The production of Rotating magnetic field in 3 phase supply is very interesting. When we apply a three-phase supply to a three-phase distributed winding of a rotating machine, a rotating magnetic field is produced which rotates in synchronous speed. This field is such that its poles do no remain in a fixed position on the stator but go on shifting their positions around the stator. For this reason, it is called a rotating field. It can be shown that the magnitude of this rotating field is constant and is equal to **1.5** fm where fm is the maximum flux due to any phase.

A three-phase induction motor consists of three phases winding as its stationary part called stator. The three-phase stator winding is connected in star or delta. The three-phase windings are displaced from each other by 120°. The windings are supplied by a balanced three phase ac supply.



Star or delta connected 3 phase winding

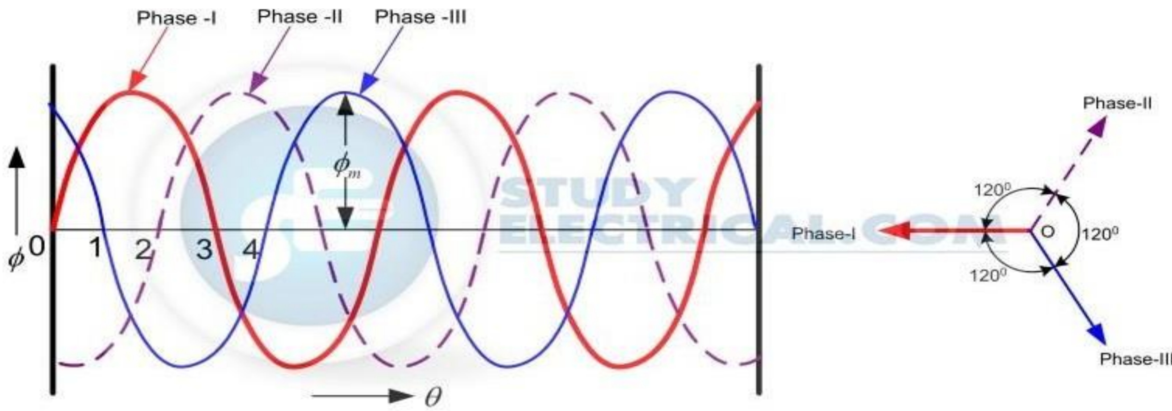
The three-phase currents flow simultaneously through the windings and are displaced from each other by 120° electrical. Each alternating phase current produces its own flux which is sinusoidal.
So all three fluxes are sinusoidal and are separated from each other by 120°.
If the phase sequence of the windings is R-Y-B, then mathematical equations for the instantaneous values of the three fluxes Φ_R, Φ_Y, Φ_B can be written as,

$$\Phi_R = \Phi_m \sin(\omega t)$$

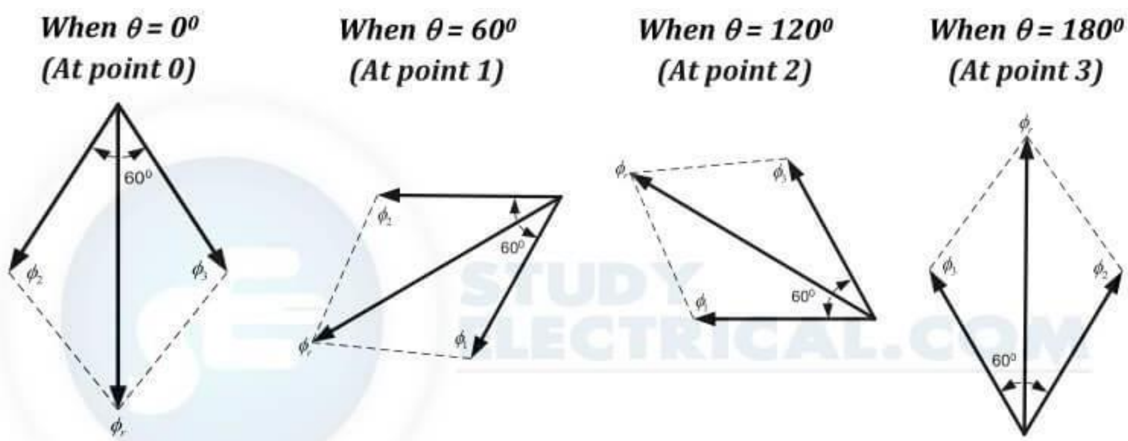
$$\Phi_Y = \Phi_m \sin(\omega t - 120)$$

$$\Phi_B = \Phi_m \sin(\omega t - 240)$$

As windings are identical and supply is balanced, the magnitude of each flux is $\mathbf{\Phi_m}$.



Case 1 : ωt = 0^0 $\Phi_R = \Phi_m \sin(0) = 0$ $\Phi_Y = \Phi_m \sin(0 - 120) = -0.866\ \Phi m$ $\Phi_B = \Phi_m \sin(0 - 240) = +0.866\ \Phi m$	**Case 2 : ωt = 60^0** $\Phi_R = \Phi_m \sin(60) = +0.866\ \Phi m$ $\Phi_Y = \Phi_m \sin(-60) = -0.866\ \Phi m$ $\Phi_B = \Phi_m \sin(-180) = 0$
Case 3 : ωt = 120^0 $\Phi_R = \Phi_m \sin(120) = +0.866\ \Phi m$ $\Phi_Y = \Phi_m \sin(0) = 0$ $\Phi_B = \Phi_m \sin(-120) = -0.866\ \Phi m$	**Case 4 : ωt = 180^0** $\Phi_R = \Phi_m \sin(180) = 0$ $\Phi_Y = \Phi_m \sin(60) = +.866\ \Phi m$ $\Phi_B = \Phi_m \sin(-60) = -0.866\ \Phi m$



$\emptyset_1 = 0$

$\emptyset_2 = -\frac{\sqrt{3}}{2}\emptyset_m$

$\emptyset_3 = \frac{\sqrt{3}}{2}\emptyset_m$

$\emptyset_1 = \frac{\sqrt{3}}{2}\emptyset_m$

$\emptyset_2 = -\frac{\sqrt{3}}{2}\emptyset_m \emptyset_3 = 0$

$\emptyset_1 = \frac{\sqrt{3}}{2}\emptyset_m$

$\emptyset_2 = 0$

$\emptyset_3 = -\frac{\sqrt{3}}{2}\emptyset_m$

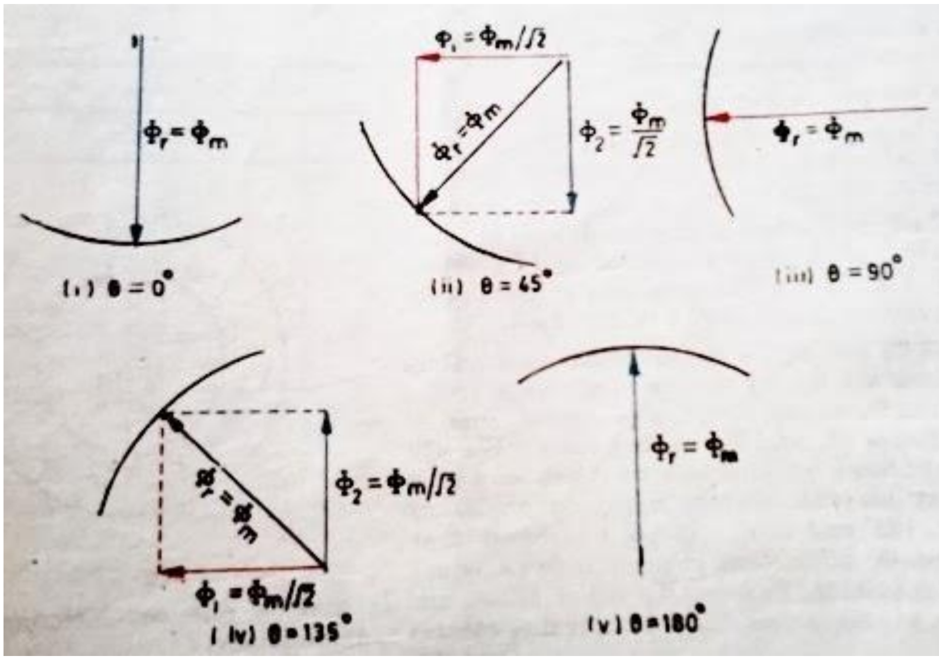
$\emptyset_1 = 0$

$\emptyset_2 = \frac{\sqrt{3}}{2}\emptyset_m \emptyset_3 = -\frac{\sqrt{3}}{2}\emptyset_m$

Shibashis Kar

By comparing the electrical and phasor diagrams we can find the flux rotates one complete 360 degrees on the 180-degree displacement of flux. And the resultant in each case is

$$\Phi_r = 2 \times \frac{\sqrt{3}}{2}\Phi_m \times \cos 30^\circ = \frac{3}{2}\Phi_m = 1.5\Phi_m$$



Speed of Rotating Magnetic Field

- The speed at which the rotating magnetic field revolves is called the **synchronous speed (N_s)**.
- Referring to the waveform of three phases, the time instant 4 represents the completion of one quarter cycle of alternating current I x from the time instant 1.
- During this one-quarter cycle, the field has rotated through 90°. At one complete cycle of current I_x from the origin, the field has completed one revolution.
- Therefore, for a 2-pole stator winding, the field makes one revolution in one cycle of current. In a 4-pole stator winding, it can be shown that the rotating field makes one revolution in two cycles of current.In general, for P poles, the rotating field makes one revolution in P/2 cycles of current.

$$\therefore \textbf{Cycles of Current} = \frac{P}{2} \times \textbf{revolutions of field}$$

$$\textbf{Or Cycles of Current per second} = \frac{P}{2} \times \textbf{revolutions of field per second}$$

Since revolutions per second is equal to the revolutions per minute (N s) divided by 60 and the number of cycles per second is the frequency f,

$$f = \frac{P}{2} \times \frac{N_s}{60} = \frac{PN_s}{120} \quad \therefore \; N_s = \frac{120f}{P}$$

Shibashis Kar

Direction of Rotating Magnetic Field

The phase sequence of the three-phase voltage applied to the stator winding in the first figure is R-Y-B. If this sequence is changed to R-B-Y, it is observed that the direction of rotation of the field is reversed i.e., the field rotates counterclockwise rather than clockwise.

However, the number of poles and the speed at which the magnetic field rotates remain unchanged. Thus it is necessary only to change the phase sequence in order to change the direction of rotation of the magnetic field. For a three-phase supply, this can be done by interchanging any two of the three lines.
And we shall see, the rotor in a 3-phase induction motor runs in the same direction as the rotating magnetic field but opposite to previous direction.
Therefore, the direction of rotation of a 3-phase induction motor can be reversed by interchanging any two of the three motor supply lines.

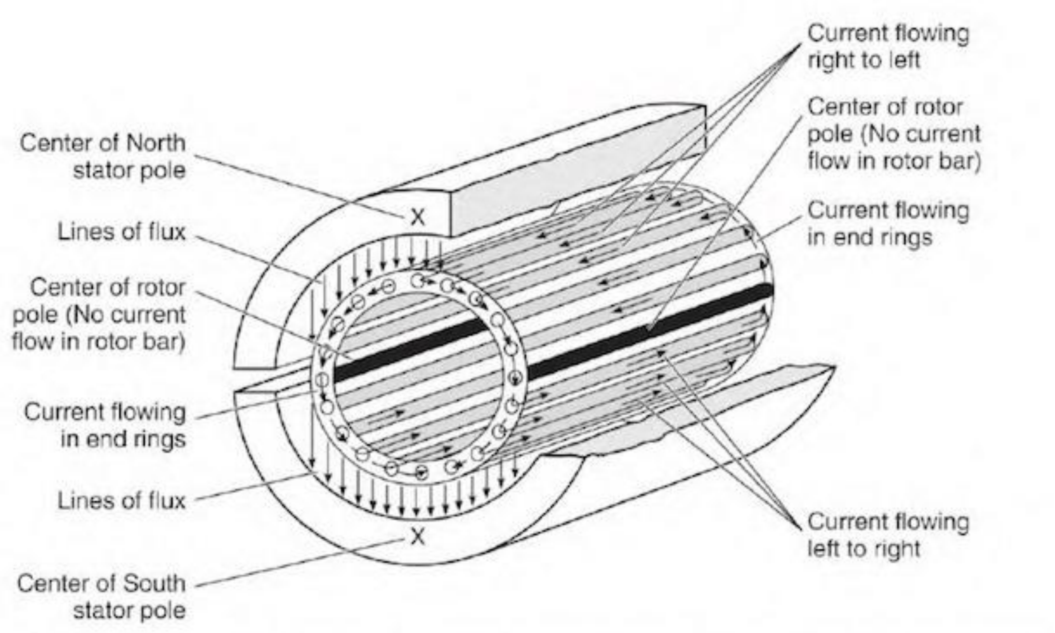
Hence, we conclude that

1. the resultant flux is of constant value = $\frac{3}{2}\Phi_m$ i.e. 1.5 *times the maximum value of the flux due to any phase.*
2. *the resultant flux rotates around the stator at synchronous speed given by $N_s = 120\ f/P$.*

Constructional features of Squirrel cage induction motor

A squirrel cage induction motor consists of the following parts:

- Stator
- Rotor
- Fan
- Bearings



Stator

It consists of a 3 phase winding with a core and metal housing(or stator frame). The frame which is made up of die-cast or fabricated steel ,provides protection and mechanical strength to all the inner parts of the induction motor and its main function is to support the stator core and the 3-phase winding. It should be also strong and rigid as the air gap length of three phase induction motor is very small. The stator core is made up of silicon steel to reduce hysteresis losses and it is laminated to reduce eddy current loss. Windings are such placed that they are electrically and mechanically 120^0 apart from in space The winding is mounted on the laminated iron core in such a way so that it can create a definite number of poles (the exact number of poles being determined by the requirements of speed) and can provide low reluctance path for generated flux by AC currents.

Rotor

It is the part of the motor which will be in a rotation to give mechanical output for a given amount of electrical energy. The rated output of the motor is mentioned on the nameplate in horsepower. It consists of a shaft, short-circuited copper/aluminum bars, and a core. The rotor core is laminated (to avoid power loss from eddy currents and hysteresis) containing parallel slots to carry rotor conductors which are generally heavy bars of aluminium, copper or alloys, (through semi closed circular slots) and they are electrically welded or bolted to two heavy and stout short-circuiting end rings thus giving a picture of squirrel cage. Conductors are skewed to reduce magnetic hum, prevent cogging (magnetic locking between stator teeth and rotor teeth) during starting operation and gives better transformation ratio between stator and rotor.

Fan

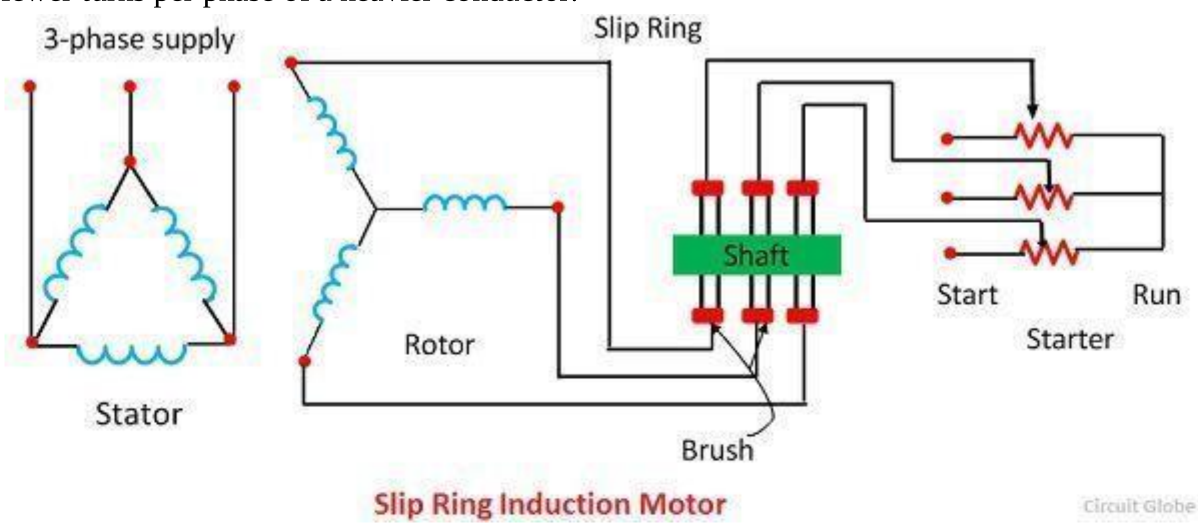
A light aluminium fan is attached to the back side of the rotor to provide heat exchange, and hence it maintains the temperature of the motor under a limit.

Bearings

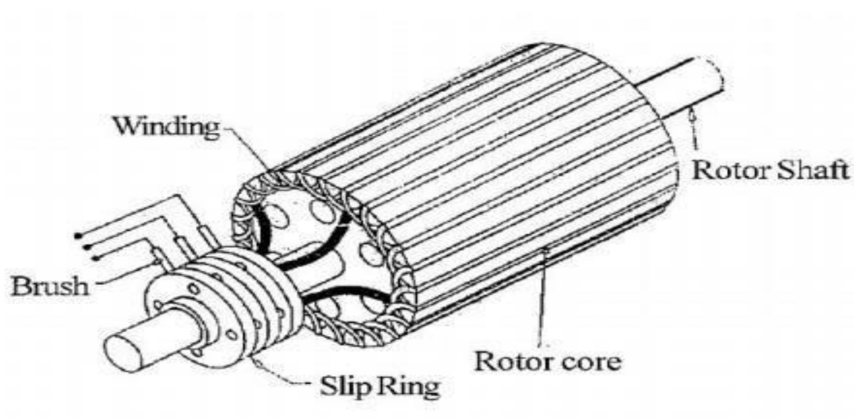
Bearings are provided as the base for rotor motion, and the bearings keep the smooth rotation of the motor.

Constructional features of Slip ring induction motor

The motor which employing the wound rotor is known as a slip ring induction motor or phase wound motor. It consists laminated cylindrical core(high quality low loss silicon steel) which has a semi-closed slot at the outer periphery and carries three-phase insulated winding. The rotor is wound for the same number of poles as that of the stator but it has less number of slots and has fewer turns per phase of a heavier conductor.



The three finish terminals are connected forming star point, and the three start terminals are connected to three copper slip rings fixed on the shaft. The mild steel shaft is passed through the centre of the rotor and fixed to the key. The purpose of the shaft is to send mechanical power. As its name indicates, three phase slip ring induction motor consists of slip rings of **high quality phosphor bronze**, connected on the same shaft as that of the rotor.

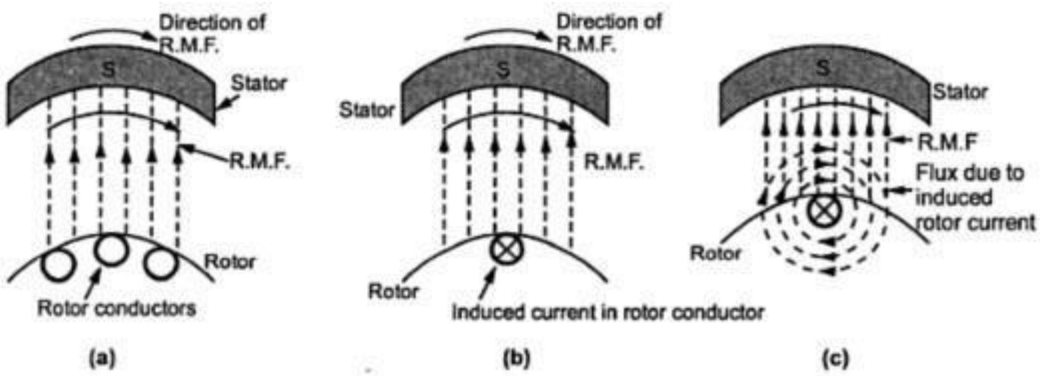


Slip Ring Rotor

The three ends of three-phase windings are permanently connected to these slip rings. The external resistance can be easily connected through the brushes and slip rings and hence used for speed controlling and improving the starting torque of three phase induction motor. The brushes are used to carry current to and from the rotor winding. These brushes are further connected to three phase star connected resistances.

All other parts are external aluminium fan, ball and roller bearings and their shields, ventilation grill, terminal box.

Working principle of operation of 3-phase Induction motor.



When the motor is excited with a three-phase supply, three-phase stator winding produces a rotating magnetic field with 120 displacements at a constant magnitude which rotates at synchronous speed. This changing magnetic field cuts the rotor conductors and induces a current in them according to the principle of Faraday's laws of electromagnetic induction. As these rotor conductors are shorted, the current starts to flow through these conductors.

In the presence of the magnetic field of the stator, rotor conductors are placed, and therefore, according to the Lorenz force principle, a mechanical force acts on the rotor conductor. Thus, all the rotor conductors force, i.e., the sum of the mechanical forces produces torque in the rotor which tends to move it in the same direction of the rotating magnetic field.

This rotor conductor's rotation can also be explained by Lenz's law which tells that the induced currents in the rotor oppose the cause for its production, here this opposition is rotating magnetic field. This result the rotor starts rotating in the same direction of the stator rotating magnetic field. If the rotor speed more than the stator speed, then no current will induce in the rotor because the reason for rotor rotation is the relative speed of the rotor and stator magnetic fields. This stator and the rotor field difference are called slip. This how a 3-phase motor is called an asynchronous machine due to this relative speed difference between the stator and the rotors.

As we discussed above, the relative speed between the stator field and the rotor conductors causes to rotate the rotor in a particular direction. Hence, for producing the rotation, the rotor speed Nr must always be less than the stator field speed Ns, and the difference between these two parameters depends on the load on the motor.

Slip

The slip in an induction motor is the difference between the main flux speed and their rotor speed. The symbol S represents the slip. It is expressed by the percentage of synchronous speed. Mathematically, it is written as

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

The value of slip at full load varies from 6% in case of small motor and 2% in the large motor. The induction motor never runs at synchronous speed. The speed of the rotor is always less than that of the synchronous speed. If the speed of the rotor is equal to the synchronous speed, no relative motion occurs between the stationary rotor conductors and the main field. Then no EMF induces in the rotor and zero current generates on the rotor conductors. The electromagnetic torque is also not induced. Thus, the speed of the rotor is always kept slightly less than the synchronous speed. The speed at which the induction motor work is known as the slip speed. **The difference between the synchronous speed and the actual speed of the rotor is known as the slip speed.** In other words, the slip speed shows the relative speed of the rotor concerning the speed of the field.

- If N_s is the synchronous speed in revolution per minute
- N_r is the actual rotor speed in revolution per minute.

The slip speed of the induction motor is given as

$$S = N_s - N_r \quad \dots\dots\dots (1)$$

The fraction part of the synchronous speed is called the **Per Unit Slip** or **Fractional Slip**. The per unit slip is called the **Slip**. It is denoted by s.

$$S = \frac{N_S - N_r}{N_S} \text{ per unit (p.u)} \quad \dots\dots..(2)$$

$$\text{Percentage slip} = \frac{N_s - N_r}{N_s} \text{ x } 100 \quad \dots\dots..(3)$$

Therefore, the rotor speed is given by the equation shown below.

$$N_r = N_S\,(1 - S)$$

Shibashis Kar

Rotor frequency

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

$Ns - Nr = \frac{120f'}{P}$ Also, $Ns = \frac{120f}{P}$, Dividing one by the other, we get, $\frac{f'}{f} = \frac{Ns-N}{Ns} = s$

Torque Equation Of Three Phase Induction Motor

Torque of a three phase induction motor is proportional to flux per stator pole, rotor current and the power factor of the rotor.

$T \propto \phi I_2 \cos\phi_2$ OR $T = k \phi I_2 \cos\phi_2$.
Where,

ϕ = flux per stator pole,
I_2 = rotor current at **standstill**,
ϕ_2 = angle between rotor emf and rotor current,
k = a constant.

Now, let E_2 = rotor emf at **standstill**
we know, rotor emf is directly proportional to flux per stator pole, i.e. $E_2 \propto \phi$.
therefore, $T \propto E_2 I_2 \cos\phi_2$ OR $T = k_1 E_2 I_2 \cos\phi_2$.

Starting Torque

The torque developed at the instant of starting of a motor is called as starting torque. Starting torque may be greater than running torque in some cases, or it may be lesser.

We know, $T = k_1 E_2 I_2 \cos\phi_2$.

Let ,

R2 = rotor resistance per phase

X2 = standstill rotor reactance

$$Z_2 = \sqrt{(R_2^2 + X_2^2)} \text{ = rotor impedence per phase at standstill}$$

Then,

$$I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{(R_2^2 + X_2^2)}} \quad \text{and} \quad \cos\phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{(R_2^2 + X_2^2)}}$$

Therefore, starting torque can be given as,

$$Tst = k_1 E_2 \frac{E_2}{\sqrt{(R_2^2 + X_2^2)}} \times \frac{R_2}{\sqrt{(R_2^2 + X_2^2)}} = \frac{k_1 E_2^2 R_2}{R_2^2 + X_2^2}$$

The constant $\mathbf{k_1 = 3 / 2\pi Ns}$

$$Tst = \frac{3}{2\pi Ns} \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Condition For Maximum Starting Torque

If supply voltage V is kept constant, then flux ϕ and E_2 both remains constant. Hence,

$$Tst = k_2 \frac{R_2}{R_2^2 + X_2^2}$$

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

$$\therefore \quad R_2 = X_2.$$

Or $\mathbf{R_2^2 + X_2^2 = 2R_2^2}$ .This implies $\mathbf{R_2 = X_2}$

Hence, it can be proved that maximum starting torque is obtained when rotor resistance is equal to standstill rotor reactance. i.e. $\mathbf{R_2 = X_2}$

Torque Under Running Condition

$T \propto \phi\, I_r \cos\phi_2$.

Where ,

E_r = rotor emf per phase under **running** condition = sE_2. (s=slip)

I_r = rotor current per phase under **running** condition

Reactance per phase under **running** condition will be = sX_2

Therefore ,

$$I_r = \frac{E_r}{Z_r} = \frac{sE_2}{\sqrt{(R_2^2 + (sX_2)^2)}} \quad \text{and} \quad \cos\phi_2 = \frac{R_2}{Z_r} = \frac{R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

$$T = \frac{k\,\phi\, sE_2\, R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

As, $\phi \propto E_2$.

$$T = \frac{k_1\, sE_2^2 R_2}{\sqrt{(R_2^2 + (sX_2)^2)}} = \frac{3}{2\pi Ns} \frac{sE_2^2 R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

Shibashis Kar

Condition For Maximum Running Torque

If we want to find the maximum value of some quantity, then we have to differentiate that quantity concerning some variable parameter and then put it equal to zero as done in previous case.. In this case, we have to find the condition for maximum torque, so we have to differentiate torque concerning some variable quantity which is the slip, s in this case as all other parameters in the equation of torque remains constant.

We know that,

$$T = KsE_2^2 \frac{R_2}{R_2^2 + (sX_2)^2}$$

So, for torque to be maximum,

$$\frac{dT}{ds} = 0$$

Now we differentiate the above equation by using division rule of differentiation. On differentiating and after putting the terms equal to zero we get,

$$s^2 = \frac{R_2^2}{X_2^2} \quad \text{or } R_2^{\,2} = s^2 X_2^{\,2} \text{ or } R_2 = sX_2$$

Neglecting the negative value of slip we get

$$s = \frac{R_2}{X_2}$$

Putting the above value of s in above torque equation, the maximum torque is equal to:

$$T_{max} = \frac{3}{2\pi N_s} \cdot \frac{E_2^2}{2X_2} \text{ N-m}$$

From the above, it is found:

1. That the maximum torque is independent of rotor resistance as such.
2. However, the speed or slip at which maximum torque occurs is determined by the rotor resistance. As seen from above, torque becomes maximum when rotor reactance equals is resistance. Hence, by varying rotor resistance (possible only in slip ring motor) maximum torque can be made to occur a any desired slip(or motor speed).
3. Maximum torque varies inversely as standstill reactance. Hence, it should be kept as small as possible.
4. Maximum torque varies directly as the square of the applied voltage.
5. For obtaining maximum at starting (s=1), rotor resistance must be equal to rotor reactance.

Shibashis Kar

Torque Slip Characteristic of an Induction Motor

The **Torque Slip Characteristic** is represented by a **rectangular hyperbola.** For the immediate value of the slip, the graph changes from one form to the other. Thus, it passes through the point of maximum torque when $R_2 = sX_2$. The maximum torque developed in an induction motor is called the **Pull Out Torque** or the **Breakdown Torque**. This torque is a measure of the short time overloading capability of the motor.

The **torque slip characteristic curve** is divided roughly into three regions. They are given below.

$$T = \frac{k\, s\, R_2 E_2^2}{R_2^2 + (sX_2)^2} \dots\dots\dots\dots (1)$$

- Low slip region
- Medium slip region
- High slip region

The torque equation of the induction motor is given below.

Low Slip Region

At the synchronous speed, s = 0, therefore, the torque is zero. When the speed is very near to synchronous speed. The slip is very low and $(sX_2)^2$ is negligible in comparison with R_2. Therefore,

$$T = \frac{k_1 s}{R_2}$$

If R_2 is constant, the torque becomes

$$T = k_2 s \dots\dots (2)$$

When $\mathbf{k_2 = k_1/R_2}$

From the equation (1) shown above, it is clear that the torque is proportional to slip. Hence, in the normal working region of the motor, the value of the slip is small. The torque slip curve is a straight line.

Medium Slip Region

As the slip increases, the speed of the motor decreases with the increase in load. The term $(sX_2)^2$ becomes large. The term R_2^2 may be neglected in comparison with the term $(sX_2)^2$ and the torque equation becomes as shown below.

$$T = \frac{k_3 R_2}{sX_2^2} \dots\dots\dots (3)$$

At the standstill condition, the torque is inversely proportional to the slip.

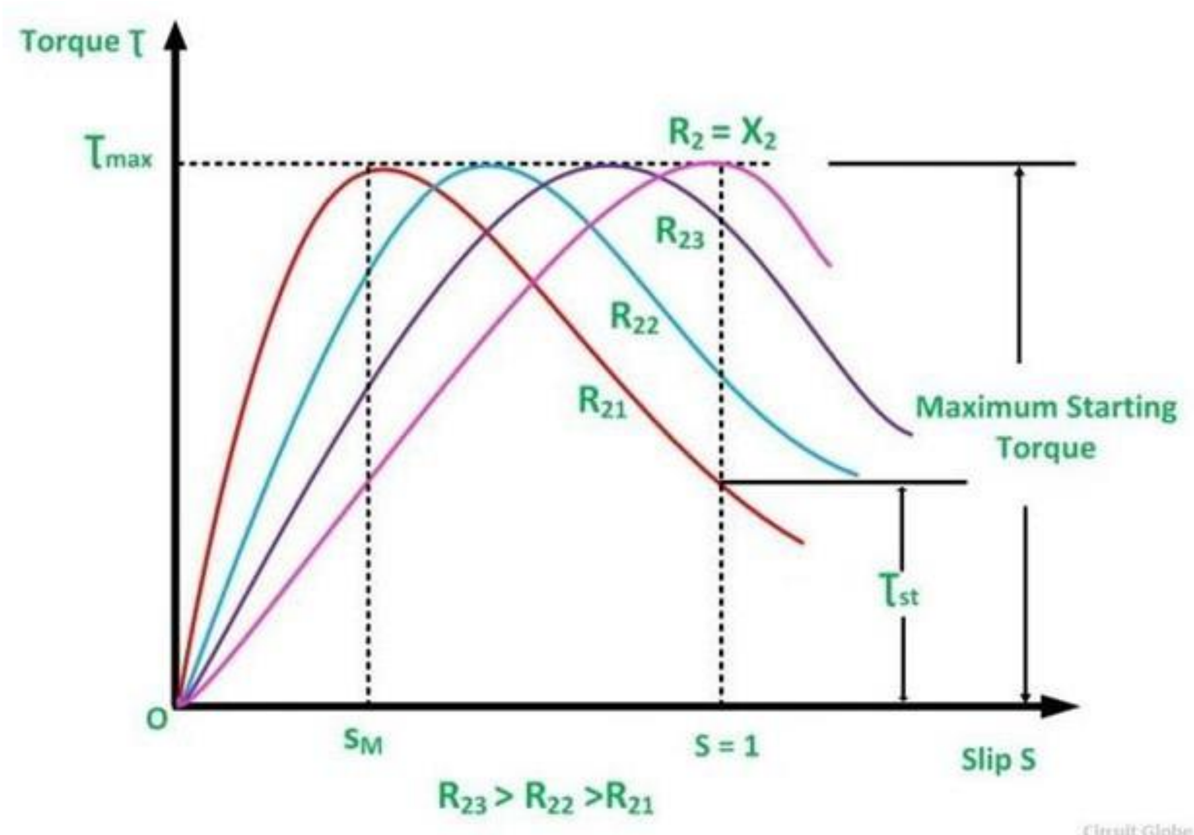
Shibashis Kar

High Slip Region

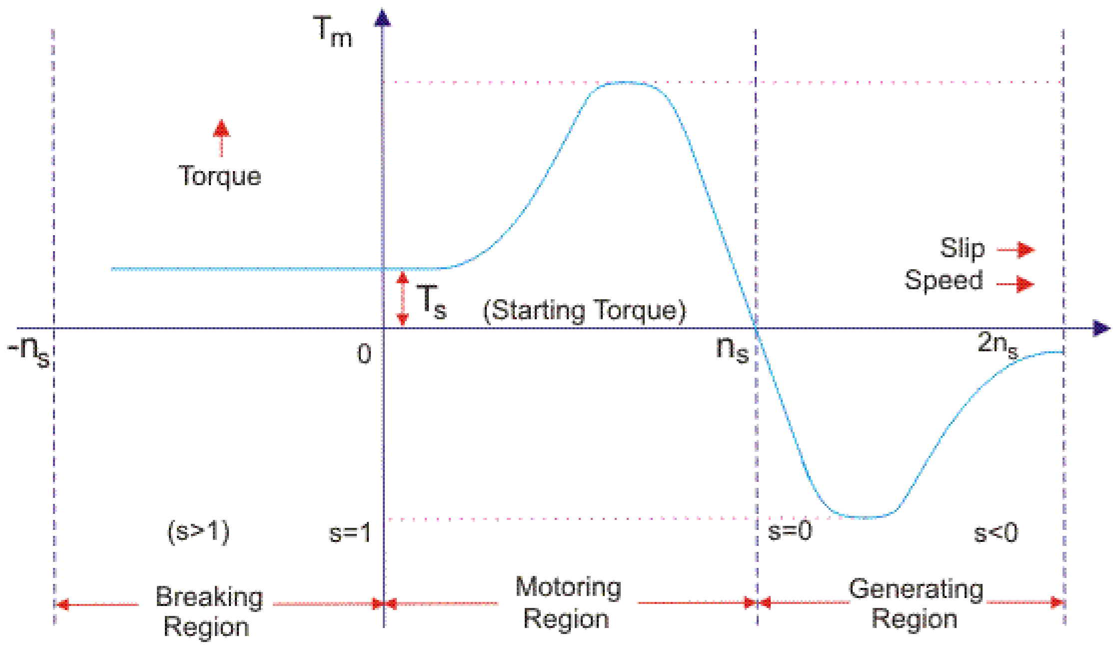
Beyond the maximum torque point, the value of torque starts decreasing. As a result, the motor slows down and stops. At this stage, the overload protection must immediately disconnect the motor from the supply to prevent damage due to overheating of the motor.

The motor operates for the values of the slip between s = 0 and s = s_M. Where, s_M is the value of the slip corresponding to the maximum torque. For a typical induction motor, the pull-out torque is 2 to 3 times the rated full load torque. The starting torque is about 1.5 times the rated full load torque.

The curve shown below shows the **Torque Slip Characteristic** of the Induction Motor.



Torque Slip Characteristic of the Induction Motor showing three modes of operation.



Torque Slip Curve for Three Phase Induction Motor

Motoring Mode
In this mode of operation, supply is given to the stator sides and the motor always rotates below the synchronous speed. The **induction motor torque** varies from zero to full load torque as the slip varies. The slip varies from zero to one. It is zero at no load and one at standstill. From the curve it is seen that the torque is directly proportional to the slip.

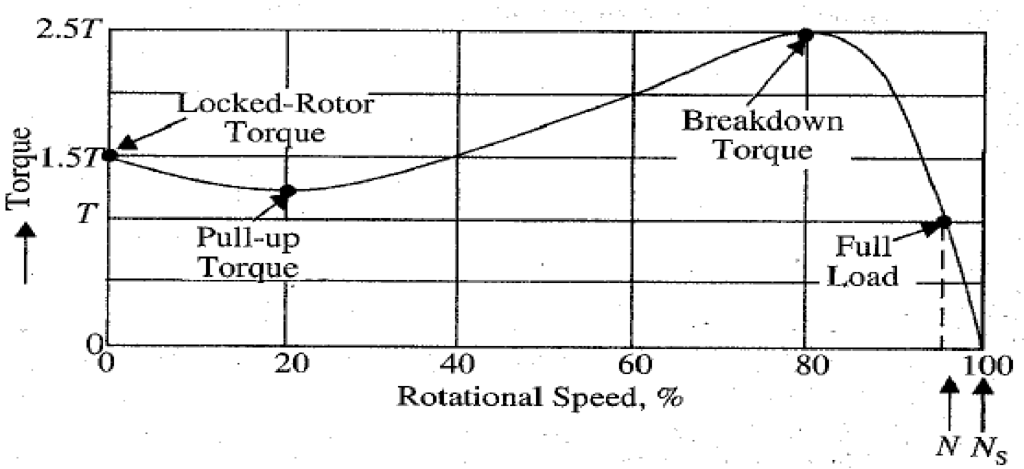
Generating Mode
In this mode of operation induction motor runs above the synchronous speed and it should be driven by a prime mover. The stator winding is connected to a three phase supply in which it supplies electrical energy. Actually, in this case, the torque and slip both are negative so the motor receives mechanical energy and delivers electrical energy. Induction motor is not much used as generator because it requires reactive power for its operation.

Braking Mode
In the Braking mode, the two leads or the polarity of the supply voltage is changed so that the motor starts to rotate in the reverse direction and as a result the motor stops. This method of braking is known as plugging. This method is used when it is required to stop the motor within a very short period of time. The kinetic energy stored in the revolving load is dissipated as heat. Also, motor is still receiving power from the stator which is also dissipated as heat. So as a result of which motor develops enormous heat energy. For this stator is disconnected from the supply before motor enters the braking mode.

Shibashis Kar

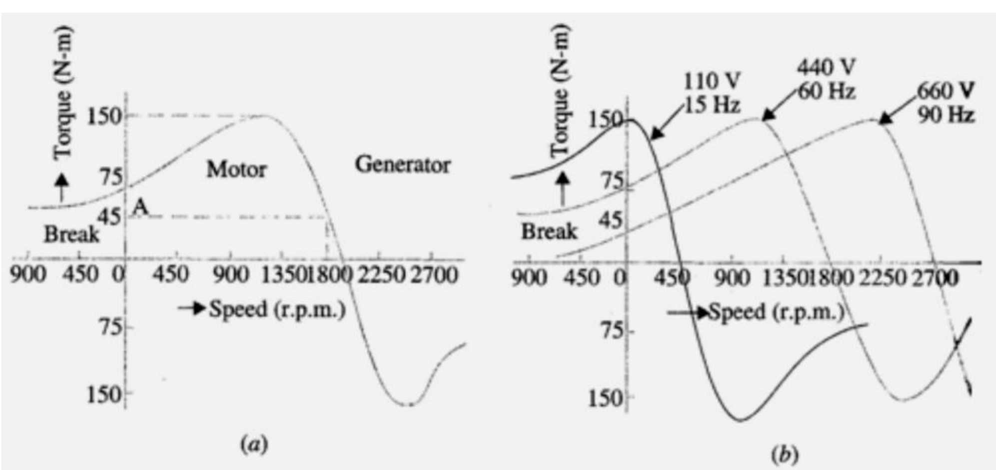
Torque/speed Curve & the effect on the speed-torque characteristics of an induction motor.

The torque developed by a 3-phase motor depends on its speed but the relation between the two cannot be represented by a simple equation. It is easier to show the relationship in the form of a curve. In this diagram, T represents the nominal full load torque of the motor. The starting torque (at N = 0) is 1.5 T and the maximum torque (break down torque) is 2.5T. At full-load, the motor runs at a speed of N. When mechanical load increases, the motor speed decreases till the motor torque again becomes equal to the load torque. As long as the two torques are in balance, the motor will run at constant (but lower) speed. However If the load torque exceeds 2.5T, the motor will suddenly stop.



Shape of Torque/speed curve:

For a squirrel-cage induction motor (SCIM) shape of its torque/speed curve depends on the voltage and frequency applied to its stator. If f is fixed, T α V2 . Also synchronous speed depends on the supply frequency. In practice, supply voltage and frequency are varied in the same proportion in order to maintain a constant flux in the air-gap. For example, if voltage is doubled, then frequency is also doubled. Under these conditions, shape of the torque/speed curve remains the same but its position along the X-axis (speed axis) shifts with frequency. Since the shape of the torque/speed curve remains the same at all frequencies, it follows that torque developed by a SCIM is the same whenever slip speed is the same.



Shibashis Kar

Note: Torque at any speed is proportional to the **square of the applied voltage**. With the change in supply frequency the major effect is seen on motor **speed**, which decreases proportionately with **decrease in frequency**, and the new breakdown torque becomes equal to original breakdown torque but starting torque is slightly reduced with p.f., efficiency, temperature rise remain satisfactory.

Relation Between Full Load Torque And Maximum Torque

Let s_f be the slip corresponding to full-load torque, then

$$T_f \propto \frac{s_f R_2}{R_2^2 + (s_f X_2)^2} \quad \text{and} \quad T_{max} \propto \frac{1}{2 \times X_2}$$

$$\therefore \quad \frac{T_f}{T_{max}} = \frac{2 s_f R_2 X_2}{R_2^2 + (s_f X_2)^2}$$

Dividing both the numerator and the denominator by X_2^2, we get

$$\frac{T_f}{T_{max}} = \frac{2 s_f \cdot R_2 / X_2}{(R_2 / X_2)^2 + s_f^2} = \frac{2 a s_f}{a^2 + s_f^2}$$

where $a = R_2/X_2$ = resistance/standstill reactance

In general, $\dfrac{\text{operating torque at any slip } s}{\text{maximum torque}} = \dfrac{2as}{a^2 + s^2}$

Relation Between Full Load Torque And Maximum Torque

$$T_{st} \propto \frac{R_2}{R_2^2 + X_2^2} \quad \text{and} \quad T_{max} \propto \frac{1}{2 \times X_2}$$

$$\therefore \quad \frac{T_{st}}{T_{max}} = \frac{2 R_2 X_2}{R_2^2 + X_2^2}$$

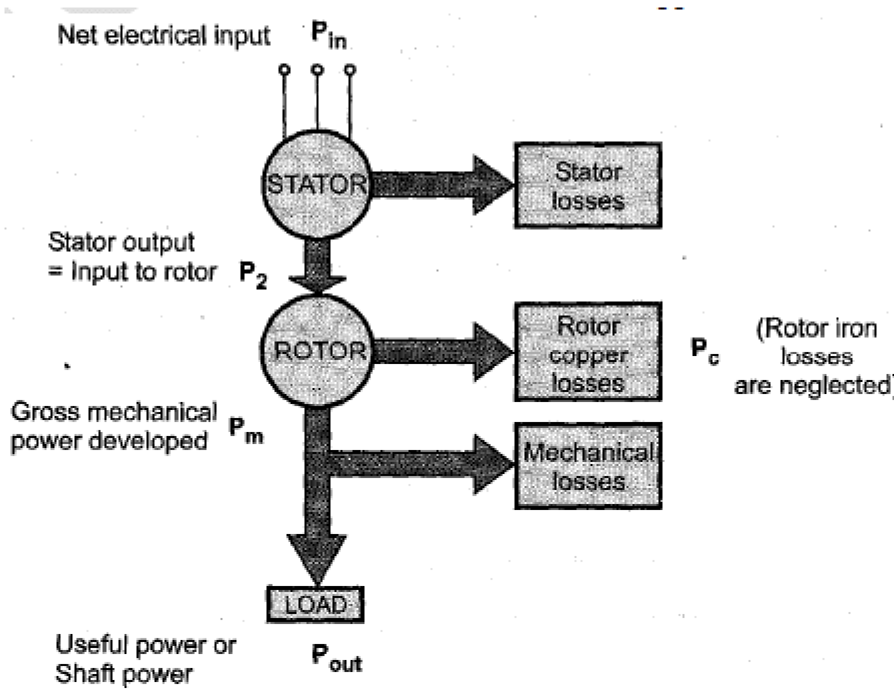
Dividing both the numerator and the denominator by X_2^2, we get

$$\frac{T_{st}}{T_{max}} = \frac{2 R_2 / X_2}{(R_2 / X_2)^2 + 1} = \frac{2a}{a^2 + 1}$$

where $a = R_2/X_2$ = resistance/standstill reactance

Shibashis Kar

Different power stages of a 3 phase induction motor with losses with the help of a power flow diagram.



Induction motor converts an electrical power supplied to it into mechanical power. The various stages in this conversion is called power flow in an induction motor. The three phase supply given to the stator is the net electrical input to the motor. The net input electrical power supplied to the motor is, $\mathbf{P_{in} = \sqrt{3}\, V_L\, I_L \cos\varphi}$ This is the stator input.

The part of this power is utilized to supply the losses in the stator which are stator core as well as copper losses. The remaining power is delivered to the rotor magnetically through the air gap with the help of rotating magnetic field. This is called rotor input denoted as P_2.

$$\mathbf{P_2 = P_{in} - \text{Stator losses (core + copper)}}$$

The rotor is not able to convert its entire input to the mechanical as it has to supply rotor losses. The rotor losses are dominantly copper losses as rotor iron losses are very small and hence generally neglected. So rotor losses are rotor copper losses denoted as

$$\mathbf{P_c = 3\, I_2^2\, R_2}$$

Where, I_2 = Rotor current per phase in running condition
R_2 = Rotor resistance per phase

After supplying these losses, the remaining part of P_2 is converted into mechanical which is called gross mechanica1 power developed by the motor denoted as $\mathbf{P_m}$.

$$\mathbf{P_m = P_2 - P_c}$$

Shibashis Kar

Part of P_m is utilized to provide mechanical friction and windage. Finally the power is available to the load at the shaft. This is called net output of the motor denoted as $\mathbf{P_{out}}$. This is also called shaft power.

Rotor efficiency $= \frac{rotor\ output}{rotor\ input} = \frac{gross\ mechanical\ power\ devoloped}{rotorinput} = \frac{P_m}{P_2}$

Net motor efficiency $= \frac{Net\ output\ at\ shaft}{net\ electrical\ input\ to\ motor} = \frac{P_{out}}{P_{in}}$

<u>Relation between input, rotor copper losses and mechanical power developed in terms of a slip of a three phase induction motor.</u>

Let T = gross torque developed by motor in N-m

Power P = T x ω

Where ω = angular speed $= \frac{2\pi N}{60}$, N = speed in r.p.m

Input to the rotor P_2 is from stator side through rotating magnetic field which is at synchronous speed $\mathbf{N_s}$.

$P_2 = T \times \omega_s$, where $\omega_s = \frac{2\pi N_s}{60}$ rad /sec ....(1)

$P_2 = T \times \frac{2\pi N_s}{60}$, where N_s is in r.p.m

Rotor output is gross mechanical power developed Pm. rotor gives the output at speed n.

$P_m = T \times \omega$ where $\omega = \frac{2\pi N}{60}$

$P_m = T \times \frac{2\pi N}{60}$ .... (2)

Rotor copper loss $P_c = P_2 - P_m = T \times \frac{2\pi N_s}{60} - T \times \frac{2\pi N}{60} = T \times \frac{2\pi}{60}(N_s - N)$.......................... (3)

Dividing equation (3) by (1),

$$\frac{P_c}{P_2} = \frac{T \times \frac{2\pi}{60}(Ns - N)}{T \times \frac{2\pi N_s}{60}} = \frac{Ns - N}{N_s} = \mathbf{s}$$

Rotor copper loss P_c = s x rotor input P_2

Thus total rotor copper loss is slip times the rotor input.

$P_2 - P_c = P_m$

$P_2 - sP_2 = P_m$

$(1\text{-}s)\ P_2 = P_m$

Thus gross mechanical power developed is (1 — s) times the rotor input.

The relationship can be expressed in the ratio form as $\mathbf{P_2 : P_c : P_m :: 1 : s : (1\text{-}s)}$

Shibashis Kar

Starting of an Induction Motor

A three phase Induction Motor is **Self Starting**. When the supply is connected to the stator of a three-phase induction motor, a rotating magnetic field is produced, and the rotor starts rotating and the induction motor starts. At the time of starting, the motor slip is **unity**, and the starting current is very large.

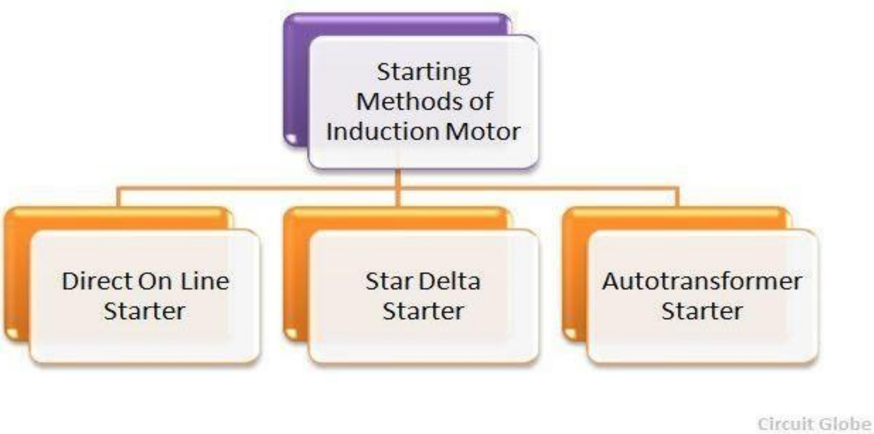
The purpose of a starter is not to just start the motor, but it performs the two main functions. They are as follows.

- To reduce the heavy starting current
- To provide overload and under voltage protection.

The three phase induction motor may be started by connecting the motor directly to the full voltage of the supply. The motor can also be started by applying a reduced voltage to the motor when the motor is started.

The torque of the induction motor is proportional to the square of the applied voltage. Thus, a greater torque is exerted by a motor when it is started on full voltage than when it is started on the reduced voltage.

There are three main methods of **Starting of Cage Induction Motor**. They are as follows.



1.Direct-On-Line (DOL) Starters

Small three phase induction motors can be started direct-on-line, which means that the rated supply is directly applied to the motor. But, as mentioned above, here, the starting current would be very large, usually 5 to 7 times the rated current. The starting torque is likely to be 1.5 to 2.5 times the full load torque. Induction motors can be started directly on-line using a DOL starter which generally consists of a contactor and a motor protection equipment such as a circuit

breaker. A DOL starter consists of a coil operated contactor which can be controlled by start and stop push buttons. When the start push button is pressed, the contactor gets energized and it closes all the three phases of the motor to the supply phases at a time. The stop push button de-energizes the contactor and disconnects all the three phases to stop the motor.
In order to avoid excessive voltage drop in the supply line due to large starting current, a DOL starter is generally used for motors that are rated below 5kW.

Theory of Direct On Line Starting of Induction Motor

Let,

- I_{st} be the starting current drawn from the supply mains per phase.
- I_{fl} is the full load current drawn from the supply mains per phase.
- τ_{est} is the starting torque.
- S_{fl} is the slip at full load.

As we know that the rotor copper loss = s x rotor input

$$3I_2^2R_2 = s \times 2\pi\, n_s \tau_e \;\ldots\ldots.\,(1)$$

Therefore,

$$\tau_e = \frac{3\, I_2^2 R_2}{2\,\pi\, n_s\, s} \;\ldots\ldots\ldots.\,(2)$$

At starting, **$s = 1$, $I_2 = I_{2st}$, $\tau_e = \tau_{est}$**
Therefore,

$$\tau_{est} = \frac{3\, I_{2st}^2 R_2}{2\,\pi\, n_s \times 1} \;\ldots\ldots\ldots.\,(3)$$

At full loads, slip= **s_{fl}, $I_2 = I_{2fl}$, $\tau_e = \tau_{efl}$**

$$\tau_{efl} = \frac{3\, I_{2fl}^2 R_2}{2\,\pi\, n_s \times s_{fl}} \;\ldots\ldots\ldots.\,(4)$$

Therefore,

$$\frac{\tau_{est}}{\tau_{efl}} = \left(\frac{3\, I_{2st}^2 R_2}{2\,\pi\, n_s \times 1}\right) + \left(\frac{3\, I_{2fl}^2 R_2}{2\,\pi\, n_s \times s_{fl}}\right) \quad \text{or}$$

$$\frac{\tau_{est}}{\tau_{efl}} = \left(\frac{I_{2st}}{I_{2fl}}\right)^2 \times s_{fl} \;\ldots\ldots\ldots\,(5)$$

If the no load current is neglected,

$$I_{st} \text{ x effective stator turns } = I_{2st} \text{ x effective rotor turns } \ldots\ldots\ldots..(6)$$

Also,

$$I_{fl} \text{ x effective stator turns } = I_{2fl} \text{ x effective rotor turns } \ldots\ldots\ldots..(7)$$

Equating the above equation (6) and (7), we get

$$\frac{I_{st}}{I_{fl}} = \frac{I_{2st}}{I_{2fl}} \ldots\ldots\ldots.(8)$$

From the equation (5) and (8) we get

$$\frac{T_{est}}{T_{efl}} = \left(\frac{I_{st}}{I_{fl}}\right)^2 \text{ x } s_{fl} \ldots\ldots\ldots(9)$$

If V_1 is the stator voltage per phase equivalent, Z_{e10} is the standstill impedance per phase of the motor referred to the stator then the current at the starting is given by the equation shown below.

$$I_{st} = \frac{V_1}{Z_{e10}} = I_{sc} \ldots\ldots..(10)$$

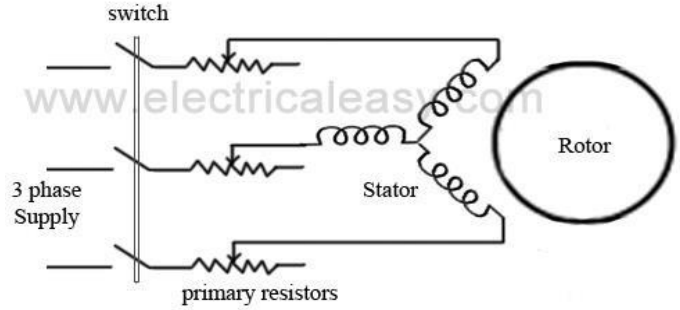
The starting current is equal to the short circuit current.

Combining equation (9) and (10) we get

$$\frac{T_{est}}{T_{efl}} = \left(\frac{I_{sc}}{I_{fl}}\right)^2 \text{ x } s_{fl} \ldots\ldots\ldots(11)$$

Direct on line starter method is the cheapest and the simplest method of the starting of the induction motor.

2.Using Primary Resistors:



Obviously, the purpose of primary resistors is to drop some voltage and apply a reduced voltage to the stator. Consider, the starting voltage is reduced by 50%. Then according to the Ohm's law (V=I/Z), the starting current will also be reduced by the same percentage. From the torque equation of a three phase induction motor, the starting torque is approximately proportional to the square of the applied voltage. That means, if the applied voltage is 50% of the rated value, the starting torque will be only 25% of its normal voltage value. This method is generally used for a **smooth starting of small induction motors**. It is not recommended to use primary resistors type of starting method for motors with high starting torque requirements.

$$I_{st} = x\,I_{sc} \quad \text{and} \quad T_{st} = x^2\,T_{sc}$$

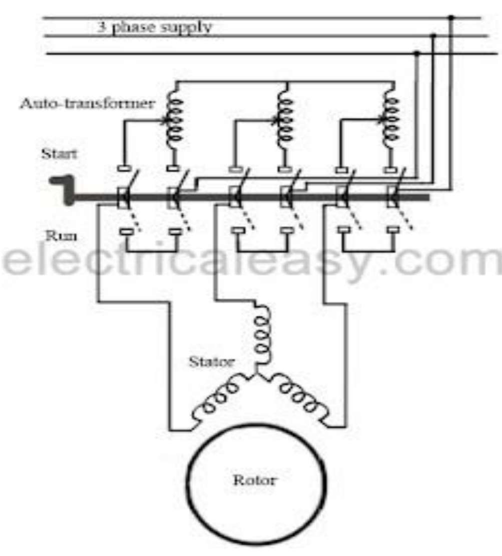
$$\frac{T_{st}}{T_f} = \left(\frac{I_{st}}{I_f}\right)^2 \cdot s_f = \left(\frac{x\,I_{sc}}{I_f}\right)^2 s_f$$

$$= x^2\left(\frac{I_{sc}}{I_f}\right)^2 s_f = x^2 \,.\, a^2 \,.\, s_f$$

By using primary resistors the applied voltage/phase can be reduced by a fraction 'x'(and it additionally improves power factor of the line slightly. It is obvious that the ratio of starting torque (T_{st}) to full-load torque (T_{fl})is x^2 of that obtained with DOL starting. **Method is useful for smooth starting of small machines.**

Resistors are generally selected so that 70% of the rated voltage can be applied to the motor. At the time of starting, full resistance is connected in the series with the stator winding and it is gradually decreased as the motor speeds up. When the motor reaches an appropriate speed, the resistances are disconnected from the circuit and the stator phases are directly connected to the supply lines.

3. Auto-Transformers:



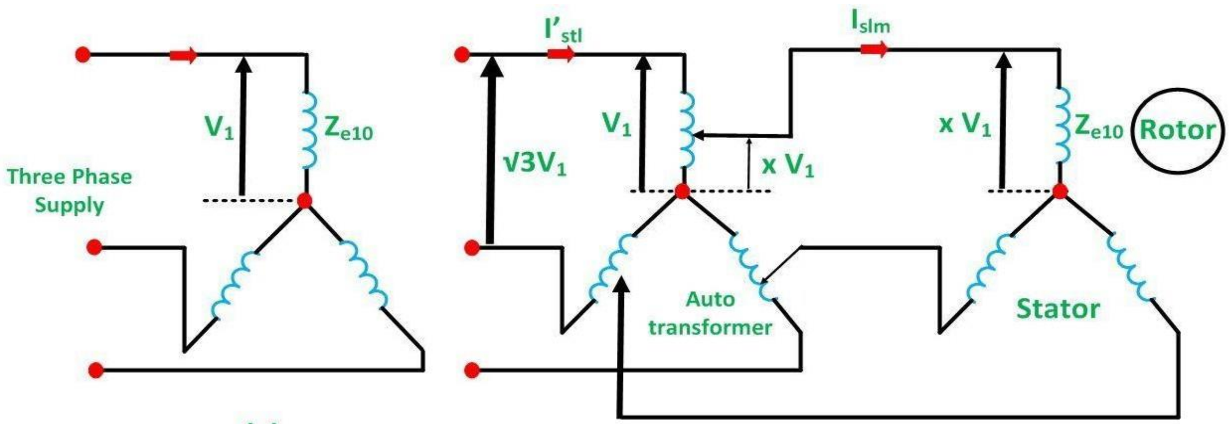
Auto-transformers are also known as auto-starters. They can be used for both star connected or delta connected squirrel cage motors. It is basically a three phase step down transformer with different taps provided that permit the user to start the motor at, say, 50%, 65% or 80% of line voltage. With auto-transformer starting, the current drawn from supply line is always less than the motor current by an amount equal to the transformation ratio. For example, when a motor is started on a 65% tap, the applied voltage to the motor will be 65% of the line voltage and the

Shibashis Kar

applied current will be 65% of the line voltage starting value, while the line current will be 65% of 65% (i.e. 42%) of the line voltage starting value. This difference between the line current and the motor current is due to transformer action. The internal connections of an auto-starter are as shown in the figure. At starting, switch is at "start" position, and a reduced voltage (which is selected using a tap) is applied across the stator. When the motor gathers an appropriate speed, say upto 80% of its rated speed, the auto-transformer automatically gets disconnected from the circuit as the switch goes to "run" position.
The switch changing the connection from start to run position may be air-break (small motors) or oil-immersed (large motors) type. There are also provisions for no-voltage and overload, with time delay circuits on an autostarter.

Theory of Auto transformer Starter

The figure (a) shown below shows the condition when the motor is directly switched on to lines and the figure (b) shows when the motor is started with the help of auto transformer.



(a)
Direct Switching of the motor

(b)
Autotransformer starting of the motor

Let,

- Z_{e10} is the equivalent standstill impedance per phase of the motor referred to the stator side
- V_1 is the supply voltage per phase.

When the full voltage V_1 per phase is applied to the direct switching, the starting current drawn from the supply is given by the equation shown below.

$$I_{stl} = \frac{V_1}{Z_{e10}} \dots\dots\dots (1)$$

With auto transformer starting, if a tapping of the transformer ratio x is used, then the voltage per phase across the motor is xV_1. Therefore, at the starting, the motor current is given by the equation.

$$I_{stm} = \frac{xV_1}{Z_{e10}} \dots\dots\dots (2)$$

Shibashis Kar

In a transformer, the ratio of currents is inversely proportional to the voltage ratio provided that the no load current is neglected. i.e.,

$$\frac{I_1}{I_2} = \frac{V_2}{V_1} \quad \text{or} \quad V_1 I_1 = V_2 I_2$$

If I'_{stl} is the current taken from the supply by the auto transformer. Then,

$$V_1 I'_{stl} = (xV_1)\, I_{stm}$$

$$I'_{stl} = x\, I_{stm} \ldots\ldots\ldots (3)$$

Substituting the value of I_{stm} from the equation (2) in the equation (3) we get.

$$I'_{stl} = x\left(\frac{xV_1}{Z_{e10}}\right)$$

$$I'_{stl} = \frac{x^2 V_1}{Z_{e10}} \ldots\ldots\ldots (4)$$

Therefore,

$$\frac{\text{Starting current with autotransformer}}{\text{Starting current with direct switching}} = \frac{I'_{stl}}{I_{stl}} = \frac{(x^2\, V_1/Z_{e10})}{(V_1/Z_{e10})} = x^2 \ \ldots\ldots (5)$$

Since the torque developed is proportional to the square of the applied voltage, the starting torque with the direct switching is given as

$$T_{std} \propto V_1^2$$

$$T_{std} = k_2 V_1^2 \ldots\ldots (6)$$

Similarly, starting torque with auto transformer starter

$$T_{sta} \propto (xV_1)^2$$

$$T_{sta} = k_2 x^2 V_1^2 \ldots\ldots (7)$$

Therefore,

$$\frac{\text{Starting torque with autotransformer starter}}{\text{Starting torque with direct switching}} = \frac{k_2 x^2 V_1^2}{k_2 V_1^2} = x^2 \ldots\ldots\ldots (8)$$

With the auto transformer, at the starting, the motor current is given by the equation shown below.

$$I_{stm} = \frac{xV_1}{Z_{e10}} = xI_{sc} \dots \dots .(9)$$

From the equation (3) and (9) we can conclude that

$$I'_{stl} = x^2 I_{sc} \dots \dots \dots .(10)$$

From the above equation (5) we get

$$\frac{T_{est}}{T_{efl}} = \left(\frac{I_{stm}}{I_{fl}}\right)^2 s_{fl} = \left(\frac{xI_{sc}}{I_{fl}}\right)^2 s_{fl}$$

$$\frac{T_{est}}{T_{efl}} = x^2 \left(\frac{I_{sc}}{I_{fl}}\right)^2 s_{fl} \dots \dots \dots \dots (11)$$

The above equation (5) and the equation (8) shows that with an auto transformer, the starting current I'_{stl} from the main supply and the starting torque are reduced to the x^2 times to the corresponding values with the direct online starting.

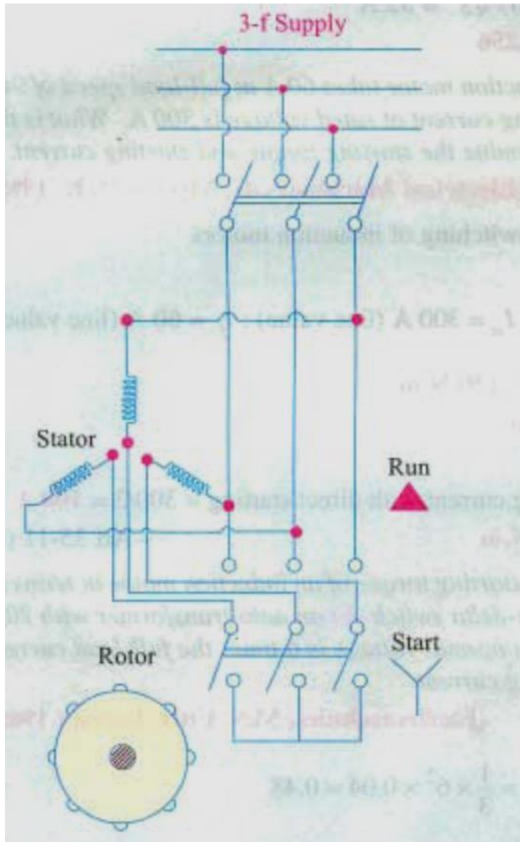
Now, comparing equation (4) and the equation (11) we get

$$x^2 = \frac{1}{3} \quad \text{or} \quad x = \frac{1}{\sqrt{3}} = 0.58$$

Thus, the star delta starter is equivalent to an auto transformer starter of the ratio x = 0.58. A Star Delta starter is much cheaper than an auto transformer starter and is commonly used for both small and the medium size motors.

4. Star-Delta Starter:

This method is used in the motors, which are designed to run on delta connected stator. A two way switch is used to connect the stator winding in star while starting and in delta while running at normal speed. When the stator winding is star connected, voltage over each phase in motor will be reduced by a factor $\frac{1}{\sqrt{3}}$ of that would be for delta connected winding. The starting torque will $\frac{1}{3}$ times that it will be for delta connected winding. Hence a star-delta starter is equivalent to an auto-transformer of ratio $\frac{1}{\sqrt{3}}$ or 58% reduced voltage.



Theory of Star Delta Starter Method of Starting of Induction Motor

At the starting of the induction motor, stator windings are connected in star and, therefore, the voltage across each phase winding is equal to **1/√3 times** the line voltage.

Let,

- V_L is the line voltage
- I_{styp} is the starting current per phase with the stator windings connected in star.
- I_{styl} is the starting line current with the stator winding in the star

For star connection, the line current is equal to the phase current

Therefore,

$$I_{styl} = I_{styp}$$

If,

- V_1 is the phase voltage
- V_L is the line voltage
- $I_{st\Delta p}$ is the starting current per phase by direct switching with the stator windings connected in delta.
- $I_{st\Delta l}$ is the starting line current by direct switching with the stator windings in the delta.
- $I_{sc\Delta p}$ is the short circuit phase current by direct switching with the stator windings in the delta.
- Z_{e10} is the standstill equivalent impedance per phase of the motor, referred to the stator

Shibashis Kar

$$I_{styp} = \frac{V_1}{Z_{e10}} = \frac{V_L}{\sqrt{3}\,Z_{e10}}$$

$$I_{st\Delta p} = \frac{V_L}{Z_{e10}}$$

For Delta connection, the line current is equal to the root three times of the phase current.
Therefore,

$$I_{st\Delta l} = \sqrt{3}\,I_{st\Delta p} = \frac{\sqrt{3}\,V_L}{Z_{e10}}$$

Therefore,

$$\frac{\text{starting line current with star delta starting}}{\text{starting line current with direct switching in delta}} = \frac{I_{styp}}{I_{st\Delta l}}$$

$$= \frac{(V_L/\sqrt{3}\,Z_{e10})}{\sqrt{3}\,(V_L/Z_{e10})} = \frac{1}{3} \quad \ldots\ldots(1)$$

With star delta starter, the starting current from the main supply is one-third of that with direct switching in the delta.
Also,

$$\frac{\text{Starting torque with star delta starting}}{\text{Starting torque with direct switching in delta}} = \frac{(V_L/\sqrt{3})^2}{V_L^2} = \frac{1}{3} \quad \ldots\ldots(2)$$

Hence, with star delta starting, the starting torque is reduced to one-third of the starting torque obtained with the direct switching in the delta.

$$\frac{\text{Starting torque with star delta starting}}{\text{Full load torque with stator winding in delta}} = \left[\frac{(I_{styp})^2 \text{ x } \frac{R_2}{1}}{2\,\pi\,n_s}\right] \div \left[\frac{I_{fl\Delta p}^2}{2\,\pi\,n_s} \text{ x } \frac{R_2}{s_{fl}}\right]$$

$$= \left(\frac{I_{styp}}{I_{fl\Delta p}}\right)^2 \text{ x } s_{fl} \quad \ldots\ldots\ldots(3)$$

Where,
$I_{fl\Delta p}$ is the full load phase current with the winding in the Delta
But,

$$I_{styp} = \frac{V_L/\sqrt{3}}{Z_{e10}}$$

Shibashis Kar

$$I_{st\Delta p} = \frac{V_L}{Z_{e10}}$$

Therefore,

$$I_{styp} = \frac{1}{\sqrt{3}} I_{st\Delta p} \quad \text{and} \quad I_{styp}^2 = \frac{1}{3} I_{st\Delta p}^2$$

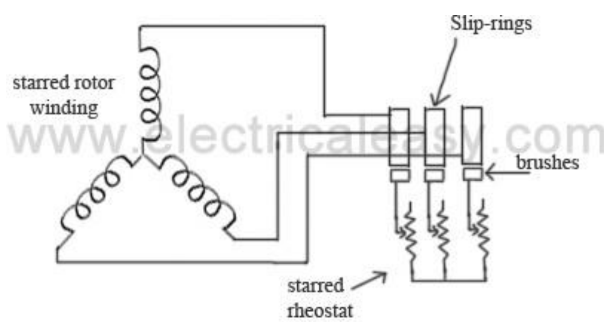
Therefore,

$$\frac{\text{Starting torque with star delta starting}}{\text{Full load torque with stator winding in delta}} = \left(\frac{I_{styp}}{I_{fl\Delta p}}\right)^2 \text{x } s_{fl}$$

$$= \frac{1}{3}\left(\frac{I_{st\Delta p}}{I_{fl\Delta p}}\right)^2 \text{x } s_{fl} \quad \dots\dots\dots (4)$$

Hence, the equation (4) shown above gives the starting torque of an induction motor in the star delta starting method.

<u>5.</u> Starting Of Slip-Ring Motors



Phase wound rotor connections

Slip-ring motors are started with full line voltage, as external resistance can be easily added in the rotor circuit with the help of slip-rings. A star connected rheostat is connected in series with the rotor via slip-rings as shown in the fig. Introducing resistance in rotor current will decrease the starting current in rotor (and, hence, in stator). Also, it improves power factor and the torque is increased. The connected rheostat may be hand-operated or automatic.

As, introduction of additional resistance in rotor improves the starting torque, slip-ring motors can be started on load.

The external resistance introduced is only for starting purposes, and is gradually cut out as the motor gathers the speed.

Speed control of Induction Motor

The Speed of Induction Motor is changed from Both Stator and Rotor Side. The speed control of three phase induction motor from stator side are further classified as :

- V / f control or frequency control.
- Changing the number of stator poles.
- Controlling supply voltage.
- Adding rheostat in the stator circuit.

The speed controls of three phase induction motor from rotor side are further classified as:

- Adding external resistance on rotor side(this method is only in scope of syllabus)
- Cascade control method.
- Injecting slip frequency emf into rotor side.
-

Speed Control from Stator Side

1.V / f Control or Frequency Control

Whenever three phase supply is given to three phase induction motor rotating magnetic field is produced which rotates at synchronous speed given by

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

In three phase induction motor emf is induced by induction similar to that of transformer which is given by

$$E \ or \ V = 4.44\phi K.T.f \ or \ \phi = \frac{V}{4.44KTf}$$

Where, K is the winding constant, T is the number of turns per phase and f is frequency. Now if we change frequency synchronous speed changes but with decrease in frequency flux will increase and this change in value of flux causes saturation of rotor and stator cores which will further cause increase in no load current of the motor . So, its important to maintain flux , φ constant and it is only possible if we change voltage. i.e if we decrease frequency flux increases but at the same time if we decrease voltage flux will also decease causing no change in flux and hence it remains constant. So, here we are keeping the ratio of V/f as constant. Hence its name is V/ f method. For controlling the speed of three phase induction motor by V/f method we have to supply variable voltage and frequency which is easily obtained by using converter and inverter set.

2.Controlling Supply Voltage

The torque produced by running three phase induction motor is given by

$$T \propto \frac{sE_2^2R_2}{R_2^2 + (sX_2)^2}$$

In low slip region $(sX)^2$ is very very small as compared to R_2. So, it can be neglected. So torque becomes

$$T \propto \frac{sE_2^2}{R_2}$$

Since rotor resistance, R_2 is constant so the equation of torque further reduces to

$$T \propto sE_2^2$$

We know that rotor induced emf $E_2 \propto V$. So, $T \propto sV^2$.
The equation above clears that if we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remain the same, and it is only possible if we increase the slip and if the slip increases the motor will run at a reduced speed. This method of speed control is rarely used because a small change in speed requires a large reduction in voltage, and hence the current drawn by motor increases, which cause overheating of the induction motor.

3. Changing the number of stator poles:

As we know that the $N_s = \frac{120f}{P}$, speed control of three phase induction motor can be done by changing the stator poles which can be performed by two methods

1. Multiple stator winding method.

2. Pole amplitude modulation method (PAM)

- **Multiple Stator Winding Method**

In this method of speed control of three phase induction motor, we provide two separate windings in the stator. These two stator windings are electrically isolated from each other and are wound for two different numbers of poles. Using a switching arrangement, at a time, supply is given to one winding only and hence speed control is possible. Disadvantages of this method are that the smooth speed control is not possible. This method is more costly and less efficient as two different stator windings are required. This method of speed control can only be applied to squirrel cage motor.

Pole Amplitude Modulation Method (PAM)

In this method of speed control of three phase induction motor the original sinusoidal mmf wave is modulated by another sinusoidal mmf wave having the different number of poles.

3. **<u>Adding Rheostat in Stator Circuit</u>**

In this method of speed control of three phase induction motor rheostat is added in the stator circuit due to this voltage gets dropped .In case of three phase induction motor torque produced is given by $T \propto sV_2^2$. If we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remains the same and it is only possible if we increase the slip and if the slip increase motor will run reduced speed.

Speed Control from Rotor Side

Adding External Resistance on Rotor Side

In this method of speed control of three phase induction motor external resistance are added on rotor side. The equation of torque for three phase induction motor is

$$T \propto \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

The three-phase induction motor operates in a low slip region. In low slip region term $(sX)^2$ becomes very very small as compared to R_2. So, it can be neglected. and also E_2 is constant. So the equation of torque after simplification becomes,

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

Now if we increase rotor resistance, R_2 torque decreases but to supply the same load torque must remain constant. So, we increase slip, which will further result in the decrease in rotor speed. Thus by adding additional resistance in the rotor circuit, we can decrease the speed of the three-phase induction motor. The main advantage of this method is that with an addition of external resistance starting torque increases but this method of speed control of three phase induction motor also suffers from some disadvantages :

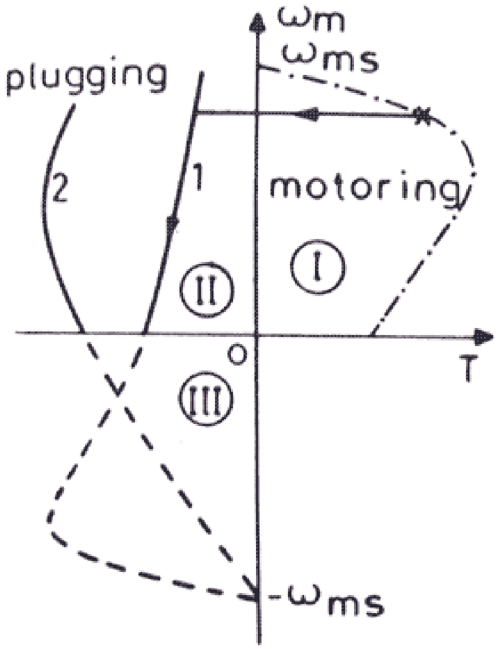
- The speed above the normal value is not possible.
- Large speed change requires a large value of resistance, and if such large value of resistance is added in the circuit, it will cause large copper loss and hence reduction in efficiency.
- Presence of resistance causes more losses.
- This method cannot be used for squirrel cage induction motor.

Plugging Braking Of Induction Motor

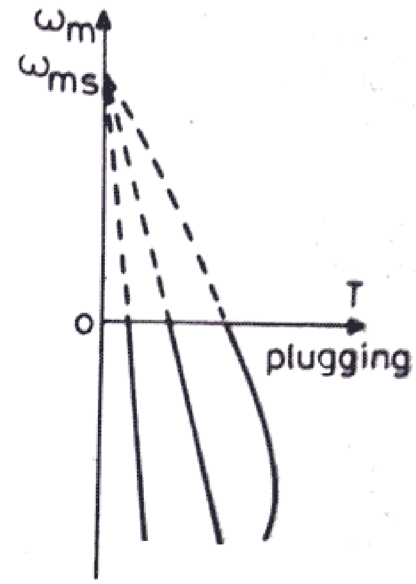
Plugging **induction motor braking** is done by reversing the phase sequence of the motor. **Plugging braking of induction motor** is done by interchanging connections of any two phases of stator with respect of supply terminals. And with that the operation of motoring shifts to **plugging braking**. During plugging the slip is (2 – s), if the original slip of the running motor is s, then it can be shown in the following way.

$$S_n = \frac{-\omega_{ms} - \omega m}{-\omega_{ms}} = 2 - s$$

Shibashis Kar



(a) 1: natural characteristic
2: with external resistance in rotor



(b) Plugging in IV quadrant with large external resistance in rotor

From the figure beside we can see that the torque is not zero at zero speed. That's why when the motor is needed to be stopped, it should be disconnected from the supply at near zero speed. The motor is connected to rotate in the reverse direction and the torque is not zero at zero or any other speed, and as a result the motor first decelerates to zero and then smoothly accelerates in the opposite direction.

During this so-called plugging period moor first absorbs kinetic energy from the still revolving load causing its speed to fall. The associated power is dissipated as heat in the rotor. At the same time, the rotor also continues to receive power from the stator which is also dissipated as heat. Consequently, plugging produces rotor I^2R losses which even exceed those when the rotor is locked.

<u>Different Types Of Motor Enclosures</u>

The enclosure of the motor must protect the windings, bearings, and other mechanical parts from moisture, chemicals, mechanical damage and abrasion from grit. NEMA standards MG1-1.25 through 1.27 define more than 20 types of enclosures under the categories of open machines, totally enclosed machines, and machines with encapsulated or sealed windings.

The 7 most common types of enclosures are:

1. Open Drip Proof (ODP)

Allows air to circulate through the windings for cooling, but prevent drops of liquid from falling into motor within a 15 degree angle from vertical. Typically used for indoor applications in relatively clean, dry locations.

2. Totally Enclosed Fan Cooled (TEFC)

Prevents the free exchange of air between the inside and outside of the frame, but does not make the frame completely air tight. A fan is attached to the shaft and pushes air over the frame during its operation to help in the cooling process. The TEFC style enclosure is the most versatile of all. It is used on pumps, fans, compressors, general industrial belt drive and direct connected equipment.

3. Totally Enclosed Non-Ventilated (TENV)

Similar to a TEFC, but has no cooling fan and relies on convention for cooling. No vent openings, tightly enclosed to prevent the free exchange of air, but not airtight.

4. Totally Enclosed Air Over (TEAO)

Dust-tight fan and blower duty motors designed for shaft mounted fans or belt driven fans. The motor must be mounted within the airflow of the fan.

5. Totally Enclosed Wash down (TEWD)

Designed to withstand high pressure wash-downs or other high humidity or wet environments. Available on TEAO, TEFC and ENV enclosures totally enclosed, hostile and severe environment motors:

6. Explosion-proof enclosures (EXPL)

The explosion proof motor is a totally enclosed machine and is designed to withstand an explosion of specified gas or vapor inside the motor casing and prevent the ignition outside the motor by sparks, flashing or explosion.

7. Hazardous Location (HAZ)

Hazardous location motor applications are classified by the type of hazardous environment present, the characteristics of the specific material creating the hazard, the probability of exposure to the environment, and the maximum temperature level that is considered safe for the substance creating the hazard.

The following hazardous locations are defined:

1) CLASS I

Group A: Acetylene

Group B: Butadiene, ethylene oxide, hydrogen, propylene oxide, manufactured gases containing more than 30ydrogen by volume.

Group C: Acetaldehyde, cyclopropane, diethyl ether, ethylene.

Group D: Acetone, acrylonitrile, ammonia, benzene, butane, ethanol, ethylene dichloride, gasoline, hexane, isoprene, methane (natural gas), methanol, naphtha, propane, propylene, styrene, toluene, vinyl acetate, vinyl chloride, xylene.

2) CLASS II

Group E: Aluminum, magnesium, and other metal dusts with similar characteristics.

Group F: Carbon black, coke or coal dust.

Group G: Flour, starch or grain dust.

3) CLASS III

Easily ignitable fibers, such as rayon, cotton, sisal, hemp, cocoa fiber, oakum, excelsior and other materials of similar nature.

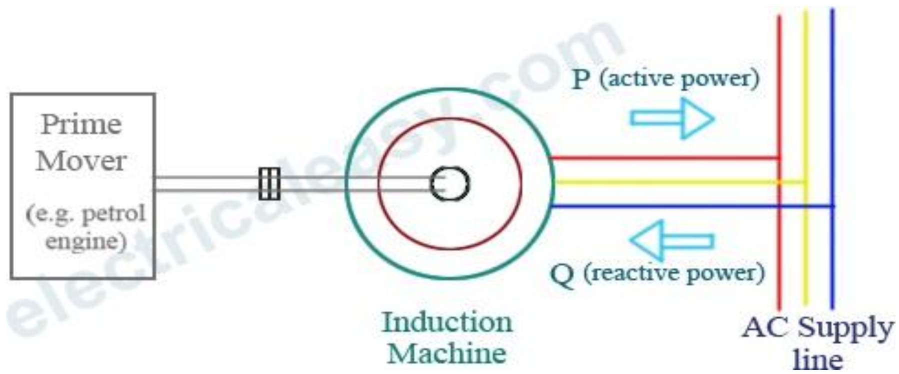
Principle of Induction Generator and its applications.

In an induction motor, the rotor rotates because of slip (i.e. relative velocity between the rotating magnetic field and the rotor). Rotor tries to catch up the synchronously rotating field of the stator but never succeeds. If rotor catches up the synchronous speed, the relative velocity will be zero, and hence rotor will experience no torque. But if the rotor is rotating at a speed more than synchronous speed, then the machine goes to generating mode.If an AC supply is connected to the stator terminals of an induction machine. Rotating magnetic field produced in the stator pulls the rotor to run behind it (the machine is acting as a motor).

Now, if the rotor is accelerated to the synchronous speed by means of a prime mover, the slip will be zero and hence the net torque will be zero. The rotor current will become zero when the rotor is running at synchronous speed.

If the rotor is made to rotate at a speed more than the synchronous speed, the slip becomes negative. A rotor current is generated in the opposite direction, due to the rotor conductors cutting stator magnetic field.

This generated rotor current produces a rotating magnetic field in the rotor which pushes (forces in opposite way) onto the stator field. This causes a stator voltage which pushes current flowing out of the stator winding against the applied voltage. Thus, the machine is now working as an induction generator (asynchronous generator).

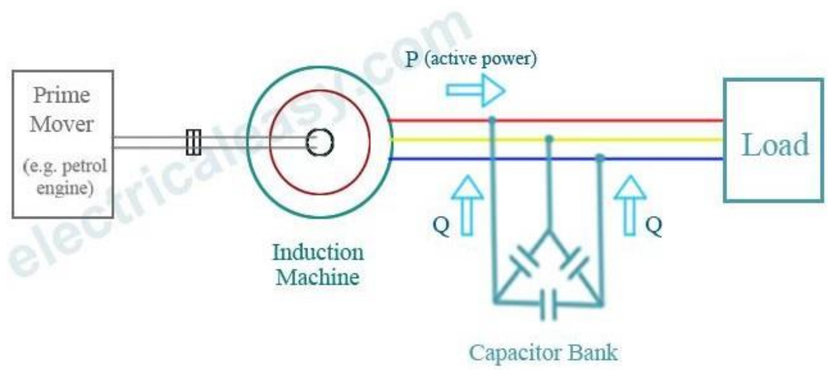


Induction generator is not a self-excited machine. Therefore, when running as a generator, the machine takes reactive power from the AC power line and supplies active power back into the line. Reactive power is needed for producing rotating magnetic field. The active power supplied back in the line is proportional to slip above the synchronous speed. The active power is directly proportional to the slip above the synchronous speed.

Self-Excited Induction Generator

It is clear that, an induction machine needs reactive power for excitation, regardless whether it is operating as a generator or a motor. When an induction generator is connected to a grid, it takes reactive power from the grid. But if we want to use an induction generator to supply a load without using an external source (e.g. grid),a capacitor bank can be connected across the stator terminals to supply reactive power to the machine as well as to the load.

When the rotor is rotated at an enough speed, a small voltage is generated across the stator terminals due to residual magnetism. Due to this small generated voltage, capacitor current is produced which provides further reactive power for magnetization.



Applications of induction generators: Induction generators produce useful power even at varying rotor speeds. Hence, they are suitable in wind turbines.

Advantages: Induction or asynchronous generators are more rugged and require no commutator and brush arrangement (as it is needed in case of synchronous generators).

One of the major **disadvantages** of induction generators is that they take quite large amount of reactive power.

****

CHAPTER 4
SINGLE PHASE INDUCTION MOTORS
INTRODUCTION:

There are two basic reasons for the use of single-phase motors rather than 3-phase motors.

1. For reason of economy, most houses, offices and also rural areas are supplied with single phase AC, as power requirements of individual load items are rather small.
2. The economics of the motor and its branch circuit.

- Fixed loads requiring not more than 0.5KW can generally be served most economically with single phase power and a single phase motor.
- Single phase motors are simple in construction, reliable, easy to repair and comparatively cheaper in cost and therefore, find wide use in fans, refrigerators, vacuum cleaners, washing machines, other kitchen equipment, tools, blowers, centrifugal pumps, small farming appliances etc. Because of above reasons motors of comparatively small ratings (mostly in fractional KW ratings) are manufactured in large number to operate on single phase ac at standard frequencies. An indication of the number of such motors can be had from the fact that the sum of total of all fractional kilowatt motors in use today far exceeds the total of integral kilowatt motors of all types.

WORKING PRINCIPLE OF SINGLE-PHASE INDUCTION MOTOR:

A single phase induction motor is inherently not self-staring can be shown easily.
Consider a single phase induction motor whose rotor is at rest. Let a single phase AC. source be connected to the stator winding (it is assumed that there is no starting winding). Let the stator be wound for two poles. When power supply for the stator is switched on, an alternating current flows through the stator winding. This sets up an alternating flux. This flux crosses the air gap and links with the rotor conductors. By electromagnetic induction e.m.f.s are induced in the rotor conductors.
Since the rotor forms a closed circuit, currents are induced in the rotor bars. Due to interaction between the rotor induced currents and the stator flux, a torque is produced. It is readily seen that if all rotor conductors in the upper half come under a stator N pole, all rotor conductors in the lower half come under a stator S pole. Hence the upper half of the rotor is subjected to a torque which tends to rotate it in one direction and the lower half of the rotor is acted upon by an equal torque which tends to rotate it in the opposite direction. The two equal and opposite torques

cancel out, with the result that the net driving torque is zero. Hence the rotor remains stationary. Thus the single phase motor fails to develop starting torque. This argument holds good irrespective of the number of stator poles and the polarity of the stator winding. The net torque acting on the rotor at standstill is zero. If, however, the rotor is in motion in any direction when supply for the stator is switched on, it can be shown that the rotor develops more torque in that direction. The net torque then, would have non-zero value, and under its impact the rotor would speed up in its direction. The analysis of the single phase motor can be made on the basis of two theories:

i. Double revolving field theory, and

ii. Cross field theory.

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 ($Ns=\frac{120f}{P}$) in opposite direction.

As shown in figure: 1.51(a) let the alternating flux have a maximum value of ϕ_m. Its component fluxes A and B will each equal to $\phi_m/2$ revolving in anti-clockwise and clockwise directions respectively. After some time, when A and B would have rotated through angle +ϴ and – ϴ, as in figure: 1.51(b), the resultant flux would be

$$= 2x\frac{\phi m}{2}\cos\frac{2\theta}{2} = \phi m.\cos\theta$$

After a quarter cycle of rotation, fluxes A and B will be oppositely-directed as shown in figure: 1.51(c) so that the resultant flux would be zero.

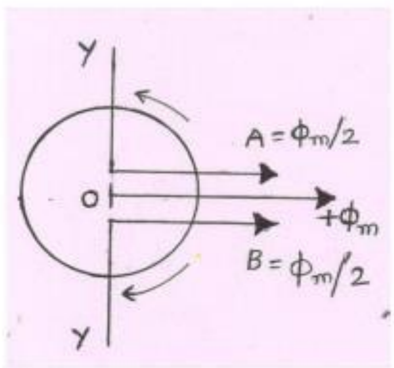


Fig: 1.51(a)

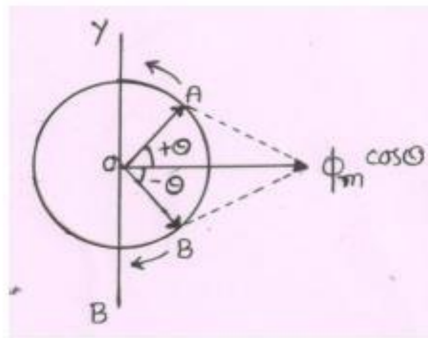


Fig: 1.51(b)

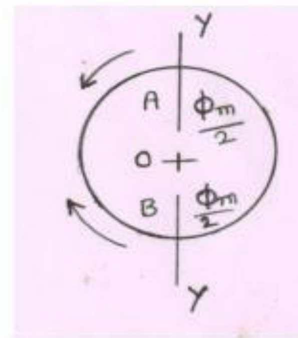


Fig:1.51 (c)

After half a cycle, fluxes A and B will have a resultant of $-2x\frac{\boldsymbol{\phi_m}}{\mathbf{2}} = -\phi m$

After three quarters of a cycle, again the resultant is zero, as shown in figure: (e) and so on. If we plot the values of resultant flux against ϴ between limits $\Theta=0^0$ to $\Theta=360^0$, then a curve similar to the one shown in figure: 1.51(f) 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.

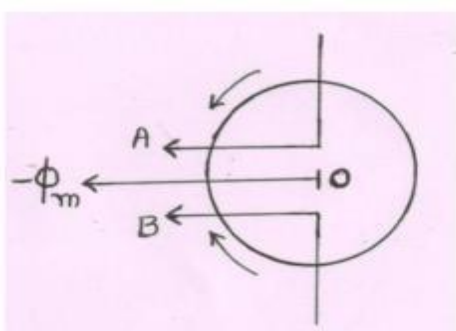


Fig: 1.51 (d)

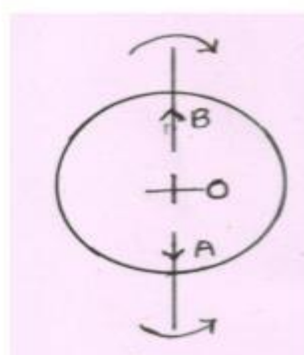


Fig: 1.51(e)

Shibashis Kar

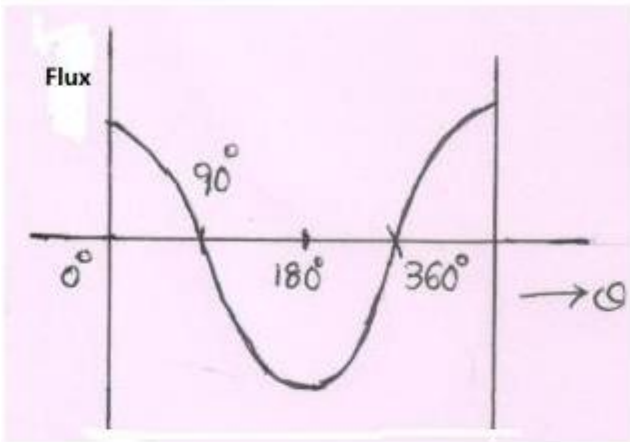


Fig: 1.51(f)

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: 1.51(g)

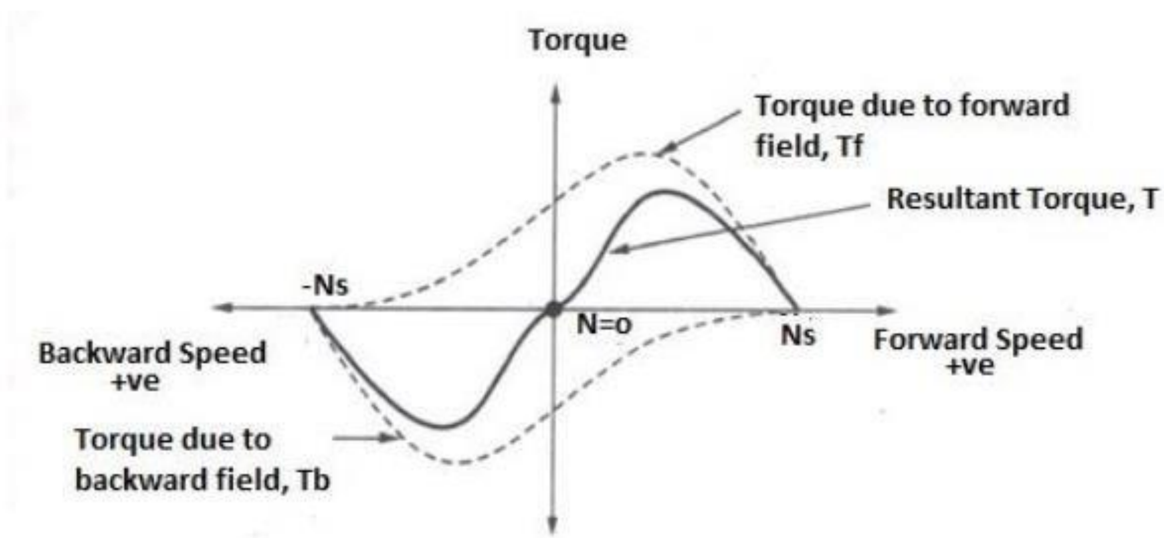


Fig: 1.51(g) Torque-Speed characteristics

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 , $T_g = \frac{1}{2\Pi N}\left(\frac{1-s}{s}\right) I_2^2 R_2$

Now, $N = N_s (1-s)$

Therefore, $T_g = \frac{1}{2\Pi N_s} \frac{I_2^2 R_2}{s} = k \frac{I_2^2 R_2}{s}$

Hence, the forward and backward torques are given by

$T_f = k \frac{I_2^2 R_2}{s}$ and $T_b = - k \frac{I_2^2 R_2}{2-s}$

$T_f = k \frac{I_2^2 R_2}{s}$ synch. watt and $T_b = - k \frac{I_2^2 R_2}{2-s}$ synch. watt

Total torque $\mathbf{T = T_f + T_b}$

Fig: 1.51(g) shows both torques and the resultant torque for slips between zero and +2. At standstill, **s=1 and (2-s) =1**. Hence, T_f and T_b 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.

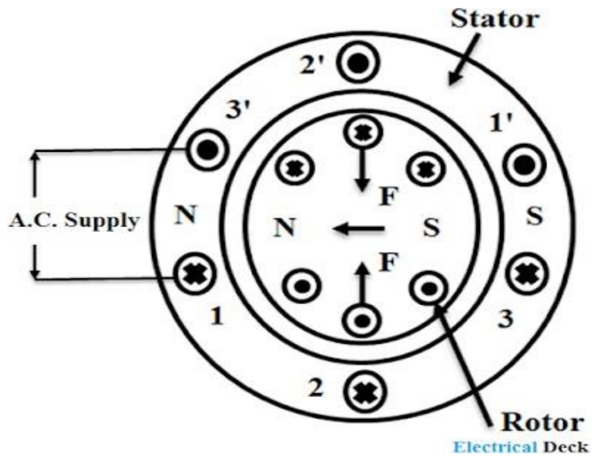
CROSS-FIELD THEORY OF SINGLE PHASE INDUCTION MOTOR

Motor at Standstill :

Consider standstill conditions with the stator winding connected to a single-phase AC supply. The stator current establishes a field acts along the horizontal axis is shown in the just below figure. The stator field is alternating in polarity and varying sinusoidally with time. The alternating field will induce an emf in the rotor winding by transformer action. This emf will cause a current to flow in the rotor winding.

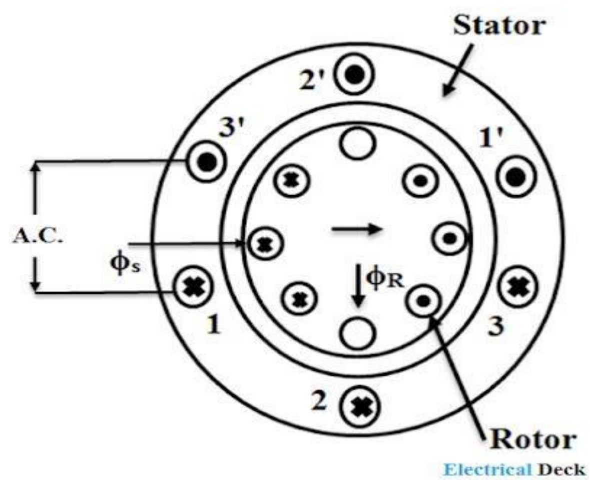
The directions of currents in the rotor conductors are also shown. The rotor currents establish poles on the rotor surface and these are in direct line (along the horizontal axis) with the stator poles. The axis of the stator and rotor fields are aligned. The forces on the rotor conductors in top the half are in a downward direction, whereas the forces on the rotor conductors in the bottom half are in the upward direction. The two sets of forces will cancel and the rotor will experience no torque.

Shibashis Kar



Motor at Running :

When, however, the rotor is made to rotate say in the clockwise direction by some external means, the rotor conductors cut across the stator field, causing an emf to be generated in them. The direction of the EMFs as determined by Fleming's Right-Hand Rule, will be outward in one side of the vertical axis and inward on the other side of the vertical axis as indicated by the dots and crosses as shown in just below figure. The generated rotor EMFs vary in phase with the stator current and flux. The rotor current due to these EMFs lags by nearly 90° owing to low 'R' and high 'X' of the rotor winding.



The field produced by the rotor currents is at right angles to the field by the stator currents hence it is known as cross field. Thus the stator field Q_s, and rotor field Q_r are in space and time quadrature. These two fields will produce a resultant revolving field which will rotate in the direction in which the rotor was given an initial rotation. Hence torque is exerted on the rotor and the motor continues to rotate.

Shibashis Kar

From the above discussion, it may be concluded that :

1. At stand still there can be no cross field only the pulsating stator field and therefore the inherent starting torque of a single-phase induction motor is zero.
2. If, however, the rotor is made to run by some external means, then it will continue to develop torque in the direction of rotation.

STARTING METHODS OF SINGLE-PHASE INDUCTION MOTORS:

A single-phase induction motor with main stator winding has no inherent starting torque, since main winding introduces only stationary, pulsating air-gap flux wave. For the development of starting torque, rotating air-gap field at starting must be introduced. Several methods which have been developed for the starting of single-phase induction motors, may be classified as follows:

a) Split-phase starting.

b) Shaded-pole starting.

c) Repulsion-motor starting and

d) Reluctance starting.

A single-phase induction motor is commonly known by the method employed for its starting. The selection of a suitable induction motor and choice of its starting method, depend upon the following:

(i) Torque-speed characteristic of load from standstill to the normal operating speed.

(ii) The duty cycle and

(iii)The starting and running line-current limitations as imposed by the supply authorities

(a) SPLIT-PHASE STARTING:

Single-phase induction motors employing this method of starting are called Splitphase motors. All the split-phase motors have two stator windings, a main (or running) winding and an auxiliary (or starting) winding. Both these windings are connected in parallel but their magnetic axes are space displaced by 900 electrical. It is known that when two windings spaced 900 apart on the stator, are excited by two alternating e.m.f. that are 900 displaced in time phase, a rotating magnetic field is produced. If two windings so placed are connected in parallel to a single phase source, the field produced will alternate but will not revolve since the two windings are equivalent to one single phase winding. If impedance is connected in series with one of these windings, the currents may be made to differ in time phase, thereby producing a rotating field. This is the principle of phase splitting. Split phase motors are of following types.

1. Resistor-split phase motors

2. Capacitor split-phase motors

3. Capacitor start and run motors

4. Capacitor-run motors

<u>Resistor split-phase motors:</u>

The stator of a split-phase induction motor is provided with an auxiliary or starting winding S in addition to the main or running winding M. The starting winding is located 90° electrical from the main winding [See figure: 1.71(a)] and operates only during the brief period when the motor starts up. The two windings are so designed that the starting winding S has a high resistance and relatively small reactance while the main winding M has relatively low resistance and large reactance as shown in the schematic connections in figure: 1.71(b). Consequently, the currents flowing in the two windings have reasonable phase difference (25° to 30°) as shown in the phasor diagram in figure: 1.71(c). Operation (i) When the two stator windings are energized from a single-phase supply, the main winding carries current Im while the starting winding carries current Is (ii) Since main winding is made highly inductive while the starting winding highly resistive, the currents Im and Is have a reasonable phase angle a (25° to 30°) between them as shown in figure: 1.71(c).Consequently, a weak revolving field approximating to that of a 2-phase machine is produced which starts the motor. The starting torque is given by; $T_s = k I_m I_s \sin\phi$ Where k is a constant whose magnitude depends upon the design of the motor . When the motor reaches about 75% of synchronous speed, the centrifugal switch opens the circuit of the starting winding. The motor then operates as a single-phase induction motor and continues to accelerate till it reaches the normal speed. The normal speed of the motor is below the synchronous speed and depends upon the load on the motor. Characteristics: (i) The sinning torque is 15 to 2 times the full-loud torque mid (starting current is 6 to 8 times the full-load current. (ii) Due to their low cost, split-phase induction motors are most popular single phase motors in the market. (iii) Since the starting winding is made of fine wire, the current density is high and the winding heats up quickly. If the starting period exceeds 5 seconds, the winding may burn out unless the motor is protected by built-in-thermal relay. This motor is, therefore, suitable where starting periods are not frequent. An important characteristic of these motors is that they are essentially constant-speed motors. The speed variation is 2-5% from no-load to full-load.

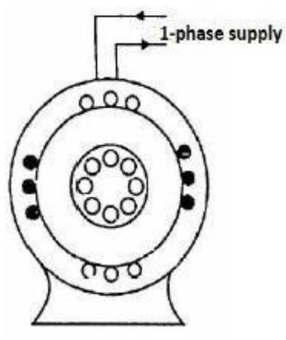


Fig: 1.71(a)

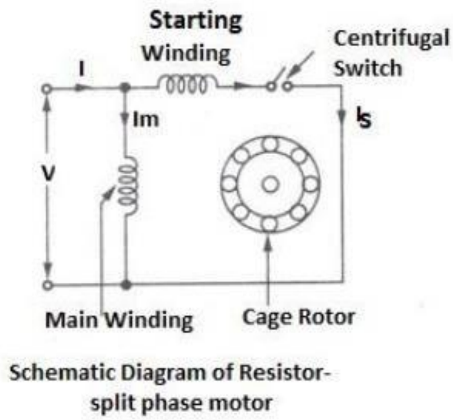


Fig: 1.71(b)

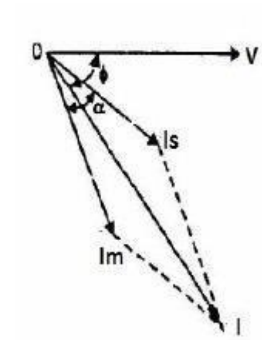
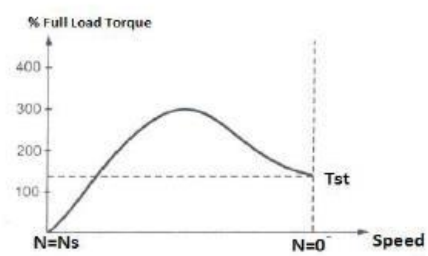


Fig: 1.71(c)



Applications:

These motors are suitable where a moderate starting torque is required and where starting periods are infrequent e.g., to drive:

a. Fans

b. washing machines

c. oil burners

d. Small machine tools etc.

The power rating of such motors generally lies between 60 W and 250 W .

Capacitor split-phase motors (or) Capacitor start motors:

The capacitor split-phase motor is identical to a resistor split-phase motor except that the starting winding has as many turns as the main winding. Moreover, a capacitor C is connected in series with the starting winding as shown in figure: 1.72(a).The value of capacitor is so chosen that

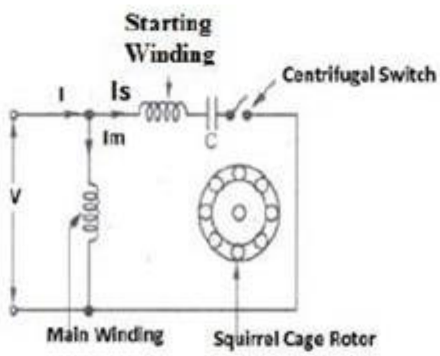
I_s leads I_m by about 80° (i.e., $\phi \sim 80°$) which is considerably greater than 25° found in resistor split-phase motor [See figure: 1.72(b).Consequently, starting torque ($T_s = k\, I_m\, I_s \sin\phi$) is much more than that of a split-phase motor Again, the starting winding is opened by the centrifugal switch when the motor attains about 75% of synchronous speed. The motor then operates as a single-phase induction motor and continues to accelerate till it reaches the normal speed.

Characteristics

(i) Although starting characteristics of a capacitor-start motor are better than those of a resistor split-phase motor, both machines possess the same running characteristics because the main windings are identical.

(ii) The phase angle between the two currents is about 80° compared to about 25° in a resistor split-phase motor. Consequently, for the same starting torque, the current in the starting winding is only about half that in a resistor split-phase motor. Therefore, the starting winding of a capacitor start motor heats up less quickly and is well suited to applications involving either frequent or prolonged starting periods because the main windings are identical.

(ii) The phase angle between the two currents is about 80° compared to about 25° in a resistor split-phase motor. Consequently, for the same starting torque, the current in the starting winding is only about half that in a resistor split-phase motor. Therefore, the starting winding of a capacitor start motor heats up less quickly and is well suited to applications involving either frequent or prolonged starting periods.



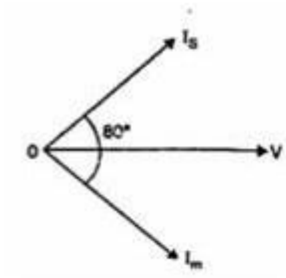
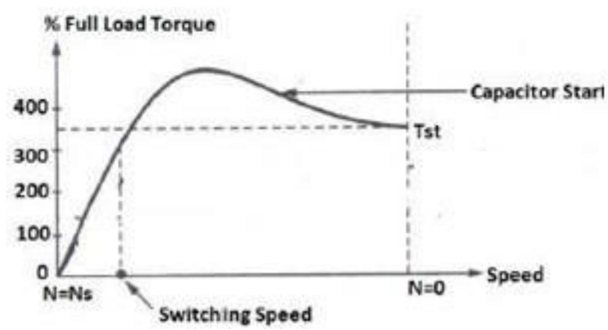


Fig: 1.72(a)

Fig: 1.72(b)



Capacitor-Start and Capacitor-Run motors:

This motor is identical to a capacitor-start motor except that starting winding is not opened after starting so that both the windings remain connected to the supply when running as well as at starting. Two designs are generally used.

(i) In one design, a single capacitor C is used for both starting and running as shown in fig: 1.73(a).This design eliminates the need of a centrifugal switch and at the same time improves the power factor and efficiency of the motor.

(ii) In the other design, two capacitors C1 and C2 are used in the starting winding as shown in fig: 1.73(b).The smaller capacitor C1 required for optimum running conditions is permanently connected in series with the starting winding. The much larger capacitor C2 is connected in parallel with C1 for optimum starting and remains in the circuit during starting. The starting capacitor C1 is disconnected when the motor approaches about 75% of synchronous speed. The motor then runs as a single-phase induction motor.

Shibashis Kar

Characteristics

(i) The starting winding and the capacitor can be designed for perfect 2-phase operation at any load. The motor then produces a constant torque and not a pulsating torque as in other single-phase motors.

(ii) Because of constant torque, the motor is vibration free.

Applications:

a. Hospitals

b. Studios and

c. Other places where silence is important

The power rating of such motors lies between 100 to 400 watts

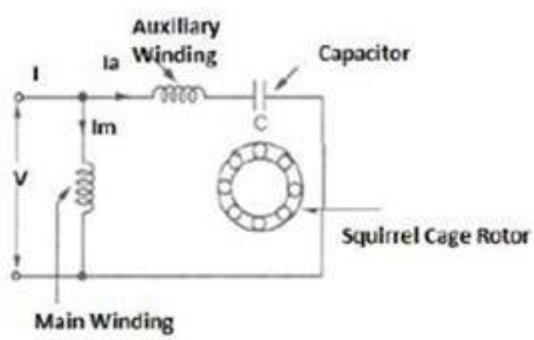


Fig: 1.73(a)

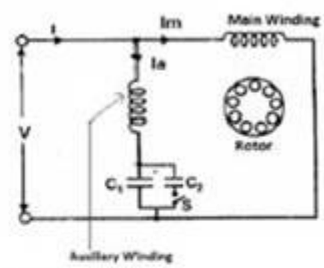


Fig: 1.73 (b)

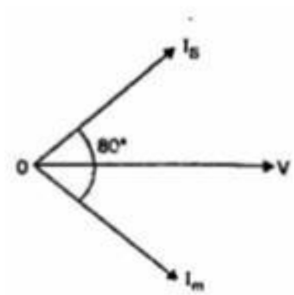


Fig: 1.73 (c)

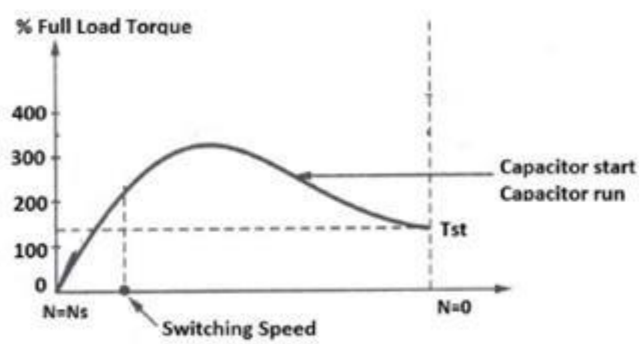


Fig: 1.73 (d)

Shibashis Kar

Capacitor-run motors:

This motor is also called permanent split capacitor motor. The same capacitor is kept permanently in series with auxiliary winding both at starting and under running conditions as illustrated in figure: 1.74 (a). There is no centrifugal switch. At a particular desired load, the capacitor and auxiliary winding can be so designed as to result in 90^0 time-phase displacement between the two winding currents. In such a case, the motor would operate as a balanced two phase induction motor, backward rotating flux would, therefore, be absent and the motor would have improved efficiency and better operating power factor. Since backward rotating field can be reduced to zero, the pulsating torque due to interaction between forward and backward rotating fields is absent and this results in a quiet motor.

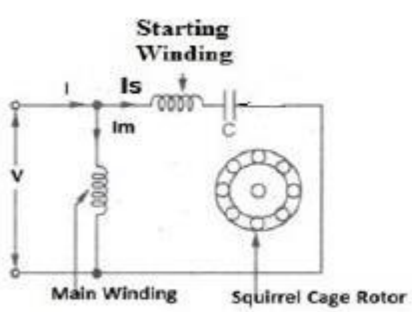


Fig: 1.74 (a)

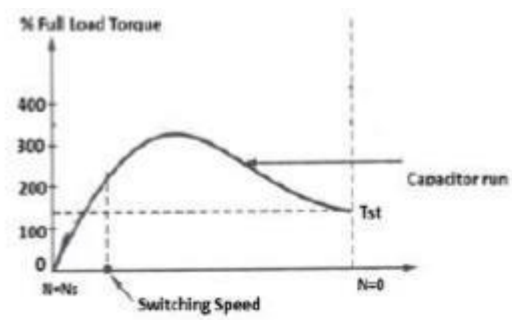


Fig: 1.74 (b)

In these motors, the value of permanent capacitor is so chosen as to obtain a compromise between the best starting and running conditions. A typical torque-speed characteristic is shown in fig: 1.74 (b)

These motors are used where quiet operation is essential as in

a. Offices

b. Class rooms

c. Theaters

d. Ceiling fans, in which the value of capacitance varies from 2 to 3μF.

Shibashis Kar

Shaded-Pole Motor:

The shaded-pole motor is very popular for ratings below 0.05 H.P. (~40 W) because of its extremely simple construction. It has salient poles on the stator excited by single-phase supply and a squirrel cage rotor as shown in figure: 1.8(a). A portion of each pole is surrounded by a short-circuited turn of copper strip called shading coil.

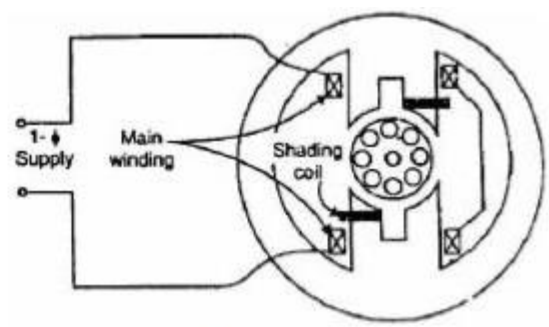


Fig: 1.8(a)

The operation of the motor can be understood by referring to figure: 1.8(b) which shows one pole of the motor with a shading coil.

(i) During the portion OA of the alternating-current cycle [See figure: 1.8(b)(i)], the flux begins to increase and an e.m.f. is induced in the shading coil. The resulting current in the shading coil will be in such a direction (Lenz's law) so as to oppose the change in flux. Thus the flux in the shaded portion of the pole is weakened while that in the unshaded portion is strengthened as shown in figure: 1.8(b)(ii)

(ii) During the portion AB of the alternating-current cycle, the flux has reached almost maximum value and is not changing. Consequently, the flux distribution across the pole is uniform [See figure: 1.8(b)(iii)] since no current is flowing in the shading coil. As the flux decreases (portion BC of the alternating current cycle), current is induced in the shading coil so as to oppose the decrease in current. Thus the flux in the shaded portion of the pole is strengthened while that in the unshaded portion is weakened as shown in figure: 1.8(b)(iv)

(iii) The effect of the shading coil is to cause the field flux to shift across the pole face from the unshaded to the shaded portion. This shifting flux is like a rotating weak field moving in the direction from unshaded portion to the shaded portion of the pole.

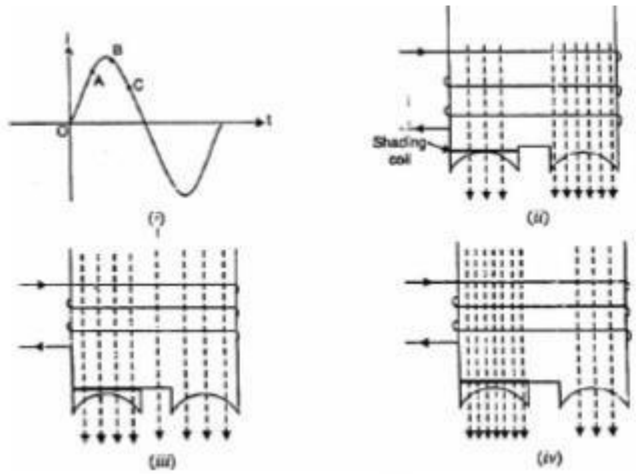


Fig: 1.8(b)

(iv) The rotor is of the squirrel-cage type and is under the influence of this moving field. Consequently, a small starting torque is developed. As soon as this torque starts to revolve the rotor, additional torque is produced by single-phase induction-motor action. The motor accelerates to a speed slightly below the synchronous speed and runs as a single-phase induction motor.

Characteristics

(i) The salient features of this motor are extremely simple construction and absence of centrifugal switch.

(ii) Starting torque, efficiency and power factor are very low

Applications:

These motors are only suitable for low power applications e.g., to drive:

(i) Small fans (ii)Toys (iii) Hair driers (iv)Desk fans etc.

The power rating of such motors is upto about 30 W.

Note: The direction of rotation (DOR) all the above single phase induction motor except shaded pole motor can be reversed by reversing the connection terminals of one of the two stator windings(not both).So four leads are brought outside the frame. But the DOR of shaded pole motor cannot be changed due to fixed position of copper rings.

****

Shibashis Kar

CHAPTER 5

COMMUTATOR MOTORS

AC SERIES MOTORS

AC series motors are also known as the modified DC series motor as their construction is very similar to that of the DC series motor. Before we discuss these modifications, here it is essential to discuss what is the need and where do we need to do modifications. If we give an AC supply to DC series motor then,

1. An AC supply will produce an unidirectional torque because the direction of both the currents (i.e. armature current and field current) reverses at the same time.
2. Due to presence of alternating current, eddy currents are induced in the yoke and field cores which results in excessive heating of the yoke and field cores.
3. Due to the high inductance of the field and the armature circuit, the power factor would become very low.
4. There is sparking at the brushes of the DC series motor.

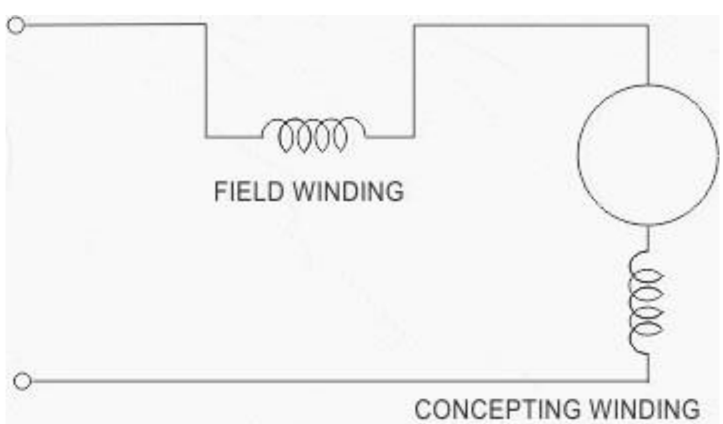
So it can be said that the performance of DC series motor on the application of AC supply is not good. The eddy currents has been reduced by laminating the yoke and field core. This is our first modification to DC series motor.

Now the power factor is directly related to reactance of the field and armature circuit and it can be reduced the field winding reactance by reducing the number of turns in the field winding. But there is one problem: on reducing the number of turns, field mmf will decrease and due to this the air gap flux decrease. The overall result of this is that there is an increase in the speed of the motor but decrease in the motor torque which is not desired. Now to overcome this problem, compensating winding is used. On the basis of the usage of compensating winding we have two types of motor and they are as below:

1. Conductively compensated type of motors.
2. Inductively compensated type of motors.

Conductively Compensated Type Of Motors

Given below is the circuit diagram of the conductively compensated type of motors. In this type of motor, the compensating winding is connected in series with the armature circuit. The winding is put in the stator slots. The axis of the compensating winding is 90° (electrical) with main field axis.

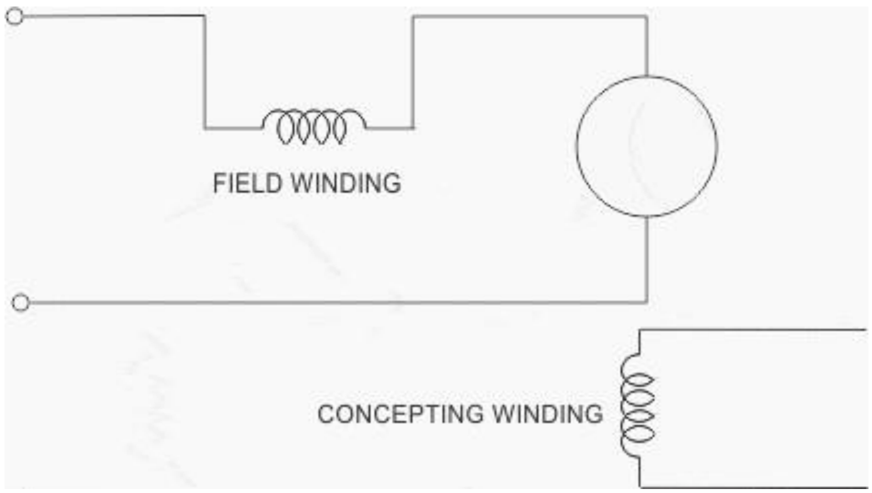


(a)

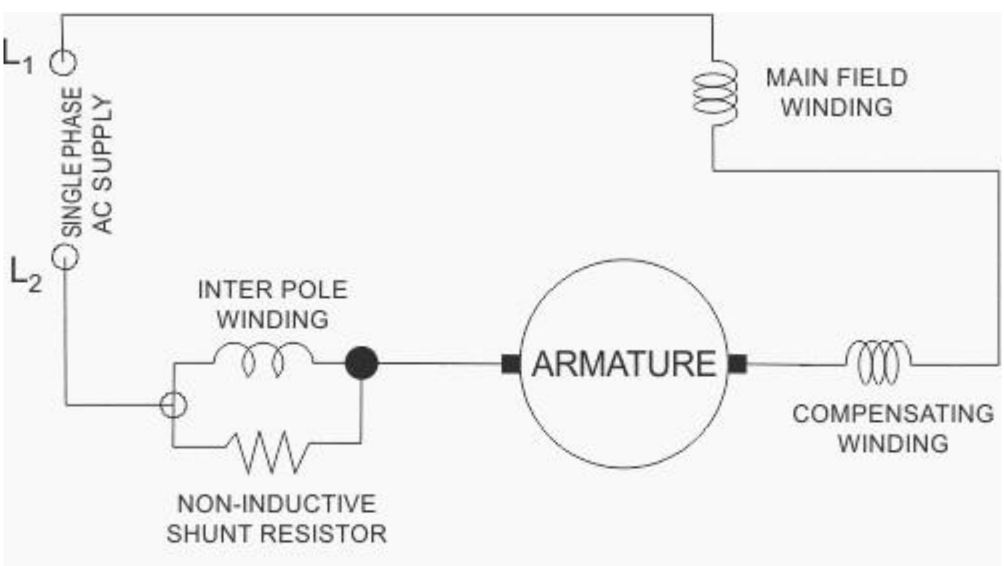
Shibashis Kar

Inductively Compensated Type of Motors

Given below is the circuit diagram of the inductively compensated type of motors. In this type of motor, the compensating winding has no interconnection with the armature circuit of the motor. In this case, a transformer action will take place as the armature winding will act as primary winding of the transformer and the compensation winding will acts as a secondary winding. The current in the compensating winding will be in phase opposition to the current in the armature winding.



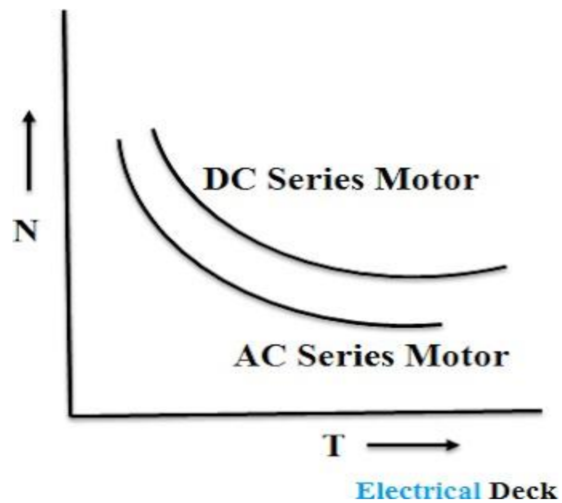
Given below is the complete schematic diagram of the single phase **AC series motor** with all the modifications (i.e. compensating winding and inter pole).



AC Series Motor with Interpoles and compensating Windings

Speed control of this type of motor is best obtained by solid state device. The motor has numerous applications such as portable drills, hair dryers, table fans, kitchen appliances, etc. We have already discussed the advantage of having compensating winding. Now, the main function of the inter poles is to improve the performance of the motor in terms of higher efficiency and a greater output from the given size of the armature core. We have taken very high reactive voltage drop of series field as compared to either armature or the compensating field in order to reduce the series filed inductance. The winding of the inter pole circuit is connected in parallel with the non inductive shunt as shown in the above figure.

Characteristic of A.C. Series Motor :



The characteristics of a.c. series motor is similar to that of d.c. series motor. The torque is proportional to the square of the armature current and speed is inversely proportional to the armature current. The series motors must always be started with some load on it because the starting speed of the motor is very high due to high starting torque i.e., 3 to 4 times the full load torque. At full-load, the power factor is about 90%. However, at starting or when carrying an overload, the power factor is lower.

Applications :

The fractional horsepower AC series motors have high-speed (and corresponding small size) and large starting torque. They can, therefore, be used to drive:

a) High-speed vacuum cleaners
b) Sewing machines
c) Electric shavers
d) Drills
e) Machine tools

UNIVERSAL MOTORS

A **universal motor** is a special type of motor which is designed to run on either DC or single phase AC supply. These motors are generally series wound (armature and field winding are in series), and hence produce high starting torque That is why, **universal motors** generally comes built into the device they are meant to drive. Most of the universal motors are designed to operate at higher speeds, exceeding 3500 RPM.

The universal motor is basically a series DC motor which is specially designed to operate on AC as well as on DC. A standard DC series motor has very poor characteristics (run at lower speed) when operated on AC, mainly due to two reasons:

- The high reactance of both the armature and field windings limits AC current to a much lower value than DC current for the same line voltage.
- If solid steel is used for the stator frame, AC flux will produce large eddy currents in the frame with consequent heating.

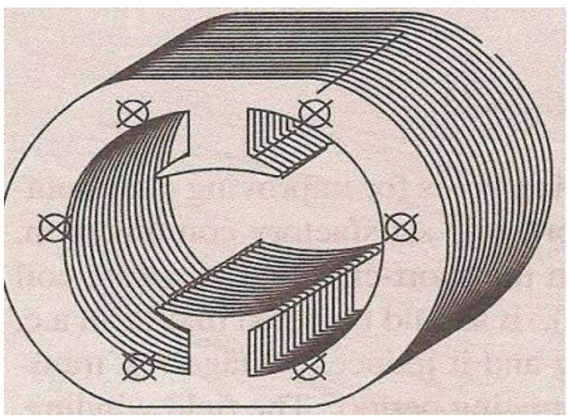
There are two **basic types of universal motor** : (i)distributed field compensated type(high power rating) and (ii) concentrated non-compensated type(low power rating).

Construction of Universal Motor:

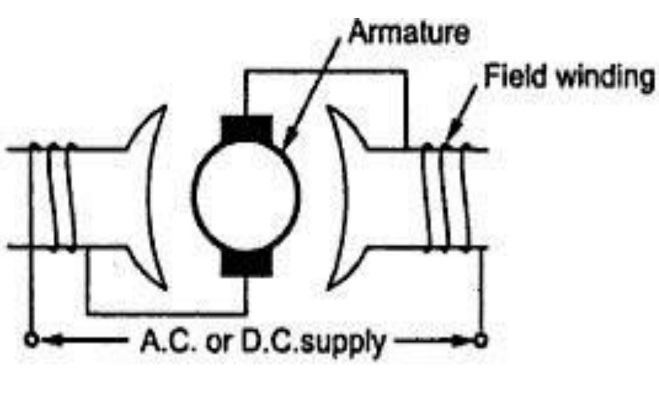
Construction of a universal motor is very similar to the construction of a DC machine. It consists of a stator on which field poles are mounted. Field coils are wound on the field poles.

Non-Compensated Universal Motor:

The Non-compensated motor has two salient poles and it is laminated as shown in figure below.

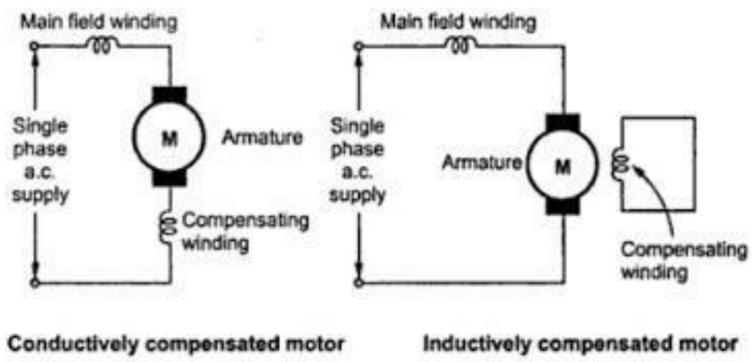


The armature is of wound type and the laminated core is either straight or skewed slots. The leads of the armature winding are connected to the commutator. High resistance brushes are used along with this type of motor to help better commutation. An equivalent Non-compensated type Universal Motor is shown in figure below.

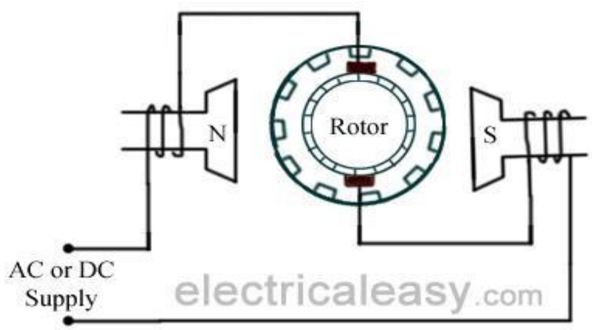


Compensated Type with Distributed Field:

The compensated type Universal Motor consists of distributed field winding and the stator core is similar to that of split-phase motor. We know that split phase motors consist of an auxiliary winding in addition to main winding. Similar to the split phase motors, the compensated type also consists of an additional winding. The compensating winding helps in reducing the reactance voltage which is caused due to alternating flux, when the motor runs with the AC supply. An equivalent Compensated type Universal Motor is shown in figure below.



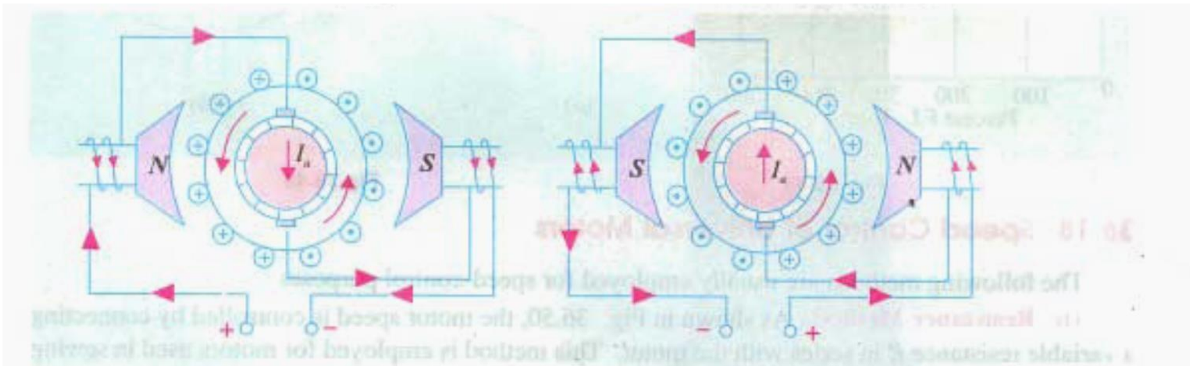
Working Of Universal Motor



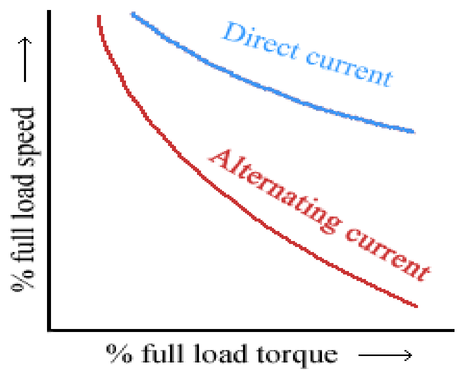
A universal motor works on either DC or single phase AC supply. When the universal motor is fed with a DC supply, it works as a DC series motor. (see working of a DC series motor here). When current flows in the field winding, it produces an electromagnetic field. The same current also flows from the armature conductors. When a current carrying conductor is placed in an electromagnetic field, it experiences a mechanical force. Due to this mechanical force, or torque, the rotor starts to rotate. The direction of this force is given by Fleming's left hand rule.

When fed with AC supply, it still produces unidirectional torque. Because, armature winding and field winding are connected in series, they are in same phase. Hence, as polarity of AC changes periodically, the direction of current in armature and field winding reverses at the same time. Thus, direction of magnetic field and the direction of armature current reverses in such a way that the direction of force experienced by armature conductors remains same. Thus, regardless of AC or DC supply, universal motor works on the same principle that DC series motor works. Below figure shows the unidirectional operation of universal motor regardless of change in the polarity of supply.

Shibashis Kar



Speed/Load Characteristics



Speed/load characteristics of a universal motor is similar to that of DC series motor. The **speed of a universal motor** is low at full load and very high at no load. Usually, gears trains are used to get the required speed on required load. The speed/load characteristics are (for both AC as well as DC supply) are shown in the figure.

Applications Of Universal Motor

- Universal motors find their use in various home appliances like vacuum cleaners, drink and food mixers, domestic sewing machine etc.
- The higher rating universal motors are used in portable drills, blenders etc.

REPULSION TYPE MOTORS

These can be divided into the following four distinct categories :

1. Repulsion Motor. It consists of

- one stator winding
- one rotor which is wound like a d.c. armature
- commutator and

- a set of brushes, which are short-circuited and remain in contact with the commutator at all times. It operates continuously on the 'repulsion' principle. No short-circuiting mechanism is required for this type.

2. Compensated Repulsion Motor. It is identical with repulsion motor in all respects, except that (a) it carries an additional stator winding, called compensating winding (b) there is another set of two brushes which are placed midway between the usual short-circuited brush set. The compensating winding and this added set are connected in series.

3. Repulsion-start Induction-run Motor. This motor starts as a repulsion motor, but normally runs as an induction motor, with constant speed characteristics. It consists of

(a) one stator winding

(b) one rotor which is similar to the wire-wound d.c. armature

(c) a commutator and

(d) a centrifugal mechanism which short-circuits the commutator bars all the way round (with the help of a short-circuiting necklace) when the motor has reached nearly 75 per cent of full speed.

4. Repulsion Induction Motor. It works on the combined principle of repulsion and induction. It consists of

(a) stator winding
(b) two rotor windings : one squirrel cage and the other usual D.C. winding connected to the commutator and

1. Repulsion Motor

Constructionally, it consists of the following:

1. Stator winding of the distributed non-salient pole type housed in the slots of a smooth-cored stator (just as in the case of split-phase motors). The stator is generally wound for four, six or eight poles.
2. A rotor (slotted core type) carrying a distributed winding (either lap or wave) which is connected to the commutator. The rotor is identical in construction to the d.c. armature.
3. A commutator, which may be one of the two types : an axial commutator with bars parallel to the shaft or a radial or vertical commutator having radial bars on which brushes press horizontally.
4. Carbon brushes (fitted in brush holders) which ride against the commutator and are used for conducting current through the armature (i.e. rotor) winding.

Repulsion Principle

To understand how torque is developed by the repulsion principle, consider Fig. 36.37 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. 36.37 (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 co-linear with magnetic axis of the main poles, the directions of the induced currents (shown by dots and arrows) will be as indicated in Fig. 36.37 (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 90º to the position shown in Fig. 36.37 (b) so that the brush axis is at right angles to the magnetic axis of the main poles, the directions of the induced voltages at any time in the respective armature conductors are exactly the same as they were for the brush position of Fig. 36.37 (a). However, with brush positions of Fig. 36.37 (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. 36.38 (a) so that the brush axis is neither in line with nor 90º from the magnetic axis Y Y′ of the 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. 36.38 (a), the armature poles lie along A A′ making an angle of α with Y Y′. 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.36.38(b)]. Since the forces are those of repulsion, it is appropriate to call the motor as repulsion motor. It should be noted that if the brushes are shifted counter- clockwise from YY ′, rotation will also be counter-clockwise. Obviously, direction of rotation of the motor is determined by the position of brushes with respect to the main magnetic axis. It is worth noting that the value of starting torque developed by such a motor will depends on the amount of brush-shift whereas direction of rotation will depend on the direction of shift [Fig. 36.39 (a)]. Maximum starting torque is developed at some position where brush axis makes, an angle lying between 0º and 45º with the magnetic axis of main poles. Motor speed can also be controlled by means of brush shift. Variation of starting torque of a repulsion motor with brush-shift is shown in Fig. 36.39 (b). A straight repulsion type motor has high starting torque (about 350 per cent) and moderate starting current (about 3 to 4 times full-load value). Principal shortcomings of such a motor are :

1. speed varies with changing load, becoming dangerously high at no load.
2. low power factor, except at high speeds.
3. tendency to spark at brushes.

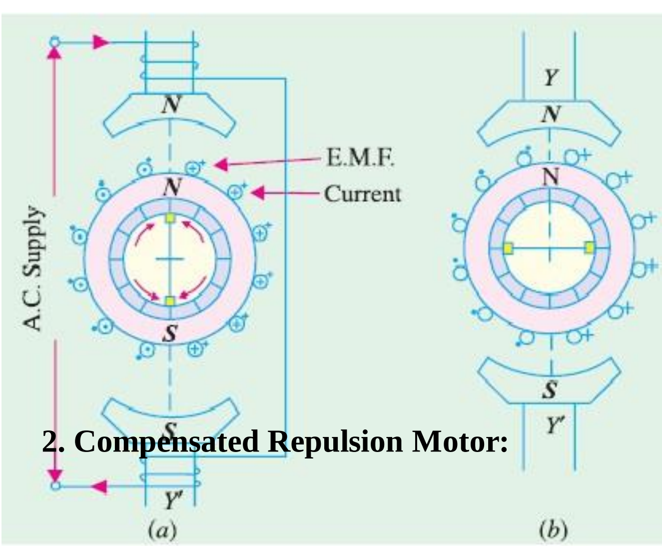


Fig. 36.37

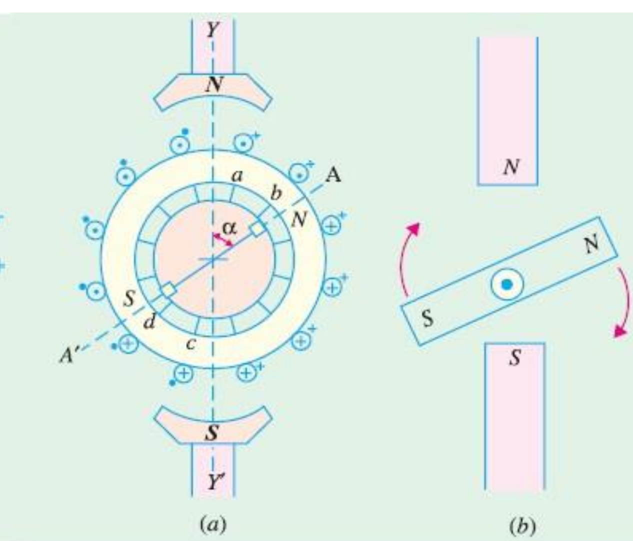


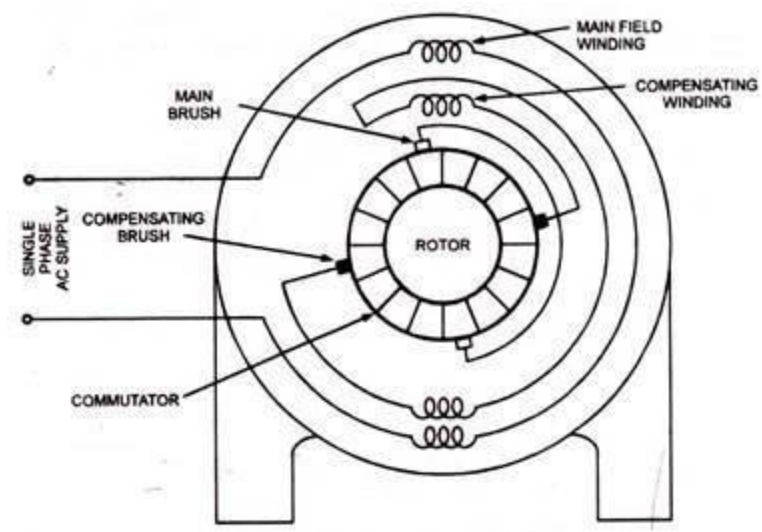
Fig. 36.38

2. Compensated Repulsion Motor:

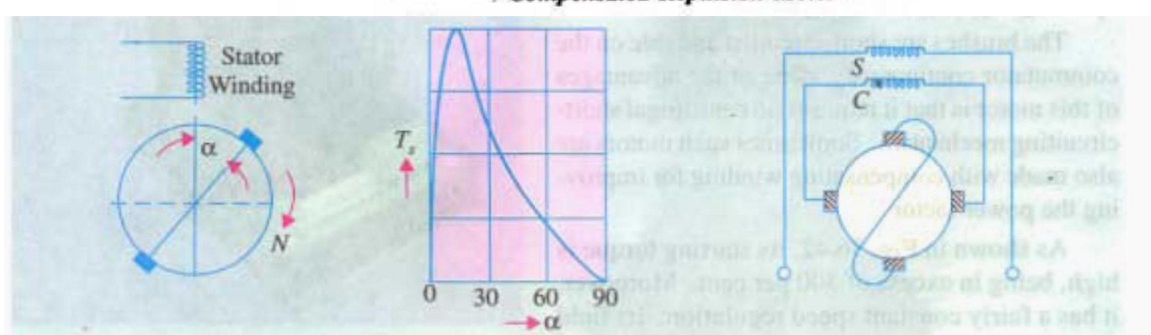
Shibashis Kar

2. Compensated Repulsion Motor:

It is provided with an additional winding, called the compensating winding(C), to improve power factor and provide better speed regulation. This winding is much smaller than the stator winding(S) and is usually wound in the inner slots of each main pole and is connected in series with rotor through an additional set of brushes placed midway between the usual short-circuited brushes, as illustrated in below figures.



Compensated Repulsion Motor



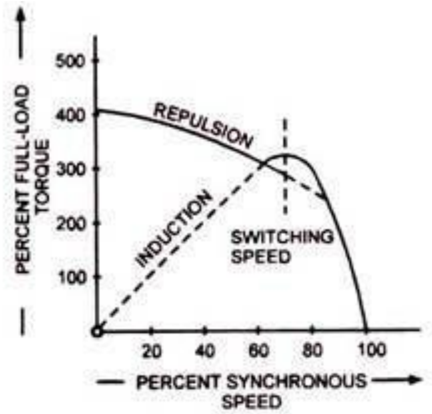
3. Repulsion-Start Induction Motor:

As the name implies the repulsion-start induction motor starts as a repulsion motor and runs as an induction motor. The general construction of a repulsion-start induction motor is quite similar to that of a repulsion motor (i.e., a laminated stator core complete with one winding similar to the main winding of a split-phase motor and a rotor, also called the armature, consisting of slots in which a winding is placed and connected to a commutator). The only difference is that in addition to the basic repulsion-motor construction it is equipped with a centrifugal device which

Shibashis Kar

operates at about 75-80 per cent of synchronous speed and short circuits all of the commutator segments.

The repulsion-start induction motor combines the desirable starting characteristics of the repulsion motor (i.e., **high starting torque with moderate starting current**) with operating characteristic (constant speed running) of the induction motor. A typical performance characteristic of a repulsion-start induction motor is given in Figure below. The starting torque is 3 to 6 times of full-load torque, and the starting current is approximately 3-4 times of full- load current.



Torque-Speed Characteristic For Repulsion-Start Induction Motor

Further there are two different designs in repulsion start motors:

BRUSH LIFTING TYPE- In this type the brush is lifted as soon as the commutator is short circuited to avoid unnecessary wear and tear and losses due to friction. So in this type the brush is present only when the motor is started as a repulsion one and the commutator is of radial form. The motors are built in small and large sizes.

BRUSH RIDING TYPE- In this type of motors the brushes ride along with the commutator at all times. So the brushes are present even after the commutator is short circuited. And the commutator is of axial form. The motors are built in small sizes only.

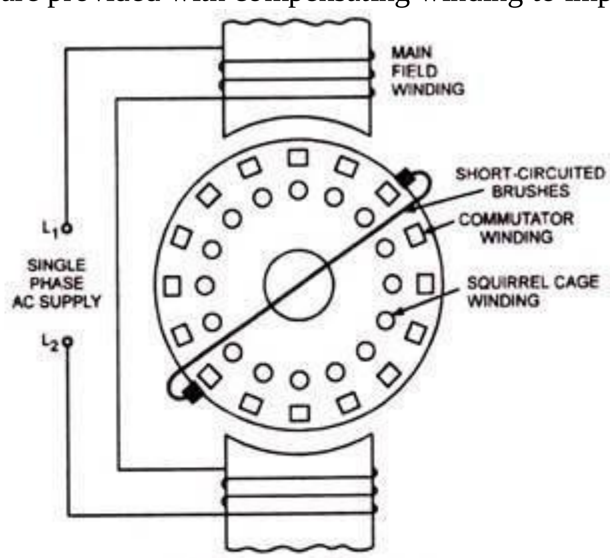
The direction of rotation of such a motor may be reversed by shifting the brushes, but the brush rigging is not readily accessible, and the method is poorer than with any of the capacitor type motors.

Such motors are suitable for commercial refrigerators, compressors, pumps, hoists and other constant speed drives, particularly those which have a high inertia and prolonged starting period. The usual rating is from 1/3 kW to 12 kW but for special applications, ratings as high as 30 kW are available.

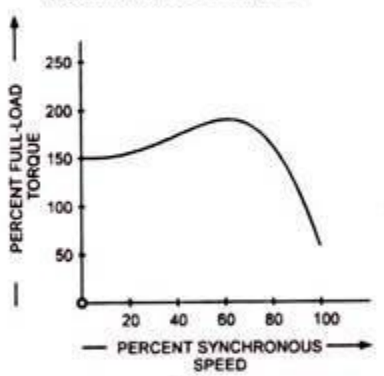
4. Repulsion-Induction Motor:

The repulsion-induction motor has a single phase stator winding, as a repulsion-start induction motor has, but it has two separate and independent windings on rotor in common slots. The inner winding is a **squirrel cage winding** with rotor bars permanently short- circuited while outer winding is a **repulsion or commutator winding** similar to a dc armature winding. When the motor starts, the squirrel cage winding, due to its high reactance, has no effect and the motor starts as a repulsion motor.

As the motor speeds up, the current shifts from the outer winding to the inner winding which takes large portion of load , owing to decreasing reactance of the inner winding with the increasing speed and the squirrel cage winding comes into action. At normal speed both of the windings develop torque and the output of the motor is the combined output of both of the rotor windings. One of the advantages it has no centrifugal short circuiting mechanism. Some motors are provided with compensating winding to improve power factor.



(a) Schematic Diagram



(b)

Torque-Speed Characteristic of a Repulsion-Induction Motor

The starting torque is about 2.5-3 times the full-load torque and its starting current is about 3-4 times the full-load current. The commutation of the motor is good at all speeds. No-load speed is above synchronous speed but normal speed is somewhat below synchronous one. No-load current is rather high, sometimes greater than the full-load current. The motor besides being costlier has brushes always on the commutator involving sparking and maintenance problems.

Shibashis Kar

This motor is particularly suitable where the load can be removed entirely by the declutching or by loose pulley.

Such a motor is used for **applications** requiring a high starting torque with essentially a constant running speed. The common ratings are 1/6 to 4 kW although in large ratings are also made. Common applications are household refrigerators, garage air pumps, gasoline pumps, compressors etc.

****

CHAPTER 6

STEPPER MOTOR

Stepper Motor is a brushless electromechanical device which converts the train of electric pulses applied at their excitation windings into precisely defined step-by-step mechanical shaft rotation. The shaft of the motor rotates through a fixed angle for each discrete pulse. This rotation can be linear or angular. It gets one step movement for a single pulse input.

When a train of pulses is applied, it gets turned through a certain angle. The angle through which the stepper motor shaft turns for each pulse is referred as the step angle, which is generally expressed in degrees. This fact makes the motor well –suited for open loop position control because no feedback need be taken from the output shaft.

If the step angle is smaller, the greater will be the number of steps per revolutions and higher will be the accuracy of the position obtained. The step angles can be as large as 90 degrees and as small as 0.72 degrees, however, the commonly used step angles are 1.8 degrees, 2.5 degrees, 7.5 degrees and 15 degrees.

The direction of the shaft rotation depends on the sequence of pulses applied to the stator. The speed of the shaft or the average motor speed is directly proportional to the frequency (the rate of input pulses) of input pulses being applied at excitation windings. Therefore, if the frequency is low, the stepper motor rotates in steps and for high frequency, it continuously rotates like a DC motor due to inertia.

The value of step angle β 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.

$$\beta = \frac{Ns - Nr}{Ns.Nr} \times 360^0 \quad \textbf{OR} \quad \beta = \frac{360^0}{mNr} = \frac{360^0}{\text{No.of stator phases x No.of rotor teeth}}$$

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

Therefore, $$\frac{\text{No.of steps}}{\text{revolution}} = \frac{360^0}{\beta}$$

A stepping motor has the extraordinsry ability to operate at very high stepping rates (upto 20000 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 rotationseems continuous.Operation at high speeds is called 'slewing'.When in the slewing range,the motor generally emits an audible while havinga funamental frequency equal to the stepping rate.If 'f' is the stepping frequency(or pulse rate) in pulses per second(pps) and β is the step angle,then motor shaft speed is given by

$$n = \beta \times \frac{f}{360^0} \text{ rps} = \text{ pulse frequency resolution.}$$

Shibashis Kar

If the stepping rate is increased too quickly, the motor looses synchronism..Same thing happens if when the motor is slewing, command pulses are suddenly stopped instead of being progressively slowed.

Stepper 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 are also used in commercial, military and medical applications where these motors perform functions like mixing, cutting, striking, metering, blending and purging. They also take part in manufacture of packed food stuffs, commercial end-products.

<u>Principle of VR(Variable Reluctance) stepper motor</u>

Variable Reluctance Stepper Motor has (i) wound stator poles (steel laminated) (ii) rotor poles made of a **ferromagnetic** material.

Direction of motor rotation is independent of the **polarity** of stator current. It is called variable reluctance because the reluctance of the magnetic circuit formed by the rotor and stator teeth varies with the angular position of rotor.

The figure below shows the stator has 6 equally spaced projecting poles(or teeth) each wound with an exciting coil. Rotor (solid or laminated) has four projecting teeth of same width as stator teeth.

There are three independent stator circuits or **phases** A, B, C in 2-coil groups and each one can be energized by a direct current pulse (from the drive circuit).Diametrically opposite pairs of stator coils are connected in series such that when one tooth becomes N-pole ,the other pole becomes a S-pole.

Although mechanical switches are shown in figure (e), in actual switching of phase currents which is done with the help of solid-state control. When there is no current in stator coils the rotor is completely free to rotate. Energising one or more stator coils causes rotor to step forward or backward to apposition that forms a path of **least** reluctance with the magnetized stator teeth. The step angle of this 3-phase, 4-rotor teeth motor is **β=360/ (4X3) =30^{0}.**

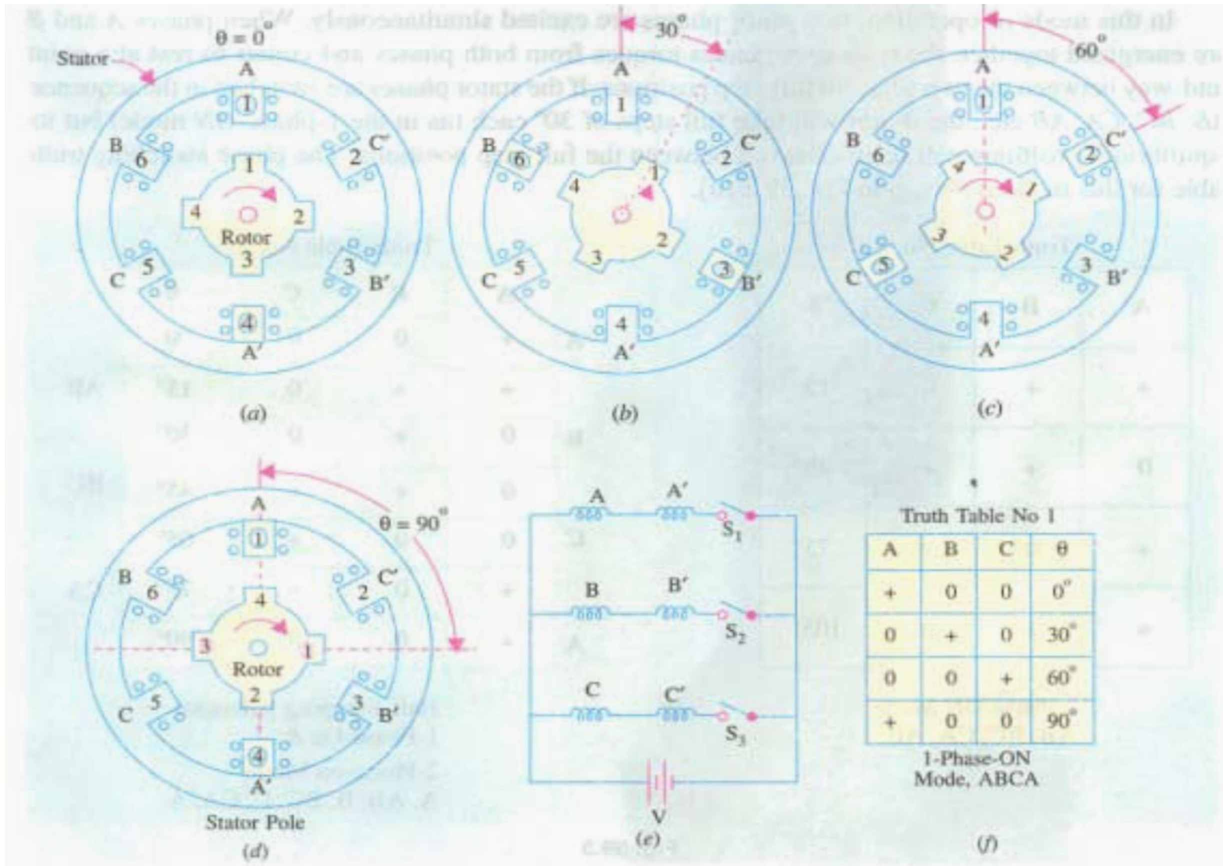


Fig. 39.2

1-phase ON or Full-Step Operation

In the above figure (a),it shows the position of the rotor when switch S1 has been closed for energizing phase A. A magnetic field with its axis along the stator poles of phase A is created. So rotor attracted to position of minimum reluctance with diametrically opposite rotor teeth 1 and 3 lining up with stator teeth 1 and 4 respectively. Closing S2 after opening S1 energizes phase B causing rotor teeth 2 and 4 to align with stator teeth 3 and 6 respectively. The rotor rotates full step of 30^0 in **clockwise** direction (CW).Similarly when S3 is closed after S2 is opened rotor teeth 1 and 3 to align with stator teeth 2 and 5 respectively and the rotor rotates further 30^0 in clockwise direction (CW).By repetitively closing the switches and energizing the phases in ABCA (1-2-3-1) sequence, the rotor rotates in clockwise direction. But if the switch sequence is reversed i.e. in CBAC sequence (3-2-1-3) rotor rotates in **anti-clockwise** direction. This mode of operation is called 1-phase ON and it is very simple. The direction of stator magnetizing current is not significant because a stator pole of either polarity will always attract a rotor pole by inducing opposite polarity.

2-phase ON Operation

When two phases are energized simultaneously the rotor experience torque from both sides and comes to a position mid way between two adjacent full step positions. If stator phases are switched in the sequence AB, BC, CA, AB etc, the motor will take full steps of 30^0 each(as in 1-

Shibashis Kar

phase ON mode) but its equilibrium positions will be interleaved between the full-step positions. This mode of operation provides greater holding torque and better damped single stack response than 1-phase ON mode. The truth table for this mode is shown below.

Truth Table No. 2

A	B	C	θ
+	+	0	15°
0	+	+	45°
+	0	+	75°
+	+	0	105°

2 Phase-ON Mode
AB, BC, CA, AB

Half Step Operation

This operation is also called **half stepping** which can be obtained by exciting the three phases in the sequence A,AB,B,BC,C etc.i.e. alternately in the 1-phase ON and 2-pase ON modes. It is sometime known as **'wave'** excitation and it causes the rotor to advance in steps of 15^0 i.e. half the full step angle and thus doubling the resolution and producing a smoother shaft rotation. The truth table for this mode and the position of the rotor is shown below.

Truth Table No. 3

	A	B	C	θ	
A	+	0	0	0°	
	+	+	0	15°	AB
B	0	+	0	30°	
	0	+	+	45°	BC
C	0	0	+	65°	
	+	0	+	75°	CA
A	+	0	0	90°	

Half-Stepping Alternate
1-Phase-On &
2-Phase-on Mode
A, AB, B, BC, C, CA, A

Shibashis Kar

Microstepping

It is also known as mini-stepping. It utilizes two phases simultaneously as in 2-phase-*ON* mode but with the two currents deliberately made unequal (unlike in half-stepping where the two phase currents have to be kept equal). The current in phase *A* is held constant while that in phase *B* is increased in very small increments until maximum current is reached. The current in phase *A* is then reduced to zero using the same very small increments. In this way, the resultant step becomes very small and is called a microstep. For example, a *VR* stepper motor with a resolution of 200 steps / rev ($\beta = 1.8°$) can with microstepping have a resolution of 20,000 steps / rev ($\beta = 0.018°$). Stepper motors employing microstepping technique are used in printing and phototypesetting where very fine resolution is called for. As seen, microstepping provides smooth low-speed operation and high resolution.

Note: VR stepper motors have a high (torque/inertia) ratio giving high rates of acceleration and fast response. A possible disadvantage is the absence of detent torque which is necessary to retain the rotor at the step position in the event of a power failure.

Principle of PM(Permanent Magnet) Stepper Motor

It has (i) wound stator poles (ii) rotor poles are **radially** permanently magnetized like magnetically hard ferrite. But the rotor is cylindrical. Its direction of rotation depends on the **polarity** of stator current. Let us consider a motor having rotor with 2 poles and stator with 4 poles as shown in below figure. Since two stator poles are energized by one winding, the motor has two windings or phases marked A and B. The step angle of this motor $\beta = 360^0/(mN_r) = 360^0/(2x2) = 90^0$.

When a particular stator phase is energized,the rotor magnetic poles move into alignment with excited stator poles.The stator windings A and B can be excited witth either polarity current(A^+ refers to positive current i_{A+} and A^{--} refers to negative current i_{A--} in phase A).From the above figure it is seen that $\theta=0^0$,if excitation is now switched to phase B as (B^+),the rotor rotates full step of 90^0 in Clockwise direction(CW),again phase A excited with A^{--} ,the rotor turns another 90^0 in CW direction.Next , phase B excited with B^{--} the rotor turns again 90^0 in the same direction.After this,excitation of phase A excited with A^+ the rotor turns one compete revolution of 360^0.

Truth Table No. 1

A	B	θ
+	0	0°
0	+	90°
−	0	180°
0	−	270°
+	0	

Truth Table No. 2

A	B	θ
+	+	45°
−	+	13[illegible]
−		

Truth Table No.

A	B
+	

Truth table for 3 modes of operation for producing clockwise direction in PM Stepper motor is shown in the above figure.Microstepping can be employed to further reduce the step size and thereby increasing the resolution.

It will be noted that in a permanent-magnet stepper motor, the direction of rotation depends on the polarity of the phase currents as tabulated below :

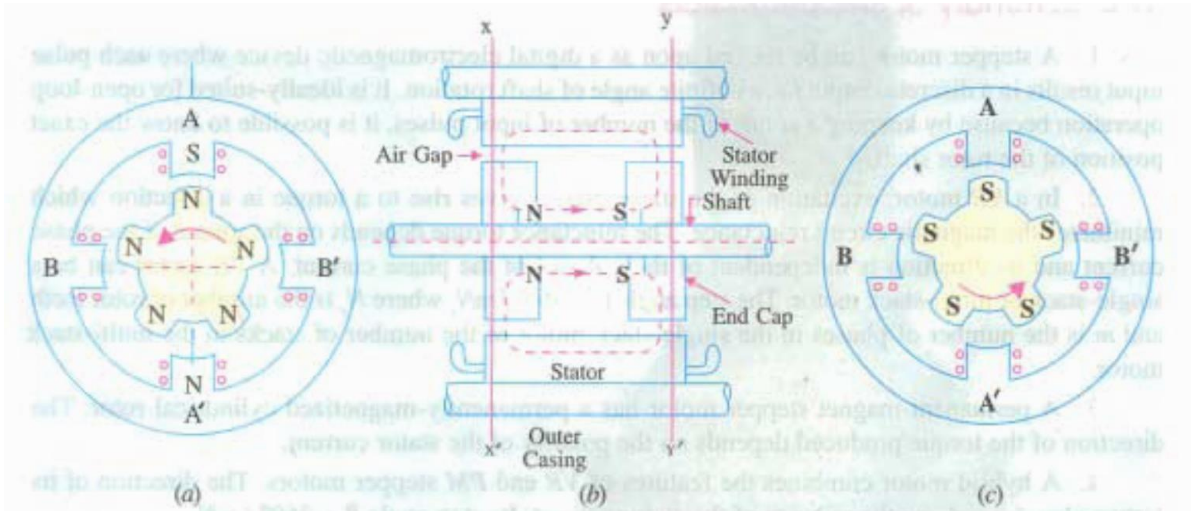
i_{A^+}; i_{B^+}; i_{A^-}; i_{B^-}; i_{A^+}, ...
A^+; B^+; A^-; B^-; A^+; .... for clockwise rotation

i_{A^+}; i_{B^-}; i_{A^-}; i_{B^+}; i_{A^+}; ....
A^+; B^-; A^-; B^+; A^+; .... for CCW rotation

Note:PM stepper motor has a low power requirement but possesses a high detent torque.It has higher inertia and hence slower acceleration and produces more torque per ampere stator current than a VR motor.Disadvanage is that it is difficult to manufacture a small permanent-magnet rotor with large number of poles.(step size in such motors largely ranging from 30^0 to 90^0).

Principle of Hybrid Motor

The hybrid motor combines the features of VR stepper motor and PM stepper motor. Its stator construction is similar to the single stack VR motor but the rotor is **cylindrical** and is composed of **radially** magnetized permanent magnets. A recent type uses a disc rotor which is magnetized **axially** to create a pair of poles N and S as shown in below figure, which give a **small** step angle and **low** inertia. Two end-caps are fitted at both ends of this axial magnet. These end-caps consist of equal number of teeth which are magnetized by respective polarities of axial magnet. The rotor teeth of one end-cap are offset by a half tooth pitch so that a tooth at one end-cap coincides with a slot at the other. The cross-sectional views perpendicular to the shaft along X-X' and Y-Y' as shown in figure below. As seen, the stator consists of four stator poles which are excited by two stator windings in pairs .The rotor has five N-poles at one end and five S-poles at the other end of the axial magnet.The step angle of such a motor is =**((5-4) x 360^0)/(5x4)=18^0.**

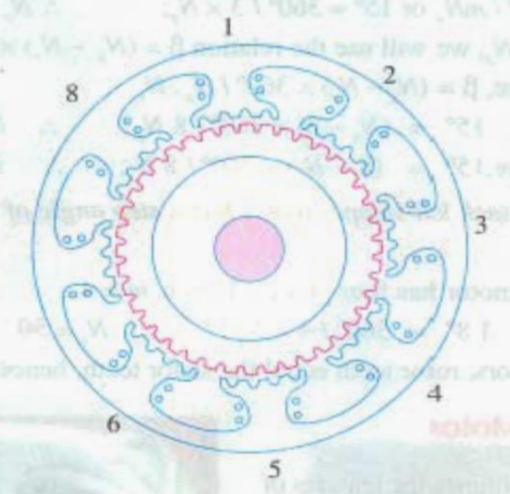


Phase A is excited first such that the top stator pole is a S-pole so that it attracts the top N-pole of the rotor and brings it in line with A-A' axis. To turn the rotor phase A is denergized and phase B is excited positively. The rotor will turn in **counter clockwise** direction by a full step of 18^0.Next ,phase A and B are energized negatively one after the other to produce further rotations of 18^0 each in same direction. The truth table is shown below. For producing clockwise direction rotation, the phase sequence should be **A$^+$;B$^-$;A$^-$;B$^+$;A$^+$**

Truth Table

A	B	
+	0	0°
0	+	18°
–	0	36°
0	–	54°
+	0	72°

1-Phase ON
Full-Step Mode
(a)



(b)

Note: Practically hybrid stepper motors are built with more rotor poles in order to give higher angular resolution. This motor also good detent torque like PM stepper motor. This torque holds the rotor stationary even if the power is switched off. But it requires less excitation to achieve a given torque as compared to VR motor.

Shibashis Kar

Summary of Stepper Motors

1. A stepper motor can be looked upon as a digital electromagnetic device where each pulse input results in a discrete output *i.e.* a definite angle of shaft rotation. It is ideally-suited for open-loop operation because by keeping a count of the number of input pulses, it is possible to know the exact position of the rotor shaft.

2. In a *VR* motor, excitation of the stator phases gives rise to a torque in a direction which minimizes the magnetic circuit reluctance. The reluctance torque depends on the square of the phase current and its direction is independent of the polarity of the phase current. A *VR* motor can be a single-stack or multi-stack motor. The step angle $\beta = 360° / mN_r$ where N_r is the number of rotor teeth and m is the number of phases in the single-stack motor or the number of stacks in the multi-stack motor.

3. A permanent-magnet stepper motor has a permanently-magnetized cylindrical rotor. The direction of the torque produced depends on the polarity of the stator current.

4. A hybrid motor combines the features of *VR* and *PM* stepper motors. The direction of its torque also depends on the polarity of the stator current. Its step angle $\beta = 360° / mN_r$.

5. In the 1-phase *ON* mode of excitation, the rotor moves by one full-step for each change of excitation. In the 2-phase-*ON* mode, the rotor moves in full steps although it comes to rest at a point midway between the two adjacent full-step positions.

6. Half-stepping can be achieved by alternating between the 1-phase-*ON* and 2-phase-*ON* modes. Step angle is reduced by half.

7. Microstepping is obtained by deliberately making two phase currents unequal in the 2-phase-*ON* mode.

Comparison of Stepper Motor Types

Types of Stepper Motor /Advantages	Permanent Magnet	Variable Reluctance	Hybrid
Step Angle	7.5° or larger	1.8° or smaller	1.8° or smaller
Output Torque	Moderate	Low	High
Detent Torque	Yes	No	Yes
Pulse Rate / Speed	Low	High	High
Acceleration / Response	Slow	Fast	Fast
Noise	Quiet	Loud	Quiet
Microstep	Yes	No	Yes
Design	Simple	Moderate	Complex

Shibashis Kar

CHAPTER 07

THREE PHASE TRANSFORMERS

Grouping of winding in 3 phase transformers

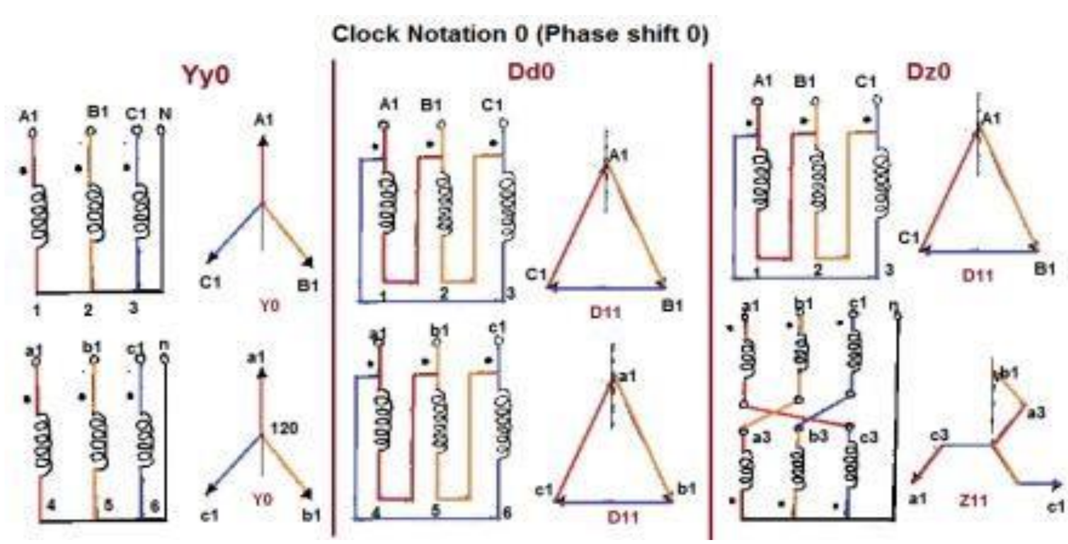
The transformer vector group show the phase difference between the primary and secondary sides of the transformer. It also determines the high voltage and low voltage windings arrangement of three phase transformers. The three phase transformer is connected in various ways. On the basis of connection, the vector group of the transformer is determined.

Winding connection designations in vector group:

- **First Symbol:** for **High Voltage**: Always capital letters.
- D=Delta, Y=Star, Z=Interconnected star, N=Neutral
- **Second Symbol:** for **Low voltage**: Always Small letters.
- d=Delta, y=Star, z=Interconnected star, n=Neutral.
- **Third Symbol:** Phase displacement expressed as the clock hour number (1,6,11)
- **Example – Dyn11**
  Transformer has a delta connected primary winding (**D**) a star connected secondary (**y**) with the star point brought out (**n**) and a phase shift of 30 deg leading (**11**).
- The point of confusion is occurring in notation in a step-up transformer. As the IEC60076-1 standard has stated, the notation is HV-LV in sequence. For example, a step-up transformer with a delta-connected primary, and star-connected secondary, is not written as 'dY11', but 'Yd11'. The 11 indicates the LV winding leads the HV by 30 degrees.
- Transformers built to ANSI standards usually do not have the vector group shown on their nameplate and instead a vector diagram is given to show the relationship between the primary and other windings.

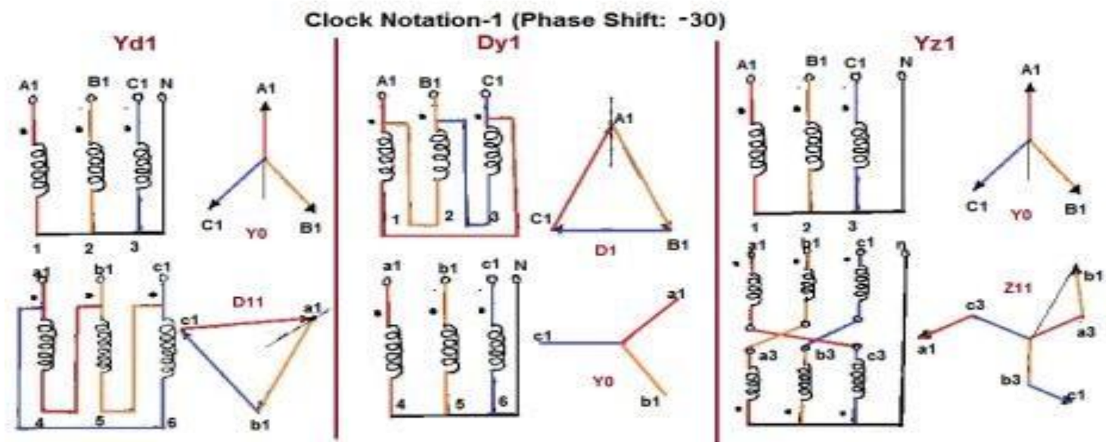
Two winding, three phase transformers can be divided into following main categories

Clock Notation: 0(0^0 phase shift)

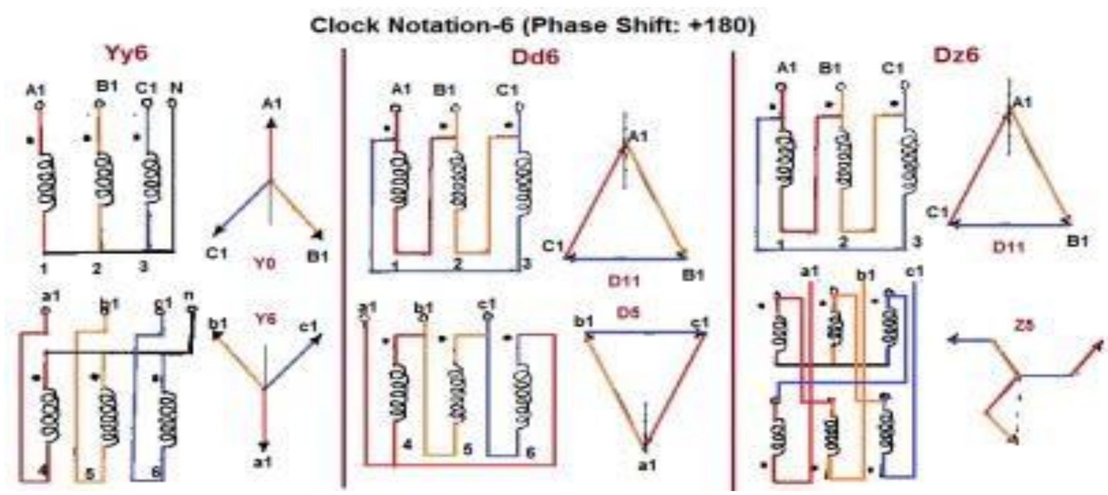


Shibashis Kar

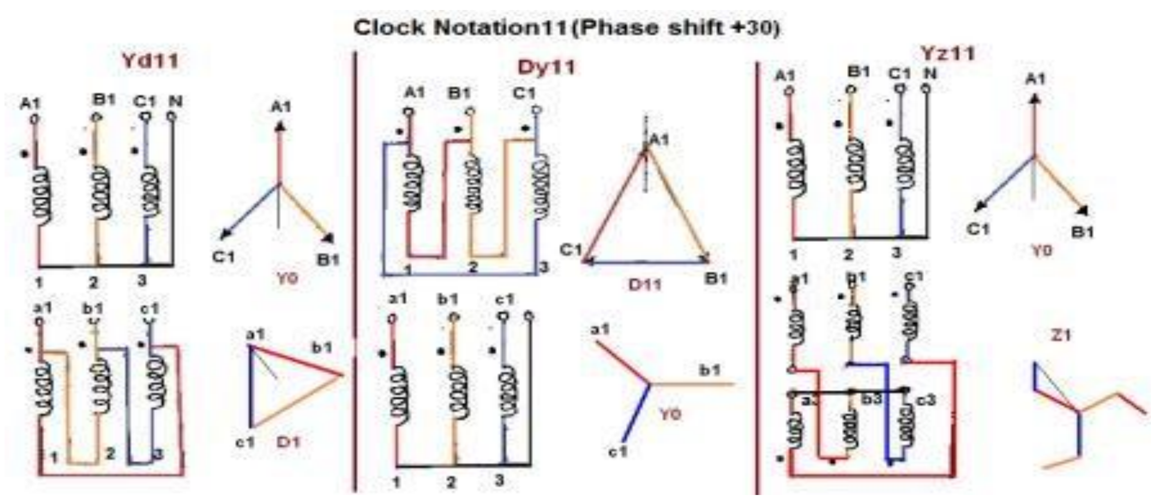
Clock Notation : 1(-30^0 phase shift)



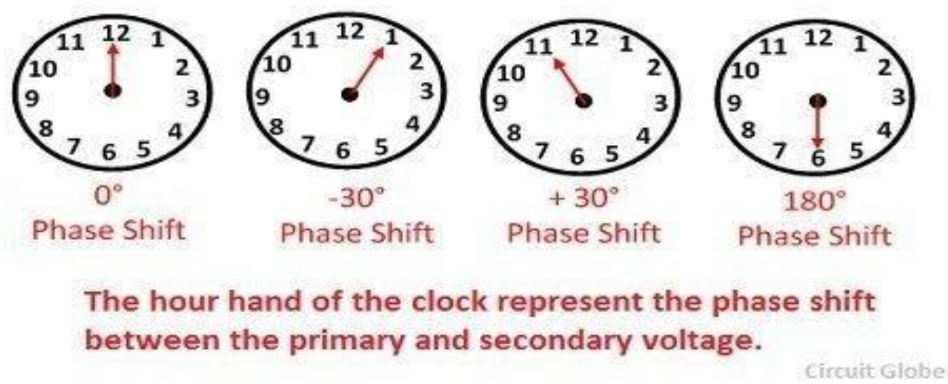
Clock Notation: 6(+180^0 phase shift)



Clock Notation: 11(+30^0 phase shift)



Shibashis Kar



Application of Transformer according to Vector Group:

(1) (Dyn11, Dyn1, YNd1, YNd11)

- Common for distribution transformers.
- Normally Dyn11 vector group using at distribution system. Because Generating Transformer are YNd1 for neutralizing the load angle between 11 and 1.
- We can use Dyn1 at distribution system, when we are using Generator Transformer are YNd11.
- In some industries 6 pulse electric drives are using due to this 5thharmonics will generate if we use Dyn1 it will be suppress the 5th harmonics.
- Star point facilitates mixed loading of three phase and single phase consumer connections.
- The delta winding carry third harmonics and stabilizes star point potential.
- A delta-Star connection is used for step-up generating stations. If HV winding is star connected there will be saving in cost of insulation.
- But delta connected HV winding is common in distribution network, for feeding motors and lighting loads from LV side.

(2) Star-Star (Yy0 or Yy6)

- Mainly used for large system tie-up Transformer.
- Most economical connection in HV power system to interconnect between two delta systems and to provide neutral for grounding both of them.
- Tertiary winding stabilizes the neutral conditions. In star connected transformers, load can be connected between line and neutral, only if
  (a) the source side transformers is delta connected or
  (b) the source side is star connected with neutral connected back to the source neutral.
- In This Transformers. Insulation cost is highly reduced. Neutral wire can permit mixed loading.
- Triple harmonics are absent in the lines. These triple harmonic currents cannot flow, unless there is a neutral wire. This connection produces oscillating neutral.
- Three phase shell type units have large triple harmonic phase voltage. However three phase core type transformers work satisfactorily.
- A tertiary mesh connected winding may be required to stabilize the oscillating neutral due to third harmonics in three phase banks.

(3) Delta – Delta (Dd 0 or Dd 6)

- This is an economical connection for large low voltage transformers.
- Large unbalance of load can be met without difficulty.
- Delta permits a circulating path for triple harmonics thus attenuates the same.
- It is possible to operate with one transformer removed in open delta or" V" connection meeting 58 percent of the balanced load.
- Three phase units cannot have this facility. Mixed single phase loading is not possible due to the absence of neutral.

(4) Star-Zig-zag or Delta-Zig-zag (Yz or Dz)

- These connections are employed where delta connections are weak. Interconnection of phases in zigzag winding effects a reduction of third harmonic voltages and at the same time permits unbalanced loading.
- This connection may be used with either delta connected or star connected winding either for step-up or step-down transformers. In either case, the zigzag winding produces the same angular displacement as a delta winding, and at the same time provides a neutral for earthing purposes.
- The amount of copper required from a zigzag winding in 15% more than a corresponding star or delta winding. This is extensively used for earthing transformer.
- Due to **zigzag** connection (interconnection between phases), third harmonic voltages are reduced. It also allows unbalanced loading. The zigzag connection is employed for LV winding. For a given total voltage per phase, the zigzag side requires 15% more turns as compared to normal phase connection. In cases where delta connections are weak due to large number of turns and small cross sections, then zigzag star connection is preferred. It is also used in rectifiers.

(5) Zig- zag/ star (ZY1 or Zy11)

- Zigzag connection is obtained by inter connection of phases.4-wire system is possible on both sides. Unbalanced loading is also possible. Oscillating neutral problem is absent in this connection.
- This connection requires 15% more turns for the same voltage on the zigzag side and hence costs more. Hence a bank of three single phase transformers cost about 15% more than their 3-phase counterpart. Also, they occupy more space. But the spare capacity cost will be less and single phase units are easier to transport.
- Unbalanced operation of the transformer with large zero sequence fundamental mmf content also does not affect its performance. Even with Yy type of poly phase connection without neutral connection the oscillating neutral does not occur with these cores. Finally, three phase cores themselves cost less than three single phase units due to compactness.

Parallel Operation of Three Phase Transformer

Parallel operation of three phase transformer is very common in three phase power generation, transmission and distribution. It is advantageous to use two or more transformer units in parallel instead of using a single large unit. This offers flexibility for maintenance as well as operation.

Advantage of Parallel Operation of Three Phase Transformers

- It increases the reliability of supply system. Let us try to understand how this happens. Suppose a fault occurs in any one of the Transformer unit. In such case, the faulty transformer may be taken out of service while the remaining transformers will feed the power supply. If there were only one large transformer unit is installed for supplying the load, the supply to the entire load will be interrupted during breakdown of the transformer. Thus the reliability of supply system is increased by parallel operation of transformers.

- The size of transformer increases with the increase of its rating. Therefore, a larger transformer will be bigger in size. Therefore, its transportation form manufacturer to the Site will be difficult. Whereas, transportation and installation of small sized transformers are comparatively easy.
- The maintenance opportunity in case of parallel operation is increases. One or more transformers may be taken under maintenance while the remaining transformers will supply the load at reduced power.

Condition for Parallel Operation of Three Phase Transformers

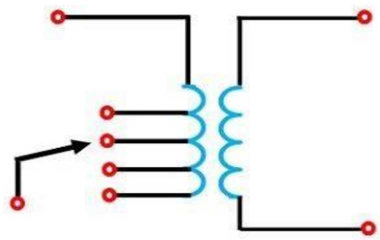
The following conditions are to be fulfilled before paralleling two three phase Transformers:-

1. The voltage transformation ratio of the both transformer must be same.
2. The polarity must be same.
3. The percentage impedance should be same.
4. The vector diagram and the phase displacement must be same.
5. The phase sequence must be same.

TAP CHANGER WITH TRANSFORMER

The tap changer is a device which regulate the output voltage of a transformer by altering the number of turns in one winding and thereby changing the turns ratio of the transformer. For sufficiently close control of voltage, taps are usually provided on the high voltage windings of the transformer. There are two types of transformer tap changers: an on-load tap changer (OLTC) and a de-energized tap changer (DETC)or off-load tap changer.

1.Off load tap changing is normally provided in low power, low voltage transformers. It is the cheapest method of tap changing. The tap changing is done manually though hand wheel provided in the cover. In some transformers arrangements to change the taps by simply operating the mechanical switches are also provided. The winding is tapped at various points. Since the taps are provided at various points in the winding single tap must be connected at a time otherwise it will lead to short circuit. Hence the selector switch is operated after disconnecting the load. To prevent unauthorized operation of an off load tap changer, mechanical lock is provided. To prevent inadvertent operation, electromechanical latching devices are provided to operate the circuit breakers and de-energize the transformer as soon as the tap changer handle is moved. The off load tap changing transformer is shown in the figure below

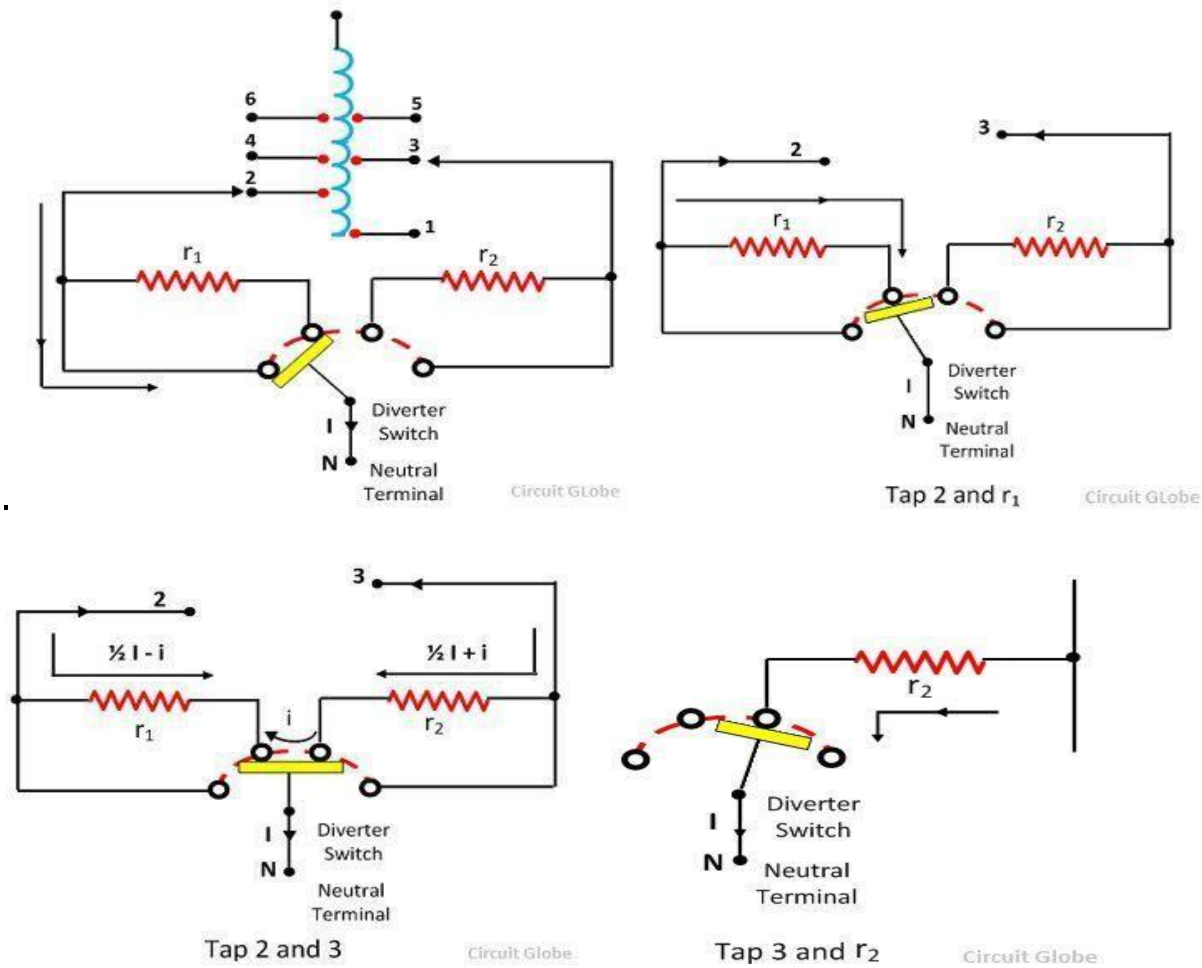


Off-load tap-changing transformer

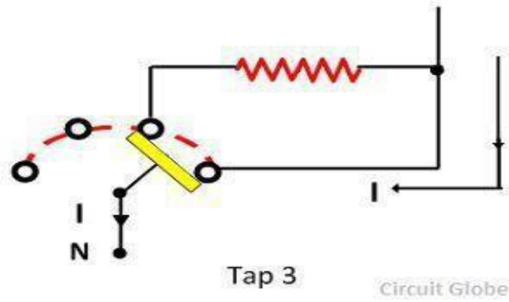
2. On-load tap-changing transformer

A) Using resistor

The on-load tap changing gear with the resistor transition, in which one winding is changed for each operating position as shown in the figure below. The sequence of operation during the shifting of one tap into the next is shown in the figure below. The backup main contactor is provided which short-circuit the resistors for normal operation.



Shibashis Kar

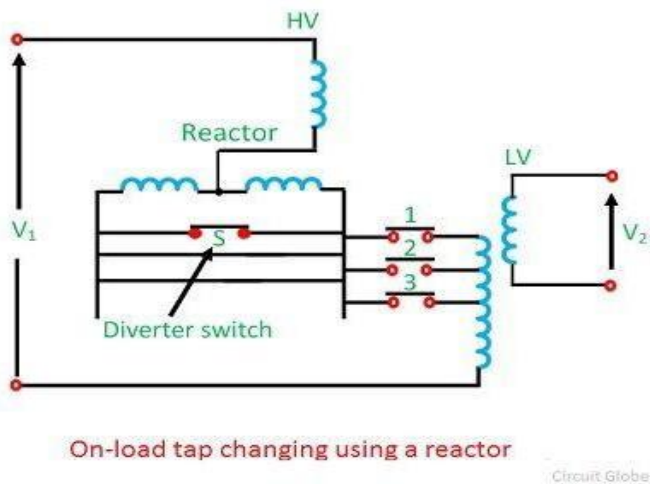


The tap changer controls gear by using the push buttons. The aim of control is to maintain a given voltage level within a specified resistance or to increase it with a load to compensate for the voltage drop in the given transmission line.

B) Using Reactor

In order that the supply may not be interrupted, on-load tap changing transformer are sued. Such a transformer is known as a tap-changing under load transformer. While tapping, two essential conditions are to be fulfilled.

- The load circuit should not be broken to avoid arcing and prevent the damage of contacts.
- No parts of the windings should be short–circuited while adjusting the tap.



On-load tap changing using a reactor

The tap changing employing a center tapped reactor R show in the figure above. Here S is the diverter switch, and 1, 2, 3 are selector switch. The transformer is in operation with switches 1 and S closed. To change to tap 2, switch S is opened, and 2 is closed. Switch 1 is then opened, and S closed to complete the tap change. It is to be noted that the diverter switch operates on load, and no current flows in the selector switches during tap changing. During the tap change, only half of the reactance which limits the current is connected in the circuit.

Note:
The tap changer is placed on high voltage side because:
1) The HV winding generally wound over LV winding hence it is easier to access the HV winding turns instead of LV winding.
2) Because of high voltage the current through the HV winding is less compared to LV windings, hence there is less "wear" on the tap changer contacts. Due this low current, in on load tap changer the change over spark will be less.

CARE AND MAINTENANCE OF TRANSFORMER

A power transformer is the most costly and essential equipment piece of equipment within an electrical substation. So it is desirable to perform various preventative maintenance activities to ensure the transformer maintains a high level of performance and a long functional life.

A power transformer requires various routine maintenance tasks including measurement and testing of different parameters of the transformer. There are two main types of **maintenance of transformer**.i.e. one group on a routine basis (known as preventative maintenance), and the second group on an ad-hoc basis (i.e. as required).

Some other types of maintenance for a transformer we perform only as they are required – known as emergency or **breakdown transformer maintenance**. But if one performs regular maintenance properly, this significantly reduces the chances of needing to perform such emergency and breakdown maintenance.

There are many different **preventative maintenance** actions to be performed on a power transformer. They can be on a daily, monthly, yearly, quarterly, half-yearly, or yearly basis. Some transformer maintenance activities only need to be performed once in a 3 to 4 years interval.

I) Monthly Basis Maintenance of Transformer

1. The oil level in oil cap under silica gel breather must be checked in a one-month interval. If it is found the transformer oil inside the cup comes below the specified level, oil to be top up as per specified level.
2. Breathing holes in silica gel breather should also be checked monthly and properly cleaned if required, for proper breathing action.
3. If the transformer has oil filled bushing the oil level of transformer oil inside the bushing must be visually checked in the oil gauge attached to those bushing. This action also to be done monthly basis. If it is required, the oil to be filled in the bushing upto correct level. Oil filling to be done under shutdown condition.

II) Daily Basis Maintenance and Checking

1. Reading of MOG (Magnetic Oil Gauge) of main tank and conservator tank.
2. Color of silica gel in breather.
3. Leakage of oil from any point of a transformer.In case of unsatisfactory oil level in the MOG, oil to be filled in transformer and also the transformer tank to be checked for oil leakage. If oil leakage is found take required action to plug the leakage. If silica gel becomes pinkish, it should be replaced.

III) Yearly Basis Transformer Maintenance Schedule

1. The auto, remote, manual function of cooling system that means, oil pumps, air fans, and other items engaged in cooling system of transformer, along with their control circuit to be checked in the interval of one year. In the case of trouble, investigate control circuit and physical condition of pumps and fans.
2. All the bushings of the transformer to be cleaned by soft cotton cloths yearly. During cleaning the bushing should be checked for cracking.
3. Oil condition of OLTC to be examined in every year. For that, oil sample to be taken from drain valve of divertor tank, and this collected oil sample to be tested for dielectric strength (BDV) and moisture content (PPM). If BDV is low and PPM for moisture is found high compared to recommended values, the oil inside the OLTC to be replaced or filtered.
4. Mechanical inspection of Buchholz relays to be carried out on yearly basis.
5. All marshalling boxes to be cleaned from inside at least once in a year. All illumination, space heaters, to be checked whether they are functioning properly or not. If not, required maintenance action to be taken. All the terminal connections of control and relay wiring to be checked an tighten at least once in a year.
6. All the relays, alarms and control switches along with their circuit, in R&C panel (Relay and Control Panel) and RTCC (Remote Tap Changer Control Panel) to be cleaned by appropriate cleaning agent.
7. The pockets for OTI, WTI (Oil Temperature Indicator & Winding Temperature Indicator) on the transformer top cover to be checked and if required oil to be replenished.
8. The proper function of Pressure Release Device and Buchholz relay must be checked annually. For that, trip contacts and alarm contacts of the said devices are shorted by a small piece of wire, and observe whether the concerned relays in remote panel are properly working or not.
9. Insulation resistance and polarization index of transformer must be checked with battery operated megger of 5 KV range.
10. Resistive value of earth connection and rizer must be measured annually with clamp on earth resistance meter.
11. DGA or Dissolve Gas Analysis of transformer Oil should be performed, annually for 132 KV transformer, once in 2 years for the transformer below 132 KV transformer and in 2 years interval for the transformer above 132 KV transformer.

The Action to be taken once in 2 years:

1. The calibration of OTI and WTI must be carried once in two years.
2. Tan & delta; measurement of bushings of transformer also to be done once in two years.

IV) Maintenance of Transformer on Half Yearly Basis

The transformer oil must be checked half yearly basis that means once in 6 months, for dielectric strength, water content, acidity, sludge content, flash point, DDA, IFT, resistivity for transformer oil.In the case of a distribution transformer, as they are operating light load condition all the time of day remaining peak hours, so there are no maintenance required.