tes Technical Education Series

# BASIC ELECTRICAL ENGINEERING

## With Numerical Problems

VOLUME II

Premier12

P S Dhogal

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# 13 Alternator

## 13.1 ALTERNATOR

The emf generated inside the armature of a dc generator is alternating and unidirectional to the external circuit which is supplied through the commutator. If instead of the commutator, sliprings are provided and the connection are brought to the external load, the current in the external circuit will be alternating. A generator supplying an alternating current is known as 'alternator or ac generator'.

**Working Principle** The working principle of an alternator is exactly the same as that of a dc generator. In fact, all dc generators are alternators in which alternating voltages are set up, and it is the commutator which converts this ac into dc. In the dc generator, it is essential for the armature to rotate in the magnetic field produced by the stationary magnetic field to give the unidirectional voltage. However, in the alternator, it is not essential for the armature to rotate, and either the armature or the field can be made to rotate while the other is kept stationary.

In modern machines, the armature is kept stationary and the field rotates under it.

*Advantages of Keeping the Armature Stationary:*

1. It facilitates the provision of sufficient space for the armature winding and hence more conductors are inserted in the stationary part, i.e. the stator, than the rotating part, i.e. the rotor.

2. The voltage rating of the alternator increases owing to the presence of more conductors in the stationary armature winding.

3. On account of there being more conductors in the stationary armature, the output of the alternator also increases.

4. Since the armature winding is stationary, the danger of loosening the armature winding or the terminals does not arise.

5. No difficulty is experienced in insulating the stationary armature coils for higher voltages up to 11000 V.

6. It is easier to wind a stationary armature than a rotating one.

7. It is also easier to collect the supply of high voltage from stationary terminals than from rotating terminals.

8. The rotating field is comparatively lighter in weight than stationary armature and can run at higher speeds. Hence, high voltages can be generated from an alternator.

9. If the field is kept stationary, four sliprings are needed to supply the current to the external circuit, and hence these sliprings have to be insulated from high voltage. If the armature is kept stationary, two sliprings for low voltage are needed to supply the direct current to the rotating field.

10. Since the brushes for stationary armature are not required to supply the current, the question of sparking at the brushes at high voltages does not arise.

Therefore, in all modern machines, the armature is kept stationary and the field rotating. The dc supply required for the field system is generated by a separate dc shunt or compound generator. However, in the modern machine, the alternating current produced is rectified and then supplied for the field system.

## 13.2 PARTS OF ALTERNATOR AND THEIR FUNCTIONS

An alternator has the following three main parts.

1. Stator
2. Rotor
3. Exciter

**Stator** The stationary part of the alternator in which the emf is induced is known as the stator. The stator is made of laminated stamping with slots on its circumference to receive the winding. These stampings are insulated from each other with varnish and housed in the yoke (frame) consisting of magnetic material, such as cast iron or silicon steel.

**Rotor** The rotor has the rotating magnetic-field poles as in a dc generator which are separately excited from a dc source known as exciter. There are two types of rotors in use as follows.

1. Salient-pole-rotor or projecting-pole rotor
2. Cylindrical rotor

*Salient-Pole Rotor* The salient-pole rotor is made of steel stampings and is suitable for low speed (375 to 500 rpm.) hydro-alternators. The poles project outwards and facing the stationary armature as shown in Fig. 13.1. This type of rotor has a large diameter and is short in length. On the circumference of the rotor, six to forty poles are fixed. The maximum speed of the rotor is 1000 rpm.

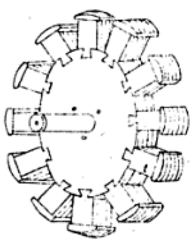


**Fig. 13.1 Salient-pole rotor**

*Smooth Cylindrical Rotor* This type of rotor is cylindrical and has a large axial length and small diameter. It is made of a solid steel piece and slots are made on the circumference of the rotor to hold the field winding. This type of rotor is suitable for high speed turbo-alternators having two or four poles in the winding and the maximum speed of this rotor is 1500 to 3000 rpm. The output of the two-pole machine is about 50,000 kVA. while with four poles it is 200,000 kVA.

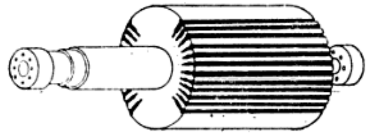


**Fig. 13.2 Smooth cylindrical rotor**

**Exciter** The exciter is a small dc shunt or compound dynamo fixed at one end of the alternator shaft. The dc supply from the exciter is supplied to the field winding through the two sliprings fixed on the shaft of the alternator. The voltage rating of the exciter is usually 110 to 250 V dc.

## 13.3 RELATION BETWEEN SPEED, POLES AND FREQUENCY OF AN ALTERNATOR

When a conductor moves from the centre of the north pole to the centre of the south pole, it completes a half-cycle, and when it again reaches the centre of north pole, it completes one cycle. So when a conductor moves under two poles, it completes one cycle. If in an alternator there are $P/2$ pairs of poles, then in one complete revolution it will develop $P/2$ cycles.

If an alternator revolves at a speed of $N$ rpm or say $\frac{N}{60}$ rps., then it will develop $\frac{P}{2} \times \frac{N}{60}$ cycles per second, i.e. $\frac{PN}{120}$ c/s. But cycle per second is called frequency.

$$\therefore \text{ Frequency, } f = \frac{PN}{120} \qquad (13.1)$$

where $P$ = number of poles

$N$ = revolutions completed per minute

$f$ = number of cycles completed per second (frequency)

EXAMPLE 13.1 *A high-speed turbo alternator has two poles and revolves at a speed of 3000 rpm. Calculate the frequency of the supply.*

TABLE 13.1

| *S. No.* | *Number of poles* | *Speed in rpm* | *Types of alternator* |
|---|---|---|---|
| *1* | *2* | *3* | *4* |
| 1 | 2 | 3000 | High-speed alternator |
| 2 | 4 | 1500 | |
| 3 | 6 | 1000 | Medium-speed alternator |
| 4 | 8 | 750 | |
| 5 | 10 | 600 | |
| 6 | 12 | 500 | Low-speed alternator |
| 7 | 14 | 429 | |
| 8 | 16 | 375 | |

***Solution:*** We know that

$$\text{Frequency, } f = \frac{PN}{120}$$

$$= \frac{2 \times 3000}{120} = 50 \text{ c/s}$$

Table 13.1 shows the speed of an alternator for 50 c/s frequency at different number of poles.

## 13.4 TYPES OF ALTERNATOR

Alternators are of two main types as given below.

1. High-speed alternator
2. Low-speed alternator

However, they can be further subdivided as follows.

1. With respect to rotation, they are:

(*a*) Rotating armature type

(*b*) Rotating field type

Nowadays rotating field type alternators are preferred as discussed earlier. The rotating armature type alternator is only used when the capacity of the alternator is small. [Ref Fig. 13.3(b)].

2. With respect to number of phase, they are:

(*a*) Single-phase alternators

(*b*) Polyphase alternators

3. With respect to excitation, they can be divided as:

(*a*) Separately excited alternator.

(*b*) Self excited alternator.

## 13.5 CLASSIFICATION OF ALTERNATOR WITH RESPECT TO ROTATING FIELD

As discussed earlier in this chapter that in the modern alternator the armature in which emf is generated is kept stationary while in the rotating field dc supply is fed for its excitation. This field is rotated in the armature and thus emf is induced in the stationary armature. The followings are the two types of alternators and the field system for all the alternators are same as stated above.

1. Single phase alternator
2. Polyphase alternator

**Single-Phase Alternator** The armature winding for single-phase alternator consists of coils connected in series in such a way as to add their emfs. It means that if the first coil is in the clockwise direction, second is anticlockwise and the third coil clockwise direction and so on. The connection for the single-phase alternator is shown in Fig. 13.3 (*a*) and 3.3 (*b*). In Fig. 13.3 (*a*) the field system is shown rotating and in Fig. 13.3 (*b*) the armature is shown to be of the rotating type.

**Polyphase Alternator** Figure 13.4 shows the connection of a three-phase alternator. In a three-phase alternator there are three windings placed 120 electrical degrees apart. Each winding has two separate coils insulated from each other. Coils 1 and 4 relate to the

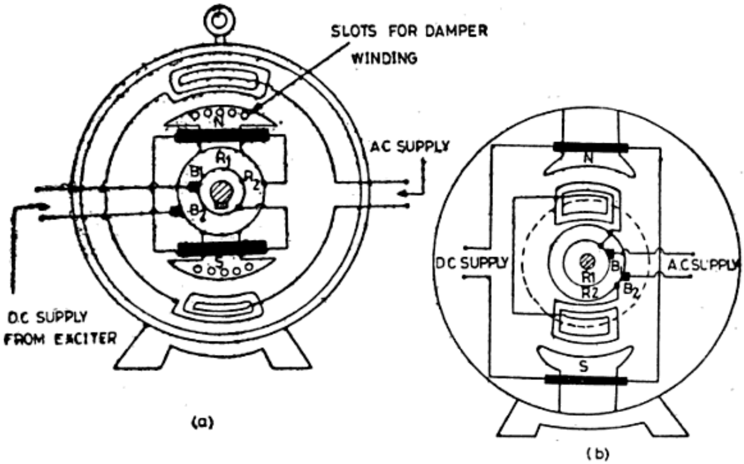



**Fig. 13.3 Types of single-phase alternator**
**(a) Field rotating type alternator; (b) Armature rotating type alternator**

first winding, coils 2 and 5 to the second, and 3 and 6 to the third. The three similar ends of the three windings *A'B'C'* are joined together to create the star (neutral) points for the system and the remaining three terminals *A, B, C* are the phase terminals of the alternator. The neutral point of the alternator is generally earthed at the generating station. Four wires are brought out as supply terminals. The voltage between any phase and neutral is $\frac{1}{\sqrt{3}}$ of that across the two phases.

If the line voltage (across two phases) is 400 V, then the phase voltage will be equal to $\frac{400}{\sqrt{3}} = 231$ V. Lighting and single-phase power load is connected between any one phase and neutral whereas for three-phase load the three phases are used.

***Damper Winding*** In low-speed high-capacity alternators, when load changes, the speed of the alternator also changes for a moment and the phenomenon is known as "hunting" or "phase swinging". To reduce the hunting, slots are made on the pole [shown in Fig. 13.3 (*a*)] face and damper winding is housed on them.

**Example 13.2** *Find the BHP of an engine to drive 373 kVA, 215.36 V three-phase alternator at full load, if the alternator has an efficiency of 80% at PF 0.5 lagging. Find also the full load current of the generating set.*

***Solution:***

Output of the alternator in kilowatts

$= \text{kva} \times \cos\theta$

$= 373 \times 0.5 = 186.5$ kW

Efficiency of the alternator $= 80\%$

Input of the alternator (i.e. output of the engine)

$$= \frac{\text{Output} \times 100}{\eta\%}$$

$$= \frac{186.5 \times 100 \times 1000}{80 \times 746} = 312.5 \text{ hp} \quad \textbf{Ans.}$$

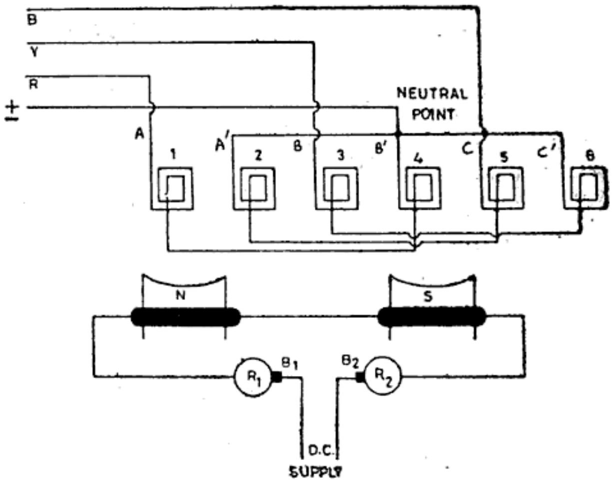



**Fig. 13.4 Rotating field type three-phase alternator**

But kVA $= \dfrac{\sqrt{3} \times V_L \times I_L}{1000}$

∴ Full-load current,

$$I_L = \frac{\text{kVA} \times 1000}{\sqrt{3} \times V_L}$$

$$= \frac{373 \times 1000}{1.732 \times 215.36}$$

$= 1000$ A **Ans.**

**Example 13.3** *A three-phase 1119-V star connected alternator supplies a three phase 72 h.p., mesh connected induction motor, the efficiency being 80% and the P.F. is 0.8. Calculate the voltage and current in each phase of the alternator and motor. Calculate also the active and reactive components of the current in each phase of the motor and alternator.*

***Solution:*** Phase voltage of delta connected motor.

$Vph = V_L = 1119$ V **Ans.**

Phase voltage of star connected Alternator,

$$\sqrt{3}\, Vph = V_L$$

∴ $Vph = \dfrac{1119}{\sqrt{3}} = 646.0$ V **Ans.**

Output of the motor $= 72$ h.p.

Input of the motor $= \dfrac{\text{Output} \times 100}{\eta\%}$

$= \dfrac{72 \times 746 \times 100}{80}$ W

Power in there phase system,

$$W = \sqrt{3}\, V_L \times I_L \times \cos\theta$$

$$\frac{72 \times 746 \times 100}{80} = \sqrt{3} \times 1119 \times I_L \times 0.8$$

∴ Line Current, $I_L$

$$= \frac{72 \times 746 \times 100}{80 \times \sqrt{3} \times 1119 \times 0.8}$$

$= 43.3$ A **Ans.**

Current in each phase of mesh connected motor

$= \dfrac{43.3}{\sqrt{3}} = \dfrac{43.3}{1.732}$

$= 25$ A **Ans.**

Current in each phase of the star connected alternator,

$I_L = Iph = 43.3$ A **Ans.**

Active component of alternator phase current,

$= I \times \cos\theta$

$= 43.3 \times 0.8 = 34.64$ A **Ans.**

Reactive component of alternator phase current

$= I \times \sin\theta$

$= 43.3 \times 0.6 = 25.98$ A **Ans.**

Active component of motor phase current

$= I \times \text{Cos}\,\theta$

$= 25 \times 0.8 = 20$ A **Ans.**

Reactive Component of Motor Phase Current

$= \sqrt{\text{Main Current}^2 - \text{Active Comp. } I^2}$

$= \sqrt{(25)^2 - (20)^2}$

$= \sqrt{625 - 400} = \sqrt{225}$

$= 15$ A **Ans.**

## 13.6 COIL SPAN FACTOR AND DISTRIBUTION FACTOR

**Coil Span Factor** Sometimes it is also called pitch factor. When the two coil sides of a coil are 180 degree apart to the magnetic field, the coil is termed as full pitched coil as illustrated in Fig. 13.5 (*a*). The emf induced in the two sides of a coil will be added arithmetically as these sides are in series. When the coil span differs from the full pitch as shown in Fig. 13.5 (*b*), then the emfs induced in the two coil sides are not in phase and the resultant emf is determined by their vector sum.

The coil span factor may be defined as the ratio of the vector sum of the emfs induced when the coils are distributed in "n" slots to the arithmetic sum of emfs induced when the coils are concentrated in one slot. It is represented by $K_c$.

$$K_c = \frac{\text{vector sum of emfs induced}}{\text{arithmetic sum of emfs induced}} = \frac{E_r}{nE}$$

Let us suppose that the two coil sides are not spaced at a distance of one pole pitch but placed at a distance of $(180 - \alpha)$. The emf induced in each coil side will be vectorially added to get the resultant emf per coil. In Fig 13.5(*c*) $AB$ and $BC$ denotes the emf induced in each coil side.

$AB = BC =$ emf induced in each coil side

$\therefore \quad \angle BAC = \angle BCA$

and $\quad \angle ABC = 180° - \alpha$

In $\triangle ABC$,

$\angle BAC + \angle BCA + \angle ABC = 180°$

or $\quad 2\angle BAC = 180° - \angle ABC$

$= 180° - (180° - \alpha)$

$= \alpha$

$\therefore \quad \angle BAC = \dfrac{\alpha}{2}$

$\therefore$ Vector sum,

$AC = 2\,AD$

$= 2\,AB \cos \dfrac{\alpha}{2}$

Arithmetic sum of emfs $= 2\,AB$

$(\because \quad AB = BC)$

$\therefore$ Coil span factor,

$$K_c = \frac{\text{Vector sum of emf}}{\text{Arithmetic sum of emf}} = \frac{2AB \cos \frac{\alpha}{2}}{2\,AB} = \cos \frac{\alpha}{2} \qquad (13.2)$$

NOTE For full pitch winding, the coil span factor (pitch factor) is always one.

**Distribution Factor** It is also sometimes known as breadth factor. In an alternator,

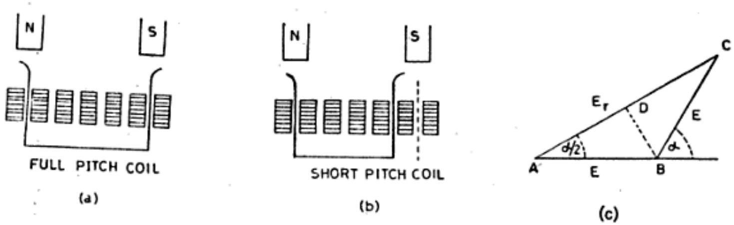



**Fig. 13.5 Coil span: (a) Full pitch coil, (b) Short pitch coil, and (c) Resultant emf**

the armature winding is distributed in several slots per pole pitch and the emfs induced in each coil are equal in magnitude but have a phase displacement $\alpha°$ between them. So the vector sum of the emf is less than the arithmetic sum of the emf when the conductors are concentrated in one slot.

*Hence the distribution factor may be defined as the ratio of the vector sum of emf induced when the winding is distributed in "n" number of slots to the arithmetic sum of the emf which would be generated if the winding were concentrated in one slot. It is denoted by $K_d$.*

$$K_d = \frac{\text{Vector sum of emf induced } (E_r)}{\text{Arithmetic sum of emf induced } (nE)}$$

Let the phase displacement between the induced emfs in the adjacent conductors in the two adjacent slots is ($\alpha°$).

$$\therefore \quad \alpha° = \frac{180°}{\text{No. of slot/pole} \times \text{No. of phase in the machine}}$$

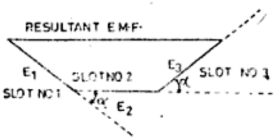



Fig 13.6 (a)

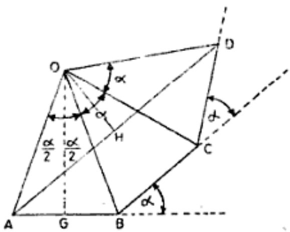



Fig. 13.6 (b)

In Fig. 13.6 (b) a vector diagram is shown for a complete distributed coil which is a polygon and the closing side AD is the resultant emf in the coil. Let there be $n$ no. of slots/pole/phase in each coil, then there will be $n$ coil sides.

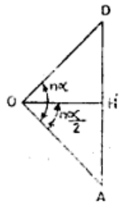



Fig. 13.6 (c)

$AB = BC = CD =$ emfs induced per slot

Draw $OG$ and $OH$ perpendicular to AB and AD respectively.

$$\angle OBA = \angle OBC$$

But $\angle OBA + \angle OBC + \angle \alpha = 180°$

$$\therefore \quad 2\angle OBA = 180° - \alpha$$

or $\quad \angle OBA = 90 - \frac{\alpha}{2}$ ...(i)

But from right angled triangle $OBG$

$\angle OBG = 90° - \angle BOG$ ...(ii)

From equations (i) and (ii)

$$\angle BOG = 90° - \angle OBG$$

$$= 90° - \angle OBA$$

$(\because \angle OBG = \angle OBA)$

$$= 90° - \left(90° - \frac{\alpha}{2}\right)$$

$$= \frac{\alpha}{2}.$$

$$\angle AOB = \angle BOC = \angle COD = \alpha$$

$$\angle AOD = n\alpha$$

From Fig. 13.6 (c)

Resultant vector sum $AD$

$$= 2AH$$

$$= 2OA \sin \frac{n\alpha}{2}$$

Arithmetic sum

$=AB+BC+CD$

$=n\times AB$

$=n\times 2AG$

$=n\times 2\,OA\sin\frac{\alpha}{2}$

∴ Distribution factor

$$=\frac{\text{Vector sum of emfs}}{\text{Arithmetic sum of emfs}}$$

$$=\frac{2\,OA\sin\frac{n\alpha}{2}}{n\times 2\,OA\sin\frac{\alpha}{2}}$$

$$=\frac{\sin n\frac{\alpha}{2}}{n\sin\frac{\alpha}{2}} \qquad (13.3)$$

NOTE Distribution factor for a distributed winding is always less than unity.

### 13.7 EQUATION OF AN ALTERNATOR

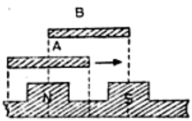



Fig 13.7

Let an alternator be wound with full pitch coils. If a coil of it is made to rotate from $A$ to $B$ as illustrated in Fig. 13.7 the flux changes from maximum to zero.

Hence if the coil has $N$ turns, then

Total variation of the flux $=\phi N$ Wb

∴ Average induced emf per coil,

$$E_{av}=\frac{\phi N}{t} - \text{V} \qquad (1\ \text{Wb/s}=1\ \text{V})$$

Where $t$ is the time in seconds required by the coil to travel from position $A$ to $B$. But the emf induced completes only quarter cycle in this displacement.

$$\therefore\ t=\frac{1}{4}\text{ of a period}=\frac{1}{4}f - \text{s}$$

$$\therefore\ E_{av}=\frac{\phi N}{1/4f}=4\,\phi Nf - \text{V}$$

Suppose the total number of coils per phase be "C", then

Emf per phase $=4\,\phi NfC$ – $V$

But each turn has two conductors.

Therefore, total conductors in an alternator

$Z=2\,CN$

or $CN=\frac{Z}{2}$

But $E_{av}=4\,\phi NfC$

∴ $E_{av}=2\,\phi fZ$ – V

or

$E_{RMS}/\text{phase}=2\,\phi fZ\,K_f K_d K_c$ – V (13.4)

where $\phi$ = Flux per pole in webers

$f$ = Frequency of generated emb in hertz

$Z$ = No. of conductors in series per phase (each turn has two conductors)

$K_f$ = Form factor, (if wave form obtained is sinusoidal, $K_f=1.11$)

$K_d$ = Distribution factor

and $K_c$ = Coil span factor

EXAMPLE 13.4 *An eight pole, three-phase, 50 Hz star connected hydro alternator has 144 slots, 10 conductors/slot and the sinusoidal flux/pole is 25 m Wb. Find:*

*(i) The speed of the alternator.*

*(ii) The emf generated if the coil span is unity*

*(iii) Line Voltage.*

*Solution*

(i) Frequency of an alternator, $f$

$=\frac{NP}{120}$

∴ Speed in rpm, $N$

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

$=\frac{50\times 120}{8}=750$ r.p.m. Ans

(ii) No. of slots/pole/phase, $n$

$$=\frac{\text{Total No. of slots}}{\text{No. of poles}\times\text{No. of phases}}$$

$=\frac{144}{8\times 3}=6$ slots

No. of conductors/phase, $Z$

$$=\frac{\text{No. of slots}\times\text{No. of conductors/slot}}{\text{No. of phases}}$$

$=\frac{144\times 10}{3}=480$

*ALTERNATOR*

VOLTAGE | 440 V | kVA | 25 |

SPEED | 1000 RPM |, Frequency | 50 c/s |

PHASES | 3 |, Type | Y |

*EXCITER*

TYPE | D.C. SHUNT GEN. | EXCITER VOLTAGE | 20 V |

EXCITER AMPS | 30 A | SPEED | 1000 R.P.M. |

Fig. 13.8

Phase displacement between adjacent slots,

$$\alpha = \frac{180^\circ}{\text{No. of slots/pole} \times \text{No. of phases}}$$

$$= \frac{180^\circ}{6 \times 3} = 10^\circ$$

Then distribution factor,

$$K_d = \frac{\sin n\frac{\alpha}{2}}{n \sin\frac{\alpha}{2}}$$

$$= \frac{\sin 6\frac{10}{2}}{6 \sin\frac{10}{2}} = \frac{\sin 30^\circ}{6 \sin 5}$$

$$= \frac{0.5}{6 \times 0.0872} = \frac{0.5}{0.5232}$$

$$= 0.9557$$

RMS value of emf generated/phase,

$$E\,\text{rms} = 2\phi f Z K_f K_d K_s \quad - \text{V}$$

$$= 2 \times 25 \times 10^{-3} \times 50 \times 480 \times 1.11 \times 0.9557 \times 1$$

$$= 1273 \text{ V}$$

∴ Line voltage $= \sqrt{3}$ phase voltage

(∵ star-connected)

$$= \sqrt{3} \times 1273 = 2205 \quad \text{V} \quad \textbf{Ans.}$$

## 13.8 RATING OF AN ALTERNATOR

The rating of an alternator is stated in kVA on the name plate of the alternator and is as given in Fig. 13.8.

It means if the dc shunt wound dynamo of an alternator is run at the 1000 rpm and is delivering a current of 30A at 20 V to the field of the alternator, it develops a three phase 440 V 50 c/s supply having an output of 25 kVA. The three phases of the alternator are connected in star.

## 13.9 VOLTAGE REGULATION

The voltage regulation of an alternator is generally expressed in terms of the rise in voltage caused by throwing off the full load. (Field excitation and speed remain constant). It is expressed as a percentage of full-load terminal voltage.

Suppose the full-load terminal voltage of an alternator is $V$ which rises to $E_o$ when load is thrown off, then the voltage regulation

$$= \frac{E_o - V}{V}$$

Percentage voltage regulation

$$= \frac{E_o - V \times 100}{V}$$

where $E_o$ = no load voltage

and $V$ = full load terminal voltage.

NOTE $E_o - V$ is the arithmatic difference and not the vector difference

## 13.10 LOSSES OF AN ALTERNATOR

The losses which occur in an alternator are the same as those in dc generator as follows.

1. **Armature Copper Losses**

This is equal to $I_a^2 R_a$ — W

Where $I_a$ and $R_a$ are the current and effective resistance of the armature respectively.

Field copper loss $= I_f^2 R_f$ W

where $I_f$ and $R_f$ are the field current and resistance of the field respectively.

**2. Iron and Friction Losses**

Iron losses include:

(*a*) Armature core hysteresis loss

(*b*) Armature core and pole shoe eddy current loss

Friction losses include:

(*a*) Friction at sliprings and in bearings

(*b*) Friction due to windage

As discussed in Sec. 11.23 of Volume I efficiency of an alternator depends upon power

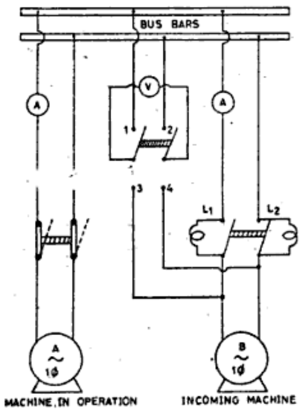



**Fig. 13.9 Dark lamp method of synchronizing of two single phase alternators**

factor. For a given load as the power factor decreases, the armature current increases and hence the copper loss increases and thus the efficiency decreases. The efficiency for a given load is maximum only when the power factor is one and it decreases as the power factor falls.

## 13.11 SYNCHRONIZATION AND PARALLEL OPERATION OF ALTERNATORS

Parallel connection of two or more alternators is known as synchronizing. The necessity of synchronizing and parallel operation of alternators is as given below.

1. It enables us to shutdown a faulty alternator for repair and overhaul.

2. If one of the alternators fails, then there will be others to supply the load and thus there will be no complete break down of supply.

3. It always enables alternator to run at full load and this increases the efficiency of the supply system.

4. During peak hours of load, additional alternators can be synchronized with the existing alternators.

**Methods of Synchronizing** There are two methods of synchronizing an alternator. They are:

1. Lamp method
2. Synchroscope method

If the two alternators are to be connected in parallel, they must fulfill the following conditions.

1. Terminal voltage of both the alternators must be same.

2. Frequency of supply of both the alternators must be equal.

3. Phase sequence of both the alternators must be identical.

*Synchronizing Single-Phase alternators by Lamp Method* In this method, assume that alternator *A* (as shown in Fig. 13.9) is already operating and alternator *B* is to be synchronized. Alternator *B* is known as incoming alternator. The incoming alternator *B* is run at its rated speed with the help of prime-mover and its voltage is adjusted equal to the bus-bar voltage. It is done by regulating the field current of the alternator.

The reading of the voltage can be either obtained by connecting two voltmeters or only one voltmeter which can be connected to both the bus-bars and incoming alternator as shown in Fig. 13.9. When the voltmeter terminals are connected to terminals 1 and 2, it will indicate the bus-bar voltage and when connected to terminals 3 and 4, it will show the voltage of the incoming alternator. As the alternators are generally rated for high voltage and the lamps available are of low voltage, more than one lamp are used in series or a step-down transformer is used.

The lamps connected across the terminal of the alternator *B* will flicker if the frequency and the phase of the bus-bar and incoming alternator are not proper. The flickering will be more if the difference is more. As the frequencies will become near to each other, the flckering will decrease. The speed of the incoming alternator, *B* is regulated by governor provided on the prime-mover so as to decrease the flickering of the lamps. The correct time for putting the main switch in the ON position for the coming alternator is one when all the lamps are dark The speed of the incoming alternator is adjusted by governor till the lamps remain dark for long period and in the middle of dark period the switch is put ON. The alternator can now be made to operate satisfactorily in parallel.

As it is difficult to judge the middle of the dark period, the connections of the two lamps are interchanged as shown in Fig. 13.10. In this procedure the proper instant for switching on the incoming alternator *B* is when the lamps are bright. In the middle of the bright period the main switch is therefore put ON. This method is known as "bright lamp method" while the first method is called the "dark lamp method".

*Synchronizing Three-Phase Alternators by Lamp Method* For the synchronizing three-phase alternators, three lamps are used. Figure 13.11 illustrate the connection for dark lamp method while Fig. 13.12. shows the connection for bright lamp method.

In the dark lamp method the correct moment for putting the main switch ON is one when all the three lamps are dark. For bright lamp method the switch of the incoming

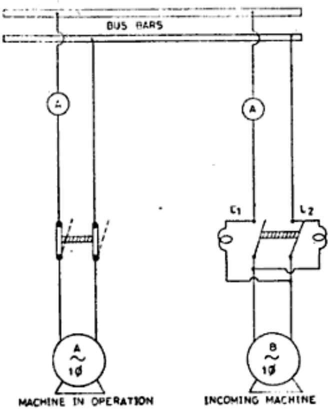



**Fig. 13.10 Bright lamp method of synchronizing of two single-phase alternators**

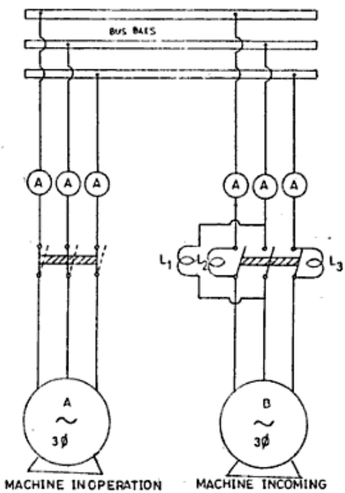



**Fig. 13.11 Synchronizing of three-phase alternators with dark lamp method**

machine is put ON in the middle of the period when lamps 1 and 2 are bright and lamp 3 dark. In this case also the lamps are either supplied through a step-down transformer or number of lamps are connected in series as the generating voltage of the alternator is usually higher than the voltage rating of the lamps.

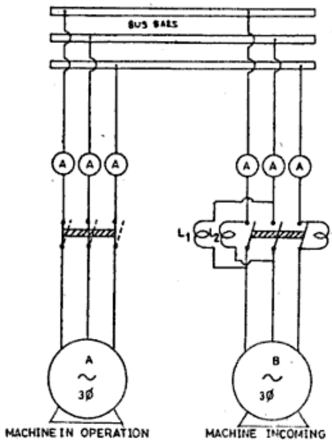



**Fig. 13.12 Synchronizing of three-phase alternators with bright lamp method**

*Synchroscope and its Function* Synchroscope is an instrument which shows the phase relationship of emf of the incoming alternator and at the same time it also indicates whether it is running slow or fast.

Synchroscope is a motor having a pointer fixed at one end of the motor's shaft which rotates over a circular scale fixed at the end of the shaft.

It works on the principle of rotating magnetic field. It consists of a rotor and stator would for two phase system and are supplied from two phase supply. If the frequency of supply to the rotor and stator is same, rotor and stator will produce a rotating magnetic field revolving at the same speed and hence there will be no change of flux in the air gap between rotor and stator, thus the rotor remains standstill. If there is difierence in frequencies of rotor and stator supply, the rotor will rotate. The speed of the rotor will depend upon the difference in frequencies. If this difference is greater, the rotor speed will be greater and if the difference is less, the rotor speed will be less. Therefore, it is clear that the synchroscope will stop revolving when the frequencies of the supply of rotor and stator become equal. The synchroscope will try to rotate in clockwise direction if the speed of the incoming machine is too fast and in anticlockwise direction if it is too low.

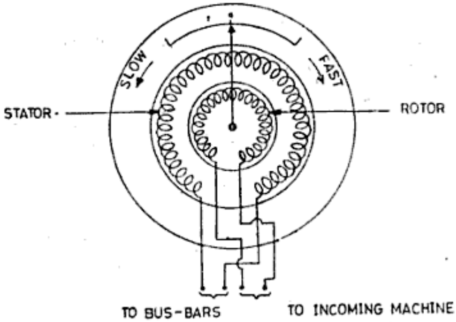



**Fig. 13.13 Internal connection of synchroscope**

*Synchronizing of Three-Phase alternator with Synchroscope* In Fig. 13.14 the connections for synchronizing three-phase alternator are shown. For synchronizing the three-phase alternator, the synchroscope is connected with the two phases only and if the two are synchronized, then the third phase will automatically be synchronized.

The alternator is first run at its normal speed and the voltage is adjusted equal to the bus bar voltage by adjusting its field excitation. After this the synchroscope switches are put on and the speed of the incoming alternator is adjusted in such a way as to decrease the speed of the needle of the synchroscope. When the pointer stands at 0 (zero) position, the main switch of the incoming alternator is put ON. After synchronizing the incoming alternator, the rotor and stator windings of the synchroscope are disconnected from the synchronizing bus-bars by putting "OFF" the main switches.

*Loadshifting of Alternator* When an alternator is synchronized, the load can be shifted from the other alternator to the incoming alternator by increasing the fuel supply to its prime-mover and at the same time reducing the fuel supply to the prime-mover of the alternator from which the load is to be transferred. Adjustment of field excitation will have a little effect in shifting the load but will change the reactive power supplied by the alternator.

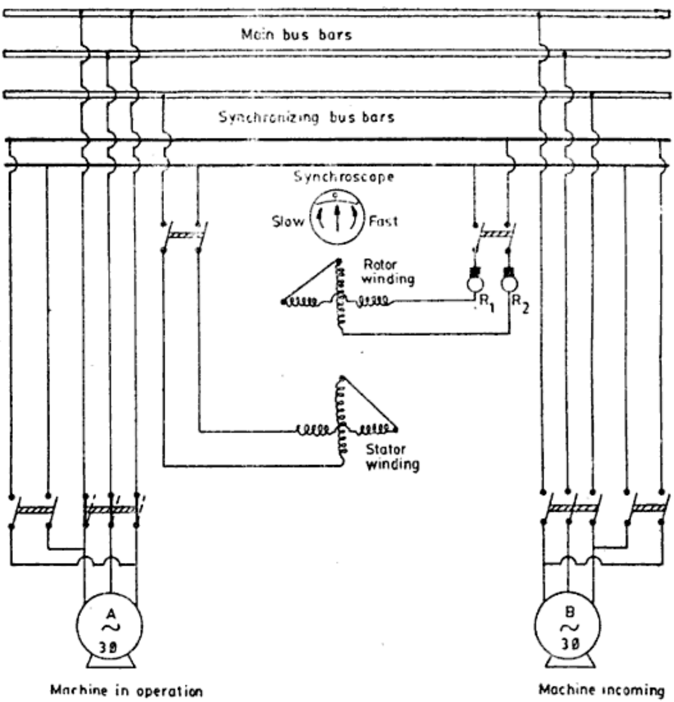



**Fig. 13.14 Synchronizing of three-phase alternators with synchroscope**

TABLE 13.2 COMPARISON OF AC TO DC GENERATION

| S. No. | Alternating Current (ac) | Direct Current (dc) |
|---|---|---|
| 1 | 2 | 3 |
| 1. | Alternators (ac generators) do not have any commutators and this enables the generating unit to be operated at high speeds. | Due to commutation, dc generators cannot run at high speeds. |
| 2. | It is easy to insulate the sliprings for high voltage and hence the generation of high voltage is possible. In India, the maximum induced voltage that can be obtained directly from an alternator is 11,000 V while in the U.S.A. it is 13,800 V. | In dc machines, it is very difficult to give extra ordinary insulation to the commutator. Therefore, the generation of high dc voltage is not possible. |
| 3. | ac voltage can be stepped up for the transmission of power and stepped down for the distribution of power by transformers. | dc voltages cannot be stepped up or down. |
| 4. | The transmission of power at high ac voltages is economical. For this reason ac is preferred to dc. | As the dc voltage cannot be stepped up or down, the question of transmission of power at high voltages does not arise. |
| 5. | Alternators can produce high voltage at high current ratings. In India, the maximum output of an alternator is 400 M W. | Owing to commutation difficulties, dc generators cannot be designed for large outputs. The maximum induced voltage and current ratings of a dc generator is 1500 V and 8000 A respectively. |
| 6. | For the same speed ac motors are cheaper, require less maintenance and, hence, are more efficient than dc motors. | dc motors are expensive and require more maintenance. |

## NUMERICAL EXERCISES

13.1 Calculate the frequency of a hydro alternator which has 20 poles and is revolving at a speed of 360 rpm (Ans. 60 Hz)

13.2 A turbo-alternator is running at 1500 rpm. Calculate the number of poles if the frequency of the supply of the alternator is 50 Hz. (Ans. 4 poles)

13.3 An eight-pole alternator is running at a speed of 600 rpm. Calculate the frequency. Also find the speed of the alternator so that it should develop 50 cycles per second. (Ans. 40 Hz, 750 rpm)

13.4 The current in each phase of a star-connected alternator is 1000 A when the generated phase voltage and power factor are 5000 V and 0.5 respectively. Calculate the line voltage and total power Output of the alternator. (Ans. 8660 V, 7500 kW)

13.5 Find the horsepower of a petrol engine which drives an alternator supplying a load current of 50 A at 373 V in a three-phase supply system. Assume the power factor of the supply to be 0.8 and the efficiency of the alternator 80 per cent. (Ans. 43.3 hp)

13.6 Find the bhp of a diesel engine driving an ac generator supplying a load current of 70 A at 400 V in a three-phase supply system. Assume the PF of the supply to be 0.84 and the efficiency of the alternator 84%. (Ans. 65 hp)

13.7 A three-phase 400 V star-connected alternator gives an output of 34.64 kW at 0.8. PF. Calculate the total load in kVA. and current supplied to the machine. (Ans. 43.3 kVA,. 62.5 A)

13.8 A three-phase star-connected alternator supplies a current of 150 A to a delta connected motor. Calculate the current and voltage in each phase of the (i) alternator and (ii) motor, if the alternator line voltage is 600 V. (Ans. (i) 150 A, 346.4 V ; (ii) 86.6 A, 600 V)

13.9 A three-phase 1492 V Star-connected alternator supplies to 192 hp mesh-connected induction motor the efficiency being 80% and the PF 0.8. Calculate the voltage and current in each phase of the motor and alternator. Also find the active and reactive components of the currents in each phase of the motor and alternator.

| Motor | | Alternator | |
|---|---|---|---|
| $I_{ph}$ | = 50 A | $I_{ph}$ | = 86.6 A |
| $V_{ph}$ | = 1492 V | $V_{ph}$ | = 861.43 V |
| $I_{act}$ | = 40 A | $I_{act}$ | = 69.28 A |
| $I_{react}$ | = 30 A | $I_{react}$ | = 51.96 A |

Ans. Reactive Component = 328.02 A.

13.10 A 12-pole, single-phase phase alternator has 50 slots and 70 conductors per slot. The flux per pole is 90 m Wb sinusoidally distributed. The distribution factor is 0.666 and the coil span factor is unity. If the speed is 600 rpm. Find : (a) the frequency, and (b) the emf generated in the alternator (Ans.(i) 60 Hz, (ii) 7984 V)

13.11 A single-phase alternator has 10 poles, 60 slots, 40 of which are wound with 10 conductors/slot. The sinusodial flux/pole is 40 mWb. The coil span factor is unity and the distribution factor 0.607. If the speed 600 rpm. Calculate (i) frequedcy and (ii) emf generated. (Ans. (i) 50 Hz, (ii) 1078 V)

13.12 A three-phase, eight-pole, 461.3-V star connected alternator is running at 750 rpm. Calculate the number of conductors in the stator winding if the flux per pole is 50 m Wb. and the distribution factor 0.96. (Ans. 50 conductors)

13.13 A three-phase eight-pole, 576.6-V star-connected alternator runs at 900 rpm. Calculate the number of turns in the stator winding if the flux/pole is 25 mWb. Assume distribution factor 0.96. (Ans. 52 turns)

13.14 A three-phase 50-cycle, two-pole star-connected alternator has 6 slots and 5 conductors/slot. If the terminal voltage on open circuit is 400 V. find the flux per pole. Assume the coil span factor as unity and distribution factor 0.94. (Ans. 110.7 mWb)

13.15 A three-phase, 4-pole, star connected alternator has 36 slots. Find the distribution factor. (Ans. 0.96)

13.16 A three-phase twelve-pole, 50-Hz star-connected alternator has 108 slots, 10 conductors per slot and the sinusoidal flux per pole is 100 m wb. Find: (i) running speed of the alternator, (ii) line Voltage on open circuit if the coil span is unity and distribution factor is 0.96. (Ans. 500 rpm, 9228 V)

13.17 A three-phase, ten-pole, 50-Hz, star-connected alternator has 10 slots, 5 coils, 15 turns in each coil, and the sinusoidal flux per pole is 100 mWb. Find the terminal Voltage on open circuit if the coil span is unity and the distribution factor 0.64. (Ans. 6152 V)

## REVIEW QUESTIONS

13.1 What is an alternator? Name the main parts of an alternator with their functions.

13.2 Explain why alternators are rated in kVA instead of kW.

13.3 Give the expression for frequency of the induced emf of an alternator. Also calculate the frequency of an alternator which has 8 pole and runs at a speed of 750 rpm. (Ans. 50 Hz)

13.4 In the modern alternator; the field is kept rotating and the armature stationary. Why is it so? State the advantages of keeping the armature stationary and field rotating.

13.5 What do you mean by synchronizing of an alternator? Explain its necessity.

13.6 What are the conditions of synchronizing two alternators? Briefly explain the dark lamp and bright lamp methods for synchronizing two single phase alternators.

13.7 (a) Explain different conditions to be fulfilled for parallel operation of alternators.

(b) What are the various methods of synchronizing three-phase alternators? Give the connection diagram of running alternators in parallel with synchronizing bar using synchroscope method. Explain the proper method of load sharing of an incoming alternator.

13.8 Give the expression for the emf induced in an alternator. A 220 V three-phase alternator is running at 300 rpm and has 24 poles. Find the number of conductors in the stator winding if the magnetic flux is $5 \times 10^{-2}$ Wb/pole. Assume distribution factor and coil span 0.96 and unity respectively. (Ans. 20 Conductors) (NCVT, 1969, Elect.)

13.9 Write short notes on:

(a) Synchroscope
(b) Prime-mover
(c) Exciter

13.10 Define the voltage regulation of an alternator. Is it possible to have the full-load terminal voltage greater than the no load terminal voltage? Explain. (NCVT, 1985, Elect.)

# 14
# Transformer

## 14.1 INTRODUCTION

*The transformer is a static machine which increases or decreases the ac voltage without changing the frequency of the supply.* As it has no rotating part, its efficiency is much higher than any rotating-type electrical machine. Energy supplied to the transformer may be converted to higher voltage or lower voltage or sometime at the same voltage. If it delivers energy at lower voltage, then is known as step-down transformer. If it delivers energy at increased voltage it is called step-up transformer. If it delivers energy at the same voltage, then it is called 1-to-1 ratio transformer. The step-down transformers are generally used to decrease the voltage at substations for the consumer's use and the step-up transformers are required to increase the voltage at the generating stations for transmission. The common voltages adopted for distribution are 1.1, 2.2, 3.3, 6.6 and 11 kV for urban area, 22, 33 kV for short distance transmission and 66, 110, 132, 220 and 440 kV for long-distance transmission. The efficiency of transformers ranges between 90 to 98 per cent.

Transformers are named power transformers or Distribution transformers according to the type or duty they perform. Power transformers are also known as "Transmission transformers" and are used for taking the supply at far-off distance by stepping up the voltage to high or extra high voltage (i.e. 33 KV to 440 KV depending upon the distance to which the supply is taken away) at generating stations or sub-stations. Transmission at high voltage, reduces the transmission line current and thus decreases the cross-sectional area of the conductor required for the lines. The secondary of this transformer is usually delta connected. These transformers are of high rating.

Transformers of outputs of up to to 500kVA are called 'Distribution Transformers' and generally step-down the voltage from 11 kV to 440 V. The primary winding of distribution transformer is delta connected and its secondary is star connected which enables to provide three phase four wire supply system.

## 14.2 WORKING PRINCIPLE OF TRANSFORMER

The working principle of a transformer is based on mutual electromagnetic induction. It means, whenever a changing flux links with a coil, an emf is induced in it which is proportional to the rate of change of flux and the number of turns in coils linking the flux.

## 14.3 CONSTRUCTION

A transformer consists of two windings insulated from each other. These windings are magnetically linked through the core. The winding which is connected to the supply is known as "primary winding" and the other winding on which the load is connected is called secondary winding.

The core of a transformer is made up of laminated stampings made of silicon steel containing 3.8 to 4.5 per cent silica. The laminations are insulated from each other and pressed together to reduce the eddy current loss. The stampings are of different shapes like *E, I, U, L, J, C* etc. The thickness of the laminations usually varies from 0.35 mm to 0.5 mm (i.e. 0.014" to 0.02".)

**Core-Type Transformer** In this type of transformer, the core is built with *L* type stampings and have two limbs which carries the primary and secondary windings. The simplest diagram of core-type transformer is shown in Fig. 14.1 and has only one magnetic path as shown by the dotted lines. The two windings are done on the two separate limbs of the core. For low-output small transformers, the section of the core is either

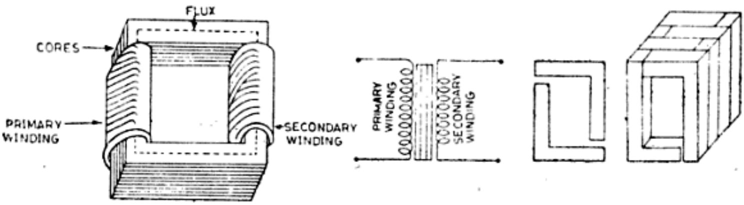



**Fig. 14.1 Core-type transformers**

rectangular or square and rectangular or square coils are employed for its winding. But in the case of high-output transformers, the core is stepped and the coils used for windings are circular in shape.

**Shell-Type Transformer** In this type of transformer, the magnetic core is built of *E* and *I* stampings and have three limbs. The central limb carries the primary and secondary winding and the magnetic circuit has two parallel paths through the core. The primary winding is wound deep near the core and secondary winding is done on it. A simple diagram of a shell-type transformer is shown in Fig. 14.2 and the two parallel paths of the magnetic flux are also shown by dotted lines. Generally all single phase transformers use shell-type core.

**Berry-Type Transformer** This type of transformer has magnetic cores in the shape of rectangular frames. One limb of all the frames passes through the centre of the core whereas other limbs are kept around the coils and thus the transformer will have as many parallel paths as the number of frames in the transformer. This type of transformers having multimagnetic paths is known as Berry-type transformer. In this case there are eight parallel paths for the flux. Figure 14.3 shows a simple Berry-type transformer.

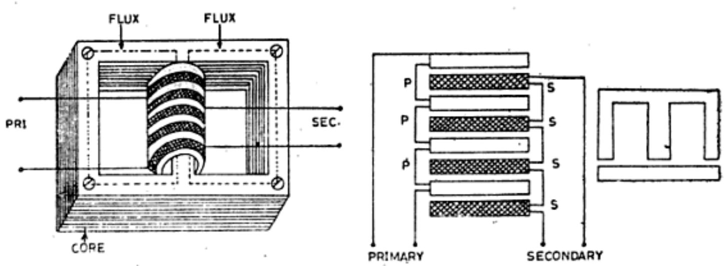



**Fig. 14.2 Shell-type transformer**

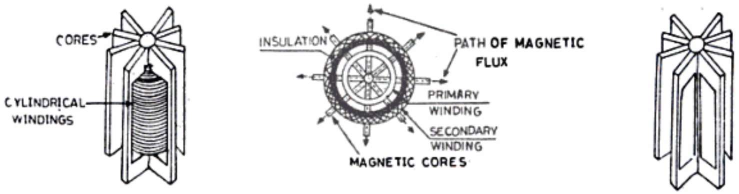



**Fig. 14.3 Berry-type transformer**

## 14.4 ADVANTAGES OF TRANSFORMER

1. The most important advantage of a transformer is that its voltage can easily be increased from low voltage to high voltage for transmission purpose and high voltages to low voltage for distribution purpose without much power loss.

2. As the transformer is a stationary device there is no wear and tear in it.

3. Practically no attention is needed for its maintenance, except in the occasional case.

## 14.5 EMF EQUATION

The emf induced in a transformer depends upon total flux in the core, frequency of the supply and the number of turns. Let us suppose that $\phi_m$ is the maximum value of flux in the core, 'f' is frequency of the supply in hertz and N the number of turns in the winding.

In a complete cycle, the flux changes four times from zero to $\phi_m$ and from $\phi_m$ to zero as shown in Fig. 14.4.

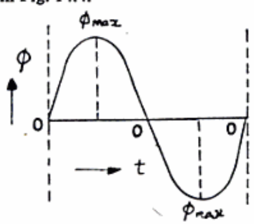



**Fig 14.4**

$\therefore$ Total change of flux in frequency $f$ Hz $= 4\,\phi_m f$.

Emf induced per turn $= 4\,\phi_m f$ V
(Wb/s = 1V)

As the coil has $N$ turns,

Emf induced in the coil $= 4\phi_m fN$ V

This is the average value of emf induced in the coil. Assuming the wave to be sinusoidal, the effective value of emf induced is given by

Emf (effective (or rms) = form factor × average value

$\because$ Form factor $= \dfrac{\text{rms value}}{\text{average value}}$

$\therefore$ Effective emf $= 1.11 \times 4\phi_m fN$ V

$= 4.44\,\phi_m fN$ V (14.1)

**Transformation Ratio** If $N_p$ is the number of turns in the primary winding, then the rms value of the emf induced in the primary winding is given by

$$E_p = 4.44\,\phi_m fN_p \quad \text{V} \qquad (14.2)$$

If $N_s$ is the number of turns in secondary winding, then the emf induced in the secondary winding is given by

$$E_s = 4.44\,\phi_m fN_s \quad \text{V} \qquad (14.3)$$

The emf induced in the secondary winding of the transformer will have the same frequency as that of the primary winding because the flux linking with it will also link with the secondary winding.

Dividing Eq. 14.3 by Eq. 14.2, we have

$$\frac{E_s}{E_p} = \frac{4.44\,\phi_m f N_s}{4.44\,\phi_m f N_p}$$

or $\dfrac{E_s}{E_p} = \dfrac{N_s}{N_p} = K$

Putting $\dfrac{N_s}{N_p} = K$, where $K$ is known as turns transformation ratio. $\frac{E_s}{E_p}$ is called voltage transformation ratio.

At no load the EMF induced in the secondary winding $E_s$ is approximately equal to secondary terminal voltag $V_s$. Similarly the EMF induced in the primary winding $E_p$ is also nearly equal to primary applied voltage $V_p$.

$$\therefore \quad \frac{E_s}{E_p} = \frac{V_s}{V_p} = \frac{N_s}{N_p} \qquad (14.4)$$

If $N_s > N_p$ (or $E_s > E_p$) then $K$ is greater than one, and the transformer is known as step-up transformer. Similarly if $N_s < N_p$ (or $E_s < E_p$) and $K$ is smaller than one, then the transformer is called as step-down transformer.

## 14.6 RELATION BETWEEN THE VOLTAGE AND CURRENT OF PRIMARY AND SECONDARY

Let $V_p$, $I_p$ and $V_s$, $I_s$ be the voltage and current in primary and secondary windings respectively. Suppose the power factor of both the primary and secondary winding is unity. If we neglect the losses in the transformer, the power output of the secondary winding, $V_s I_s$ is equal to the power input of the primary winding $V_p I_p$

$$\therefore \quad V_s I_s = V_p I_p$$

$$\text{or} \quad \frac{V_s}{V_p} = \frac{I_p}{I_s} = K$$

(known as current transformation ratio).

But $\quad V_s \simeq E_s$ and $V_p \simeq E_p$.

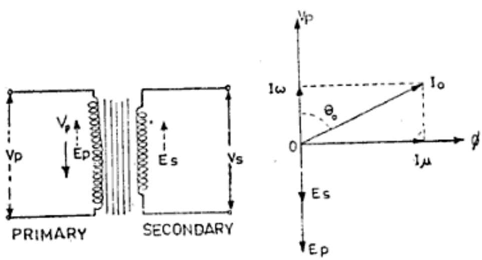
$$\therefore \quad \frac{E_s}{E_p} = \frac{I_p}{I_s} = K$$

or transformation ratio in one step,

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} = \frac{I_p}{I_s} = K \quad (14.5)$$

## 14.7 TRANSFORMER ON NO-LOAD

When an ac. supply is given to the primary winding of the transformer and no load is connected across the secondary winding (i.e. secondary terminals are left open), its primary winding takes very small current known as no-load current and is represented by $I_o$. This no-load current is usually 2 to 5% of its full load current which produces flux in the core and fulfill the iron losses at no load. This flux $\phi_0$ will induce an emf in the primary winding as well as in the secondary winding. Both the emfs induced in the primary and secondary winding will be in phase with each other as they are produced by the common flux. The emf induced in the primary winding $E_p$ will be approximately equal to the applied voltage of the primary ($V_p$). As the secondary winding is on open circuit, it will not carry any current hence the flux due to it will be zero. The no-load current of the transformer performs two functions, viz. produce magnetic flux in the core and supplying no-load losses. The no-load phasor diagram of a transformer is shown in Fig. 14.5. In the no-load phasor




(a) (b)

**Fig. 14.5 (a) Secondary on no-load**
**(b) Vector diagram of secondary on no-load**

diagram, the no-load current $I_o$ is shown having two components. One component is known as magnetising component and is responsible for setting up magnetic flux in the core. This component of $I_o$ lags behind the primary applied voltage by 90 degrees and is termed as the wattless component, and is represented by $I_\mu$. The other component is denoted by, $I_w$ and is called as loss component (working component) and is supplying iron losses. This component of current is therefore shown in phase with applied voltage.

*Solution:* We know Power at no-load.

$$W_o = V_p S_o \cos\theta \quad (14.6)$$

**Example 14.1** *A single-phase 220/110 V transformer takes no-load current of 0.5A and the power absorbed in 66 W. Find the loss component and the magnetising component of the no-load current.*

Therefore, the loss component of current,

$$I_w (I_o \cos\theta) = \frac{W_o}{V_p} = \frac{66}{220} = 0.3\text{A} \quad \textbf{Ans.}$$

Magnetising component of current,

$$I_\mu = \sqrt{I_o^2 - I_w^2}$$

$$I_\mu = \sqrt{(0.5)^2 - (0.3)^2}$$

$$= \sqrt{0.25 - 0.9}$$

$$= \sqrt{0.16}$$

$$= 0.4\text{A} \quad \textbf{Ans.}$$

**Example 14.2** *A single-phase transformer has 450 primary turns and 90 secondary turns. If the primary winding of the transformer is supplied 2200 V, find the secondary voltage. Neglecting losses of the transformer, what will be the primary current when the current in the secondary winding is 220 A?*

*Solution:*

We know that the transformation ratio,

$$K = \frac{V_s}{V_p} = \frac{N_s}{N_p}$$

$$\frac{V_s}{2{,}200} = \frac{90}{450}$$

Therefore secondary terminal voltage,

$$V_s = \frac{2{,}200}{450} \times 90 = 440 \text{ V} \quad \textbf{Ans.}$$

Neglecting losses, power input = power output.

$$V_p I_p = V_s I_s$$

(assuming unity PF)

$$2200 \times I_p = 440 \times 220$$

∴ Primary current,

$$\therefore \quad I_p = \frac{440 \times 220}{2{,}200} = 44\text{A} \quad \textbf{Ans.}$$

**Example 14.3** *A three-phase transformer is used to step down the supply Voltage from 10,000 V in 433 V. The output of the Transformer is 150 kVA. Find the secondary and primary currents of the transformer.*

*Solution:*

We know $\dfrac{\sqrt{3}\, V_L \times I_L}{1000} = k\,VA$

$$\frac{\sqrt{3} \times 433 \times I_L}{1000} = 150$$

∴ Secondary line current,

$$I_s = \frac{150 \times 1000}{\sqrt{3} \times 433} = \frac{150 \times 1000 \times \sqrt{3}}{\sqrt{3} \times \sqrt{3} \times 433}$$

$$\frac{150 \times 1000 \times 1.732}{3 \times 433} = 200 \text{ A} \quad \textbf{Ans.}$$

Similarly,

$$\text{Primary current,} \quad I_p = \frac{150 \times 1000}{\sqrt{3} \times 10{,}000} = 8.66 \text{ A} \quad \textbf{Ans.}$$

## 14.8 TRANSFORMER ON LOAD

In Sec. 14.7, it was explained that the wattless component of no-load current will develop a flux in the iron core. This flux induces emfs in both primary and secondary windings.

Let $OV_p$ be the applied voltage to the primary winding and let induced emfs be $OE_p$ and $OE_s$ in primary and secondary windings respectively. When the load is put on the secondary winding of the transformer, the secondary current $I_s$ starts flowing through it. This current will produce a flux in the core in opposition to the flux produced by the primary current. This reduces the total flux and thereby the emf induced in the primary winding $OE_p$ is reduced. Due to the decrease of $OE_p$, the current in the primary winding increases. The increase of current in the primary winding is such that it neutralizes the flux of the secondary winding and thus the total flux remains the same from no-load to full-load.

The increased current which flows in the primary winding due to the load on the secondary winding is equal and opposite to the secondary current and is known as primary balancing current $I'_p$ or primary current due to secondary current. Therefore, the total current in the primary winding $I_p$ is the phasor

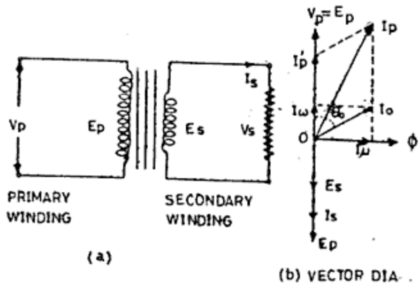



Fig. 14.6 (a) Secondary on resistive load
(b) Vector diagram of secondary on resistive load

sum of the balancing current $I_p'$ and no-load current $I_o$. The primary balancing current and the secondary currents are in phase opposition to each other. Figure 14.6 shows the phasor diagram of a transformer for a resistive load.

The phasor diagram of a transformer for lagging power factor load can be drawn in a similary way.

## 14.9 PARTS OF A TRANSFORMER

Figure 14.7 shows the various parts of a transformer. As mentioned in Sec. 14.3, two windings, primary and secondary are wound on a laminated core. The details of the various parts are given below.

**Primary Winding** The winding which is connected to the supply is called the primary winding. If it is to operate on high voltage (as compared to the other winding), it is known as HT (High-tension) winding. The porcelain bushings connected on the HT side for insulating the terminals of the transformer are known as HT bushings.

**Secondary Winding** The winding of the transformer which is connected to load is termed as a secondary winding. If it is to work on low voltage as compared to the primary winding, it is called LT (Low Tension) winding. The insulating bushing used on LT side is called L.T. bushing.

**Transformer Tank** It is a metallic container in which transformer oil (mineral oil) is filled for cooling the windings. The oil after taking the heat from the winding gives it to the surface of the tank for cooling. For better cooling, the surface area of the tank is increased either by providing corrugated sheets in case of small transformers around the tank or by providing round pipes (usually 5 cm dia) or elliptical tubes on the sides of the tank for large transformers.

**Temperature Gauge** It is a temperature indicating device which is used to indicate the temperature of the transformer oil and is fitted to the side of the tank.

**Explosion Vent** The explosion vent is a safety device of the transformer and is also known as the emergency pressure release valve. It is a projected pipe one end of which is fitted at the top of the tank and the other end left open to the atmosphere through a diaphragm. When an excessive high pressure is developed in side the tank due to internal fault the pressure breaks the diaphragm and oil thus goes out through the broken diaphragm.

**Conservator** A drum containing transformer oil is mounted at the top of the transformer

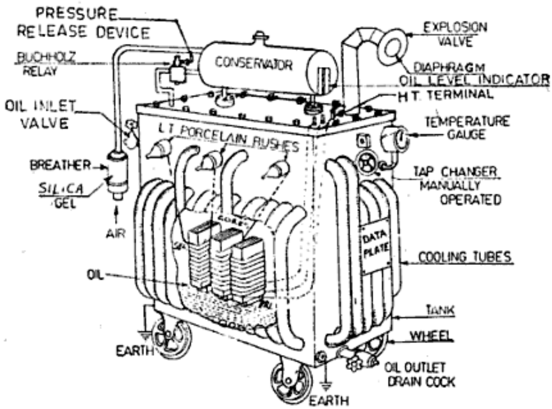



**Fig. 14.7 Parts of a 50kVA, 6600/400V, oil cooled transformer**

tank and connected to the transformer tank by a pipe. One-fourth of the drum is usually kept empty. For indicating the level of the oil in tank, an oil level indicator is fixed to it as shown in Fig. 14.7. Oil in the transformer tank expands and contracts according to the heat developed and causes the level of the oil in the conservator to rise and fall. A conservator performs the following functions.

1. It maintains the oil level in the tank.

2. It provides space for the expansion of oil when the temperature of the transformer varies from 20°C to 95°C.

3. It prevents transformer oil from moisture (which reduces dielectric strength of oil) when it breathes in.

**Breather** The function of the breather is to prevent entry of moist air in the transformer tank after its breath out. Even a small amount of moisture absorbed by the oil reduces the insulating properties of the oil considerably.

A pipe connected at the top of the conservator is left open to the atmosphere through a breather. The breather is a cylindrical tube containing oil, silica gel or calcium chloride in different chambers. When the pressure inside the tank reduces due to breath out, it is the breather that absorbs moisture from the air entering the conservator. The entering air is to first pass through the oil which filters the moisture and then through the silica gel which further dries the air.

The silica gel when dry is blue in colour and when it absorb moisture, its colour becomes some what whitish. Silica gel in the breather is replaced at certain intervals time.

**Tap-Changer** It is a device operated either manually or through a motor, used for keeping the output voltage of a transformer constant.

When the load on the transformer increases, the output voltage falls. For keeping the terminal voltage constant, a tap-changer is connected to the secondary side of the transformer. Different tappings from the secondary winding are brought to it. With the help of tap-changer, the secondary turns can be either increased or decreased and thus secondary voltage can be increased and decreased as desired.

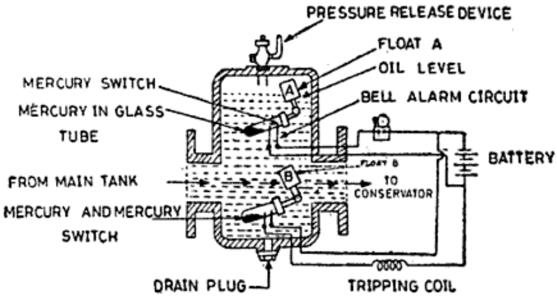



**Fig. 14.8 Buchholz relay**

**Buchholz Relay** It is also a protection relay of the transformer. This device signals the fault as soon as it occurs and cuts the transformer out of circuit immediately.

This relay operates on the excessive formation of the oil vapours or gas inside the transformer tank due to any internal fault of of the transformer. It is used in a power transformer (transformer above 500 kva output) in between the pipe connecting the tank and the conservator as shown in Fig. 14.8.

It consists of two operating floats *A* and *B* and is operated by the two mercury switches separately provided for the float *A* and float *B*. The float *A* is meant for bell alarm while float *B* for operating the tripping circuit.

In normal condition, the relay is completely filled with oil and the contact points of the mercury switches are opened. When the oil level falls below the permissible level due to either leakage of oil or collection of abnormal gas at the top of the float *A* (because of minor fault like overloading, etc.), the float *A* moves downward which closes the contact points of the mercury switch meant for float *A* and thereby gives an alarm to the operator.

When a heavy internal fault like short circuit or earth fault (due to failure of insulation) occurs in the system, it rapidly increases the temperature of the oil. Due to this abnormal increase of temperature, the oil expands quickly and rushes fastly to the conservator through the relay. On the way it presses the float *B*, which short circuits the two contact points of the tripping circuit. Thus the relay operates the circuit breaker and thus the transformer is saved from possible damage.

## 14.10 LOSSES IN A TRANSFORMER

The transformer is a static device and therefore has no rotational losses. The losses which occurs in the transformer are as follows.

**Copper Losses** These are the losses taking place in the transformer windings due to their resistance. Primary winding copper losses are given by $I_p^2 R_p$ and the secondary by $I_s^2 R_s$.

The copper losses are variable losses. They vary with the square of the current or output. If the output is doubled, the copper losses becomes four times.

**Iron Losses** Iron losses consist of eddy current loss and Hysteresis loss.

*Eddy Current Loss* This loss occurs in the core of the transformer as induced eddy currents appear in the form of heat ($I^2Rt$) in the core. This loss is reduced by using laminated iron cores.

*Hysteresis Loss* When alternating current is supplied to the primary winding, the iron core is alternately magnetised and demagnetised. This causes waste of energy as heat. This loss can be minimized by making a core of silicon steel that enables easy magnetisation.

### 14.11 METHODS OF DETERMINING LOSSES OF A TRANSFORMER

The simplest methods of determining the iron and copper losses are by performing two tests, viz. (1) open-circuit test and (2) short-circuit test.

**Open Circuit (No-load) Test** The aim of this test is to determine the iron losses of the transformer. As the iron losses depend upon voltage and frequency of the supply, this test is performed at normal supply voltage and frequency.

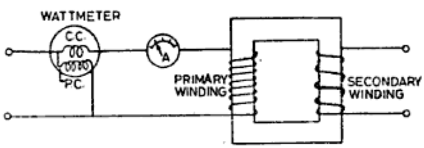



**Fig. 14.9 Open-circuit test**

In this experiment, the primary winding (preferably low-voltage winding) is supplied with normal working voltage at normal frequency and the other winding is kept open. As the no-load iron losses and no-load current will be very small, an ammeter and an wattmeter of low range are connected in the primary winding circuit as shown in Fig. 14.9.

The no-load current being very small, the copper losses may be neglected and the reading of the wattmeter will indicate the iron losses only.

**Short-Circuit-Test** This test is conducted to find the copper losses of the transformer which are directly proportional to the square of the current in the transformer windings.

In this test, the primary winding (usually high-voltage winding) is supplied with reduced voltage of normal frequency from a variac or auto transformer and the other winding is kept short-circuited directly or through an ammeter of high range shown in Fig. 14.10. Applied voltage is gradually increased till full-load current flows through the primary winding. As the applied voltage is only a small percentage of normal working voltage, the core loss will be very small. Hence iron losses in this case can be neglected and the wattmeter reading at full load current can be considered as the full-load copper losses of the transformer.

### 14.12 EFFICIENCY OF A TRANSFORMER

The efficiency of the transformer is of two types, viz. (i) Ordinary efficiency, and (ii) All-day efficiency.

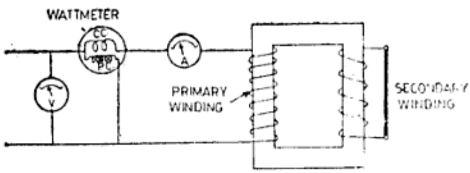



**Fig. 14.10 Short-circuit test**

**Ordinary Efficiency** It is defined as the ratio of the output in kilowatts to the input in kilowatts.

Ordinary efficiency of a transformer

$$= \frac{\text{Output in kilowatts}}{\text{Input in kilowatts}}$$

When expressed in percentage, η %

$$= \frac{\text{Output in kilowatts}}{\text{Input in kilowatts}} \times 100 \qquad (14.7)$$

*All-Day Efficiency* Sometimes it is also known as watt-hour efficiency. When connected to lines, a transformer primary winding always draws a small amount of no-load current where as the secondary winding carries current only when the transformer is loaded. This means that iron losses will always occur in the core of the transformer throughout the day and night and the copper losses will take place only when the transformer is loaded. It is necessary therefore, to select such type of transformers as distribution transformers, which have less iron loss. The performance of such types of transformers is determined by

All-day efficiency

$$= \frac{\text{Kilowatt—hour output in a given period}}{\text{Kilowatt—hour input in the same period}}$$

All-day efficiency in %

$$= \frac{\text{kwh output}}{\text{kwh input}} \times 100 \qquad (14.8)$$

### 14.13 REGULATION OF TRANSFORMER

The regulation of the transformer is the difference in voltage on the secondary side from no load to full load. It is genrally expressed as a percentage of the secondary no load voltage.

Regulation of a transformer

= (No-load secondary voltage—full-load secondary voltage)/No-load secondary voltage

$$= \frac{E_s - V_s}{E_s}$$

When expressed in percentage,

$$\text{Regulation } \% = \frac{E_s - V_s}{E_s} \times 100 \qquad (14.9)$$

where $E_s$ = No-load secondary voltage
$V_s$ = Full-load secondary voltage

### 14.14 RATING OF TRANSFORMER

The rating of the transformer is taken in kVA instead of kW. If the output of the transformer is 25 kVA, it means that the transformer can supply full load power of 25 kVA. on the secondary side (neglecting losses).

When a transformer is in normal working condition, some losses will occur due to the flow of current through the load. The losses in the transformer depend upon the value of current flowing and the power factor of the circuit.

To understand it let us consider a single-phase transformer is delivering its maximum current of 100 A at 250 V.

∴ Rating of the single-phase transformer

$$= \frac{\text{voltage} \times \text{current}}{1000}$$

$$= \frac{250 \times 100}{1000} = 25 \text{ kVA}$$

If the transformer is operating at unity PF,

Load supplied = kVA × cos $\theta$
= 25 × 1 = 25 kW.

When the PF of the load decreases to 0.8,

Load supplied = kVA × cos $\theta$
= 25 × 0.8 = 20 kW.

Suppose, the PF of the load further decreases to 0.4. Then,

Load supplied = kVA × cos $\theta$
= 25 × 0.4 = 10 kW.

From the above, it is clear that the power output of the transformer is 25 kW at unity PF, 20 kW at 0.8 PF and 10 kW at 0.4 PF. It means the power output of the transformer in kilowatts varies with the variation of the power factor of the load but the rating of the transformer is $\frac{250 \times 100}{1000}$ = 25 kVA (constant) whatever may be the power factor of the circuit. For this reason transformers are rated in kVA instead of kW.

**Example 14.4** *A 6600/433 Volts three-phase 50 HZ transformer is star connected on primary and secondary sides. There are 100 turns per phase on low voltage side and the iron on each limb has net cross-sectional area of 50 cm.². Calculate the maximum value of the flux density.*

***Solution:***

As per phase turns on secondary side is given therefore find per phase voltage. We know that

$$\sqrt{3}\ V_{ph} = V_L = 433 \text{ V} \quad (\because \text{ star connected})$$

$$\therefore \text{ Phase voltage } V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{433}{\sqrt{3}} \quad (V_s = E_s)$$

We know $E_s = 4.44\ \phi_{max} \cdot fN_s$

$\therefore$ Maximum flux, $\phi_{max}$.

$$= \frac{E_s}{4.44\ fN_s} = \frac{433}{\sqrt{3} \times 4.44 \times 50 \times 100}$$

$$\text{Flux density} = \frac{\phi_{max}}{\text{Area}}$$

$$= \frac{433}{\sqrt{3} \times 4.44 \times 50 \times 100 \times \frac{10}{100} \times \frac{5}{100}}$$

$= 2.25$ Wb/m$^2$ **Ans.**

**Example 14.5** *The efficiency of a 30 kVA, 10 : 1 single-phase transformer is 96%. Calculate the primary current and voltage when the secondary voltage is 240 V and the transformer is working on full load at power factor 0.8.*

***Solution:***

$$\text{Output} = 30 \text{ kVA}$$

$$\text{Output in kW} = \text{Output in kVA} \times \cos\theta$$

$$= 30 \times 0.8 = 24 \text{ kW}$$

But $V_s \times I_s \times \cos\theta = W$ (as $\cos\theta$ and $W$ of both sides are the same)

$$\therefore \text{ Secondary current, } I_s = \frac{W}{V_s \times \cos\theta}$$

$$= \frac{24 \times 1000}{240 \times 0.8} = 125 \text{ A}$$

When efficiency is given, current can be transferred by their turns ratio only.

$$\frac{N_s}{N_p} = \frac{I_p}{I_s}$$

$$\therefore \text{ Primary current, } I_p = \frac{N_s \times I_s}{N_p}$$

$$= \frac{1}{10} \times 125 = 12.5 \text{ A} \quad \textbf{Ans.}$$

$$\text{Input of transformer} = \frac{\text{Output}}{\eta\ \%} \times 100$$

$$= \frac{24 \times 1000 \times 100}{96} W$$

But Primary input, $W_p = V_p \times I_p \times \cos\theta$

$\therefore$ Primary applied voltage,

$$V_p = \frac{W}{I_p \times \cos\theta}$$

$$= \frac{24 \times 1000 \times 100}{96 \times 12.5 \times 0.8}$$

$$= 2500 \text{ V}$$

$= 2.5$ kV **Ans.**

**Example 14.6** *A single-phase 2000/250 V, 40 kVA, 50 Hz transformer has full-load copper losses of 320 W and iron losses of 200 W. Calculate the efficiency of the transformer at full load, half load and one-fourth of the full load when there is* **(a)** *unity PF, and (b) PF is 0.8 lagging.*

***Solution:***

(*a*) When PF is unity, the results are as in the following table. Full load output at unity PF = kVA $\times \cos\theta = 40 \times 1 = 40$ kW $= 40{,}000$ W

| *Load* | | *Output in watts* | | *Iron losses in watts* | | *Copper losses in watts* | | *Input in watts* | *Efficiency Percentage* |
|---|---|---|---|---|---|---|---|---|---|
| Full-load | – | 40,000 | + | 200 | + | 320 | = | 40,520 | $\eta\ \% = \frac{40{,}000 \times 100}{40{,}520} = 98.72\%$ |
| Half-load | – | 20,000 | + | 200 | + | 80 | = | 20,280 | $\eta\ \% = \frac{20{,}000 \times 100}{20{,}280} = 98.6\%$ |
| One-fourth Load | – | 10,000 | + | 200 | + | 20 | = | 10,220 | $\eta\ \% = \frac{10{,}000 \times 100}{10{,}220} = 97.84\%$ |

(*b*) When pF is 0.8 lagging,

$$\text{Full load output in kVA} = \text{output in kVA} \times \cos\theta$$

$$= 40 \times 0.8 = 32 \text{ kW.}$$

| *Load* | *Output in watts* | | *Iron losses in watts* | | *Copper losses in watts* | | *Input in watts* | *Efficiency percentage* |
|---|---|---|---|---|---|---|---|---|
| Full load | 32,000 | + | 200 | + | 320 | = | 32,520 | $\eta\ \% = \frac{32{,}000 \times 100}{32{,}520} = 98.4\%$ |
| Half load | 16,000 | + | 200 | + | 80 | = | 16,280 | $\eta\ \% = \frac{16{,}000 \times 100}{16{,}280} = 98.28\%$ |
| One-fourth Load | 8,000 | + | 200 | + | 20 | = | 8,220 | $\eta\ \% = \frac{8{,}000 \times 100}{8{,}220} = 97.32\%$ |

**EXAMPLE 14.7** *A 24-kVA single-phase lighting load transformer has a full load copper loss 500 watts and iron loss 250 W. During a day the transformer operates on full load for 6 hours, at half load for 8 hours and on no load for the remaining period. Calculate the all-day efficiency of the transformer.*

***Solution:***

Transformer operating on lighting load should be considered to have unity power factor.

Copper loss for 6 h on full load

$= 500 \times 6 = 3000$ Wh

Copper loss for 8 h on half load

$= 500 \times (1/2)^2 \times 8$

$= 500 \times \frac{1}{4} \times 8$

$= 1000$ Wh

Iron loss for 24 h a day

$= 250 \times 24 = 6000$ Wh

Total losses = FL Cu loss + HL Cu loss + Iron loss

$= 3000 + 1000 + 6000 = 10{,}000$ Wh

$= 10$ kWh.

Full-load output of transformer at unity PF for 6 h

= out put in kVA × cos 0 × time in hours

$= 24 \times 1 \times 6$

$= 144$ kWh

Half-load output of transformer at unity PF for 8 h

$= \frac{24}{2} \times 1 \times 8 = 96$ kWh

Total output of transformer = FL output + HL output $= 144 + 96 = 240$ kWh

Input of the transformer = Total output + total losses

$= 240 + 10 = 250$ kWh

∴ All-day efficiency in % percentage,

$= \frac{\text{output}}{\text{Input}} \times 100$

$= \frac{240}{250} \times 100 = 96\%$ **Ans.**

## 14.15 CONSTRUCTION AND USES OF AN AUTOTRANSFORMER

Autotransformer works on the principle of self induction. It has only one winding which performs the function of both primary and secondary winding. As in ordinary transformer, the transformation ratio in auto-transformer is also equal to the turns ratio,

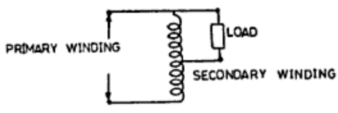
i.e. $$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

An autotransformer may step up or step down the voltage. In case of step down transformer, the complete winding acts as primary winding while the tapped section of this winding works as secondary winding. The transformation ratio is the ratio of the number of turns in the tapped winding to the number of turns in the whole winding functioning as primary winding.

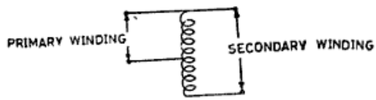
∴ Secondary voltage,

$$V_s = \text{Primary voltage} \times \frac{\text{Tapped turns}}{\text{Total turns in the whole winding.}} \quad (14.10)$$

In the step-up transformer, the whole winding works as a secondary winding and its portion performs the function of primary winding as shown in Fig. 14.11 (b). The transformation ratio is the ratio between the number of turns to the whole winding in the secondary to the number of turns in the portion acting as primary winding.




(a)




(b)

**Fig. 14.11 (a) Step-down auto-transformer (b) Step-up auto transformer**

In the auto transformer, there is much saving of copper, and this depends upon the transformation ratio. The saving of copper increases as the transformation ratio increases near unity. For the same capacity and voltage ratio, an auto-transformer require less copper than an ordinary transformer. These transformers are used as regulating transformers where only a small variation of voltage is required. Autotransformers are generally used for starting and speed control of induction motors, etc. It can also be used as line booster. These transformers should not be used where the transformation ratio is higher than unity.

An autotransformer suffers from a disadvantage that the two windings are not electrically separate and in case of failure of insulation between the two, either a severe shock may be felt on the low-voltage side.

## 14.16 THREE-PHASE TRANSFORMER

A transformer wound for a three-phase system and is given three phase supply for its operation is known as a three-phase transformer. A three-phase transformer has three separate windings, housed in a common enclosure. Like a single-phase transformer, the three-phase transformers are also of core or shell type. Transformers of high output rating are of core type.

For transmission, it was previously preferred to use three single-phase transformers instead of one three-phase transformer. It was due to the reason that in case of its failure, only one transformer is required to be replaced. This system suffers from the disadvantage that it occupies greater floor space.

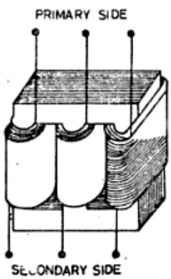



**Fig. 14.12 Three-phase transformer**

But now a days, a three-phase transformer is used (instead of three single-phase transformers) to step up or step down the generated voltage of the alternator for transmission and distribution purpose. As compared to single-phase transformers, the chief advantages of a three-phase transformer are that it is heavier in weight, occupies less floor space and reduces the initial cost. Further it also requires less maintenance being a single unit.

## 14.17 DIFFERENT METHODS OF CONNECTING THE WINDINGS OF A THREE-PHASE TRANSFORMER

There are four different methods of connecting the windings of a three-phase transformer. They are:

1. Primary-star secondary-star
2. Primary-star secondary-delta
3. Primary-delta secondary-delta
4. Primary-delta Secondary-star

**Primary-Star Secondary-Star** Figure 14.13 shows the connection of a transformer whose primary and secondary windings are star-connected. Let $V_{LP}$ is the primary line voltage and as the primary winding is in star.

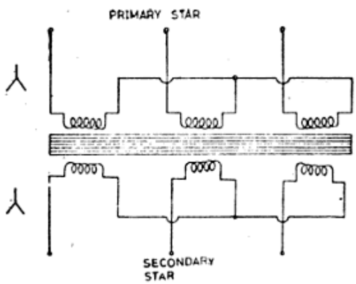



**Fig. 14.13 Primary star, secondary star of a three-phase transformer**

∴ Primary phase voltage

$$= \frac{V_{L_P}}{\sqrt{3}}$$

If $K$ is the transformation ratio,

Secondary phase voltage

$$= \frac{V_{L_P}}{\sqrt{3}} \times K$$

As the secondary winding is also in star,

secondary line voltage,

$$V_{L_S} = \frac{V_{L_P} \times K \times \sqrt{3}}{\sqrt{3}} \qquad (14.11)$$

$$= V_{L_P} \times K \quad \text{V}$$

**Primary-Star Secondary-Delta** In this case also primary phase voltage

$$= \frac{V_{L_P}}{\sqrt{3}}$$

∴ Secondary phase voltage

$$= \frac{V_{L_P}}{\sqrt{3}} \times K, \text{ and}$$

Secondary line voltage,

$$V_{L_S} = \frac{V_{L_P}}{\sqrt{3}} \times K \quad \text{V}$$

(∵ Secondary is in delta) (14:12)

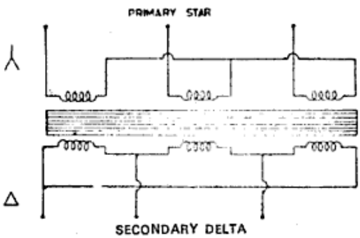



**Fig. 14.14 Primary star, secondary delta of a three-phase transformer**

**Primary-Delta Secondary-Delta** Since the primary is delta connected,

Primary phase voltage = $V_{L_P}$ (Primary line voltage)

∴ Secondary phase voltage

$$= V_{L_P} \times K$$

As the secondary is delta connected,

∴ Secondary line voltage,

$$V_{L_S} = V_{L_P} \times K \quad \text{V} \qquad (14.13)$$

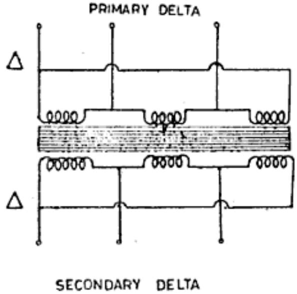



**Fig. 14.15 Primary delta, secondary delta**

**Primary-Delta Secondary-Star** As the primary is delta connected,

Primary phase voltage

$$= V_{L_P} \text{ (Primary line voltage)}$$

∴ Secondary phase voltage

$$= V_{L_P} \times K$$

As the secondary is star connected,

Secondary line voltage,

$$V_{L_S} = V_{L_P} \times K \times \sqrt{3}$$

$$= \sqrt{3}\, V_{L_P} \times K \quad \text{V} \qquad (14.14)$$

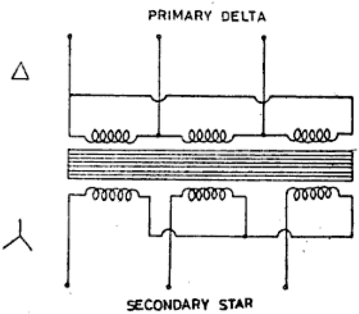



**Fig. 14.16 Primary delta, secondary star**

The advantage of star connection (specially on the high-voltage side) is that the insulation has to bear stress for only $\frac{1}{\sqrt{3}}$ (57.7%) of the line voltage. Further it facilitates in providing three phase four wire system of connections.

The advantage of delta connection is that if one phase is opened due to some fault, supply to all the three phases of the load can be continued up to 57.7 per cent of full output. This gives "V" or open delta connection.

**Example 14.8** *A three-phase 11,000/440 V, 330-kVA star-connected transformer has 55 turns on secondary side. Find (a) the number of primary turns and (b) primary and secondary line and phase currents.*

*Solution:*

Primary phase voltage

$$= \frac{11000}{\sqrt{3}} \text{ V}$$

Secondary phase voltage

$$= \frac{440}{\sqrt{3}} \text{ V}$$

∴ Transformation ratio,

$$K = \frac{V_p}{V_s} = \frac{11{,}000/\sqrt{3}}{440/\sqrt{3}} = \frac{11{,}000}{440} = 25$$

i.e. $K = 25 : 1$.

As $\frac{V_s}{V_p} = \frac{N_s}{N_p}$,

∴ No. of primary turns,

$$N_p = \frac{V_p \times N_s}{V_s} = \frac{25 \times 55}{1} = 1375 \quad \textbf{Ans.}$$

As $\frac{\sqrt{3}\, V_L \times I_L}{1000}$ = Power in kVA

$$\frac{\sqrt{3} \times 440 \times I_L}{1000} = 330$$

∴ Secondary line current,

$$I_s = \frac{330 \times 1000}{\sqrt{3} \times 440} = 433 \text{ A}$$

As secondary is connected in star,

∴ Secondary line current = phase current = 433 A **Ans.**

We know $\frac{V_s}{V_p} = \frac{I_p}{I_s}$

∴ Primary phase current,

$$I_{ph} = \frac{V_s \times I_s}{V_p} = \frac{1}{25} \times 433 = 17.32 \text{ A} \quad \textbf{Ans.}$$

∵ Primary line current $= I_{ph} = 17.32$ A. **Ans.**

**Example 14.9** *An 11,000/440 V, 100-kVA step-down, three phase, 50 Hz transformer is delta-connected on the primary side and star connected on secondary side. Calculate the ratio between the number of turns of primary and secondary. Also calculate the value of line and phase currents in both the windings.*

*Solution:*

It should be kept in mind that in a three-phase transformer, the phase transformation ratio is equal to the turns ratio but usually the line voltage (or current) is given, and the transformation ratio depends upon the star or delta connection adopted in the system.

As the primary is delta-connected,

Line voltage = phase voltage = 11,000 V

Since secondary is star-connected,

Secondary phase voltage,

$$= \frac{V_L}{\sqrt{3}} = \frac{440}{\sqrt{3}} \text{ V}$$

∴ Transformation ratio,

$$K = \frac{V_p}{V_s} = \frac{11{,}000}{440/\sqrt{3}} = 43.3$$

i.e. $K = 43.3 : 1$ **Ans.**

But $\frac{\sqrt{3} \times V_L \times I_L}{1000}$ = Power in kVA

∴ Secondary full load line current, $I_L$

$$= \frac{\text{Power in kVA} \times 1000}{\sqrt{3} \times V_L} = \frac{100 \times 1000}{440 \times \sqrt{3}} = \frac{2500}{11\sqrt{3}}$$

$$= 131.2 \text{ A} \quad \textbf{Ans.}$$

In star connection, line current = phase current = 131.2 A **Ans.**

As $\frac{V_s}{V_p} = \frac{I_p}{I_s}$,

∴ Primary phase current,

$$I_{ph} = \frac{V_s}{V_p} \times I_s = \frac{440\sqrt{3}}{11{,}000} \times \frac{2500}{11\sqrt{3}}$$

$$= 9.09 \text{ A} \quad \textbf{Ans.}$$

Primary line current due to delta connection,

$$I_L = I_{p\Delta} \times \sqrt{3}$$

$$= 9.09 \times \sqrt{3} = 15.74 \text{ A}$$

Ans.

## 14.18 SCOTT CONNECTION OF TRANSFORMER WINDINGS

Scott connection, also known as Tee connection, is used in the transformers to convert three-phase supply to two-phase supply specially required for electric furnaces. This connection can also be used to supply a three-phase machine from a two-phase supply system.

For this connection, two single-phase transformers are required, on transformer is known as main transformer and the other as teaser transformer. The primary of the main transformer is centre-tapped to which the one end of primary of the teaser transformer is connected. The three-phase supply is given to the three ends, two of main and one of the teaser transformer as shown in Fig. 14.17. The secondaries of both the transformers have equal turns but the primary of the teaser transformer has 0.866 times (i.e. 86.6%) turns of the primary of the main transformer. Neutral point tapping may be taken from one-third of the primary of the teaser transformer from the end of the main transformer side.

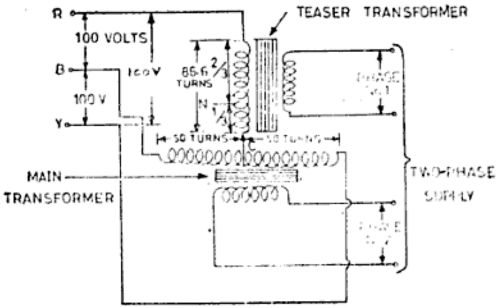



Fig. 14.17 Scott or tee-connection

## 14.19 COOLING OF TRANSFORMERS

In rotating machines like motors and generators cooling fan of the machine rotates and thus causes the circulation of air and hence provides cooling. However, the transformer is a static machine and so cooling is difficult. When a transformer is operating, some heat will always be produced due to the losses in the transformer and means are to be taken to avoid the winding from attaining high temperature. The different methods of cooling the transformer are as follows.

**Natural Cooling** In small transformers of rating 10 to 15 kVA cooling is provided through natural circulation of air. The surface area of the core and the transformer winding are sufficient to dissipate the heat generated. However, in transformers of higher ratings, extra means are provided for the dissipation of generated heat.

**Natural Oil Cooling** In this system, the transformer is placed in a tank filled with oil known as transformer oil as shown in Fig 14.18. The oil used in the tank not only helps to cool the transformer but also provides insulation for the winding. The oil takes the heat from the core and the winding and gives it to the tank surface from where the air takes away the heat.

To make this system more efficient, the surface area of the tank is increased either by making it of corrugated sheets or by providing round pipes (usually 5 cm in diameter) or elliptical tubes. Due to the heat produced by the transformer, the oil circulates through the pipes (or tubes) and tank. The hot oil becomes lighter in weight and goes up from where comes down through the pipes

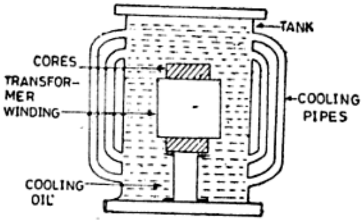



Fig. 14.18 Oil-cooled transformer

(or tubes) to the bottom of the tank after cooling. The oil level in the tank should never fall below the upper ends of pipes (or tubes).

**Oil Blast Cooling** This is another method of cooling the transformer and is employed with transformers of ratings above 500 kVA. In this method radiator tanks are provided to the side walls of the main tank. The oil circulates through these radiator tanks from the main tank. The radiator tanks are cooled by air blast. This system of cooling is known as OB (oil blast) type.

**Forced Water Cooling** In all transformers with outputs greater than 500 kVA forced water cooling is employed. Figure 14.19 shows the principle of forced water cooling. The winding of the transformer is placed inside the tank containing oil and cold water is passed through the copper pipe spiral kept in the transformer oil. The cold water absorbs and carries away the heat of the oil. The

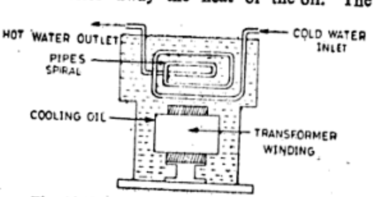



Fig. 14.19 Forced water cooled transformer

pressure of the water in the pipe spiral is not kept greater than the pressure of the oil in the tank because in the case of leakage in the pipe, the water will enter into the oil and will damage the insulating property of the oil. This may damage the insulation of the winding.

**Forced Air Cooling** This system of cooling is used at such places where there is a scarcity of water. In this method the air is first filtered to eliminate moisture and dust particles and then this filtered air under pressure is forced to pass through the winding, core of the transformer and the ducts provided in them as shown in Fig. 14.20.

### 14.20 TRANSFORMER OIL AND ITS TESTING

The oil used in the transformer must have high dielectric strength and should not contain any impurities in it. For this reason the testing of transformer oil is essential.

First of all, a sample of oil to be tested is taken from the bottom of the tank because if

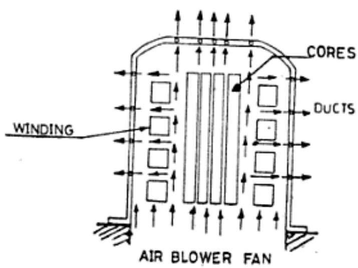



Fig. 14.20 Forced air-cooled transformer

moisture or sludge, (i.e. mud) is mixed with it, it will collect at the bottom. Then the sample of oil is physically checked for the presence of mud. After this, a red hot iron bar is introduced in the sample of the oil, and a chattering sound is produced (like the one produced when a red hot rod is introduced in the water), it means there is a moisture in the oil.

**Oil Testing Equipment** For testing the dielectric strength of the oil, an equipment known as oil testing equipment is used. It is a portable device which has a step up transformer, a glass container, a voltmeter and two well polished sphere electrode as shown in Fig. 14.21.

For testing the oil, the distance between the two electrodes is adjusted to 4 mm and then the oil is poured in the glass container. After this the voltage on the primary side of the transformer is gradually increased (with the help of voltage controller known as dimmerstat) till a spark does not appear in between the electrodes of the container. The voltage at which the spark occurs in between the electrodes provides a measure of the dielectric strength of the sample of oil tested.

NOTE This test should only be performed when the oil is cooled and not when hot because the dielectric strength of oil is directly proportional to temperature.

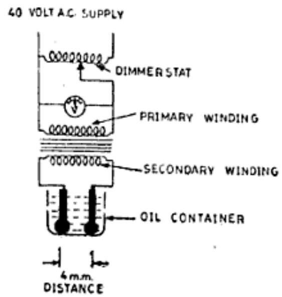



**Fig. 14.21 Oil-testing equipment**

## 14.21 PARALLELING OF TRANSFORMERS

For delivering electrical energy to an increased load more than the rating of an existing transformer, additional transformers are run in parallel. The undermentioned conditions must be fulfilled for running two transformers in parallel.

1. *Polarities of the two transformers must be the same.* If care is not taken emf induced in the two secondaries in parallel will cause a flow of circulating current through them even without load. On load, there will be excessive $I^2R$ loss and winding temperature rise and thereby, damage to the transformer may be caused.

2. *The voltage ratios of the two transformers must be same.* If there is difference in voltage ratio of the two transformers then there will again be flow of circulating current through the secondaries. Paralleling of three-phase transformers is only possible if they are connected star/star or delta/delta.

3. *The percentage impedance of the two transformers must be the same.* Load sharing of transformers in parallel depends upon the percentage impedance of the transformers.

4. *The two transformers must be of the same group.*

Conditions (1) and (4) are absolutely necessary where as condition (2) must be satisfied to a very close degree and condition (3) should also be satisfied as far as possible.

Figure 14.22(b) shows two single-phase transformers operating in parallel and sharing load. It is essential to check their polarities before putting them in parallel and for this the two terminals of secondaries are connected in phase opposition as in Fig. 14.22 (a) and a voltmeter is connected on the rest of the two terminals of the secondaries. On energising both the primary in parallel across the rated voltage of the supply mains, if the voltmeter indicates zero reading, it means the polarity of the two terminals is same which are to be operated in parallel. If the voltmeter shows a reading equal to twice the rated voltage of the transformer, it means that the points where the terminals are connected are of opposite polarity and must be changed for successful parallel operation.

**Advantages of Parallel Operation** In substations many transformers are installed instead of one high capacity transformer. It has the following advantages.

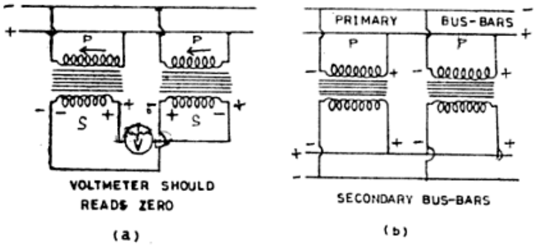



**Fig. 14.22 Parallel operation of transformer**

1. The stand-by transformer can be connected in parallel to the busbars during the time of need to meet the demand of increasing load.

2. It enables transformers to operate on full-load.

3. If a transformer fails to operate due to any defect, the other transformer can provide supply to the load and thus there will be no complete break down of supply.

4. The replacement cost of a small transformer is less than a bigger transformer.

5. Preventive maintenance is very easy.

**Disadvantages**

1. It requires greater floor space since many transformers of smaller output are used.

2. Many transformers of smaller output cost more than a bigger transformer having output equal to their total output.

3. Due to wrong parallel operation, a transformer may get damaged.

## 14.22 HUMMING OF TRANSFORMERS

Humming is a sound which is produced due to the vibration of the cores in the transformer. The vibrations are produced due to the change in polarity of an alternating current. When the current is in its positive half all the cores of the transformer are magnetised with the same polarity and this produces repulsion between the core ends and hence core expands at the ends. When the current decreases to zero, the cores attain their normal position. This happens four times in a complete cycle and produces vibration at the ends of the core, and this results in noise. This noise can be decreased by tightening the core of the transformer.

## 14.23 TROUBLESHOOTING OF TRANSFORMERS

Whenever a trouble in a transformer is observed, it should be rectified immediately. The faults which generally occurs in a transformer, their causes and remedies are discussed below, in table No. 14.1.

TABLE 14.1 TROUBLE SHOOTING CHART OF TRANSFORMER

| *S. No.* | *Defects* | *Causes* | *Remedies* |
|---|---|---|---|
| 1. | **Failure in the Magnetic Circuit** | | |
| | (*a*) Insulation of core clamping bolts may fail. This will allow eddy current to flow which will cause local heating and may damage the coil insulation. | The cause of this is the vibrations of care due to the core's looseness of bolts which can be detected by an increase in the normal hum (sound) of the transformer on load. | Test with meggar and replace the insulating bushes and washers if required and tighten the nuts and bolts properly. |

| S. No. | Defects | Causes | Remedies |
|---|---|---|---|
| | (b) Failure of insulation between yoke and yoke-clamping plates. | It is due to the poor insulation between the plates or due to bad workmanship during manufacturing processes. | Test and rectify the fault. |
| | (c) Loose core and tie bolts may allow vibration which produces friction between turns resulting in failure of insulation between them. | An increase in the normal hum (sound) of the transformer on load may lead to vibration and looseness. | Test for the cause of failure of insulation. If the fault is not traced, it will result to produce partial or complete short circuit between the winding. |
| 2. | **Failure in the Electric Circuit** | | |
| | (a) Short circuit between adjacent turns. | Short circuit may occur due to the presence of sharp edges on the copper conductors. If the windings are subjected to repeated electromagnetic shocks, through external short circuit or repeated switching on load, these sharp edges will damage the insulation and produce short circuit. | Regular careful inspection is required. Such types of defect can only be rectified after removing the winding for repair. |
| | (b) Moisture penetrates in the fabric insulation of coil. | Insufficient varnish. | Remove the winding and bake it. Then varnish it thoroughly and again bake it for drying the varnish. |
| | (c) Shrinkage of the insulation (in case of new transformer after few months use) require adjustment of the adjustable coil supports. | Careless tightening or over adjustment of coil supports may force turns to be out of position and a short circuit may occur between the turns. | Care in adjustment of coil supports (i.e. packing pieces) will avoid this trouble. |
| 3. | **Failure in the dielectric circuit** (a) **Insulation failure** | | |
| | | (a) Due to the absorption of moisture by the oil during breathing action of the transformer. | (a) Take all precautions to avoid absorption of moisture by the oil. |
| | | (b) Accidental over pressure due to lighting on the system. | (b) In this case provide lightening arrestors on or near the out-door transformer. |
| | | (c) Narrow oil ducts provide insufficient cooling and causes insulation to become brittle. Due to this a fault occurs between turns. | (c) Provide sufficient size of ventilating ducts. |

| S. No. | Defects | Causes | Remedies |
|---|---|---|---|
| 4. | Structural failure | | |
| | (a) Cooling pipes clogged in water cooled transformer. | (a) It is due to the reason that lime or other material get deposited in the cooling tubes. | (a) Tubes should be thoroughly cleaned. |
| | (b) Transformers operating in parallel are not having equal percentage impedance. | (b) One transformer will be over loaded and may burn out. | (b) Both the transformers must have same percentage impedance. |
| 5. | Over heating | (a) Over load.<br>(b) Abnormal voltage or frequency across the winding.<br>(c) Badly soldered joints between coils, loose terminals.<br>(d) Insufficient ventilation.<br>(e) Transformer oil level below the tops of the cooling pipes.<br>(f) Continuous use of transformer when badly sludged (as shudging limits the cooling effect).<br>(g) Incorrect connection during parallel operation of transformer. | Have a careful watch on the temperature gauge. If temperature increases more than as specified, immediately remove the fault to avoid any harm to the insulation or winding of the transformer. |

## NUMERICAL QUESTIONS

**14.1** A single-phase 250/110 V transformer takes no-load current of 0.5 A and the power absorbed is 75 W. Find the working component of current and the magnetising current. (Ans. $I_w = 0.3$ A, $I_\mu = 0.4$ A)

**14.2** A single phase 250/110 V transformer takes no load current of 0.55 A and power absorbed is 60 W. Find the working component of current and magnetising current both. (Ans. $I_w = 0.24$ A, $I_\mu = 0.494$ A)

**14.3** A Single-phase transformer has 550 primary turns and 66 secondary turns. If the primary winding of the transformer is connected across 3,300 V supply, find the secondary voltage. Neglecting the losses in the transformer, calculate the primary current when secondary current is 250 A. (Ans. 396 V, 30 A)

**14.4** A single-phase transformer has 200 primary turns and 100 secondary turns. If the primary is connected to 1,100 V supply, find the secondary P.D. Neglecting losses, what is the primary current when the secondary current is 150 A. (Ans. 550 V, 75 A)

**14.5** A single-phase 2,200/220 V, 22-kVA transformer has 75 turns in the secondary winding. Find the primary turns. Neglecting losses, what are the primary and secondary currents at full load.

(Ans. 750 turns, 10 A, 100 A)

**14.6** A 2,200/400 V, single phase 400 kVA transformer has 80 turns in the secondary winding. Calculate; (i) primary turns, (ii) emf per turn of primary (iii) secondary current at unity power factor.

(Ans. 440 turns, 5 V, 1000 A)

**14.7** A 440/6660 V single-phase 50 hertz transformer has 100 turns on high voltage side and iron in each limb has net cross-sectional area of 50 sq. cm. Calculate the maximum value of flux. (Ans. 0.3 Wb)

**14.8** A 1110/555 V, 50 Hz, single-phase transformer has maximum value of flux density of 1 Wb/m² in the iron core. If the net cross-sectional area of the core is 100 sq. cm. Calculate the number of primary and secondary turns of the transformer. (Ans. 500, 250 turns)

**14.9** A 444/2220 V, 50 Hz, single phase transformer has maximum flux density 1 Wb/sq. m in the core. If the emf induced per turn is 11.1 V, find :—

(i) Primary turns (Ans. 40

(ii) Secondary turns 200

(*iii*) Net cross-sectional area of the core. 500 sq.cm.

14.10 A single phase transformer has 500 turns on primary side and 250 turns on secondary side. The primary winding is connected across 222-V 50 Hz supply. If the net cross-sectional area of the core is 100 $cm^2$. Calculate :

(*i*) Maximum value of flux density in the core.

(*ii*) Voltage induced in the secondary winding. (Ans. 0.2 $Wb/m^2$, 111 V)

14.11 A 6600/400 V, three phase, 50 Hz transformer is delta connected on the high voltage side and star connected on the low-voltage side. There are 50 turns per phase on low voltage side and the iron on each limb has a net cross-sectional area of the 100 $cm^2$. Calculate the maximum value of flux density of the core. (Ans. 2.08 $Wb/m^2$)

14.12 A 1,100/440 V, three-phase, 50 Hz transformer is delta connected in the primary and secondary side. There are 100 turns per phase on low voltage side and iron on each limb has net cross-sectional area of 150 $cm^2$. Find the flux density of the core. (Ans. 1.32 $Wb/m^2$)

14.13 The efficiency of 27.5-kVA, 20 : 1 transformer is 80%. Calculate the primary current and voltage when the secondary voltage is 440 V and transformer is operating on full load at power factor 0.8.

(Ans. 3.125 A, 11 kV)

14.14 A three-phase transformer is used to step-down the supply voltage from 10,000 V to 440 V. If the output capacity of the transformer is 132 kVA, find the secondary and primary currents of the transformer.

(Ans. 173.2 A, 7.621 A)

14.15 A three-phase 2500/250 V transformer is installed in a factory to supply a load of 866 kW at power factor 0.8. The efficiency of the transformer is 80%. Calculate secondary and primary line currents.

(Ans. 2500 A, 312.5 A)

14.16 A three-phase 5000/500 V, 173.2-kVA star connected transformer has 75 turns on the secondary side. Find the number of primary turns and primary and secondary currents. (Ans. 750 turns, 20 A, 200 A)

14.17 A 2000/200 V, three-phase, 50 Hz transformer is delta-connected on the primary winding and star connected on the secondary winding. Calculate the turns per phase of the primary winding when turns in the secondary per phase is 50. (Ans. 866 turns)

14.18 A 33000/1100 V, 330 kVA step-down transformer is star connected on the primary side and delta connected on secondary side. Find the ratio between the number of turns of primary and secondary. Also calculate the value of line and phase currents in both the windings.

$$\left[\begin{array}{l} \text{Ans. } K = 17.32 : 1 \\ \quad \text{Delta } I_L = 173.2\text{ A},\ I_{ph} = 100\text{ A} \\ \quad \text{Star } I_L = I_{ph} = 5.773\text{ A} \end{array}\right]$$

14.19 A 22,000/500 V, three-phase, 50-Hz transformer is delta connected on the primary side and star connected on the secondary side. The line current on the primary side is 10 A and the secondary has a balanced load at 0.85 power factor lagging. Calculate (i) the line current on the secondary side, and (ii) the output of the transformer. Ans. (i) 440A (ii) 323.8 kW)

14.20 A three-phase step down transformer is connected to 3,300 V supply mains and takes 20 A. The per phase transformation rates is 10 : 1. When neglecting the losses, *calculate the* secondary line voltage and line current for the following connections.

(*i*) Star/Star — Ans. $V_L = 330V$, $I_L = 200A$

(*ii*) Delta/Delta — $V_L = 330V$, $I_L = 200A$

(*iii*) Delta/Star — $V_L = 571.56V$, $I_L = 115.46V$

(*iv*) Star/Delta — Ans. $V_L = 190.5V$, $I_L = 346.4A$

**14.21** A single-phase 440/220V, 20 kVA, 50 Hz transformer is working at 0.9 PF has full load copper losses 1600 W and iron losses 600W. Calculate the efficiency of the transformer at 75% of full load. **(Ans. 90%)**

**14.22** A 48-kVA, single-phase, 50 Hz, 1600/160 V transformer has primary resistance of 0.5 Ω and a secondary resistance of 0.01 Ω. Calculate the full load efficiency of the transformer at unity PF if the iron losses are 650 W. **(Ans. 96%)**

**14.23** A single-phase 110/440 V, 50-kVA, 50 Hz transformer has full load copper loss of 200 W and iron loss 200 W. Calculate the efficiency of the transformer at full load and half load when:

(*i*) PF is unity — Ans. (99.2%, 99%)

(*ii*) PF 0.8 lagging — (99%, 98.76%)

**14.24** A single-phase 500/250 V, 98 kVA transformer has full load copper loss of 1200 W and iron loss of 800 W. Calculate the efficiency of the transformer at full load, half load and 1/4th of full load when:

(*i*) PF Unity — Ans. (98%, 97.8%, 96.55%)

(*ii*) PF 0.75 lagging — (97.35%, 97.09%, 95.45%)

**14.25** A 50-kVA single-phase lighting load transformer has full load losses of 6 kW, the losses being equally divided between copper and iron losses. During 24 hours, the transformer operates on full load for 12 hours, at half load for 8 hours and at no load for the remaining period. Find the all day efficiency. **(Ans. 87.5%)**

**14.26** A 80-kVA distribution transformer operates at unity PF has full load efficiency of 80% and the full load copper loss is equal to the constant iron loss. Calculate its all-day efficiency if it is loaded as under:

(*i*) Full load for 5 hours.

(*ii*) Half load for 8 hours.

(*iii*) One-fourth of full load for 8 hours.

(*iv*) No load for 3 hours. **(Ans. 73.64%)**

**14.27** A 108-kVA transformer operate at unity power factor has full load efficiency 90% and the full-load copper loss is equal to iron loss. Find its all day efficiency if it is loaded as

(*i*) full load for 5 hours, (*ii*) half load for 6 hours (*iii*) 1/4th of full load for 8 hours (*iv*) no load for 5 hours. **(Ans. 85.31%)**

**14.28** A 100-kVA single phase transformer is working at 0.9 PF has full load efficiency of 90% and the full-load copper loss is equal to constant loss. Calculate its all-day efficiency when loaded as (*i*) Full load for 6 hours (*ii*) half load for 6 hours (*iii*) one-fourth of full load for 8 hours (*iv*) no load for 4 hours. **(Ans. 86%)**

**14.29** A 150-kVA step-down transformer has a voltage ratio of 6600/220V. The open circuit loss (iron loss) is 600W when 130V at normal frequency is applied to high voltage side, the secondary winding being short circuited and full load current is circulated on the secondary side and the wattmeter indicates 1500W. Calculate (*i*) Efficiency (*ii*) the secondary PD when taking 110 kW at a lagging PF of 0.8. **(Ans. 98.28%, 216.7V)**

## REVIEW QUESTIONS

**14.1** What is a transformer? Explain its working principle. What do you understand by step-down and step-up transformer. How a transformer is kept cool. *(NCVT, 1974 Elect.)*

**14.2** What is the function of transformer in transmission and distribution circuits. What are the common voltages adopted for transmission and distribution. *(NCVT, 1962 Elect.)*

**14.3** Describe the protective devices attached to a power transformer. *(NCVT, 1976 Elect.)*

**14.4** (*a*) Describe the construction and principle of operation of a transformer.

(*b*) Why is the core of a transformer constructed from lamination?

**(Hint: Refer Chap., 7, Vol. 1, Sec. 7.5)**

(c) What are the different cooling methods in use for dissipating heat produced in a power transformer?

(d) What are the protective devices used for the safe operation of a transformer.
*(NCVT, 1980 Elect., W/man, 1983)*

14.5 (a) What are the various functioning components of a power transformer?

(b) What is the function of breather?

(c) What is Buchholz Relay and how does it function?

(d) Explain with neat diagrams as to how current transformer and voltage transformer may be used. State briefly the difference between these two types of transformers. (Refer to Chap. 19) *(NCVT, 1970, 1979 Elect.*

14.6 Name the losses which takes place in a distribution transformer. Explain how they vary with the) load. Explain the function of a breather, conservator and explosion vent in the transformer or give experimental methods to determine copper and iron losses in a transformer. *(NCVT, 1974 Elect.)*

14.7 What do you mean by transformer efficiency. What is all-day efficiency? What are the different losses of a transformer? *(NCVT, 1964 Elect.)*

14.8 What is an autotransformer? Describe the different types of transformers used for measuring very high voltage and current. *(NCVT, 1969 Elect.)*

or

Explain with neat sketch the difference between a two winding transformer and an autotransformer and give the uses of each. (state level Compt. 1971 Elect)

14.9 Explain no load losses in a transformer. A 125-kVA single-phase transformer having a primary voltage of 2000V at 50Hz has 182 primary turns and 40 secondary turns. Neglecting losses, calculate (i) full load primary and secondary currents (ii) the no-load secondary induced emf.

[Ans. $I_p = 62.5A$, $I_s = 284.37A$ (Approx)
$V_s = 439.56V$ (approx)]
*(NCVT, 1969 Elect.)*

14.10 (a) What do you understand by rating, Efficiency and regulation of a transformer?

(b) How is the temperature rise of a transformer is measured? *(NCVT, 1975 Elect.)*

14.11 A three-phase transformer is used to step down 11000V to 400V. If the primary winding is delta connected and secondary star connected, calculate: (i) the ratio between the number of turns of primary and secondary windings, (ii) Give the value of line and phase currents in both the windings if the rated capacity of the transformer is 200 kVA.

[Ans. 47.63 : 1, $I_{LS} = I_{ph} = 288.67A$ (approx)
$I_{ph} = 6.056A$ (approx), $I_{Lp} = 10.49A$ (approx)]
*(NCVT, 1971 Elect.)*

14.12 (a) What is meant by transformation ratio and turns ratio in a transformers. Calculate the efficiency at full load and at 50% full load input of a transformer at unity PF and 0.85 PF lagging. The transformer is of 250 kVA with 3000W iron losses and 8000W copper losses at full load.

[Ans. At unity PF : FL $\eta\%$ = 95.78% (approx), 96.15% (approx)
At PF 0.85 : FL $\eta\%$ = 95.07% (approx), 95.4% (approx)]
*(1965 Elect. C.I/S.I test)*

14.13 State the working principle of a transformer and describe the function of each part. Discuss the advantages of using it in an alternating current supply. *(NCVT, 1978 Elect.)*

14.14 (a) Illustrate with a neat sketch the chief parts of a single-phase transformer and state the function of each.

(b) A step-down single-phase transformer has ratio 15 : 1 and primary voltage of 3300V. Calculate the (i) secondary voltage and primary, and (ii) secondary line currents when a load of 30 kW at 0.8 power factor is supplied.

(Ans. 220V, 170.45A (approx), 11.36A (approx)
*(All India Skill Compt., 1969 Elect.)*

14.15 (a) Write each part of a step down 500 kVA, 11000/400 V three-phase transformer installed at sub-station.

(*b*) A 50kVA, three-phase star/star connected transformer has a primary voltage of 6600V and a secondary voltage of 400V and it has 50 secondary turns. Find (i) the number of primary turns, and (ii) secondary and primary currents at full load. Neglect losses. (Ans. 825 turns, 72.16A (approx), 4.37A (approx)) (*NCVT, Sept. 1972*, supplementary test)

14.16 (a) Describe different cooling methods in a distribution transformer and a power transformer (b) state the purpose of the following in a transformer (i) Conservator (ii) Breather (iii) Buchholzrdly. (*NCVT 1981 Elect.*).

or

Why is cooling essential for a transformer and what methods are generally employed for cooling the commercial transformers? Also, explain one of them in detail.

14.17 What do you understand by transformation ratio? A 11000/400V, three-phase step-down transformer is delta connected on the primary side and star connected on the secondary side. If the turns per phase of the secondary winding are 40, find the number of turns per phase of the primary winding.

(Ans. 1905 turns)
(*NCVT, 1973, Elect.*)

14.18 (*a*) What is meant by (*i*) the transformation ratio and (ii) voltage regulation of a transformer.

(*b*) Explain with the help of a sketch the working of an auto-transformer. (*NCVT, 1983 Elect.*)

14.19 Describe briefly the construction of a three phase transformer. Describe the points to be considered while operating these transformer in parallel. (*NCVT, 1984 Elect.*)

14.20 (*a*) Define a transformer. How is the energy transferred from one circuit to another? Distinguish between primary and secondary windings.

(*b*) The transformer is the main reason for the widespread popularity of the ac system over the dc system. Explain.

(*c*) What current flows in the transformer primary when the secondary is open? Give its order of magnitude. (*NCVT, 1985 Elect.*)

14.21 (*a*) What are the basic conditions for the parallel operation of the transformer ? Discuss briefly

(*b*) Discuss briefly the tests required to calculate iron losses and copper losses in a transformer.
(*NCVT 1987 Elect.*)

14.22 Show with the help of diagram the various parts of a power transformer. (*NCVT 1988 Elect.*)

# 15
# Three-Phase Induction Motors

## 15.1 INTRODUCTION

Polyphase induction motors are self-starting motors and are more widely used than any other type of ac motors. This motor is so named because no supply is given to the rotor from any external source of supply, but the current which flows in the rotor conductors is induced by the relative motion of the rotor conductors and the stator rotating magnetic field which can be defined as the "magnetic field of constant magnitude rotating with uniform angular velocity." The stator of the induction motor is similar in construction to the stator of an alternator.

*Working Principle* When a three-phase stator winding is supplied by a three-phase supply, a rotating magnetic field of constant magnitude is set up. This rotating flux cuts the stationary rotor conductors and induces emf in them which causes the heavy circulating current to flow due to very small resistance of rotor. The frequency of the induced current at the time of starting is equal to the supply frequency (as the stationary rotor is similar to the secondary of a transformer). The rotor induced current, according to Lenz's Law, flows in such a direction that it opposes the cause which is inducing the current. In this case, the cause producing the rotor current is the relative speed between the rotating magnetic field of stator and the stationary rotor. Hence to reduce this relative speed, rotor conductors start to rotate in the same direction in which the field is rotating and tries to catch it up.

## 15.2 PRODUCTION OF TORQUE

Let us suppose that a conductor *A* of the stationary rotor is lying under the influence of North pole and the field flux is rotating in clockwise direction as shown is Fig. 15.1(a).

In this case the relative motion of the rotor conductor as compared to stator is anticlockwise as shown by dotted arrow in Fig. 15.1(b). By applying Fleming's right-hand rule, the induced current is found to be outward. If the current is allowed to complete its path, it will produce a magnetic field around the conductor which is anticlockwise (shown in Fig. 15.1 (b) as determined by applying Cork Screw Rule. As these two field fluxes are acting in the same space, the total field will be the resultant of the two and is shown in Fig. 15.1(c). From this figure it is clear that the field on the left hand side of the conductor is more and on the right hand side is less. Hence a clockwise torque will act on the rotor causing rotation of the rotor in the same direction as that of the rotating magnetic field.

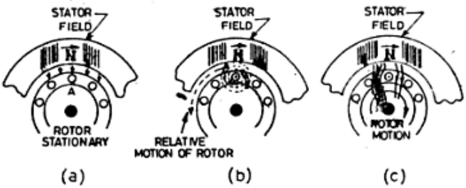



**Fig. 15.1 How the torque is produced**

## 15.3 ROTOR SLIP

It is clear from the above description that a rotor will tend to rotate in the same direction in which the stator magnetic field is rotating. But the rotor cannot run at the same speed of the stator field because if it happens, then there will be no relative motion between the conductors of the rotor and the magnetic field of the stator, hence the rate of change of flux will be zero. Therefore there will be no induced emf in the conductors of the rotor and hence no torque will be developed. However when the rotor starts revolving, some torque is needed to overcome windage and friction even without load, the rotor conductors will move at a speed little less than the speed of the stator magnetic field. The speed of the rotor conductors reduces with the increase of the load because additional torque is required for the increased load. *The difference in speed of stator magnetic field and rotor speed is called "absolute slip"*. If $N$ is the speed of the stator magnetic field (known as synchronous speed) and $N_r$ is the speed of the rotor, then

$$\text{Absolute Slip} = N - Nr \qquad (15.1)$$

Absolute slip is represented by the letter "S". When the slip is termed as fractional slip it is represented as slip speed (or fractional slip ,

$$S = \frac{N - N_r}{N} \qquad (15.2)$$

When the slip is expressed as a percentage of the synchronous speed, it is called as percentage slip and is expressed as
Percentage slip,

$$S\,\% = \frac{N - N_r}{N} \times 100 \qquad (15.3)$$

The percentage slip of induction motors varies from 4 to 5 per cent in small motor's where as in big motors it varies from 1.5 to 2.5 percentage.

## 15.4 ROTOR FREQUENCY

As discussed in Sec. 15.1, when a rotor is at standstill, the frequency of the rotor current is the same as that of the supply frequency. But when the rotor is rotating, its frequency depends upon the slip-speed. Assume the frequency of the rotor current be $fr$ at any slip speed, then

$$N - N_r = \frac{120\ f_r}{P} \qquad (i)$$

But synchronous speed,

$$N = \frac{120 \times f}{P} \qquad (ii)$$

Dividing Eq. (*i*) by (*ii*), we have

$$\frac{f_r}{f} = \frac{N - N_r}{N}$$

or $$\frac{f_r}{f} = S$$

or $$f_r = f \times s$$

$\therefore$ Rotor frequency, $f_r = f \times s$ (15.4)

EXAMPLE 15.1 *An induction motor having six poles operates on 50 Hz supply. If it works on full load at 960 rpm. Find the percentage slip.*

*Solution*

Synchronous speed, $N = \frac{f \times 120}{P}$

$$= \frac{50 \times 120}{6} = 1000 \text{ r.p.m.}$$

Rotor speed, $N_r = 960$ rpm

$\therefore$ Percentage slip, $S\% = \frac{(N - N_r)}{N} \times 100$

$$= \frac{(1000 - 960)}{1000} \times 100$$

$$= \frac{40}{1000} \times 100$$

$$= 4\% \text{ Ans.}$$

EXAMPLE 15.2 *A 10 pole alternator runs at 600 r.p.m. and supplies power to an eight pole induction motor. If the slip of the induction motor at full load is 4%, calculate*

(*i*) *The frequency of its rotor emf.*
(*ii*) *The full load speed of the rotor.*

*Solution* Frequency of the alternator,

$$f = \frac{NP}{120}$$

$$= \frac{600 \times 10}{120} = 50 \text{ c/s}$$

Rotor frequency, $f_r = f \times s$

$$= 50 \times 4\%$$

$$= \frac{50 \times 4}{100} = 2 \text{ c/s Ans.}$$

Synchronous speed of the motor,

$$N = \frac{f \times 120}{P}$$

$$= \frac{50 \times 120}{8} = 750 \text{ rpm}$$

Percentage slip, $S\% = \frac{(N - N_r)}{N} \times 100$

$$4 = \frac{(750 - N_r)}{750} \times 100$$

$$750 - N_r = \frac{4 \times 750}{100}$$

∴ Full load speed of the rotor

$$N_r = 750 - \frac{4 \times 750}{100}$$

$$= 750 - 30$$

$$= 720 \text{ rpm} \quad \textbf{Ans.}$$

## 15.5 RELATION BETWEEN TORQUE AND ROTOR POWER FACTOR

The torque of dc motor is expressed as

$$T \propto I_a \phi$$

where $I_a$ = armature current in amperes

$\phi$ = field flux per pole in webers

and $T$ = torque developed in newton-metres

Similarly the torque of an induction motor is also directly proportional to

$$T \propto I_r \phi \cos \theta_r \qquad (15.5)$$

where $I_r$ = rotor current in amperes at stationary position

$\phi$ = flux per pole of stator in weber.

$\cos \theta_r$ = rotor power factor.

and $T$ = Torque of the motor in Newton-metre.

But $\cos\theta_r = \frac{R_r}{Z_r}$

$$\therefore \quad T \propto I_r \phi \frac{R_r}{Z_r}$$

It means that the torque of an induction motor is directly proportional to the resistance of the rotor winding. So to have high starting torque, rotor must have high resistance. To obtain maximum torque at the time of starting, the rotor is wound so as to insert external resistance in it (as in slipring motor). No doubt by inserting external resistance in the rotor the copper losses increases which lowers down the speed and efficiency. To decrease the copper loss and to increase the torque and efficiency, the slipring motors are started through a star-connected rheostatic starter which is connected in the rotor winding at the time of starting. The motor thus starts as a high resistance rotor and develops high torque at the time of starting. After starting, the external resistance of rheostatic starter is cut off from the rotor windings so that the copper loss under running condition is reduced and thus the efficiency of the motor is increased.

## 15.6 STARTING TORQUE

We know that

Torque $T \propto I_r \phi \cos \theta_r$

At rotor standstill,

Rotor current/phase

$$= \frac{\text{rotor induced emf}}{\text{rotor impedance/phase}}$$

$$I_r = \frac{E_r}{\sqrt{R_r^2 + X_r^2}} \qquad (15.6)$$

where $E_r$ = emf induced per phase of rotor at starting

$R_r$ = rotor resistance per phase

$X_r$ = standstill rotor reactance per phase

and $I_r$ = rotor current per phase

The angle of lag of rotor current,

$$\cos \theta_r = \frac{R_r}{Z_r} = \frac{R_r}{\sqrt{R_r^2 + X_r^2}}$$

The expression for the torque becomes,

$$T \propto \frac{E_r}{\sqrt{R_r^2 + X_r^2}} \times \phi \times \frac{R_r}{\sqrt{R_r^2 + X_r^2}}$$

or

$$T \propto \frac{E_r \phi R_r}{R_r^2 + X_r^2}$$

As the stator applied voltage $V$ is constant, $\phi$ is constant and hence $E_r$ is constant.

$$\therefore \quad T \propto \frac{R_r}{R_r^2 + X_r^2}$$

To have maximum torque at starting, $R_r^2 + X_r^2$ should be minimum.

It can can be proved that

$$R_r^2 + X_r^2$$

is minimum when $R_r = X_r$.

Hence $R_r = X_r$ is the condition for getting maximum torque at starting.

At starting the rotor is stationary and therefore its slip is one. So the rotor frequency at starting is equal to the supply frequency (i.e, $f_r = f \times s$) and hence rotor reactance ($X_r = 2\pi f L$) is high as compared with rotor resistance ($R_r$). Rotor current in this condition lags behind the rotor induced emf ($E_r$) by an angle $\theta$ which is very large and therefore starting torque is also very low. The power factor of the rotor circuit can be improved by either increasing the rotor resistance or reducing the rotor reactance. The reactance of the rotor cannot be reduced where as resistance can be increased (in case of wound rotor only) by connecting a series resistance at the time of starting. When the motor gains its normal speed, this extra resistance is cut off from the rotor circuit. By increasing the resistance in the rotor circuit, impedance of the rotor increases which reduces the starting current of the motor but improves the power factor of the rotor. Thus, the starting torque is increased even at small rotor current.

From above,

$$T \propto \frac{E_r \phi R_r}{R_r^2 + X_r^2}$$

But $E_r \propto \phi \propto V$ (the supply voltage).

$$\therefore \quad T \propto \frac{V^2 R_r}{R_r^2 + X_r^2} \qquad (15.7)$$

Hence any variation in stator applied voltage will effect the starting torque to a great extent.

## 15.7 TYPES OF POLYPHASE INDUCTION MOTORS

Poly phase induction motors are also called "asynchronous motors" because the rotor does not revolve with the same speed of rotating magnetic field.

There are three types of induction motors which are commonly used for commercial purposes. The stator of all these motors are exactly similar in construction to the stator of alternator but the difference between them exists merely in the method of winding the rotor. There are three types of rotor winding as given below.

(*i*) Squirrel-cage type rotor

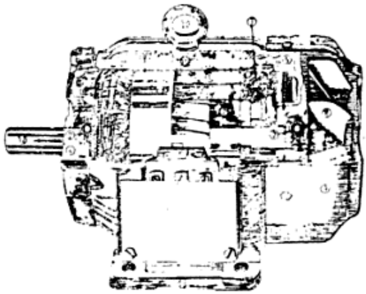


Fig. 15.2 (a) Sectional view of a totally enclosed fan ventilated squirrel cage induction motor

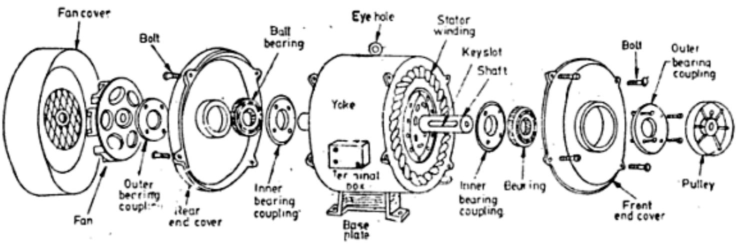



Fig. 15.2 (b) Squirrel cage inductor motor in displayed condition

(*ii*) Slipring type rotor or phase wound rotor
(*iii*) Double-squirrel-cage type rotor

## 15.8 SQUIRREL-CAGE INDUCTION MOTOR

**Construction** A three phase squirrel cage induction motor has two main parts namely stator and rotor.

*Stator* It consists of silicon laminations insulated from each other and give path to the magnetic flux of machine. It is hollow and cylindrical in shape having slots in its inner surface to carry the windings. The stator winding of an induction motor is identical to the stator winding of an alternator and is held in frame of the motor. The stator is wound for three phase supply and its connection are brought out to terminal box fitted to the side of the frame.

*Rotor* The rotor of squirrel cage induction motor is cylinderical in shape and is built up of number of laminations (shown in Fig. 15.3) having slots on its outer surface. Solid copper conductors are inserted in these slots and are short circuited at the ends of the rotor by soldering (or braizing) the copper rings.

In small motors, the rotors are also manufactured with squirrel cage aluminium diecasting. The rotor is then mounted on the shaft and supported on the bearings housed in the side covers of the motor. This system of arrangement of copper conductors in the slots of the rotor resembles to a cage of a pet squirrel and hence is so named as squirrel cage rotor. This type of rotor has very low resistance and is cheap as compared to other types. The gap between rotor and stator is kept very small which varies from 0.25 to 0.4 mm. Construction of squirrel cage rotor, is similar irrespective of number of poles and phases for which the stator is wound since the rotor adjusts itself according to the stator's number of poles and phases.

*Working Principle* When a three-phase wound stator is connected to the three-phase supply, a rotating field is set up which cuts the rotor conductors and thus some emf is induced in them. This emf causes heavy current to flow in the rotor circuit at the time of starting because its resistance is very small (short circuited rotor acts as a short circuit secondary of a transformer) and moreover it is stationary. Beside this heavy current, the starting torque is minimum due to low power factor and high reactance of the rotor at starting.

When the rotor attains its normal speed, the frequency of the induced emf in the rotor decreases as the relative speed between the rotor and the rotating magnetic field is decreased. The decrease in the rotor frequency reduces the reactance of the rotor. After starting therefore, the effect of the resistance of the rotor become apparent which improves the power factor of the motor. Hence the

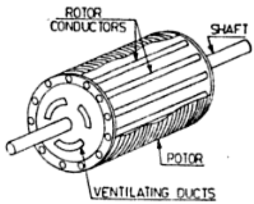



**Fig. 15.3 (a) Squirrel cage rotor**

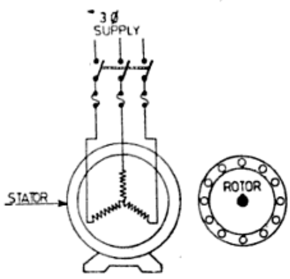



**Fig. 15.3 (b) Rotor and stator of a squirrel-cage motor**

necessary condition for the improvement of the power factor is fulfilled and thus the running torque of the squirrel cage induction motor is improved. The power factor of induction motor further increases with the increase of load.

*Applications* Squirrel cage induction motors are practically constant speed motor and have low starting torque due to low power factor of the motor at starting. Hence these motors are started without load where low starting torque is required such as lathes, water pumps, drill machines, grinder, slotters, saw mills, flour mills etc.

The direction of rotation of squirrel cage inductions motor can be changed by interchanging any of the two phase of the supply line.

**Example 15.3** *Find the horsepower developed by a 433 V, three phase 50 Hz induction motor when it takes a current of 74.6 A, at 0.8 PF. The efficiency of the motor is 80%.*

*Solution* Power input of three-phase motor,

$$W = \sqrt{3}\, V_L\ I_L \cos\theta$$

$$= \sqrt{3} \times 433 \times 74.6 \times 0.8 \text{ W}$$

But efficiency percentage,

$$\eta\% = \frac{\text{Output} \times 100}{\text{Input}}$$

∴ Output of the motor

$$= \frac{\text{Input} \times \eta\%}{100}$$

$$= \frac{\sqrt{3} \times 433 \times 74.6 \times 0.8 \times 80}{100} \text{ W}$$

Output of the motor in horsepower

$$= \frac{\sqrt{3} \times 433 \times 74.6 \times 0.8 \times 80}{100 \times 746} \text{ hp}$$

$$= \frac{\sqrt{3} \times \sqrt{3} \times 433 \times 74.6 \times 0.8 \times 80}{\sqrt{3} \times 100 \times 746}$$

$$= \frac{3 \times 433 \times 74.6 \times 0.8 \times 80}{1.732 \times 100 \times 746}$$

$= 48$ hp **Ans.**

**Example 15.4** *A delta-connected three phase induction motor delivers 45 hp to a pump. The efficiency of the motor is 93.25% and its PF is 0.8. If the supply voltage is 433 V at 50 HZ, calculate the line and phase currents of the motor.*

*Solution*: We know,

Efficiency percentage,

$$\eta\% = \frac{\text{Output} \times 100}{\text{Input}}$$

∴ Input of the motor

$$= \frac{\text{output in bhp} \times 100}{\eta\%}$$

$$= \frac{45 \times 100 \times 746}{93.25} \text{ W}$$

Electrical power input of the three-phase motor,

$$W = \sqrt{3}\, V_L \times I_L \times \cos\theta$$

$$= \sqrt{3} \times 433 \times I_L \times 0.8 \text{ W}$$

Electric power input of the motor = Mech. power input of the motor

$$\sqrt{3} \times 433 \times I_L \times 0.8$$

$$= \frac{45 \times 100 \times 746}{93.25}$$

∴ Line current of the motor,

$$I_L = \frac{45 \times 100 \times 746 \times \sqrt{3}}{93.25 \times \sqrt{3} \times \sqrt{3} \times 433 \times 0.8}$$

$$= \frac{45 \times 100 \times 746 \times 1.732}{93.25 \times 3 \times 433 \times 0.8} = 60\text{A} \textbf{ Ans.}$$

Phase current of delta connected motor,

$$I_{ph} = \frac{\text{Line current}}{\sqrt{3}} = \frac{60}{1.732} = 34.64 \text{ A} \textbf{ Ans.}$$

## 15.9 SLIPRING INDUCTION MOTOR

**Construction and Working** The stator of a slipring induction motor is similar to the stator of squirrel cage motor. But the rotors of these motors are wound with a winding which is identical to that of the stator of the motor. The rotor winding is wound for the same number of poles and phases as that of the stator winding. For a three-phase rotor winding, the three ends of the three-phases are generally connected in star at one junction and the remaining three free ends are brought out for connection to the sliprings mounted on the shaft of the motor. The sliprings, are then connected to the external starting resistances connected in star through the carbon brushes placed on the sliprings.

At the time of starting, the rheostatic resistances are put in the rotor circuit as shown in Fig. 15.4 (b) to improve the starting torque and to decrease the starting current. As soon as the motor attains its normal speed, the rheostatic resistances, are cut off

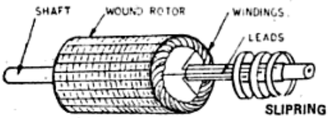



**Fig. 15.4(a) Wound rotor**

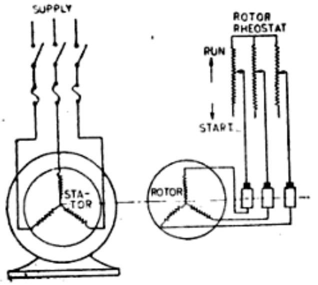



**Fig. 15.4(b) Rotor and stator of slipring induction motor**

gradually from the rotor circuit and finally sliprings are short circuited.

If the rotor resistances of a slipring motor are connected in delta, they will form a parallel circuit. In parallel circuit total resistance will be less than the least resistance connected in parallel. Therefore, the resistance when connected in delta will not fulfill the condition of getting maximum torque. Hence the rotor resistances are connected in star instead of delta.

Phase wound rotors are more costly as compared to squirrel cage rotor because it is difficult to construct them. But the starting torque of the phase wound rotor is much greater than the squirrel cage rotor and will be maximum when the total resistance of the rotor circuit is equal to the total reactance of the rotor at starting.

**Applications** Slipring motors are used at places where high starting torque is required, such as in plainers, cranes, rolling mills, lifts etc. These motors are started on load within its capacity.

The direction of rotation of this motor can be changed by changing any of the two phases of the supply.

**EXAMPLE 15.5** *A three-phase sliprings induction motor is connected to a normal supply voltage when its rotor is connected in star. The emf induced between the sliprings at standstill is 86.6 V and the resistance and standstill reactance per phase are 1.5 and 2Ω respectively. Calculate (i) the rotor per phase current and (ii) pf at starting when the sliprings are:*

(*a*) *Short-circuited.*
(*b*) *Joined to a star connected rheostatic resistance of 8.3Ω per phase.*

***Solution:***

Phase emf of rotor connected in star at standstill,

$$E_{phr} = \frac{\text{line emf}}{\sqrt{3}} = \frac{86.6}{1.732} = 50 \text{ V}$$

(*a*) When sliprings are short-circuited

Rotor current, $I_r = \frac{E_{phr}}{Z_r}$

$$= \frac{50}{\sqrt{(1.5)^2 + (2)^2}} = \frac{50}{\sqrt{2.25 + 4}}$$

$$= \frac{50}{\sqrt{6.25}} = \frac{50}{2.5} = 20 \text{ A} \quad \textbf{Ans.}$$

Power factor in this case,

$$\cos \theta_r = \frac{R_r}{Z_r} = \frac{1.5}{2.5} = 0.6 \quad \textbf{Ans.}$$

(*b*) When the rotor is connected to a star-connected rheostatic resistance,

∴ Starting current, $I_s = \frac{E_{phr}}{Z_s}$

$$= \frac{50}{\sqrt{(1.5 + 8.3)^2 + (2)^2}} = \frac{50}{\sqrt{(9.8)^2 + (2)^2}} = \frac{50}{\sqrt{96.04 + 4}} = \frac{50}{\sqrt{100.04}}$$

$$= \frac{50}{10} = 5\text{A} \quad \textbf{Ans.}$$

Power factor at starting,

$$\cos \theta s = \frac{R}{Z} = \frac{9.8}{10} = 0.98 \quad \textbf{Ans.}$$

**NOTE:**—Observe the effect of increasing the rotor resistance at the time of starting.

**EXAMPLE 15.6** *A three-phase, eight-pole, 50Hz slipring induction motor is running on full load at 720 rpm. The rotor is star connected and has resistance and standstill reactance of 0.08 and 1.5Ω per phase respectively. The emf between sliprings at standstill is 86.6 V. Find for full-load condition:*

*(a) Emf induced in each rotor phase*
*(b) Per-phase impedance of rotor*
*(c) Rotor current*
*(d) Power Factor*

*Assume sliprings are short circuited.*

*Solution:*

Synchronous speed,

$$N = \frac{f \times 120}{P} = \frac{50 \times 120}{8} = 750 \text{ r.p.m.}$$

Percentage slip of motor,

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

$$= \frac{750 - 720}{750} \times 100$$

$$= \frac{30 \times 100}{750} = 4\%$$

Per phase emf of star connected rotor when stationary

$$= \frac{E_r}{\sqrt{3}}$$

$$= \frac{86.6}{1.732} = 50\text{V}$$

Rotor per-phase emf induced when running normally = standstill per-phase emf × $S\%$

$$= \frac{50 \times 4}{100} = 2\text{V} \quad \textbf{Ans.}$$

Rotor reactance per phase

$$= \frac{1.5 \times 4}{100} = 0.06\Omega$$

Rotor impedance per phase

$$= \sqrt{R^2 + X^2}$$

$$= \sqrt{(0.08)^2 + 0.06)^2}$$

$$= \sqrt{0.0064 + 0.0036}$$

$$= \sqrt{0.01}$$

$$= 0.1\Omega \quad \textbf{Ans.}$$

Rotor current, $I_r = \frac{E_r}{Z_r} = \frac{2}{0.1} = 20\text{A}$ **Ans.**

PF of rotor, $\cos\theta_r = \frac{R_r}{Z_r} = \frac{0.08}{0.1} = 0.8$ **Ans.**

**EXAMPLE 15.7** *A 45 hp motor is run for 25 hours at 80% of full load when connected to a 433 V, three phase 50 Hz supply. The power factor of the motor is 0.75 and the efficiency of the motor is 80%. Calculate:*

*(a) The line current of the motor.*
*(b) Cost of energy consumed at the rate of 40 paise per unit.*

*Solution:*

Output of the motor at 80% of full load

$$= \frac{45 \times 80}{100} = 36 \text{ hp.}$$

Input of the motor

$$= \frac{\text{output} \times 100}{\eta\%}$$

$$= \frac{36 \times 100 \times 746}{80} \text{ W}$$

Power taken by the motor,

$$W = \sqrt{3}\ V_L \times I_L \times \cos\phi$$

$$\frac{36 \times 100 \times 746}{80} = 1.732 \times 433 \times I_L \times 0.75$$

∴ Line current

$$I_L = \frac{36 \times 100 \times 746}{80 \times 1.732 \times 433 \times 0.75}$$

$$= 59.68\text{A} \quad \textbf{Ans.}$$

Energy consumption in 25 hours

$$= \frac{36 \times 100 \times 746 \times 25}{80 \times 1000} \text{ kWh}$$

Energy charges at the rate of 40 paise per unit

$$= \frac{36 \times 100 \times 746 \times 25}{80 \times 1000} \times \frac{40}{100}$$

$$= \text{Rs. } 335.70 \quad \textbf{Ans.}$$

## 15.10 DOUBLE SQUIRREL CAGE INDUCTION MOTOR

**Construction** The stator winding of this motor is also exactly similar to the stator of an ordinary squirrel cage induction motor. As discussed before, it is seen that an ordinary squirrel cage induction motor has low starting torque due to low resistance of the rotor. If the squirrel cage rotor is made of high resistance to get high starting torque, it will have low efficiency due to increased copper losses. To have high starting torque and high efficiency squirrel cage rotors are manufactured in double cage as shown in Fig. 15.5.

The rotor's outer squirrel cage winding is either made of aluminium or of any other high resistance material like brass etc. and is done near the circumference of the rotor. The other squirrel cage winding of (low resistance) is built of copper which is placed

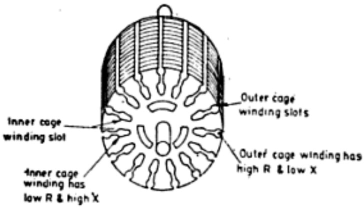



**Fig. 15.5** **Rotor of double squirrel-cage induction motor**

comparatively deep in the rotor thus has high reactance.

**Working** When the motor is started, the stator frequency is 50 cycles per second. The induced emf in the stationary rotor will also have the same frequency as that of the stator supply frequency. At this instant, the reactance of the inner cage winding is comparatively high because it is linking more iron. Having higher frequency than its normal running condition frequency, it will have very high impedance. Hence the current through inner cage winding at the time of starting is very small as compared to the outer cage winding which is of high resistance. Thus in this condition the current through the outer cage will be maximum. So the motor starts as a high resistance rotor and will have high starting torque.

When the rotor starts running, the speed of the rotor will be increased and the rotor frequency will be very low. For example the synchronous speed of a 4 pole induction motor is 1500 rpm, and if its rotor speed is 1440 rpm then its percentage slip is as under:

$$\text{Percentage slip}, S\% = \frac{N - N_r}{N} \times 100$$

$$= \frac{1500 - 1440}{1500} \times 100$$

$$= \frac{60 \times 100}{1500}$$

$$= 4\%$$

$$\text{Rotor frequency}, f_r = f \times s$$

$$= \frac{50 \times 4}{100}$$

$$= 2\text{c/s}$$

Hence the rotor frequency during running condition will 2 c/s which will cause decreased reactance or impedance of the inner cage in this condition and thus the current in the internal cage winding will be comparatively more than the outer cage winding Therefore the torque and efficiency will be more. It is easy to remember that at the time of switching "on" the motor, the outer cage winding will function and during normal working condition the outer cage winding will automatically be cut off due to high resistance and inner cage winding will work.

*Applications* These motors are used where high starting torque is required at the time of starting as plainers, cranes, lifts, rolling mills etc. D.O R. can be changed by changing any two phases of the supply mains.

## 15.11 STARTING OF INDUCTION MOTORS

For starting a three-phase induction motor if rated voltage is applied to the stator winding, a very high starting current will flow through the motor windings. This high starting current has the following two main disadvantages:

1. The stator winding or the wiring installation may damage due to this heavy starting current.

2. The high starting current may have bad effect on the voltage regulation of the line. Due to poor voltage regulation, the relays of the other motors operating near this motor may unnecessary trip off again and again whenever a big horse power motor is started. This causes unnecessary interruption of work.

   According to I.E. rules this type of voltage regulation is not allowed and therefore to improve the voltage regulation and to decrease the starting current, big horse power motors are always started through starters.

Starters are operated either by mechanical or electrical system. If for switching on, a mechanical system is used in the starter, then it is known as manually operated starter and

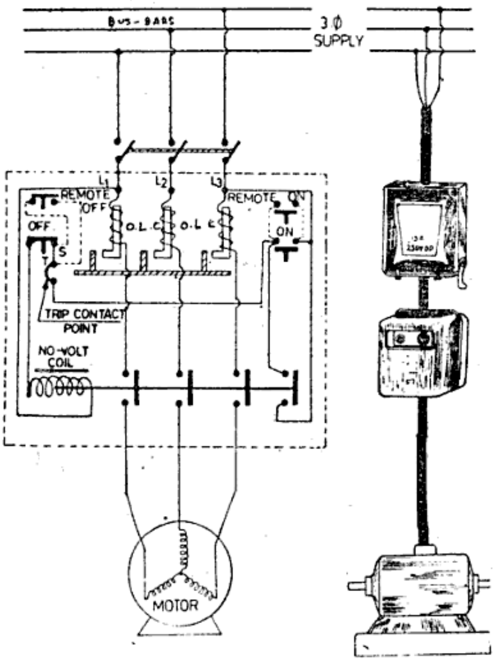



Fig. 15.6 Connection of direct-on-line starter and its layout

if an electromagnetic contactor is utilized, then it is called as electrically operated starter. All starters above 2 hp are usually electrically operated. In addition to starters are provided with safety devices like overload relay coil and no-volt relay coil for the protection of the motor. Various types of starters are in commercial use as mentioned below:

1. Direct-on-Line (Mechanically operated) Air Break Starter.
2. Direct on line (electrically operated) Air break or oil immersed starter.
3. Star-delta starter.
4. Slipring motor starter.
5. Auto-transformer starter.

*Direct-on-Line starter* Fig. 15.6 shows the connection of a direct-on-line starter. In this type of starter there is no arrangement for reducing the line voltage at the time of starting and therefore full line voltage is applied to the motor. This starter has the following main parts.

There are two push buttons, one is green for starting and the other is red for stopping the motor. There is one plunger whose three strips contacts connects the motor to the line and fourth strip works as an hold-on-contact when start push button is released after pressing it. There is one coil which is known as no-volt coil which on energising attract the plunger and thus motor starts. In case of failure of supply or if the voltage drops unduly, it releases the plunger and thus motor is disconnected from the supply.

In this starter, an arrangement is also provided to protect the motor from overload. The overload relays are made of thick heating elements inside of which there are bi-metallic strips. When abnormal current flows through the motor, the overload coil becomes hot and the bi-metallic strip expands which opens the trip contact point. The tripping system should operate at approximately 20 to 30% overload. After tripping off the contact point, the current through the no-volt-coil stops flowing and thus the plunger comes to off position. Near these over-load-coils, there is one current adjuster with the help of which the tripping current of the overload coil is adjusted.

When the start push button is pressed, the no-volt-coil becomes magnetised and the plunger makes contact with the motor and supply terminals which causes to start the motor. This type of starters are used with the motor of range from 1/4 hp to 5 hp.

For a big hp motor of range from 3 to 25 hp, oil immersed direct on-line starters are used. In this type of starter the contact points of the starters are dipped in an insulating oil for reducing the sparking on the contact points and thus increases the life of the starter.

With remote control facilities, a motor can be started or switched "OFF" from any number of desired places. For remote control of a motor, it should be remembered that all the remote, "ON" push buttons must be connected in parallel to the "ON" push button of the starter whereas all the remote "OFF" push-buttons are connected in series with the starter's OFF push button. For remote control of DOL starter, remove connection between *S* and *T* and connect remote OFF and ON switches as shown in dotted lines in Fig. 15.6.

**Star-Delta Starter** The motors which are supplied with star-delta starters are first started in star connection and after this are run in delta connection.

This starter consists of fixed contact points, moveable contact point with handle, stop-push button, overload relays and a no-volt-coil. The no-volt-coil is connected across the two phases of the supply through a trip relay point and stop push button as shown in Fig. 15.7. Under normal working condition, this coil becomes magnetised and holds the handle in "Run" position. When the supply voltage is below 85% of its rated voltage or it suddenly fails, the no-volt-coil becomes demagnetised and leaves the handle to "OFF" position.

Overload coils consist of three heating elements wound over three asbestos insulated bi-metallic strips. Due to abnormal current taken by the motor (either due to short circuit or due to overload) these bemetallic strips on heating will bend and open the trip contact point of no-volt-coil circuit and thus handle comes to "OFF" position. For overload setting, there is a current adjuster which is marked in percentage ampere setting starting from 75 to 125%. The 100% setting of the starter refers to the normal rating of the starter.

In star delta starting, the motor is first started in "star" condition and when the motor gains about 75% speed, the connection is changed to delta by moving the handle quickly in "Run" position. By connecting the motor in star connection during starting, the applied voltage is reduced to $\frac{1}{\sqrt{3}}$ of the line voltage in delta connection.

Thus the starting line current in star is only one-third that in delta. For most motors started with direct-on-line starter, the current at the time of starting is about 6 to 8 times than its rated current and therefore by starting it in star, the current is decreased to about 2 to 2.5 times the rated current. The torque in "star" connection is also decreased and is only one-third that in delta. Hence the star-delta starter can be used only with motors where the load torque at the moment of starting is not more than about 50% of the rated torque.

Mechanically operated star-delta starters are generally used with motor having an output from 5 to 10 hp on a 400/440 V, 50 c/s supply.

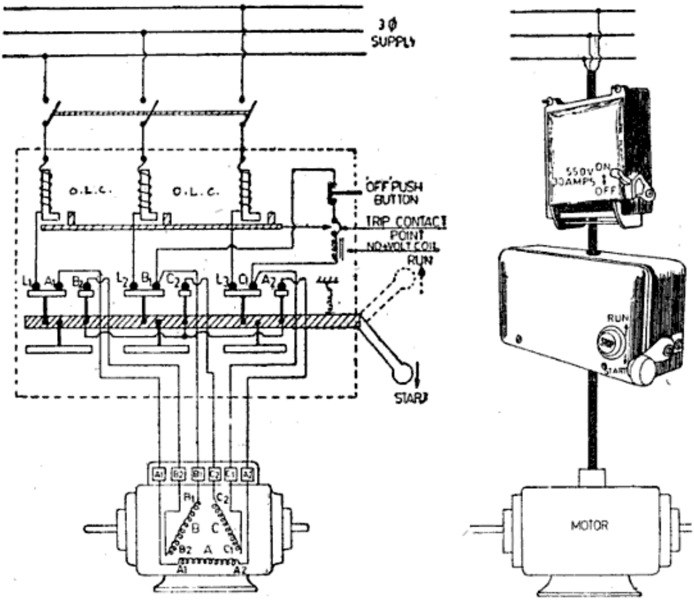



Fig. 15.7 Connection and layout of star-Delta starter

Automatic air break star-delta starters are employed with motors up to 20 hp and oil immersed starters of this type are suitable for squirrel cage induction motors of up to 50 hp on 400/440 V 50 c/s supply.

**Automatic Star-Delta Starter** Automatic star-delta starter consists of three contactors having a star contactor, a delta contactor, a line contactor with overload relay, "on" and "off" push buttons and an accurate timer for automatic changeover from star to delta. A timer has two operating position. At first position, the upper contact is closed and lower one is opened. But when lower contact is closed, upper contact opens.

The fourth contact known as hold-on contact of star and line contactor are normally open (NO) while of delta contactor is normally closed (NC). Figure 15.8 shows the connection diagram of an automatic star-delta starter. Motor terminals $A_1$ $B_1$ $C_1$ and $A_2$ $B_2$ $C_2$ are connected to the corresponding terminals on starter and supply is given to terminals $L_1$, $L_2$ and $L_3$ as shown in Fig. 15.8.

When the ON push button is pressed the line contactor and the star contactor get energised. Then the motor starts running with its stator "windings" star connected.

After the preset time (3 to 12s), the timer switch put "off" the star contactor and switch "on" the delta contactor. The motor now

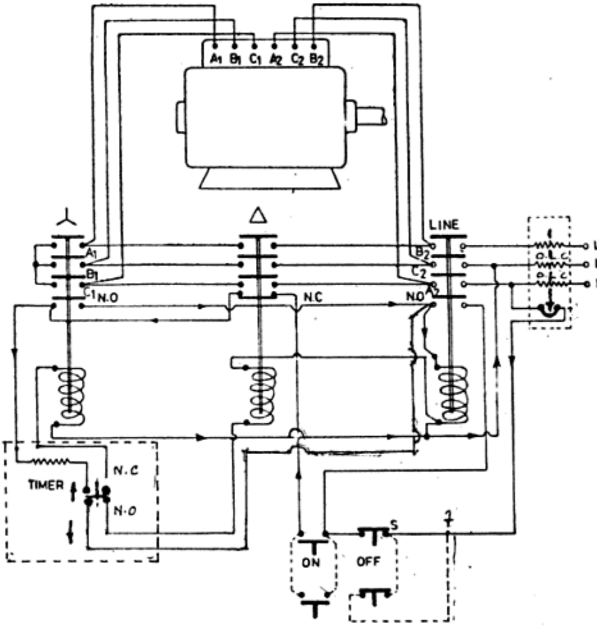



**Fig. 15.8 Connection diagram of automatic star delta starter (dotted lines show remote control)**

runs in delta connection automatically. It should be noted that the timer can be adjusted between 3 to 12s depending upon how long the motor takes to reach about 75% of its synchronous speed.

For remote control remove connection between terminals *S* and *T* and connect as shown in Fig. 15.8. For reversing the direction of rotation, interchange any two supply wires $L_1$, $L_2$ and $L_3$.

**Slipring Motor Starter** For starting the slipring motor, a starter is required which is known as slipring motor starter. It consists of rotor resistance, overload relays, start and stop push button, no-volt-coil and a plunger. Connection diagram of a slipring starter is shown in Fig. 15.9.

Slipring motors are started by putting resistance in rotor circuit at the time of starting. The rotor resistance improves the power factor which reduces the rotor current and there by decreases the stator starting current. As the motor starts rotating and attains its normal speed, this additional rotor resistance is gradually cut off from the circuit and thus the rotor sliprings are now short circuited. These resistances are immersed in oil in case of big horse power motor for cooling them but in small motor, it is not required to dip them in oil. Its direction of rotation (D.O.R.) can be changed as explained earlier.

**Auto Transformer Starter** In this type of starter reduced voltage for starting the motor is obtained from a three-phase star connected auto transformer. While starting the voltage is reduced by selecting suitable tappings from the auto transformer. Once the motor starts rotating 75% of its synchronous speed, full line voltage is applied across the motor and the auto transformer is cut off from the motor circuit.

Figure 15.10 shows the connection of an auto transformer starter. To start the motor the handle of the starter is turned downward and the motor gets a reduced voltage from the auto transformer tappings. When the motor attains about 75% of its synchronous speed the starter handle is moved upward and the motor gets full voltage. The auto transformer gets disconnected from the motor circuit.

Hand operated auto transformer starters are suitable for motors from 20 to 150 hp whereas automatic auto transformer starters are used with large horse-power motors upto 425 hp.

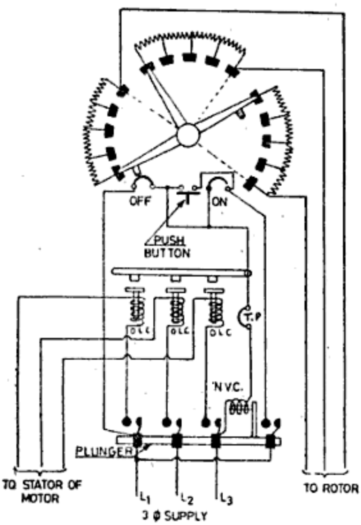



**Fig. 15.9** Slip-ring motor starter

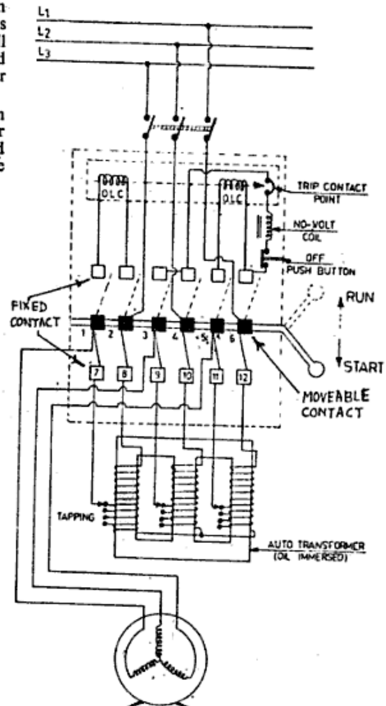



**Fig. 15.10** Connection dia of auto-transformer starter

## 15.12 DETERMINING OF PHASE SEQUENCE

If the phase sequence of a three phase induction motor is not marked on the six leads or wrongly changed and on connecting them in star or delta across the 3$\phi$ supply the motor may refuse to start or it may run slowly with loud buzzing noise. The motor in this condition takes a heavy circulating current even on no load. Therefore it is essential to identify the corresponding terminals of different phases.

To understand the meaning of the word corresponding terminal consider Fig. 15.11(a) in which three single turn coils $A$, $B$, $C$ placed at 120° apart from each other are shown and represents the three winding of the stator. If the current enters in the coil $A$ through terminal $A_1$, then a flux will set up which comes out from stator and enter the rotor. Assume this flux as positive flux ($N$) and the current which produces this flux as positive current. In the very same manner, the positive current flowing in the coil $B$ and coil $C$ through terminals $B_1$ and $C_1$, produce +ve flux in them. Figure 15.11(b) shows the positive currents are flowing in the three coils and the fluxes due to them is also +ve. When the coils link with these fluxes an E.M.F. is induced in each coil which acts around the coils from terminal $A_2$, $B_2$ and $C_2$ towards terminal $A_1$, $B_1$, and $C_1$ respectively as shown in Fig. 15.11 (b). Therefore a set of terminals $A_1$, $B_1$ and $C_1$ thus indicates the points of induced voltage rise in the coils when they all link +ve fluxes. Similarly terminals $A_2$, $B_2$ and $C_2$ relates to the points of induced voltage drop due to +ve fluxes.

Now consider the case when coil $A$ is alone connected to single phase supply as shown in Fig. 15.11 (c) and assume the current at this instant in a cycle is increasing in positive half. So the +ve flux is set up in coil $A$ while at the very same moment the coils $B$ and $C$ carry −ve fluxes as shown in Fig. 15.11 (c) and the directions of instantaneous induced E.M.F.'s $e_A$, $e_B$ and $e_C$ can be marked as shown in Fig. 15.11 (c). If now the corresponding terminals $A_2$, $B_2$ and $C_2$ are connected together in star as represented in Fig. 15.11 (d) then:

$V_1$ = Voltage between terminals $A_1$ and $A_2$

$= e_A$

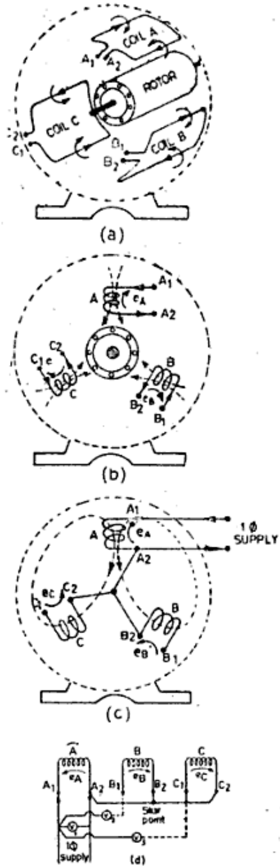



Fig 15.11 Determining the phase sequence

$V_2$ = Voltage between terminals $A_1$ and $B_1$
$= e_A + e_B$

and $V_3$ = Voltage between terminals $A_1$ and
$C_1 = e_A + e_C$

It is clear $V_2 = V_3 > V_1$ or $V_2$ & $V_3 > V_1$ ...(since $e_B = e_c$). This becomes the criteria for determining the terminals $A_2$, $B_2$ and $C_2$ forms a set of corresponding terminals. Therefore in short the six leads coming out from the three phase stator of an induction motor can be determined as given below.

1. Find out the pairs of each winding and arrange them in the sequence of $A$, $B$ and $C$.
2. Allot assumed number $A_1A_2B_1B_2$ and $C_1C_2$ to windings $A$, $B$ and $C$ respectively.
3. Connect the winding ends $A_2$, $B_2$ & $C_2$ in star and give single phase supply to any one phase winding. Let in this case it is given to phase $A$.
4. Now measure the voltage between $A_1A_2$, $A_1B_1$ and $A_1C_1$ which is denoted by $V_1$, $V_2$ and $V_3$ respectively.

In this case if $V_2$ and $V_3$ read more than $V_1$, it means the winding ends connected in star are arranged in proper sequence. If in any case $V_2$ or $V_3$ or both read less than $V_1$, then both the finish or starting ends of winding must have been connected together and should be changed.

NOTE: A voltmeter of range 0—500 V ac/dc should be used for this purpose or a double test lamp of high and equal wattage lamp in series should be used for the judgement of light.

## 15.13 SPEED CONTROL OF INDUCTION MOTORS

All ac motors suffer from the disadvantage that they are basically single speed motors. Economical large variation in speed of an induction motor is very difficult to obtain as compared to a dc motor. The followings are the few easy methods of speed control of induction motor.

(i) By varying applied voltage (voltage control)

(ii) By varying applied frequency (Frequency control)

(iii) By varying number of poles of the stator winding (Pole changing control)

(iv) By rotor rheostatic control.

**By Varying Applied Voltage** This method is very easy but rarely used in commercial practice because a large variation of voltage produces a very small change in speed and much energy is wasted. In this method three resistances are inserted in series with the stator winding of the motor and the value of these resistances is varied by a common handle so that equal resistances come in the stator circuit.

**By Changing Applied Frequency** The synchronous speed of an induction motor is given by $N = \frac{f \times 120}{P}$. It is clear from the equation that the speed of the induction motor can be changed by changing the frequency of the supply. The speed of the motor will increase if frequency is increased and it will decrease if frequency is decreased. Changing the frequency of suply to the motor is not an easy job. Therefore this method is only employed where the load on the alternator is only induction motors and the speed of all the motors is to be increased or decreased simultaneously. This method is utilized for the speed control of motors used in the ships etc.

**By Varying Number of Poles** This method of speed control is generally employed in squirrel-cage induction motors because a squirrel cage rotor adjusts itself according to any number of poles of stator winding.

From the equation of synchronous speed it is clear that if the number of poles of the stator is decreased, the speed of the motor will increase and when the number of poles are increased, the speed will decrease The poles of the stator winding can be changed either by having two separate windings not having the same number of poles on the stator and using one of them at a time or by reconnecting the coils of the single stator winding as shown in Fig. 15.12. The figure shows the connections of one phase winding for 8 poles and 4 poles: and in this case, the speed increases from 750 to 1500 r.p.m.

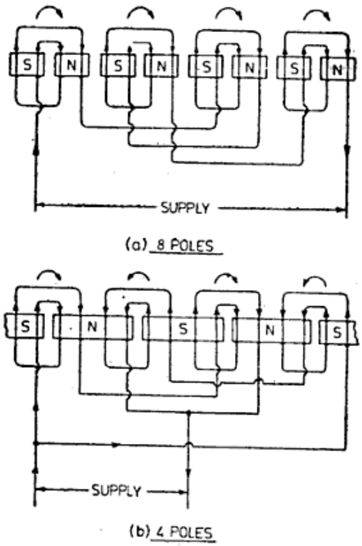



**Fig. 15.12 Speed control by changing the number of poles**

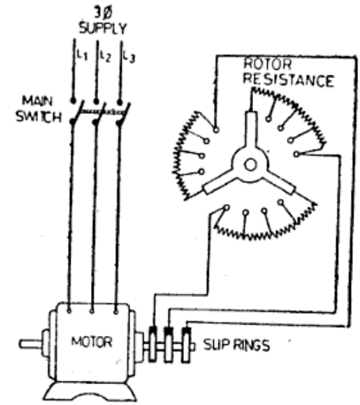



**Fig. 15.13 Rotor rheostatic speed control**

It is clear from the above that the speed control of motor by this method is not smooth. This method of speed control is utilized with the motors used in lifts, etc.

**By Rotor Rheostatic Control** This method of speed control is only applied to slipring induction motors. In this method star connected external resistances (of continuous ratings) are connected in the rotor circuit as shown in Fig. 15.13.

The speed of the motor increases with the decrease of resistance in the rotor circuit. The change in speed is approximately inversally proportional to the external resistance connected in the rotor circuit. This method of speed control is applied where a small variation of speed is required and the power wasted is of no great importance.

## 15.14 MAGNETIC LOCKING

In squirrel cage induction motor if the number of rotor slots are equal to the number of statorslots, then it is possible that the rotor slots may face the stator slots when the motor is stationary and in this condition the reluctance between rotor and stator conductors will be minimum and hence attract each other. If the motor is connected to the supply for starting when the rotor is in such a condition, the motor may refuse to start. This is known as magnetic locking or cogging effect of a squirrel cage induction motor. Magnetic locking in such type of motor can be avoided either by skewing the rotor slots or by selecting the rotor slots such that there is no common factor between the rotor slots and stator slots. This effect is observed in the squirrel cage induction motors only as they have low starting torque.

## 15.15 LOSSES IN AN INDUCTION MOTOR

The losses occurring in an induction motor are as given below.

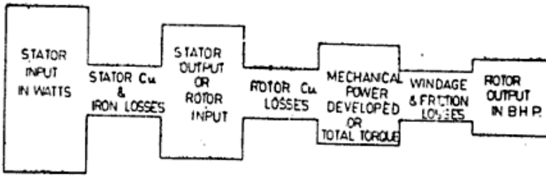



**Fig. 15.14 Power stages of an induction motor**

(*i*) Stator losses

(*ii*) Rotor losses

(*iii*) Windage and friction losses

Stator losses comprise

(*a*) Stator copper loss and

(*b*) Stator iron loss.

The stator copper loss occurs in the winding of the stator.

The stator iron loss is constant and depends upon the frequency of the supply and flux density in the core of the stator.

Rotor losses comprise

(*i*) Rotor copper loss and

(*ii*) Rotor iron loss.

Rotor copper loss takes place in the rotor bars or winding of an induction motor.

As the frequency of the rotor current at normal running is always very small rotor iron loss can be neglected.

Windage and friction losses occur in the motor during its normal operation due to windage friction and bearing friction.

The above losses can be represented diagramatically as given in Fig 15.14.

From Fig. 15.14, it is seen that Stator input—stator losses (i.e. copper and iron losses) = Stator output

But stator output = rotor input

Rotor output = Rotor input − rotor copper losses)

(iron losses are negligible)

$$\frac{\text{Rotor output}}{746}\ (\text{hp}) = \frac{2\pi\ TN_r}{60 \times 746}\ (\text{hp})$$

or $2\pi\ TN_r \times 746$ = rotor output × 60 × 746

Total torque developed,

$$T = \frac{\text{rotor output} \times 60 \times 746}{2\pi \times 746 \times N_r\ (\text{rotor speed})}\ Nm$$

$$\therefore \quad T = \frac{9.55 \times \text{rotor output}}{N_r} \qquad [15.8]$$

Let the rotor copper loss is equal to zero, then rotor output will be equal to rotor input and hence the rotor speed will be equal to synchronous speed (i.e. $N$).

$$\therefore T = 9.55 \times \frac{\text{Rotor input}}{N} \qquad [15.9]$$

From Eq. 15.8, we have, rotor output

$$= \frac{TN_r}{9.55} \qquad [15.10]$$

Similarly, from Eq. 15.9, we have rotor input

$$= \frac{TN}{9.55} \qquad [15.11]$$

Rotor copper loss = rotor input − rotor output

∴ Rotor copper loss

$$= \frac{TN}{9.55} - \frac{TN_r}{9.55}$$

$$= \frac{TN - TN_r}{9.55}$$

$$= \frac{T(N - N_r)}{9.55} \qquad [15.12]$$

But $N - N_r$ = Slip speed ($N_s$)

Rotor copper loss

$$= \frac{TN_s}{9.55}$$

$$\therefore \quad T = 9.55 \times \frac{\text{Rotor copper loss}}{N_s\ (\text{Slip speed})} \qquad [15.13]$$

Dividing Eq. 15.12 by Eq. 15.11, we have

$$\frac{\text{Rotor copper loss}}{\text{Rotor input}} = \frac{\frac{T(N - N_r)}{9.55}}{\frac{TN}{9.55}} = \frac{T(N - N_r)}{TN}$$

$$\frac{\text{Rotor copper Loss}}{\text{Rotor input}} = \frac{N - N_r \times 100}{N}$$

$$\frac{\text{Rotor copper loss}}{\text{Rotor input}} = \text{slip}$$

$\therefore$ Rotor copper loss

$$= \text{Rotor input} \times S \text{ (slip)} \qquad [15.14]$$

But Rotor output

= Rotor input − rotor copper loss

= Rotor input − rotor input × $S$

$\therefore$ Rotor Output

$$= \text{Rotor input } (1 - S) \qquad [15.15]$$

**NOTE:** Rotor shaft torque is always less than the total torque developed in the rotor due to windage and friction losses.

**EXAMPLE 15.8** *A three phase induction motor is taking 60 kW when slip is 4% The stator losses amounts to 4050 W. Find (i) per phase rotor copper loss (ii) total mechanical power developed in the rotor in hp.*

***Solution:***

Stator input

= 60 kW = 60,000 W

Stator losses

= 4050 W

Stator output (or rotor input)

= stator input — stator losses

= 60,000 — 4050

= 55950 kW.

But rotor copper loss

= Rotor input × slip

$$= 55950 \times \frac{4}{100} = 2238 \text{ W}$$

$\therefore$ Per phase rotor copper loss

$$= \frac{2238}{3} = 746 \text{ W} \qquad \textbf{Ans.}$$

Total mechanical power developed

= rotor input — rotor copper loss

= 55950 — 2238

= 53712 W

$\therefore$ Total mechanical power developed in hp

$$= \frac{53712}{746} = 72 \text{ hp} \qquad \textbf{Ans.}$$

**EXAMPLE 15.9** *A four-pole, three-phase 50 Hz induction motor takes 50 kW when the speed of the motor is 1455 rpm. The stator losses are 1.6 kW and the windage and friction losses 2.0 k W Find:*

*(i) Slip percentage*

*(ii) Rotor copper loss*

*(iii) Bhp*

*(iv) Efficiency of the motor*

***Solution:***

Synchronous speed, $N$

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

$$= \frac{50 \times 120}{4} = 1500 \text{ rpm}$$

Percentage slip, $S\%$

$$= \frac{N - N_r}{N} \times 100$$

$$= \frac{1500 - 1455}{1500} \times 100$$

$$= \frac{45 \times 100}{1500} = 3\% \qquad \textbf{Ans.}$$

Stator output

= Stator input — Stator losses

= 50 — 1.6 = 48.4 kW or 48,400W

But Stator output

= Rotor input = 48,400W

Rotor copper loss

= rotor input × slip

$$= \frac{48{,}400 \times 3}{100} = 1452 \text{ W} \qquad \textbf{Ans.}$$

Rotor output

= rotor input — (rotor copper loss + windage and friction losses)

= 48,400 — (1452 + 2000)

= 48,400 — 3452 = 44948 W

$\therefore$ Rotor output in Bhp

$$= \frac{44{,}948}{746} = 60.25 \text{ hp} \qquad \textbf{Ans.}$$

Efficiency percentage $\eta\%$

$$= \frac{44,948}{50,000} \times 100$$

$$= 89.89\%$$

**Ans.**

**Example 15.10** *A three phase six pole, 50 Hz induction motor is taking 20 kW. when the slip is 4.5% The stator losses amount to 1.0 kW. If the mechanical torque lost due to windage and friction is 24.79 N-m, find (i) B.H.P. (ii) Efficiency of the motor.*

*Solution:*

Stator output

$$= \text{Stator input} - \text{Stator losses}$$

$$= 20,000 - 1000 = 19000 \text{ W}$$

Stator output

$$= \text{Rotor input} = 19000 \text{ W}$$

Rotor. copper loss

$$= \text{Rotor input} \times \text{slip}$$

$$= 19000 \times \frac{4.5}{100}$$

$$= 855 \text{ W}$$

∴ Rotor output

$$= \text{Rotor input} - \text{Rotor copper loss}$$

$$= 19000 - 855$$

$$= 18145 \text{ W}$$

Synchronous speed $N$

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

$$= \frac{50 \times 120}{6} = 1000 \text{ rpm}$$

Rotor speed,

$$N_r = 1000 \times \frac{95.5}{100} = 955 \text{ rpm}$$

Total torque developed in rotor

$$T = 9.55 \times \frac{\text{rotor output}}{\text{rotor speed}}$$

or

$$T = \frac{9.55 \times 18145}{955}$$

$$= 181.45 \ N\text{—}m$$

Torque lost due to windage and friction.

$$= 24.79 \ N\text{—}m$$

Shaft torque

$$T_{sh} = \text{Total torque} - \text{lost torque}$$

$$= 181.45 - 24.79$$

$$= 156.66 \ N\text{—}m$$

∴ Bhp developed of motor

$$= \frac{2\pi T_{sh} N_r}{60 \times 746}$$

$$= \frac{2 \times 22 \times 156.66 \times 955}{7 \times 60 \times 746}$$

$$= 21.01$$

**Ans.**

Efficiency of the motor

$$= \frac{\text{Output} \times 100}{\text{Input}}$$

$$= \frac{21.01 \times 746 \times 100}{20,000}$$

$$= 78.36\%$$

**Ans.**

**Example 15.11** *A four-pole, three phase, 400 V, 50 Hz induction motor develops 10 hp. at 1455 rpm., the PF. being 0.8. Stator losses amount to 500 W and the frictional losses to 0.6 hp Find:*

*(i) Slip Percentage*

*(ii) Rotor copper loss.*

*(iii) Input of motor*

*(iv) Line current*

*(v) Efficiency*

*Solution:*

Synchronous speed,

$$N = \frac{f \times 120}{P} = \frac{50 \times 120}{4} = 1500 \text{ rpm}$$

Percentage slip

$$S\% = \frac{N - N_r}{N} \times 100 = \frac{1500 - 1455}{1500} \times 100$$

$$= \frac{45}{1500} \times 100 = 3\%$$

Output of motor

$$= 10 \times 746 = 7460 \text{ W}$$

Developed rotor output = Motor output + windage and frictional losses

$$= 7460 + 0.6 \times 746$$

$$= 7460 + 447.6$$

$$= 7907.6 \text{ W}$$

Rotor output

$$= \text{rotor input } (1-S)$$

$$7907.6 = \text{rotor input}\left(1 - \frac{3}{100}\right)$$

∴ Rotor input

$$= \frac{7907.6 \times 97}{100} = 7670.3 = \text{Say } 7670 \text{ W}$$

**Ans.**

Rotor copper loss

$$= \text{Rotor Input} \times \text{Slip}$$

$$= 7670 \times \frac{3}{100} = 230.1 \text{ W}$$

**Ans.**

Input of motor or stator

= Rotor input (i.e. output of stator) + Stator losses

$$= 7670 + 500 = 8170 \text{ W}$$

**Ans.**

But $\sqrt{3}\ V_L \times I_L \times \cos\phi = W$

∴ Line current

$$I_L = \frac{W}{\sqrt{3}\, V_L \times \cos\theta}$$

$$= \frac{8170}{\sqrt{3} \times 400 \times 0.8}$$

$$= 14.74 \text{ A}$$ **Ans.**

Efficiency percentage,

$$\eta\,\% = \frac{\text{output}}{\text{input}} \times 100$$

$$= \frac{7460 \times 100}{8170}$$

$$= 91.30\%$$ **Ans.**

**EXAMPLE 15.12** *A 400-V, three-phase induction motor has per-phase resistance of 100 Ω. Calculate (i) the power taken from the supply mains in:*

*(a) Star*

*(b) Delta*

*(ii) If one phase of the three windings is disconnected from the other two windings, what would be the power taken from the mains in each case.*

***Solution:***

(*a*) In Star Connection

$$\sqrt{3}\, V_{ph} = V_L$$

∴ Phase voltage

$$= \frac{V_L}{\sqrt{3}} = \frac{400}{\sqrt{3}} \text{ V}$$

Resistance/phase = 100Ω

Current in per phase winding $= \dfrac{\text{Phase voltage}}{\text{Resist/phase}}$

$$= \frac{\frac{400}{\sqrt{3}}}{100}$$

$$= \frac{400}{\sqrt{3} \times 100} = \frac{4}{\sqrt{3}} \text{ A}$$

But $I_{ph} = I_L$

∴ Line current,

$$I_L = \frac{4}{\sqrt{3}} \text{ A.}$$

Power Factor,

$$\cos\phi = \frac{R}{Z} = \frac{100}{100} = 1$$

Power taken in star,

$$W = \sqrt{3} \times V_L \times I_L \times \cos\theta$$

$$= \sqrt{3} \times 400 \times \frac{4}{\sqrt{3}} \times 1$$

$$= 1600 \text{ W}$$ **Ans.**

(*i*) (*a*) *Star Connection*

This circuit will now function as a simple series circuit.

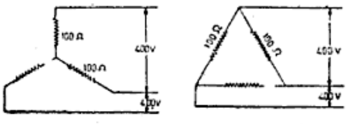
∴ Current between *A* and *B*

$$= \frac{V_L}{R_1 + R_2} = \frac{400}{100 + 100}$$

$$= \frac{400}{200} = 2 \text{ A}$$

Power absorbed

$$W = V \times I = 400 \times 2 = 800 \text{ W}$$ **Ans.**




(a) (b)

(*i*) (*b*) *Delta Connection*

As $V_{ph} = V_L = 400$ V

Current per phase

$$= \frac{V_{ph}}{R_{ph}} = \frac{400}{100} = 4 \text{ A}$$

∴ Line current

$$= \sqrt{3}\, I_{ph}$$

$$= 4\sqrt{3} \text{ A.}$$

∴ Power taken in delta,

$$W = \sqrt{3}\, V_L \times I_L \times \cos\phi$$

$$= \sqrt{3} \times 400 \times 4\sqrt{3} \times 1$$

$$= 4800 \text{ W}$$ **Ans.**

(*ii*) *In Delta Connection*

Voltage across each phase = 400 V

Current per phase

$$= \frac{400}{100} = 4 \text{ A}$$

Power consumption

$$= 2 \times I^2 R$$

$$= 2 \times (4)^2 \times 100$$

$$= 3200 \text{ W}$$ **Ans.**

## 15.16 COMPARISON OF A SLIPRING AND SQUIRREL CAGE INDUCTION MOTOR

| Sl. No. | Factors | Squirrel cage induction motor | Slipring induction motor |
|---|---|---|---|
| 1. | Starting Current | Starting current of the motor is large and is approximately 6 times its rated current. | The motor takes low starting current which is nearly twice the rated current of the motor. |
| 2. | Power Factor | Power factor of the motor is low. | Power factor as compared to squirrel cage motor is high. |
| 3. | Starting Torque | Starting torque is poor but running torque is good. | Starting torque of slipring induction motor is higher than a squirrel cage induction motor. |
| 4. | Speed Control | Speed can be changed by changing the number of poles of the stator winding. | Speed cannot be changed by changing the poles but can to some extent be changed by inserting resistance in the rotor circuit. |
| 5. | Starting Device | Motor can be started with a star—delta starter. There is no need of starting resistance, and starting gear as in case of slipring starter. | For starting motor requires slipring starter alongwith starting resistance. |
| 6. | Cost | Cheaper than slipring induction motor. | Costlier |
| 7. | General Maintenance | Less | More |
| 8. | Application | Used for constant speed works where low starting torque is required such as water pumps, lathes, drill machines, grinders, etc. | Employed where only high starting torque is needed as in cranes, lifts, etc. |

## 15.17 GENERAL TROUBLES AND REMEDIES OF THREE-PHASE INDUCTION MOTORS

The undermentioned are the general troubles and remedies of three phase induction motors.

**1. Motor Fails to Start**

| S. No. | Cause | Test | Remedy |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| | (i) Too low or high voltage. | Measure Voltage at the terminals of motor with voltmeter and compare it with its rated voltage. | Repair circuit and rectify the causes of low voltage such as loose contacts in starter, main switch, distribution box, etc. |
| | (ii) Failure of supply (completely or partially) | (i) Test the presence of supply in starter. | (i) Renew fuses. |
| | | (ii) Check connection and contacts of starter for loose and open circuit. | (ii) Tighten connections properly and repair starter if required. |

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| (iii) | Wrong connection | Compare connection with original diagram of motor. | Still motor does not start, reconnect after disconnecting the connection of motor. |
| (iv) | Wrong phase-sequence | Reverse stator phases one by one and start the motor. | If still trouble remains, then check phase sequence of motor. |
| (v) | Overload | Measure starting torque required by load. | (i) Reduce load; (ii) raise tapping on auto-transformer; (iii) install motor of higher output. |
| (vi) | Damaged bearings | Open motor and check the play of bearings. | Replace if required. |
| (vii) | Faulty stator winding | Measure per phase current and they should be equal; if required, measure per phase resistance; check insulation resistance between winding and earth. | Repair fault if possible or rewind stator. |
| (viii) | Brushes and rings in bad condition. | Measure brush pressure by spring balance; check whether sticking in brush holders, examine bedding of brushes and surface of sliprings. | (i) Adjust brush pressure as recommended; grind and (ii) re-bed if surfaces are not smooth; smoothen surfaces of slipring with sand paper. |

**2. Motor Starts but does not Share Load (i.e. Runs at Low Speed when Loaded)**

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| (i) | Too low a voltage | Measure voltage at motor terminals and varify it with name plate. | (i) Renew bad fuses; (ii) repair circuit and remove the cause of low voltage like loose or bad contacts in starter, switches, distribution box, etc. |
| (ii) | Bad connection | Check connection and contact of starter for loose contact. | Remove the fault as required. |
| (iii) | Wrong adjustment of current adjuster. | Check current adjusting knob for proper adjustment. | Adjust the current adjusting knob at proper range as necessary. |
| (iv) | Too low or high tension on driving belt. | Measure tension and varify it with the instruction of manufacturer. | Adjust belt tension. |
| (v) | Open circuit in rotor winding. | (i) Examine rotor bars and joints in case of squirrel cage rotor (which causes heat) | (i) In case of squirrel cage rotor resolder the bar joints. |
| | | (ii) Disconnect starter from sliprings. Supply reduced voltage to the stator and measure the voltage between the sliprings which should be equal. | (ii) Repair if possible or rewind slipring rotor. |

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| (vi) | Faulty stator winding | Check for continuity, short circuit and leakage test as described before. | Repair the circuit if possible or rewind the stator. |
| (vii) | Defective bearings. | Examine bearings for small play. | Replace bearings. |
| (viii) | Incorrect condition, size or grade of replaced brushes. | Check condition, size and grade of brushes against manufacturer's specifications. | (i) Use correct size and grade of brushes; (ii) adjust brush pressure; (iii) re-bed the brushes; (iv) smoothen the surface of sliprings. |
| (ix) | Excessively loaded | Measure the line current of the motor and compare it with its rated current. | Reduced mechanical load on the motor. |
| (x) | Low frequency | Measure the line frequency with frequency meter. | Motor should be of the same frequency as that of the supply. |

**3. Motor Blows off Fuses**

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| (i) | Incorrect size of fuses | Check the size of the fuse wire (it should be rated for three times than its normal current); Connect ammeter in the circuit and test for excess load current. | (i) Replace the fush wire if necessary; (ii) repair the motor if it is due to electrical fault of stator or rotor. |
| (ii) | Low Voltage | Measure line voltage. | Remove the cause of low voltage. |
| (iii) | Excessively loaded | Measure line current and compare it with its rated current. | Rectify the cause of overload or instal motor of higher output rating. |
| (iv) | Faulty stator winding | Check for open circuit, short circuit or leakage test of the stator as explained earlier. | Repair the fault and if not possible then rewind the stator. |
| (v) | Loose connection in starter | Check for loose or bad connection in starter because it may cause unbalancing of current. | Rectify the loose connection; Clean all the contact points of starter with sand paper. |
| (vi) | Wrong connection | Check connection with original diagram. | Reconnect the motor if it still does not start. |
| (vii) | Wrong phase-sequence | Change stator phases one by one and run the motor. | If motor does not run, find the phase sequence. |

**4. Over Heating of Yoke**

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| (i) | Too high or low a voltage. | Check voltage at the terminal of the motor. | Rectify the cause of low or high voltage as the case may be. |
| (ii) | Wrong connection | Compare connection with circuit given diagram. | Reconnect the connection if required. |

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| (iii) | Wrong phase-sequence | Reverse stator phases one by one, and try to start the motor. | If trouble remains find the phase sequence of the motor. |
| (iv) | Open circuit or faulty rotor winding as short circuit or leakage. | (i) In case of squirrel cage rotor, loose joints of rotor bars causes heat. | (i) Resolder the joints of rotor bars and end rings. |
| | | (ii) In case of slipring rotor, there should be no-short circuit, open circuit or leakage. Measure per phase resistance and insulation resistance of rotor. | (ii) Repair if possible or rewind slipring rotor. |
| (v) | Faulty stator winding | Check for continuity, short circuit and leakage test as stated before. | Remove the fault if possible otherwise rewind the stator winding. |
| (vi) | Dirt in ventilation ducts | Inspect ventilation ducts for any dust or dirt in them. | Remove dirt and dust from them if any. |

**5. Overheating of Bearings**

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| (i) | Too much grease in bearings of unsuitable grade | Check grade and quantity of grease after removing the bearing coupling. | Put grease of proper grade and quantity in bearings. |
| (ii) | Loose or damaged bearings | Open end-covers of motor and check condition of bearings. | Raplace new bearings if old ones are damaged. |
| (iii) | Loose housing of bearings | Remove end covers and check fitting of outer race of bearings in housing. | (i) Put shim in housing if loose. (ii) If too loose housing, send for filling of material in workshop. |
| (iv) | Inner race of bearing loose on shaft. | Remove rotor and check fitting of inner race of bearings on shaft. | Send rotor in repair shop for filling the material on shaft, if necessary. |
| (v) | Wrong size of bearings | Remove end covers and check number and make of bearing. | Replace bearing as recommended by the manufacturer. |
| (vi) | Bad fitting of new bearings. | Open end-covers and inspect any friction on rotor or stator. | Refit bearing properly. |
| (vii) | Too high tension on driving belt. | Inspect tension on belt. It should be as directed. | Open and refit belt. |
| (viii) | Wrong alignment of mechanical (or belt) coupling. | Check alignment with spirit level or with thread in case of belt coupling. | Re-align the coupling system properly. |

6. **Overheating of Brushes or Sliprings**

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| (i) | Too low (or high) voltage. | Measure voltage at the motor terminals, it should be as instructed. | Rectify the cause of too low (or high) voltage as explained before. |
| (ii) | Overloaded | Measure line currents and compare with rated current. | Reduce load or install motor of greater output. |
| (iii) | Faulty rotor winding | Test for continuity, short circuit and leakage. | Remove the faults. |
| (iv) | Faulty stator winding | Same as above. | Same as above. |
| (v) | Brushes or sliprings in Worn-out condition | Inspect brushes and sliprings for damaged surfaces like pits, carbonised etc. | (i) Grind and re-bed the brushes tension. (ii) Smoothen surfaces of sliprings with sand paper. |
| (vi) | Wrong size and grade of replaced brushes | Check size and grade of brushes installed. | Replace brushes of correct size and grade according to instructions of supplier. |

7. **Magnetic Noise due to Stator**

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| (i) | Wrong connection | Check connection according to drawing supplied. | Reconnect the connection. |
| (ii) | Wrong phase-sequence | Reverse stator phases turn by turn and attempt to start the motor. | If still trouble persists, find phase sequence of motor. |
| (iii) | Partial Failure of supply | Measure voltage across the motor terminals. | Renew fuses and repair the circuit if necessary. |
| (iv) | Open circuit in rotor | Check for open circuit in rotor winding of slipring motor. | Repair if possible or rewind rotor. |
| (v) | Open circuit in stator winding. | Test for open circuit in stator winding. | Same as above. |

8. **Magnetic Noise due to No-Volt-Coil**

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| (i) | Low voltage | Measure voltage across coil, it should not be less than 85 per cent of rated voltage. | Remove the cause of low voltage as discussed earlier. |
| (ii) | Dust, dirt on the face of core. | Examine the face of core for dust, dirt. | Clean the face of core. |
| (iii) | Open-circuit in shaded ring. | Confirm the continuity. | Remove open circuit, if any. |
| (iv) | Face of core not lined up correctly. | Inspect mechanical fitting of core. | Adjust alignment properly. |
| (v) | Shaded ring lost | Examine the existance of rings. | Provide new ring on the face of core if lost. |
| (vi) | Both shaded rings on same side. | Check for the said cause. | Open and adjust the rings on opposite to each other. |

9. **Mechanical Noise**

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| (i) | Improper fitting of end-covers. | Measure air-gap at four different points for uneven position of rotor covers. | (i) Open screws of side covers and then tighten one by one. (ii) If trouble still persists, remove end cover, shift for next position and tighten screws again. |
| (ii) | Improper alignment of coupling. | Check alignment as instructed before. | Realign coupling. |
| (iii) | Foreign material in air-gap. | Examine air-gap. | File or clean out air-gap. |
| (iv) | Loose fan or bearings. | Check looseness of fan screw or bearings. | Tighten fan screw or refit new bearings, if necessary. |
| (v) | Slackness in bearing on shaft or in housing. | Remove bearings and inspect inner looseness of race on shaft and outer race in housing. | Send motor for repairshop to remove the looseness of shaft or housing, if any. |
| (vi) | Improper fitting of bearings. | Remove end-covers and examine assembly of bearings on shaft or in housing. | Refit bearings on shaft or in housing. |
| (vii) | Minor bend in shaft. | Check for alignment on lathe. | Remove bend or replace shaft, if required. |

10. **Sparking at Brushes**

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| (i) | Low voltage | Check voltage at motor terminals. | Remove the cause of low voltage. |
| (ii) | Motor overloaded | Measure line current and compare with rated current. | Remove cause of overload. |
| (iii) | Faulty rotor circuit | Perform continuity, short circuit and leakage test. | Repair circuit if possible or rewind rotor. |
| (iv) | Faulty stator circuit | Same as above. | Same as above. |
| (v) | Sliprings or brushes in bad condition. | Check condition of surfaces of sliprings and brushes. | Clean surfaces of sliprings with sand paper and re-bed brushes. |
| (vi) | Improper grade and size of of brushes. | Check grade and size of brushes. They should be according to the instructions of manufacturer. | Replace proper grade of brushes. |

11. **Vibration**

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| (i) | Loose foundation bolts or nuts. | Inspect nuts and bolts of foundation for improper tightening. | Tighten foundation nuts. |
| (ii) | Wrong alignment of coupling. | Check alignment with spirit level or thread. | Realign the coupling system. |
| (iii) | Faulty magnetic circuit of stator or rotor. | Check in same way as before. | Same as earlier. |

TABLE 15.1 DRIVING MACHINE TOOL MOTORS FOR SMALL WORKSHOP (APPROXIMATE VALUES OF HP OF MOTORS)

| *Sl. No.* | *Particulars of machine* | *Hp required* |
|---|---|---|
| 1. | **Pedestal Grinder** | |
| | Single-stone or double-stone wheel | $\frac{1}{2}$ to 2 |
| 2. | **Drill machine** | |
| | Portable small drill machine | $\frac{1}{4}$ to $\frac{1}{2}$ |
| | Portable heavy drill machine | $\frac{1}{2}$ to 1 |
| | Verticle radial drill machine | 2 to 4 |
| 3. | **Lathe machine** | |
| | Screw cutting Lathe machine upto 15 cm | $\frac{1}{2}$ to 1 |
| | Screw cutting lathe machine from 30 to 75 cm | 2 to 5 |
| | Turret Lathe Machine | 2 to 4 |
| 4. | **Milling machine** | |
| | Small milling machine | $\frac{1}{2}$ to 1 |
| | Medium milling machine | 2 to 4 |
| | Heavy milling machine | 4 to 5 |
| 5. | **Shaper machine** | |
| | Stroke upto 30 cm | $\frac{1}{2}$ to 1 |
| | Stroke from 30 to 60 cm | 1 to 2 |
| 6. | **Planner machine** | |
| | 180 cm × 60 cm, stroke 60 cm | 3 to 5 |
| 7. | **Slotter machine** | |
| | Stroke upto 30 cm | 2 to 5 |
| | Stroke 30 cm to 60 cm | 5 to 10 |

## NUMERICAL EXERCISES

15.1 An induction motor has eightpoles and operates on 40 Hz supply. If it operates on full load at 570 rpm, calculate the percentage slip. (Ans. 5%)

15.2 An induction motor having 4 pole operates on 60 Hz supply. If it works on full load at 1746 rpm, calculate the percentage slip. (Ans. 3%)

15.3 A 12 pole motor running from 50 Hz supply, has an emf in the rotor of frequency 2 c/s. Find:

(i) Percentage slip.

(ii) The actual speed of the motor. (Ans. (i) 4% (ii) 480 rpm)

15.4 An eight-pole alternator runs at 750 rpm and supplies power to a four pole induction motor which has a slip of 3 per cent at full load. Find the full load speed of the motor. (Ans. 1455 rpm.)

15.5 A three phase supply of 373V is given to an induction motor which takes a current of 43.3 A at power factor 0.8. If the efficiency of the motor is 85 per cent, find the hp developed of the motor. (Ans. 25.5 hp)

15.6 Find the horse power developed by a 433 V three-phase 50 Hz induction motor when it takes a current of 74.6 A at PF 0.8 when the efficiency of the motor is 75%. (Ans. 45 hp)

15.7 A three phase supply at 373 V is given to an induction motor, taking a current of 86.6 A at power factor 0.8. If the efficiency of the motor is 90 per cent, calculate the output of the motor. (Ans. 54 hp)

15.8 Find the hp metric developed by a 433 V, three-phase, 50 Hz induction motor when it takes a current of 147.1 A at 0.8 power factor. The efficiency of the motor is 75%. (Ans. 90 hp metric)

15.9 Find the power factor of a 500 V, three-phase induction motor giving an output of 30 H.P. metric while taking a current of 58.84 A. At this load the efficiency of the motor is 86.6%. (Ans. 0.5)

15.10 Calculate the current in each of the supply line of a three phase, 373 V, 27 hp induction motor at 0.8 power factor. Assume the efficiency of the motor as 90%. (Ans. 43.3 A)

15.11 The full-load efficiency of a delta-connected, three-phase induction motor is 90 per cent and the power factor is 0.8. The output of the motor is 40.5 hp at 2238 V supply. Calculate the line and phase current.

(Ans. 10.825 A, 6.252 A)

15.12. An ac three-phase 433V induction motor of 81 hp is operating at Power Factor 0.8 and the efficiency of the motor is 90 per cent. Calculate (i) the current in the mains, (ii) the current in each phase winding if motor is:

(a) Star connected.
(b) Mesh connected.

(Ans. $I_L$ = 111.9 A, $I_{ph}$ star = 111.9A, $I_{ph}$ mesh = 64.6A)

15.13 An ac motor coupled to dc generator operating on a three phase 866V mains at PF 0.8 and delivers 25A at 270V. Assume the efficiency of the each to be 75 per cent. Find:

(i) The line current of the motor
(ii) Phase current of the motor if it is delta connected (Ans. (i) 10A, (ii) 5.773A)

15.14 A 54-hp (metric), three-phase, delta-connected motor is supplied from 433V mains. The efficiency of the motor at full load is 75 per cent and the power factor is 0.8. Find:

(i) Line current
(ii) Current through each phase winding
(iii) kVA input of the motor

Ans. 88.26A, 50.94A, 66.19 kVA

15.15 The rotor of a three phase star connected slipring induction motor has a resistance and standstill reactance of 3Ω and 4Ω per phase respectively. The emf induced between the sliprings at standstill is 90V. When the stator is connected to the normal supply voltage, calculate (i) the rotor phase current and (ii) PF at starting when rings are:

(a) short-circuited
(b) jointed to a star-connected rheostatic resistance of 6.16Ω per phase.

Ans. (i) 10.392A, 0.6 (ii) 5.199A, 0.9164

15.16 A three-phase, 12-pole, 50-Hz, sliprings induction motor is running at full load with a slip of 5%. The rotor is star connected and has resistance and standstill reactance of 0.4Ω and 6Ω per phase respectively. The EMF between sliprings at standstill is 173.2V. Find for full load condition:

(i) Per-phase emf induced in rotar
(ii) Per-phase impedance of rotor
(iii) Rotor per phase current
(iv) Power factor (Ans. (i) 5V, (ii) 0.5Ω, (iii) 10A, (iv) 0.8)

Assume the sliprings are short circuited.

15.17 A 54-hp metric, 441.3V, three phase Induction motor has full load PF 0.75 and efficiency 80 percent. Calculate the current in the stator coil of the motor if:

(i) Star connected
(ii) Mesh connected
(iii) Find also cost of energy at the rate of 40 paise per kWh when running on full load for 16 hours.

(Ans. (i) 86.6A, (ii) 50A, (iii) Rs. 317.74)

15.18 A 75-hp motor runs for 20 hours at 80 per cent of the load when connected to a 400V, three phase, 50-Hz supply. The P.F. of the motor is 0.75 and the efficiency of the motor is 93.25 per cent. Calculate:

(i) Line current of the motor
(ii) Cost of energy consumed at the rate of 35 paise/kWh (Ans. (i) 92.37A, (ii) Rs. 336.00)

15.19 The input to a three phase induction motor is 75 kW. The stator losses are 5062.5W. Find:

(i) Rotor copper loss per phase
(ii) Total mechanical power developed in hp if the slip is 4%.

(Ans. (i) 932.5W, (ii) 90 hp)

15.20 The power input to a three-phase induction motor is 42 kW, the slip being 3 per cent. Stator losses amount to 850W. Calculate the total power developed of the rotor in hp. (Ans. 53.5 hp)

15.21 A four pole squirrel cage induction motor is connected to 40 Hz supply and at full load the frequency of the induced current in rotor is 120 cycles in 2 minutes. Find (i) the percentage slip and (ii) rotor speed.
(Ans. (i) 2.5%, (ii) 1170 rpm)

15.22 A three-phase, four-pole 400V, 50 Hz induction motor develops 23 hp at 1440 rpm. The efficiency of the motor is 92 per cent and its PF is 0.8. Stator losses amount to 1200W and the friction and windage losses, 1,500W. Calculate:
(i) Percentage slip
(ii) Rotor copper loss (Ans. (i) 4%, (ii) 698W)

15.23 A three-phase, six-pole, 50 Hz induction motor develops 10 hp at 960 rpm. What is stator input if the stator losses are 529.17W. (Ans. 8.3 kW)

15.24 The power input to a six pole, three-phase, 50 Hz induction motor is 45 kW when the speed of the motor is 960 rpm. The stator losses are 1.5 kW and windage and friction losses 1476W. Find:
(i) Percentage slip
(ii) Rotor copper loss
(iii) Bhp
(iv) Efficiency of the motor (Ans. (i) 4%, (ii) 1740W, (iii) 54 hp, (iv) 89.52%)

15.25 A four-pole, three phase, 50 Hz, sq, cage induction motor takes 20 kW when the speed of the motor is 1440 rpm.. The stator losses are 1000W and the windage and friction losses are 588W. Find :
(i) Percentage slip
(ii) Rotor copper loss
(iii) Bhp metric
(iv) Efficiency of the motor (Ans. (i) 4%. (ii) 760W, (iii) 24hp, (iv) 88,26%)

15.26 A three phase induction motor is taking 25 kW, the slip being 4 per cent. Stator losses are 500W. Find the total power developed in the rotor. (Ans. 23.52 kW)

15.27 A three-phase, 8 pole, 50 Hz induction motor is taking 40 kW when running at 720 rpm. Stator losses amount to 800 W and windage and friction losses to 1824 W. Calculate:
(i) Rotor copper loss
(ii) Bhp
(iii) Efficiency of the motor (Ans. (i) 1568 W, (ii) 48 hp, (iii) 89.52%)

15.28 A three-phase, six-pole, 50 Hz induction motor is taking 32 kW when slip is 4%. The stator losses are 2 kW. If the mechanical torque lost due to windage and friction is 51.51 N m, find (i) Bhp, (ii) efficiency of the motor. (Ans. (i) 31.68 hp, (ii) 73.86%)

15.29 A 12-pole, three-phase, 50 Hz induction motor develops 77 hp at 490 rpm. Stator losses amounts to 2500 W and friction losses to 27 N m. Find (i) slip percentage, (ii) input to motor, (iii) rotor copper loss, (iv) efficiency of the motor. (Ans. (i) 2%, (ii) 60 kW, (iii) 1.2 kW, (iv) 91.9%)

15.30 A 12-pole, three-phase, 2 50 V, 50 Hz induction motor develops 38.5 hp at 490 rpm, the PF being 0.8. Stator losses are 3000 W and friction losses 13.5 N m. Find (i) percentage slip, (ii) input to motor, (iii) rotor copper loss, (iv) efficiency of the motor, (v) line current to motor.
(Ans. (i) 2%, (ii) 33kW, (iii) 600 W, (iv) 87.04%, (v) 95.26 A)

15.31 An eight-pole, three-phase, 50 Hz induction motor gives its full load output of 25 hp when runs at 720 rpm. Stator losses are 1.5 kW and mechanical torque lost is 16 Nm. Calculate:
(i) rotor copper loss, (ii) input to motor, (iii) efficiency of motor
(Ans. (i) 826.96 W, (ii) 22174 W, (iii) 84.1%)

15.32 A three-phase, 250 V induction motor has per phase resistance of 50 Ω. Calculate (i) the power taken from the supply main in (a) star and (b) delta connections, (ii) if one phase of the three-phase winding is disconnected from the other windings, what would be the power taken from the mains in each case.
(Ans. (i) star—1250 W, Delta—3750 W, (ii) star—625 W, Delta—2500 W)

15.33 A three-phase 400 V induction motor has per phase resistance of 50Ω. Find (i) the power taken in (a) star and (b) delta connections. (ii) If one of the effect on supply main is disconnected due to single phasing, what would be the effect on power drawn from the mains in each case.
(Ans. (i) Star—3200 W, Delta—9600 W, (ii) Star—1600 W, Delta—4800 W)

15.34 A three-phase 250-V, 50-Hz star-connected induction motor has per phase resistance and reactance of 11.88Ω and 0.0W respectively. Calculate (i) the power taken from the supply mains. (ii) If one of the three phases is disconnected from star point, what would be the power taken and its effect on the motor. (Hint: From (ii), it is clear that the motor would take twice the current to meet the required full load of 1188 W during its normal course. Hence, it would be burnt).

(Ans. (i) 1188 W, (ii) 594 W)

## REVIEW QUESTIONS

15.1 ( ) How is rotation produced in a three-phase induction motor? What do you understand by slip of the motor?

(ii) How can the speed of a three-phase induction motor be changed? *(NCVT 1979, 1982 Elect)*

15.2 (i) What is "slip" of an induction motor.

(ii) A star-connected, three-phase induction motor draws 4 A when connected across a 400-V 50 Hz supply. If the power factor is 0.8 and efficiency of the motor 90%, how much Bhp will the motor develop.

(Ans. 2.674 hp approx.)
*(NCVT 1980 Elect.)*

15.3 An eight-pole alternator runs at 750 rpm and supplies power to a 6 pole induction motor which has a full load slip of 3 per cent. Find the full load speed of the induction motor. (Ans. 970 rpm.)
*(NCVT 1969 Elect.)*

15.4 Describe the principle of an induction motor. What are the various methods of starting it? Explain with diagram the star-delta starter method of starting. *(NCVT 1968 Elect.)*

15.5 Describe briefly the difference in principle and construction between a squirrel cage induction motor and a slipring induction motor. *(NCVT 1970 Elect.)*

15.6 An ac three-phase, 440-V, 30 hp, induction motor is running at 0.8 power factor and at 86 per cent of full load. Calculate the line current. (Ans. 31.56 A)
*(NCVT 1963 Elect.)*

15.7 Describe briefly the working principle of slipring type induction motor. How its speed control is effected. *(NCVT 1962 Elect.)*

15.8 Explain the working of a slipring type induction motor and the accessories that are required for operation of the same. A wiring diagram giving connections of the motor including starting equipment etc. to the main supply should be drawn. *(NCVT 1965 Elect.)*

15.9 (i) Explain the need of a starter for starting a three-phase squirrel cage induction motor.

(ii) Describe three different types of starters used for such motors and briefly compare their merits and demerits.

(iii) What are the safety devices used in the stator. Which type of starter will you prefer for a 10-hp squirrel cage induction motor and why. *(NCVT 1978 Elect. 1983 W/man)*

15.10 Describe with a neat sketch the working of a star-delta starter. Explain the protective devices in it.
*(NCVT 1980 W/man, 1984 Elect.)*

15.11 Describe two different types of starter for a three phase squirrel cage motor and compare their relative advantages and disadvantages. *(NCVT 1971 Elect.)*

15.12 Mention the different types of starting equipments required for induction motors. Show with the help of a sketch internal arrangement of a rotor resistance starter for slipring induction motor. What is an overload safety device and explain how it functions in a starter. *(NCVT 1970 W/man)*

15.13 Describe the effects of inserting resistance in the rotor circuit of a slipring induction motor.

15.14 Describe two different types of starters for a three phase squirrel cage motor and compare their relative advantages and disadvantages. *(NCVT 1971 Elect.)*

15.15 What type of ac and dc motors will you prefer for the following:

(i) Railway traction

(ii) Lifting cranes

(iii) Driving workshop machinery
(iv) Constant speed grinding machines
(v) Large-size centrifugal pumps
(vi) House-hold fans

15.16 Define the following:
(i) Slip
(ii) Fractional slip
(iii) Synchronous speed
(iv) Rotating magnetic field

15.17 Draw the connection diagram of 400 V, three-phase, 50 Hz supply, 30-hp induction motor with resistance starter. Provide an ammeter to indicate the load current. What is the full load current if PF is 0.8 at full load. (Ans. 40.37 A)
(*NCVT, 1967 Elect.*)

15.18 A four-pole 50 Hz induction motor is running at 1445 rpm. Find the fractional slip. (Ans. 0.0367)
(*NCVT. 1981 Elect.*)

15.19 A six-pole induction motor is connected to 25 c/s frequency supply at full load, rotor emf makes 105 complete cycles in 2 minutes. Find the percentage slip and rotor speed of motor.

(Ans. 3.5%, 482.5% rpm)
(*State level compt. 1982 Elect.*)

15.20 (a) Why it is necessary to use starter for starting ac motor

(b) Draw a neat sketch of a direct on line three phase ac starter showing essential protection provided in the starter. (*NCVT 1983 Elect.*)

15.21 (a) What are the types of three phase induction motor. What are the specialities of each type and for which uses is each of them suitable.

(b) Why are startors necessary for starting induction motors. (*NCVT 1984 Elect.*)

# 16

# Synchronous Motors

A synchronous motor is a machine which converts electrical energy into mechanical energy while rotating at a constant speed equal to synchronous speed.

When a dc generator is supplied with electrical energy, it runs as a dc motor. Similarly an alternator can also run as an ac motor, if ac supply is given to the armature winding and dc supply to the field winding. Such type of motor is known as synchronous motor.

## 16.1 WORKING PRINCIPLE AND APPLICATIONS

In Fig. 16.1, a part of the stationary field type synchronous machine is shown in which North and South are two field poles and 1,2,3 are the poles of the armature. The polarity of the armature poles will change according to the frequency of the supply to which they are connected.

Suppose at the moment of starting pole 1 be the South pole, 2 the North pole and 3 the South pole. At this moment a torque will act on the rotor which will tend to rotate the rotor in clockwise direction as shown in Fig. 16.1 (a). During the next moment, the polarity of the rotor poles 1,2,3 will change and will become North, South, North respectively as shown in Fig. 16.1 (b) and in this position an anticlockwise torque will act on the rotor. But the time for the change of polarity is very short, so the rotor will remain standstill against the alternating torque developed as explained.

It is clear from the above that the motor is not self-starting type when dc supply is given to its field winding and ac supply to the armature winding. So to enable the motor self starting, its rotor is rotated at such a speed that in the time when the rotor poles change their polarity, the rotor must moves through one pole pitch and thus a torque will again act on the rotor in the clockwise direction as shown in Fig. 16.1 (c).

From the above, we conclude that the synchronous motors are not self starting type and for continuous motion they have to be rotated at the time of starting at the synchronous speed, which is given by the formula:

$$N = \frac{f \times 120}{\text{No. of Poles}}$$

It is also clear from the above that a synchronous motor can only operate at fixed speed which is known as synchronous speed. For example if a synchronous motor is of 4-pole, 50-Hz supply, it will only operate at 1500 rpm. The motor can neither operate at

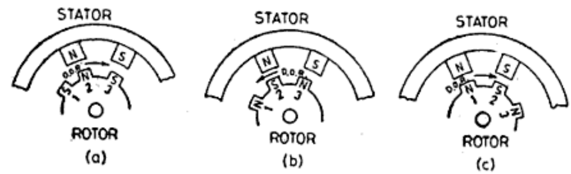



Fig. 16.1 Working principle of synchronous motor

speed 1501 nor at speed 1499. It is a great disadvantage of this motor.

*Advantages*

1. It is a constant-speed motor and its speed remains constant from no load to full load.
2. By varying the field excitation, the power factor can be adjusted as desired.

*Disadvantages*

1. These motors cannot be used for variable mechanical load.
2. As this motor is not self starting type, so can not be started on load.
3. To operate the motor its field system specially requires dc supply only.
4. This motor cannot be utilized for variable speed work.
5. Hunting is also produced in this motor.

**Industrial Application of Synchronous Motor**

1. These motors are used in power houses, in sub-stations for the improvement of power factor. For this purpose, it is connected in parallel to supply line and is run without load under over-excitation of field.

2. These motors are also employed in big industries where many induction motors are installed to improve the power factor of the supply.

3. These motors can also be used at constant mechanical load only because a slight variation of load causes to stop the motor action.

## 16.2 STARTING OF SYNCHRONOUS MOTOR

It is clear from the above explanation that the synchronous motors are not self starting and have to be rotated at the time of starting to their synchronous speed. A synchronous motor can be started by any one of the following methods:

(i) By pony motor
(ii) As an induction motor.

**Starting by Pony Motor** In this method another small ac induction motor (or an oil engine) of pair of poles one less than the pair of poles of synchronous motor is mechanically coupled with the shaft of the synchronous motor. This small pony induction motor is first started from ac supply mains and then dc supply from the exciter of the motor is given to the field poles of the synchronous motor. At this time the ac supply to the armature (i.e. stator) of the synchronous motor is switched off. The synchronous machine now operates as a synchronous generator and an alternating emf is generated in its armature winding. After this, the synchronous machines, now operating as a synchronous alternator and is synchronized with the supply. After synchronizing, the supply to the pony motor is cut off and now the machine continues to work as a synchronous motor.

**Starting as an Induction Motor** In this method, the motor starts as an ordinary squirrel cage induction motor and later on operates as a synchronous motor. In this method damping winding is provided on the face of the salient poles of the rotor as shown in Fig. 16.2 which acts as a squirrel cage winding on the rotor. The damping winding consists of thick copper bars placed in the slots made on the pole faces of the rotor and short circuited by heavy copper rings at both the sides of the rotor.

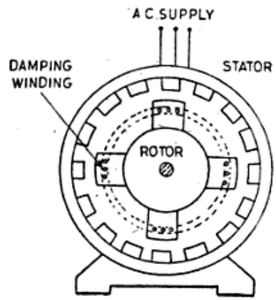



**Fig. 16.2 Synchronous motor starts as a squirrel-cage induction motor**

To start the synchronous motor, the dc supply to the field winding is kept disconnected and the ac supply is given to the

TABLE 16.1 COMPARISON OF SYNCHRONOUS INDUCTION MOTOR AND INDUCTION MOTOR

| *S. No.* | *Synchronous motor* | *Induction Motor* |
|---|---|---|
| 1. | It runs at constant synchronous speed and does not decrease within the constant load of its capacity. | The speed of an induction motor falls somewhat with the increase of load. Its speed is always less than synchronous speed due to slip. |
| 2. | It is not a self-starting motor. | It is a self-starting motor. |
| 3. | Speed control is not possible. | Speed can be controlled to somewhat limits. |
| 4. | It can operate at all power factors, such as lagging or leading etc. | Induction motor always runs with lagging power factor only. |
| 5. | A dc excitation is required for the field excitation of the synchronous motor. | No need of dc excitation as it is a self starting motor. |
| 6. | Synchronous motor has high efficiency. | Induction motor has low efficiency. |
| 7. | Synchronous motors are more costly and complicated in construction. | Induction motors are cheaper in cost comparatively and less difficult to construct. |
| 8. | In addition to mechanical power, this motor improves the power factor also. | This motor gives only mechanical power. |

armature winding. The motor then starts as a squirrel cage induction motor with damping winding acting as a squirrel cage rotor on the field poles. When the motor revolves at its maximum speed, the dc supply is switched on, for the field excitation. Now the rotor and stator poles get interlocked with each other because the flux of the rotating magnetic field is seeking the minimum reluctance through the core of the salient poles and the motor now acts as a synchronous motor.

The three-phase synchronous motor with direct current (d.c) excitation is extensively used in large sizes due to its high efficiency, constant speed and controlable power factor. Its initial cost is high as compared to induction motor.

**EXAMPLE 16.1** *Calculate the speed of a three phase, 50 Hz synchronous motor having 8 poles.*

*Solution*: We know

$$\text{Synchronous speed, } N_s = \frac{f \times 120}{P}$$

$$= \frac{50 \times 120}{8}$$

$$= 750 \text{ rpm} \quad \textbf{Ans.}$$

## 16.3 HUNTING OR PHASE SWINGING

Momentry speed fluctuation of motor due to the change of load is called hunting or phase swinging.

An increase of load on synchronous motor causes the rotor poles to fall behind the stator poles by a certain angle $\alpha$. Necessary driving torque may be produced to meet the increase of load. When the load is small, the angle $\alpha$ (alpha) is also small (as shown in Fig. 16.3) and the angle increases with the increase of load.

Let us assume that a motor is operating on full load and the load is suddenly removed from the motor. Now according to new load, the angle between rotor and stator poles will change and the rotor will try to attain its new balanced position. In doing so, it will gain

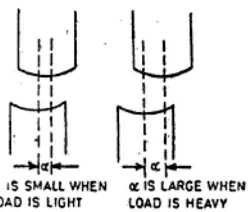



**Fig. 16.3 Hunting or phase swinging**

some momentum and the rotor will move beyond this position. Thus the rotor will fluctuate about the final stable position and

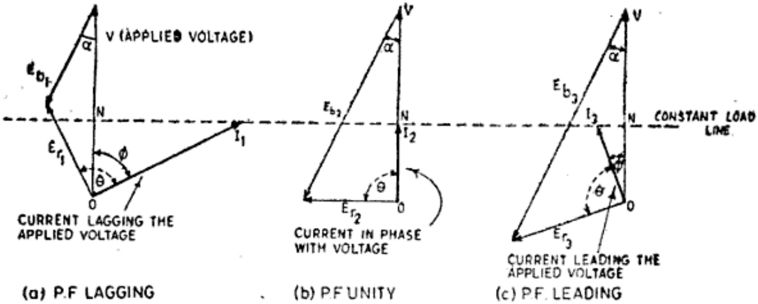



**Fig. 16.4 Effect of change of excitation**

this oscilation of the rotor is known as hunting or phase swinging.

Hunting is reduced by using damper winding which is provided on the rotor as explained before. When hunting occurs, a difference in speed of rotor and stator magnetic field is developed which induces emf in the damping winding bars. According to Lenz's law, this emf acts in such a way as to reduce the difference in the rotor and stator magnetic field speed and thus tends to keep the rotor speed equal to the speed of the stator magnetic field.

### 16.4 SYNCHRONOUS CONDENSER

Consider the case of a synchronous motor on which the load is constant and let the field current be changed. As the synchronous motor is a constant speed motor, change in the field excitation will cause variation in the induced emf which varies directly.

Figure 16.4 shows the vector diagram of a synchronous motor operating at constant load output (denoted by ON) with constant supply voltage and constant frequency. Diagrams at (a), (b) and (c) are for different values of excitation. When a voltage of '$V$' volts is applied to stator winding of the motor an emf will be induced in the motor which is represented by $E_b$ and is also shown in the figure. $Er_1$ is the resultant voltage of $V$ and $Eb_1$ which causes a current of $I$ amperes to flow in the armature circuit. This current lags behind the applied voltage "$V$" by an angle $\phi$ and makes an angle $\theta$ with the resultant voltage $Er$. The angle between this current $I$ and resultant voltage $Er$ is the power factor of the motor and is always constant and is approximately equal to 90 degrees (as the rotor winding is highly inductive). Angle $\alpha$ is the angle between the stator pole and rotor pole known as the angle of retardation of the rotor which changes with the load and varies directly. At low excitation, the motor takes lagging current as shown in Fig. 16.4(a) If the field excitation is increased, the value of $E_{b1}$ increases but the angle $\alpha$ (alpha) does not change due to constant load. This changes the value and position of the resultant voltage $E_{r2}$(See Fig. 16.4 (b)). Thus the magnitude of the current consequently varies but its angle with the resultant voltage does not change. It means, with the increase of field excitation, the current $I$ ampere will go on decreasing and for a certain excitation the current will be minimum and become in phase with the applied voltage $V$ as shown in Fig. 16.4 (b). It is clear that in this case power factor is unity.

If now the excitation is further increased, the current taken by the motor again increases but now it is leading instead of lagging (shown in Fig. 16.4 (c). An over-excited synchronous motor takes a leading current just like a condenser and therefore is called a synchronous condenser or phase advancer. This advantage of the motor is used to improve the power factor of the circuit having low power factor. If the values of the field excitation and corresponding armature current are plotted on the graph, we shall have curves (of Vee shapes) which are known as "Vee" curves of the motor. A typical set of such curves is shown in Fig. 16.5.

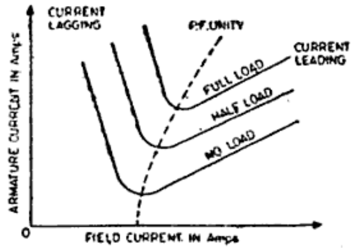



**Fig. 16.5 Vee curves of synchronous motor**

## REVIEW QUESTIONS

**16.1** Describe the principle of working, uses and function of a synchronous motor. *(NCVT 1976 Elect.)*

**16.2** Describe the working of a synchronous motor and any two methods of starting it. What are its advantages and disadvantages as compared to the induction motor.

**16.3** What do you understand by synchronous speed of an ac motor? At what speeds do (i) an induction motor, (ii) a synchronous motor, run?
State briefly the reasons for your answer. *(State Level Compt., Delhi 1970 Elect.)*

**16.4** Describe the construction and working of an auto-synchronous motor. What are its relative advantages and disadvantages with respect to an induction motor. *(State Level Compt., UT 1969 Elect.)*

**16.5** Describe the construction and operation of a synchronous motor. Enumerate some of the industrial applications of a synchronous motor stating the reasons for its use. *(NCVT 1960 Elect.)*

# 17

# Single-Phase Motors

## 17.1 SINGLE-PHASE INDUCTION MOTOR

A single-phase induction motor is similar in construction to that of a polyphase induction motor with the difference that its stator has only one winding. If such a stator is supplied with single phase alternating current, the field produced by it changes in magnitude and direction sinusoidally. Such an alternating field is equivalent to two fields of equal magnitude rotating in opposite directions at equal speed as explained below:

Consider two fields represented by quantities *OA* and *OB* of equal magnitude revolving in opposite direction as shown in Fig. 17.1.

The magnitude of the resultant of *OA* and *OB* is alternating. Hence the resultant of the two fields of equal magnitude rotating in opposite directions is alternating. Therefore an alternating current can be considered as having two components which are of equal in magnitude and rotating in opposite directions.

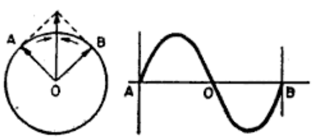



**Fig. 17.1 Single-phase field represented by two oppositely rotating field**

From the above it is clear that when a single phase alternating current is supplied to the stator of a single phase motor, the field produced will be of alternating in nature which can be divided into two components of equal magnitude one revolving in clockwise and other in counter-clockwise direction. If a stationary squirrel cage rotor is kept in such a field, equal forces in opposite direction will act and the rotor will simply vibrate and there will be no rotation. But if the rotor is given a small jerk in any direction in this condition, it will go on revolving and will develop torque in that particular direction. The rotor can also operate equally well in the opposite direction under the component working in their direction.

It is clear from the above that a single phase induction motor when having only one winding is not a self starting. To make it a self starting, several methods are employed as given below:

(*i*) By shading the poles (known as shaded-pole motor)

(*ii*) By spliting the phase (called as split-phase motor)

Single phase induction motors are generally manufactured in fractional hp ratings for economical reasons.

## 17.2 SHADED-POLE INDUCTION MOTORS

It is a single-phase motor having one winding and starting torque is produced by means of spliting the phase by using shaded rings placed on the poles. A shaded pole motor has a squirrel cage rotor and salient poles on which main pole winding is done as shown in Fig. 17.2.

In addition to the main pole winding on the salient poles, a short circuited low resistance copper ring is also put to enclose about 1/3rd of the pole shoe. This short circuit thick copper ring is known as shading ring and acts as another winding.

When the main winding is supplied from single phase ac supply, it produces a field flux which induces emf in the shaded ring. This emf causes current to flow in the short circuited ring which produces flux. According to Lenz's law, this flux opposes the main flux produced by the main winding. Due to this opposition of flux, the maximum value

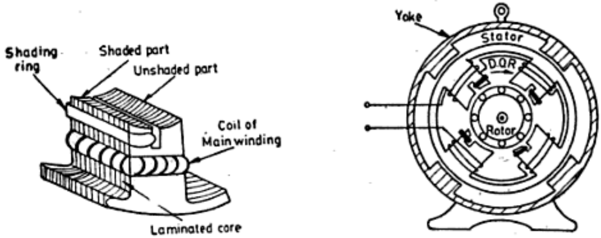



**Fig. 17.2 Shaded-pole motor**

of flux in the shaded part of the pole lags behind the flux in the unshaded part of the pole. In other words it can be said that the flux shifts from unshaded portion to shaded portion of a pole. This shifting of flux produces the same effect as the rotating magnetic field in a three phase motor. If now a stationary rotor is placed in such a field it will rotate in the direction of unshaded to the shaded part of the pole. The direction of rotation of this motor cannot be changed. The shaded pole motors have low starting torque and hence are used as small table fans, ceiling fans motors etc.

## 17.3 SPLIT-PHASE INDUCTION MOTORS

The rotor of this type of motors is of squirrel cage type and stator has two windings which are placed at a space with a phase difference of 90 degrees electrical. One winding is called running winding while second winding is known as starting winding. Sometimes one winding is cut out from the circuit when the motor has gained about .75% of its normal speed. This winding is known as starting winding and is designed for short rating. The second winding which always remain in the circuit is called running winding and is designed for continuous rating. A phase difference in the currents in the two windings is produced by either having different $R/X$ ratio of the running and starting windings or by using a condenser in series with the starting winding. Classification of these motors are :

(*i*) Split phase Induction Motor
(*ii*) Capacitor Motor
(*iii*) Capacitor start induction motor
(*iv*) Capacitor start capacitor run motor.

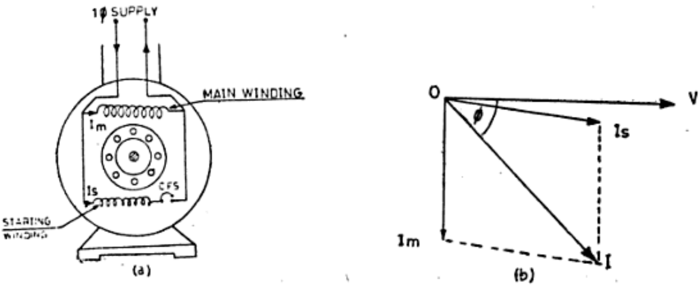



**Fig. 17.3 Split phase resistance start induction motor**

**(i) Types of Split Phase Induction Motor** (Using Different Ratios of $R/X$) The winding which is to produce more effect of inductive reactance is placed deep in the slots and has less number of turns per coil (known as Running Winding) as compared with the other winding. The current in this winding lags behind the voltage by nearly 90 degrees electrical. The other winding (known as starting winding) is placed at 90° electrical to the running winding near tips of the slots and has high resistance and low inductance and therefore the current in this winding is approximately in phase with the voltage. These two currents are approximately 90 degree out of phase with each other as shown in Fig. 17.3.

These two currents produce an effect of rotating magnetic field as in the case of two phase system. Hence if a rotor is kept under the influence of such a magnetic field, it starts rotating. If both these windings remain in the circuit during normal operation, then such a motor is known as a "split-phase induction motor".

In some cases, the winding which has high resistance is connected through an automatic switch (known as centrifugal switch) attached to the rotor. If such a motor attains its normal speed, the torque developed in the motor is maintained by one winding known as running winding or main winding only and the second winding (i.e. starting winding) can be disconnected. As the starting winding is in operation for a few seconds during the starting period, it is disconnected by a centrifugal switch automatically and such a motor is known as "Resistance Start Induction Motor".

The direction of rotation of all the induction motor can be changed by either changing current through the running winding or starting winding as shown in Fig. 17.4.

Such motors have a very low power factor (0.3 to 0.4) and so have a low starting torque. Hence they have been replaced by capacitor or capacitor start motors. Such motors are used for small pumps, grinders, fans, buffing machines etc.

**(ii) Capacitor Motor** This motor also has two phase windings as in the case of split phase motor. In this case no centrifugal switch is provided for the starting winding as this winding is designed for continuous rating. The phase difference between the currents in the two windings is created by connecting a

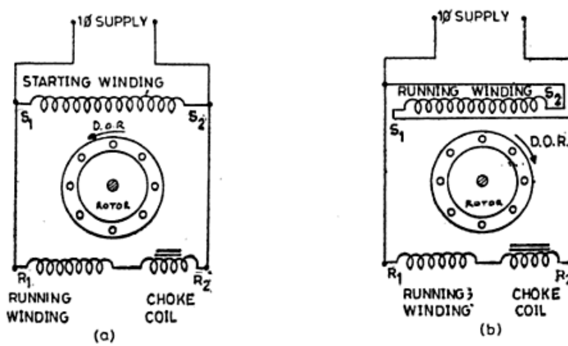



**Fig. 17.4(a)** DOR origional of split phase inductor motor. **(b)** DOR changed by changing current in starting current in running winding

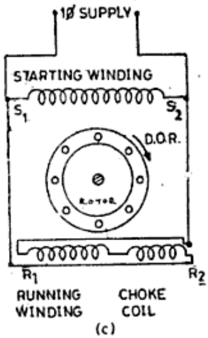



**Fig. 17.4(c) DOR changed by changing current in running winding**

condenser of low capacity 2 to 2.5 μF in series with the starting windings. This winding is housed near the tip of the slots and has less inductance than other winding which is placed deep in the slots. A condenser is permanently connected in the circuit as shown in Fig. 17.5.

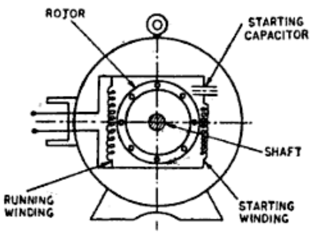



**Fig. 17.5 Capacitor motor**

Such types of motors are used where low starting torque is required as small table and ceiling fans small blower motor of airconditioners.

**(iii) Capacitor Start Induction Motor** This motor is exactly similar in construction to the capacitor motor. In this motor a centrifugal switch is provided in series with the capacitor (of capacitance 60 to 120 μF) and starting winding as shown in Fig. 17.6.

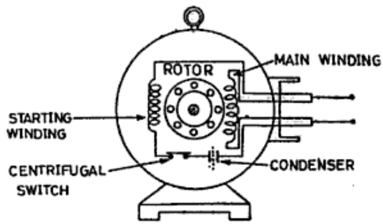



**Fig. 17.6 Capacitor start induction motor**

This centrifugal switch automatically disconnects the starting winding when the motor attains 75 per cent of its normal speed. This type of motor is known as "Capacitor Start Induction motor". The starting winding of the capacitor-start induction rotor is designed for short time rating.

This type of motor has good starting torque even from low starting current and therefore is suitable for driving compressors, pumps, etc. The method of change of direction of rotation of this motor is similar to that of split phase induction motors.

**(iv) Capacitor Start Capacitor Run Motor** It is the only single phase motor which has high starting torque and high power factor from no load to full load. In this motor there are two condensers connected in parallel to each other but in series with starting winding as shown in Fig. 17.7 and hence is more costly than any other type of single phase motors.

At the time of starting, the starting condenser remains in the circuit which is three times higher in value than a running condenser. After the motor has achieved its normal speed, the starting condenser is cut out from the circuit by a centrifugal switch and thus only running condenser is left in the circuit which is comparatively of low value.

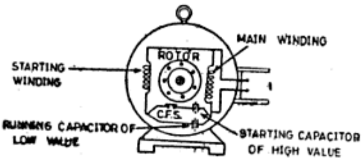



**Fig. 17.7 Capacitor start capacitor run induction motor**

This type of motor has high starting torque from low starting current and is used for operating compressors of airconditioner, big water cooler etc.

## 17.4 UNIVERSAL MOTOR OR AC SERIES MOTOR

The motor which operates on both ac and dc supply is called universal motor. If through a dc series motor alternating current is passed, it will develop a torque which is always unidirectional because the current in both the armature and field windings changes simultaneously.

Consider the case of a two pole motor and let the alternating current be in its positive half, then the polarity of the field poles and the current flowing through the armature conductors be as indicated in Fig. 17.8(b) By applying Fleming's Left Hand Rule it will be seen that the torque developed in the armature will try to rotate in anticlockwise direction. During the next instant, the alternating current goes through the negative half cycle. Now the current through the field winding and armature will also change as shown in Fig. 17.8(c). It will be again seen that the armature will tend to rotate in the anticlockwise direction. Hence the armature will always rotate in one direction whatever the polarity of the supply may be.

From the above, it is clear that a dc series motor can operate on ac single phase supply continuously if some modifications are done in it. For this reason its armature and field cores are made of laminations of silicon steel to reduce the eddy current and hysteresis losses. The air gap between the armature and field poles is also kept as small as possible.

This motor suffers from a disadvantage that it has very poor commutation. Owing to poor commutation, the motor is generally manufactured in small capacity ratings. However, for large capacity motors, the sparking at the commutator is reduced by providing compensating winding in it. The compensating winding is connected in series

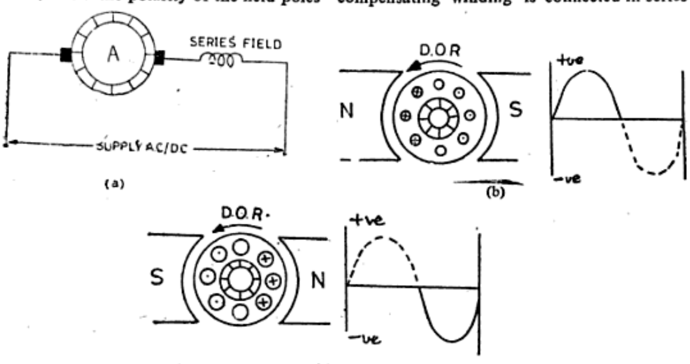



**Fig. 17.8 Universal motor or ac series motor**

with the armature. This compensating winding produces a flux which neutralizes the armature flux.

Universal motors are used in portable drilling machines, mixies, vacuum cleaners, sewing machines etc. Direction of rotation of this motor can be changed by changing the direction of either the armature current or the field current.

### 17.5 REPULSION MOTOR

Repulsion motors are single phase commutator motors having a rotor and stator winding and are of the following three types.

(*i*) Plain repulsion motor
(*ii*) Repulusionstart induction motor
(*iii*) Repulsion induction motor

**(i) Plain Repulsion Motor** The stator winding of the repulsion motor is similar to a split phase induction motor having only one distributed concentric winding. The rotor (i.e. armature) is exactly similar to a dc armature having lap winding for the same number of poles as that of the stator. Ac single phase supply is given to the stator winding and no current is supplied to the armature but an emf is induced in it due to induction. The brushes at the commutator are short circuited together (as shown in Fig. 17.9) and the emf induced due to induction causes the current to flow through the armature.

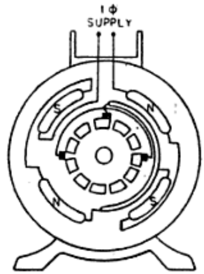



**Fig. 17.9 Connection of four-pole repulsion motor**

The number of the brushes on the commutator is equal to the number of poles of the machine. For example if a machine is designed for 2 poles, it will have 2 brushes which are short circuited on the rocker. The brushes in the repulsion motor are neither placed at right angle to the field nor mid way between the field poles but are kept at a particular angle to get the torque.

Now consider the working of a two pole repulsion motor with brushes placed at right angle to the main field pole (i.e. stator) as shown in Fig. 17.10.

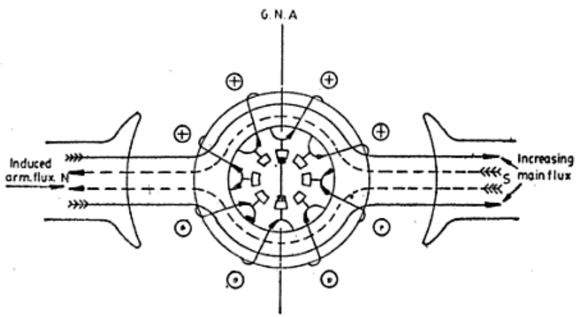



**Fig. 17.10 Two Pole repulsion motor with brushes at GNA**

The armature winding is shown ring type but in actual practice it is always drum type. The field poles are shown salient pole type but practically they are distributed type.

When a single phase alternating current is fed to the stator winding, an alternating field will be produced. Let at this particular moment, the alternating current is passing through its +ve half and is increasing in magnitude. It will set up a stator flux of increasing nature which acts from North to South as shown in Fig. 17.10 with arrow headlines. This increasing flux will induce an emf in the armature winding which, if current can flow in the winding as marked in the Fig. 17.10, will set up a flux (shown in dotted arrow heads lines) in opposite direction to the stator flux according to Lenz's Law. By applying Right Hand Grip Rule mark the arrow ends of the flow of current in the armature conductors. In this case arrows ends on the armature conductors indicate emf only. It will be seen that this statically induced emf will act as shown with arrow heads on the conductors of armature winding. In this condition, the statically induced emf in the upper and lower half of the armature conductors are equal and hence no current will flow through the armature winding and hence no torque will be developed.

So in this case the arrow heads on the armature conductors indicate emfs only.

If now the brushes are placed midway between the field poles as shown in Fig. 17.11 which is made for the same moment of time as in the previous case, a clockwise current will flow through the brushes in the upper half of the armature winding and anticlockwise in the lower half of the winding. These currents will produce equal and opposite torque around the armature. For easy understanding of the torque developed, armature current and stator main flux is again shown in Fig. 17.11. According to Fleming's Left Hand Rule, it will be seen that there are as many clockwise torques as anticlockwise torques as shown by arrow heads on the armature conductors and hence there will be no torque and motor will not operate.

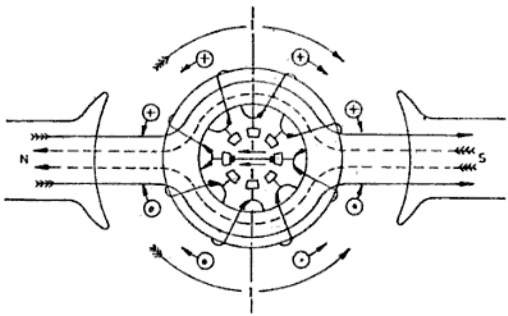



**Fig. 17.11 Two Pole-repulsion motor with brushes midway between the field poles**

Now suppose the brushes are placed at a particular angle $\alpha$ (alpha) to the field axis ($\alpha = 20°$ elect.) as shown in Fig. 17.12.

At this position of the brushes the current through the winding is again shown with arrow heads outside the winding and the torque developed due to this current by the arrow heads in the outer most area of the winding. The torque A and C is in clockwise direction while B and D in anticlockwise direction. But torque A and C is much

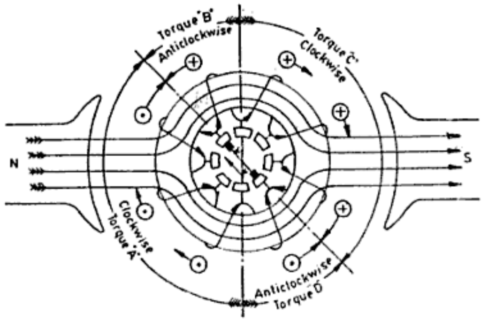



**Fig. 17.12 Shows how clockwise torque is developed**

greater than torque B and D, so the resultant torque is in clockwise direction and therefore the motor will operate in the clockwise direction. If the brushes are shifted to the opposite direction, the direction of rotation of the motor will change from clockwise to anticlockwise direction because the maximum torque developed on the armature conductors is now anticlockwise shown in Fig. 17.13. It should also be remembered that by varying the angle of brushes, the speed of the motor can be varied and torque will be maximum when $\alpha$ is 45°.

It is also clear from the Fig. 17.12 that the portion of the winding under North and South poles attains the same polarity as that the main poles and hence repulsion takes place and the motor starts to rotate due to repulsion. Therefore this motor is known as Repulsion Motor.

Since the rotor of this motor possesses high resistance due to dc armature winding, its starting current is low. However it has high starting torque and therefore can be started on load. In other words we can say that this motor has similar speed torque characteristics as that of dc series motor and is therefore used in lifts, cranes, etc.

**(ii) Repulsion Start Induction Motor** The construction of this motor is similar to an ordinary repulsion motor but an arrangement is provided in its rotor so that the commutator segments are short circuited after the motor speeds up. For this purpose a spring type centrifugal device is fitted inside the commutator segments which remains separate from the commutator segments when the rotor is stationary.

When ac single phase supply is fed to the stator winding, the motor starts as a plain repulsion motor giving high starting torque. When the speed reaches a pre-determined value, the spring of the centrifugal device expands and short circuits all the commutator segments and the motor operates as an ordinary induction motor. The motor is named as repulsion start induction motor as it starts as a repulsion motor and runs as an induction motor.

This motor developes large starting torque as repulsion motor but has running characteristics of the induction motor which is somewhat like dc shunt motor. Therefore, this motor is used at such places where it is required to have high starting torque and constant speed as in lathes, saw-mills, water pumps, etc.

**(iii) Repulsion Induction Motor** The stator of the repulsion induction motor has only one winding but the rotor has two distinct windings such as commutator winding similar to dc armature and a low resistance and high reactance squirrel cage winding. The two windings are housed in separate slots as in

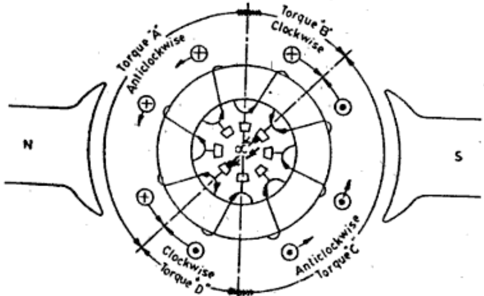



**Fig. 17.13 Represents how anti-clockwise torque is produced**

the case of double squirrel cage induction motor. The armature winding is done in upper slots and its connections are brought to the commutator segments. The squirrel cage winding is made of copper bars and is placed deep in slots which are short circuited by copper rings.

At the time of starting the squirrel cage winding will be practically uneffective due to high frequency of the induced current and hence have high reactance. Therefore, the motor starts as a repulsion motor giving high starting torque at low starting current. As the motor speeds up, the frequency of the rotor current lowers down and thus reducing the reactance of the squirrel cage and now the squirrel cage winding becomes effective in producing torque. Now there is no need of short circuiting the commutator segments.

This motor is also a constant speed motor, having high starting torque. The motor has shunt speed characteristic similar to that of an induction motor. They are suitable for machine tools, lifts, pumps, blowers, mixing machines etc.

## REVIEW QUESTIONS

17.1 Describe how a single-phase induction motor can be made self-starting. *(NCVT, 1978, 1982 Elect.)*

17.2 Describe the principle of working of an ac single-phase-squirrel cage induction motor. Briefly compare it with a slipring motor. *(NCVT, 1974 Elect.)*

17.3 What are the methods of starting single phase induction motors. Explain with diagram in detail any one of them. *(NCVT, 1964 Elect.)*

17.4 A single-phase squirrel-cage induction motor is not self starting. What are the two methods to make it start rotating? *(NCVT, 1980 W/man)*

17.5 Mention different type of ac single-phase motors. Explain the principle of working of ac fan motor. How is power factor improved in ac fan. *(NCVT, 1970 W/man.)*

17.6 Describe briefly at least three types of ac single-phase motors and explain with diagrams the method of starting of each type. *(NCVT, 1979 Elect.)*

17.7 Briefly describe the principle of working of a repulsion induction motor. For what special purpose this motor is used and why. *(NCVT, 1962 Elect.)*

17.8 (i) Draw circuit diagrams and explain the working of an ac ceiling fan motors with and without a capacitor.

(ii) How are ceiling fans specified and what is the average consumption of a medium size fan. *(NCVT, 1967 Elect.)*

17.9 (a) Why is a synchronous motor not self starting. Name any two ways in which it is started.

(b) Why is the power factor of a lightly loaded induction motor very low.

(c) Why is the starting winding of a split phase motor disconnected after the motor has been started.

*(All India Skill Compt. 1985)*

# 18

# Armature Winding

## 18.1 INTRODUCTION

Armature winding is the main part of an electrical machine in which emf is generated. In case of ac machines this part is wound on the semi enclosed or open type of slots made on the stator whereas armature winding is rotating in the case of dc machines. Hence armature winding is a collection of coils arranged systematically.

## 18.2 ARMATURE WINDING MATERIALS

The materials required for rewinding an armature may be grouped into two classes, namely, (i) Conducting Material and (ii) Insulating Material.

**Conducting Material** In small machines round copper conductors are used in armature but in machines of large output, rectangular conductors are utilized which are also known as strip conductors. The conductors are named according to the type of insulation used on them to insulate. The following conductors are used in the armature of electrical machines.

1. (*i*) Enamelled wire
   (*ii*) Super-enamelled wire: sizes available from 6 SWG to 44 SWG
2. (*i*) Single-cotton covered Copper-enamelled wire
   (*ii*) Double-cotton covered Copper-enamelled wire: sizes available from 12 SWG to 48 SWG
3. (*i*) Single-silk covered Copper-enamelled wire
   (*ii*) Double-silk covered Copper-enamelled wire: sizes available from 14 SWG to 48 SWG
4. Strip conductors: These conductors are flat in shape and are used with machines of high current carrying capacity. These strips are covered with good quality insulating tape.

All the above winding wires are available in reels of Kilograms by weight.

**Insulating Materials** The insulating materials used in electrical machines should be resistant to moisture to avoid short circuit or earth fault in them. The type of insulation required depends upon the voltage of the machine. For high voltage machines, the slots are lined with a layer of impregnated mica or micanite. The following materials are used as an insulation in electrical machines.

*Empire cloth* It is a black or yellow slot lining insulation. Its size is measured according to thickness in mil $\left(\text{one mil} = \frac{1''}{1000}\right)$ and is available from 7 to 10 mil. It is non-hygroscopic and has good dielectric strength.

*Millinex* It is a very good slot insulation, milky white in colour and is available in rolls of metres of thickness 5 to 10 mil. It is also a resistant to moisture and heat both to great extent.

*Leatheriod Paper* It is also used as slot lining insulation and has good mechanical and dielectric strength. It is light grey in colour available from 5 to 10 mil in rolls of kg or metres.

*Film Leatheriod* Leatheriod paper covered with insulating film is known as film leatheriod. It is a good slot insulation material and is available in rolls of metres from 5 to 15 mil. It is costlier than leatheriod paper.

*Micanite* It is prepared by combining mica with shellac and sometimes with paper or cloth and is then called as micanite, micanite paper or micanite cloth respectively. It provides very good slot insulation and has good dielectric strength. It is non-hygroscopic and is fire proof. It is used in the slot after heating it slightly. It is available in sheets of thickness 2 to 6 mm.

*Fibre* It is also used as slot insulation which is either used to close the slots after completing the winding or to make the terminal plate. It is brown in colour and is available from 1.5 to 10 mm.

*Cotton Tape or Silk Tape* It is used for tapping the coils or winding and are available in rolls of 50 or 100 metres of width 12, 20 and 25 mm. Silk tape can withstand higher temperatures as compared to cotton tape.

*Empire Tape* It is made from empire cloth and is used to insulate the wires and cables etc. It resists the moisture and is available in rolls of 50 and 100 metres of width 12, 20 and 25 mm.

*Glass Tape* It is prepared from the glass cotton and is specially used at high temperatures to insulate coils and winding. It is also available in the same sizes as mentioned above.

*Sleeves* It is used to insulate the winding joints and the main leads of motor. It is made of cotton, empire cloth, P.V.C. and glass cotton and are known as cotton sleeve, empire sleeve, PVC sleeve and glass cotton sleeve respectively. Cotton sleeves are used in dc armature winding and its field windings. It is available from 1 to 4 mm in different colours in length of 50 and 100 m rolls.

Empire sleeves are generally used in ac armature winding and are available in length of one metre each the diameter of which varies from 1 mm to 6 mm. The PVC sleeves are usually used to protect the main leads only as it soften and melts due to heat produced inside the winding. Therefore its use inside the ac armature winding is restricted. Glass sleeves are used where a machine has to operate at high temperatures.

*Binding Thread* It should be made of strong insulating material as it is used to bind coils, joints and windings.

*Bamboo* It should be totally dry as it is used for making wedges for the slots. The function of wedges is to avoid the coils from coming out during normal working.

*Insulating Varnish* It is the main and important insulating material which is used after the completion of winding. It is available in container of 1, 2, 5 and 10 litres. It performs the following functions.

(i) It strengthens the insulation of the winding.
(ii) It binds the winding strongly.
(iii) It resists the moisture to enter in the winding.

*Resin Cored Solder* It is very essential to solder all the joints in the armature winding and for this purpose an alloy of tin and lead in the ratio of 60% : 40% or 50% : 50% is used. Hollow solder wire is filled with resin and is then termed as resin cored solder which is available in 10, 12 and 14 SWG. It is available in rolls of 400, 500 grams each.

*Resin or Soldering Paste* Resin is a very common flux which is specially used for soldering the commutator segment as it is free from acidic effect.

Soldering paste generally known as "flux" is also used for soldering the joints of ac armature winding only. It is available in half-kilogram containers.

## 18.3 FUNDAMENTAL TERMS USED IN AC ARMATURE WINDING

Terms used in an ac Armature Winding are explained as follows:

*Active Side of a Coil* It is that part of the coil which lies in the slots of the armature and emf is induced in this part only. It is also known as an inductor.

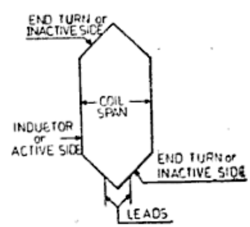



**Fig. 18.1 Simple coil showing leads of coil active and inactive sides**

*Inactive Side of a Coil or End Turn* It is the portion of the conductor which joins the two inductors.

*Turn* It is the close path of the conductor which is formed by connecting the two inductors under the two dissimilar poles.

*Coil* Two or more than two turns connected in series, forms a coil. A coil has two active sides and two inactive sides.

*Leads of a Coil* These are the starting and finishing ends of a coil which are used for doing the connection. Leads are also known as jumpers, which may be:

(a) Symmetrical.
(b) Unsymmetrical. (Shown in Fig. 18.2.)

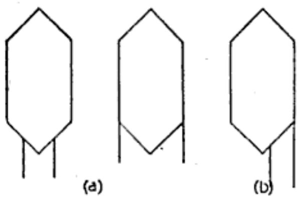



**Fig. 18.2 Types of Leads**
**(a) Symmetrical leads**
**(b) Unsymmetrical leads**

*Coil Span or Coil Throw* The distance between the two active sides of a coil under the adjacent dissimilar poles is called coil span.

*Coils per pole* The number of coils connected in series to produce a single pole when current is passed through them is called "coils per pole". In such groups all the coils are connected in series in such a way that the end of one coil is connected with the start of the next and so on.

*Coil Groups* The total number of coil groups in a machine is called "coil groups". It is the product of number of phases and number of poles in a machine, i.e.

Coil groups = no. of phases × no. of poles

*Pole Pitch* The distance between the centre of two adjacent opposite poles is called pole pitch. Pole pitch is measured in terms of slots.

$$\text{Pole Pitch} = \frac{\text{No. of slots in a machine}}{\text{No. of poles}} \quad (18.1)$$

*Coil Pitch (or winding pitch)* It is the distance between the two active sides of a coil in terms of slots. If winding pitch is 6, then the coil throw is 1 to 7 and one side of the coil is put in slot No. 1 and other side is inserted in slot No. 7 as shown in Fig. 18.3. Then the winding Pitch is 7 − 1 = 6.

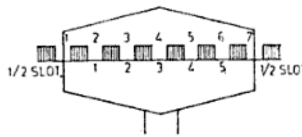



**Fig. 18.3 Coil pitch**

Winding Pitch may or may not be equal to pole pitch. While rewinding it is always preferred not to change the winding pitch as it has been choosen by the designer after considering different factors leading to good performance of the machine. Any change in original winding pitch of a machine will effect the performance of that machine.

*Pitch Factor* Pitch factor is the ratio between the winding pitch and pole pitch.

$$\text{Pitch factor} = \frac{\text{winding pitch}}{\text{pole pitch}} \quad (18.2)$$

*Full Pitch Winding* In this winding, the winding pitch is equal to pole pitch. In other words, for a full pitch winding the pitch factor is equal to unity and the winding is known as "Full Pitched Winding"

*Chorded Winding* In this winding, the winding pitch is not equal to pole pitch. If in the winding, the pitch factor is less than unity, then the winding is called as "Short Pitch or Chorded Winding". If the winding pitch is more than unity, the winding is then termed as "Long Pitch Winding".

Short pitch winding is usually used in all machines (except variable speed motor). The followings are the four main reasons of adopting the short pitch winding:

1. Saving in copper, as $I^2R$ loss is less.
2. Increase in efficiency.
3. Uniform sine wave is obtained.
4. Winding occupies less space.

*Coil Connection* The connection which joins a coil lead of one coil to the other coil lead of the same coil group is called "coil connection." It is shown in the Fig. 18.4.

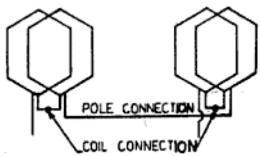



**Fig. 18.4 Shows coil connection and pole connection**

*Pole Connection* It is the connection which joins a coil group of one phase to another coil group of the same phase of the winding. It is also sometimes called "Group Connection" and is shown in Fig. 18.4.

*Adjacent Pole Connection* The connection between the two or more than two adjacent poles formed by the same phase is known as "adjacent pole connection" and are shown in Fig. 18.5. Sometimes they are also known as start to start and end to end connection.

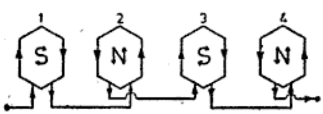



**Fig. 18.5 Four poles in adjacent pole connection**

*Alternate Pole Connection* The connection between two or more than two alternate poles produced by the same phase is called "alternate pole connection" as shown in Fig. 18.6. This connection is also known as "start to end" connection.

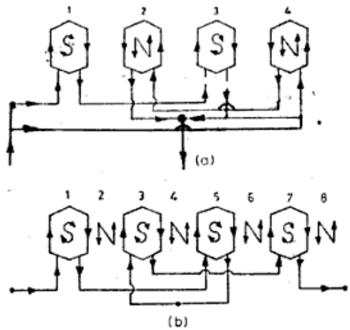



**Fig. 18.6 Alternate poles connection**
**(a) Four poles in alternate pole connection**
**(b) Eight poles in alternate pole connection**

*Phase Connection* Inter connection between the phases of a machine is called "phase connection" and they are either in star or delta.

*Whole-Coil Winding* A whole coil winding is one in which the number of coils per phase is equal to the number of poles in the machine.

*Half Coil Winding* It is that winding in which number of coils is equal to half the number of poles in the machines. Half coil winding is generally done in the winding of ceiling fans, double speed motors etc.

*Single Layer Winding* In single-layer winding each slot contains only one coil side (i.e. either upper or lower) and the number of coils in the machine is equal to half the number of slots in the stator or armature. In single layer winding coil pitch is usually taken in odd numbers.

*Double Layer Winding* In double layer winding each slot contains two coil sides (i.e. one upper and one lower) and the number of coils is equal to number of slots in the stator.

*Balanced Winding* When each pole of the same phase contains equal number of coils, then the winding is termed as "balanced winding". It is also known as "Even Group" winding.

*Unbalanced Winding* If each pole of the same phase has unequal number of coils, then the winding is called as "unbalanced winding". It is also sometimes called as "odd group" winding.

It is important to note that there must be equal number of coils in each phase whether the winding is balanced or unbalanced.

*Concentrated Winding* If in any winding the number of coils/pole/phase is one, then the winding is known as "Concentrated Winding". In this winding each coil side occupies one slot.

*Distributed Winding* In this winding number of coils/pole/phase is more than one arranged in different slots and is known as "distributed winding". In this case each coil has same pole pitch.

*Partially Distributed Winding* In this winding coils sides do not occupy all the slots, but some slots remain empty.

*Fully Distributed Winding* 'It is the winding in which not a single slot remain, empty.

## 18.4 DIFFERENT TYPES OF AC WINDING

The types of ac windings according to shape are as follows:

(*i*) Basket winding
(*ii*) Concentric winding
(*iii*) Skein winding
(*iv*) Flat loop Non-over lapped winding
(*v*) Flat loop overlapped or chain winding
(*vi*) Skew winding
(*vii*) Diamond coil winding
(*viii*) Involute coil winding

(*i*) *Basket Winding* After the completion of the winding, the side of the winding resembles the weaving of a basket and hence it is known as Basket Winding. Basket winding is of two types, (*a*) single layer basket winding. (*b*) double layer basket winding.

(*ii*) *Concentric (or Box Type) Winding* This winding has two or more than two coils in a group and the coils in each group has the same centre. In each group, the coil pitch is not equal and therefore do not overlap each other. In this winding as the coil pitches are not equal and each coil of the group has a difference of 2 slots in its pitch, it requires more labour to insert coils due to different coil spans but cooling space is more. This winding is usually provided in single phase motor winding and is known as "set winding".

(*iii*) *Skein Winding* In skein winding a very long coil is first prepared which is put in the slot and after turning it is again inserted in the adjacent slots, as shown in Fig. 18.7(c).

(*iv*) *Flat Loop Non-over lapped Winding* The coils of this winding do not overlap each other and hence is known as "Flat loop non-overlap winding." In such winding each group has only one coil.

(*v*) *Flat Loop Overlapped or Chain Winding* In this winding, the number of coils/pole/phase is more than one having different pitches and the coils overlap each other in the form of a chain.

(*vi*) *Skew Winding* The coil-sides of this winding are unequal and have greater space for heat radiation.

(*vii*) *Diamond Coil Winding* The shape of the coil used in this winding is just like a diamond, the coil occupies more space.

(*viii*) *Involute Coil Winding* This type of coil is first made in the shape of a diamond coil and then it is pressed at the end turn so as to make it in the shape of involute coil. Some times this winding is also known as "Nuckled winding".

## 18.5 STEPS FOR DISMENTLING AND REWINDING AN AC MACHINE

The following points are to be kept in mind before opening and dismentaling an ac motor.

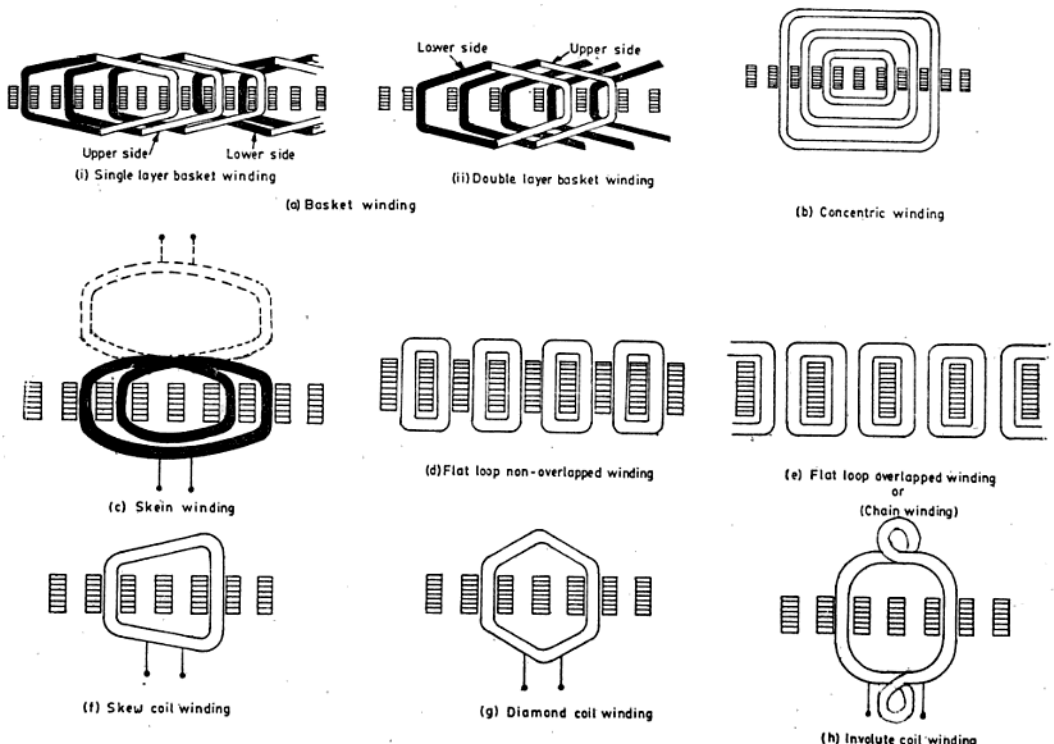



**Fig. 18.7 Types of coils and winding**

1. Remove the pulley from the shaft after loosening the pulley screw and key.

2. Put one dot on the top of front end cover and on the frame of the machine in front of each other with the help of a centre punch. Similarly mark two dots on the rear end cover and on the frame.

3. Now unscrew of coupling be side covers and remove the side cover which is fitted opposite to the pulley of the motor.

4. Similarly unscrew the otherside cover and remove the rotor outside from the stator after careful slipping.

5. Inspect the outer surface of rotor and stator for any sign of friction due to loose bearings if any.

6. If any sign of friction on the rotor or stator,remove bearing from side covers, check for looseness. If it is there, replace the bearings.

7. Clean the winding of the motor with air blower.

8. Tabulate all the data obtained from the stator as given in Sec. 18.6.

9. Make a connection diagram of the winding.

10. Dislodge the damaged winding from stator without damaging one coil for making former. Now clean the stator.

11. Make a wooden former and prepare the required number of new coils.

12. Insulate the stator as recommended by the manufacturer.

13. Insert the new coils in the slots and test them for any possible earthfault.

14. Connect all the coils according to the connection diagram.

15. Recheck the connection.

16. Now test the wound stator for leakage, short circuit or open circuit if any.

17. Re-assemble the motor.

18. Run the motor under test and measure per phase currents which should be equal.

19. Preheat, impregnate and then bake the stator at temperature between 80 to 90°C.

## 18.6 DATA OBTAINED FROM STATOR AND NAME PLATE

*Name Plate Data* 1. Horse power, 2. Volts, 3. Amperes, 4. Frequency, 5. Phases, 6. Revolutions per minute, 7. Class of insulation make.

*Stator Data*

| *S. No.* | *Before Dismantling* | *After Removing Coils* | |
|---|---|---|---|
| 1. | No. of phases and poles | Size of wire | Main winding<br>Auxilary winding |
| 2. | No. of slots | No. of turns<br>Single or Double | Main winding<br>Auxilary winding |
| 3. | No. of coils | Size of coil | |
| 4. | No. of coils in main winding | Shape of coil | |
| 5. | No. of coils in auxilary winding | Weight of wire per coil | Main winding<br>Auxilary winding |
| 6. | Whole coil winding/half coil winding | Total weight of wire | Main winding<br>Auxilary winding |
| 7. | Wire insulation | Slot insulation | |
| 8. | Coil span of main winding | Coil insulation | |
| 9. | Coil span of auxilary winding | Group insulation | |
| 10. | Pole connection or group connection | Pole insulation | |
| 11. | Phase connection | Phase insulation (sleeve etc.) | |

## 18.7 METHOD OF DEVELOPING THREE-PHASE WINDING DIAGRAM

All the three-phase motors are usually wound with coils either in single or double layers. These coils are so connected as to produce three separate windings known as phases. Each of the phases must have the same number of coils. The following points should be kept in view while developing a winding diagram.

1. The number of coils in each phase must be equal and one-third the total number of coils in the stator;
2. Each coil should span 180° electrical;
3. The winding should produce adjacent North and South Pole (depending upon types of winding) and coils per pole should contain same number of coils as far as possible;

There should be magnetic balance in the winding.

4. Three different windings should have a phase difference of 120° electrical. Total electrical degree in a magnetic field may be determined as under:

Total electrical degree = 360° × pair of poles

Therefore, if a three-phase 4 pole, 24 slots motor has 24 coils, each phase will have 8 coils. These phases are generally known as phases *A*, *B* and *C*.

The following rules are followed in developing a winding diagram:

*Rule I* To find the number of coils in each phase, divide the total number of coils in the motor by the number of phases.

*Rule II* To find the number of coils per pole, divide the number of coils in each phase by the number of poles in the machine.

*Rule III* A simple method to determine the number of coils/pole/phase is to divide the total number of coils in the stator by the product of number of poles and phase of the machine.

*Rule IV* Electrical degrees/slot for proper phase displacement, i.e.

Elect. degrees/slot

$$= \frac{\text{Total elect degrees}}{\text{No. of slots}} = \frac{360° \times \text{pair of poles}}{\text{No. of slots}}$$

*Rule V* No of slots required for proper phase displacement of 120° elect.

$$= \frac{120° \text{ elect.}}{\text{Elect. deg./slot}}.$$

## 18.8 FINDING OF THE NUMBER OF POLES

The number of poles can be determined by the frequency and the speed of the machine as given on the name plate.

$$\therefore \text{ No. of poles} = \frac{\text{frequency} \times 120}{\text{speed in rpm}}$$

If the name plate is missing, then the number of poles can be found with the help of pole pitch of the motor thus,

$$\text{Pole pitch} = \frac{\text{No. of slots}}{\text{No. of poles}}$$

$$\therefore \text{ No. of poles} = \frac{\text{No. of slots}}{\text{Pole Pitch}}$$

EXAMPLE 18.1 *Draw a developed single layer winding diagram of a star-connected three-phase, 50 Hz, 1450 rpm squirrel-cage induction motor having 24 slots.*

*Solution:* As the winding is in single layer, each slot contains one coil side only.

$$\therefore \text{ Total no. of coils} = \frac{\text{No. of slot} \times \text{coil sides/slot}}{\text{No. of coil sides/coil}} = \frac{24 \times 1}{2} = 12 \text{ coils}$$

Motor speed = 1450 rpm.

Synchronous speed, $N$ = 1500 rpm

$$\text{Number of poles}, P = \frac{120 \times f}{N} = \frac{120 \times 50}{1500} = 4$$

$$\text{Poles pitch} = \frac{\text{No. of slots}}{\text{No. of Poles}} = \frac{24}{4} = 6$$

In case of single-layer winding, the pole-pitch is generally taken in odd numbers only, such as 5, 7, 9 etc. One slot will remain unoccupied, if the pitch is taken as even numbers.

Let pole pitch = 5 (for short-pitch winding)

∴ Coil span or coil throw = 1 to 6

No. of coils/pole/phase

$$= \frac{\text{Total no. of coils}}{\text{No. of poles} \times \text{No. of phases}} = \frac{12}{4 \times 3} = 1 \text{ Coil (Balanced winding)}$$

$$\text{Elect. degrees/slots} = \frac{\text{total elect. degrees}}{\text{No. of slots}} = \frac{360 \times \text{pair of poles}}{\text{No. of slots}}$$

$$= \frac{360° \times 2}{24} = 30° \text{ electrical}$$

No. of slots required for proper phase displacement

$$= \frac{120°}{30°} = 4 \text{ slots}$$

i.e. Lead of phase $A_1$ from slot No. = 1

Lead of phase $B_1$, from No. = (1 + 4) = 5

Similarly lead of phase $C_1$, from No. = (5 + 4) = 9.

*Pole Connection* End to end and start to start. From the above data, the winding table and group connection can be made as given below.

| *Coil No.* | *Connection Lead From* | *Coil Span* | *Phase and group no* |
|---|---|---|---|
| 1. | $A_1$ | 1–6 | $A_1$ |
| 2. | | 3–8 | $C_4$ |
| 3. | $B_1$ | 5–10 | $B_1$ |
| 4. | | 7–12 | $A_2$ |
| 5. | $C_1$ | 9–14 | $C_1$ |
| 6. | | 11–16 | $B_2$ |
| 7. | | 13–18 | $A_3$ |
| 8. | | 15–20 | $C_2$ |
| 9. | | 17–22 | $B_3$ |
| 10. | | 19–24 | $(A_4)$ |
| 11. | | 21–2 | $C_3$ |
| 12. | | 23–4 | $B_4$ |

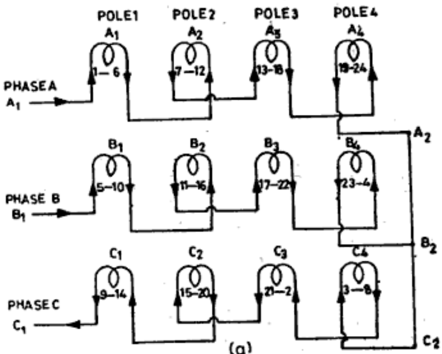



Fig. Example 18.1(a) Group and phase connection

Fig. 18.1(b) Developed winding dia (Ref. to page 354)

Fig. 18.1(c) Winding is shown in a circular laminated stator (Ref. to page 355)

**Example 18.2** *Draw developed diagram of a three-phase, double-layer, balanced whole coil basket winding having 24 slots, 4 poles, winding pitch 5.*

*Solution:* As the winding is in double layer, each slot contains two coil sides.

$$\therefore \text{ Total no. of coils} = \frac{\text{total no. of coil sides}}{\text{no. of coil sides/coil}}$$

$$= \frac{\text{no. of slots} \times \text{coil sides/slot}}{\text{no. of coil sides/coil}}$$

$$= \frac{24 \times 2}{2} = 24 \text{ coils}$$

$$\text{Pole pitch} = \frac{24}{4} = 6$$

Coil pitch = 5 (given)

Coil throw = 1–6

No. of coils/pole/phase

$$= \frac{\text{total no. of coils}}{\text{poles} \times \text{phases}}$$

$$= \frac{24}{4 \times 3} = 2 \text{ coils (Balanced winding)}$$

$$\text{Elect. degrees/slot} = \frac{360° \times \text{pair of poles}}{\text{no. of slots}}$$

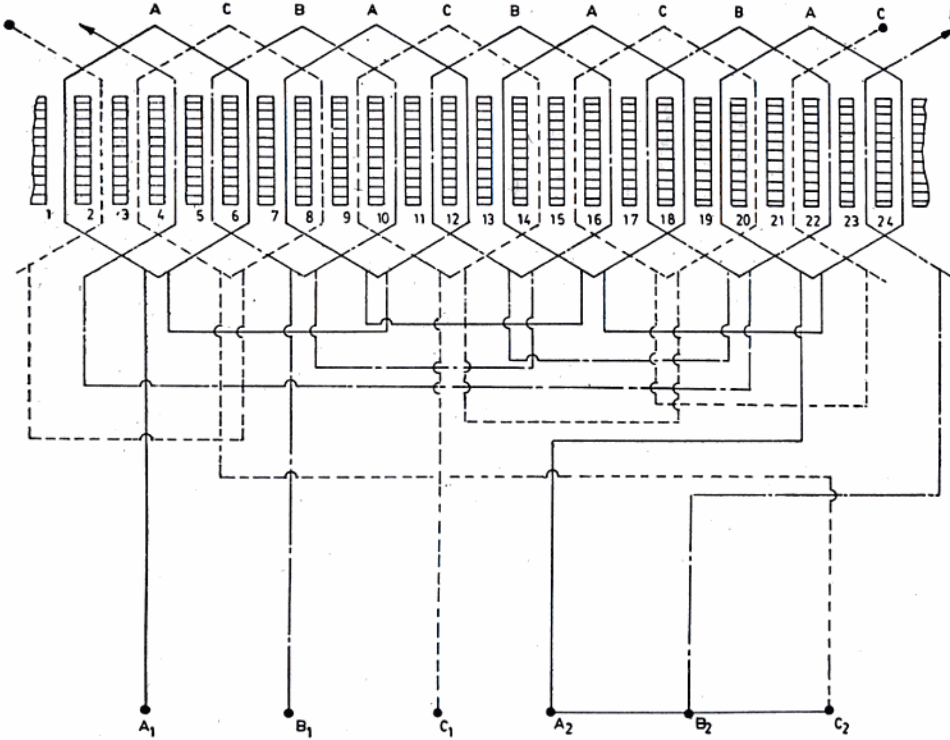



Fig. Example 18 (b) Developed diagram of three-phase stator winding having 24 slots, 12 coils, four poles, single layer balanced basket winding Pitch = 5 coil throw = 1–6

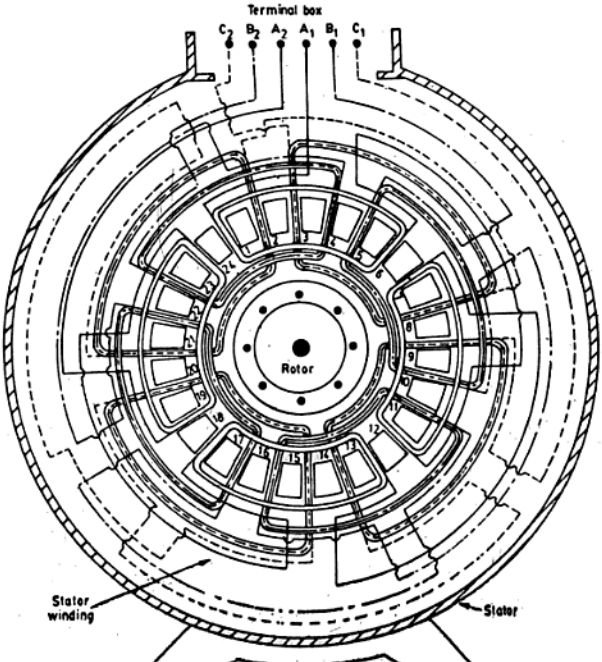



**Fig. Example 18 (c) Winding shown in a circular laminated stator**

$= \frac{360° \times 2}{24} = 30$ degrees elect.

No. of slots required for phase displacement

$= \frac{120°}{30°} = 4$ slots

i.e. phase $A_1$ is brought out from slot No. = 1,
phase $B_1$ at slot No. $= (1 + 4) = 5$
and phase $C_1$ at slot No. $= (5 + 4) = 9$

Coil connection—end to start

Pole connection—end to end and start to start.

From the above data, the winding table and pole connection can be done as under:

*Winding Table*

| Coil No. | Phase Connection Lead From | Coil Throw | Phase and Group No. |
|---|---|---|---|
| 1. | $A_1$ | 1– 6 | $A_1$ |
| 2. | | 2– 7 | |
| 3. | | 3– 8 | $C_4$ |
| 4. | | 4– 9 | |
| 5. | $B_1$ | 5–10 | $B_1$ |
| 6. | | 6–11 | |
| 7. | | 7–12 | $A_2$ |
| 8. | | 8–13 | |
| 9. | $C_1$ | 9–14 | $C_1$ |
| 10. | | 10–15 | |
| 11. | | 11–16 | $B_2$ |
| 12. | | 12–17 | |
| 13. | | 13–18 | $A_3$ |
| 14. | | 14–19 | |
| 15. | | 15–20 | $C_2$ |
| 16. | | 16–21 | |
| 17. | | 17–22 | $B_3$ |
| 18. | | 18–23 | |
| 19. | | 19–24 | $A_4$ |
| 20. | | 20– 1 | |
| 21. | | 21– 2 | $C_3$ |
| 22. | | 22– 3 | |
| 23. | | 23– 4 | $B_4$ |
| 24. | | 24– 5 | |

**EXAMPLE 18.3** *Draw a developed winding diagram of a three-phase, single-layer, whole-coil unbalanced basket winding having 36 slots, 18 coils, four poles. The winding pitch is equal to 7.*

*Solution:*

Total no. of coils = 18

Pole pitch $= \frac{36}{4} = 9$

Coil pitch = 7

Coil throw = 1 – 8.

No. of coils/phase $= \frac{\text{total no. of coils}}{\text{no. of phases}}$

$= \frac{18}{3} = 6$ coils

No. of coils/pole $= \frac{\text{no. of coils/phase}}{\text{no. of poles}}$

$= \frac{6}{4} = 1\frac{2}{4}$ (unbalanced winding)

On dividing $\frac{6}{4}$, it is seen that the coil groups equal to remainder (i.e. 2 coils groups) will have coils = Quotient + 1 i.e. 1 + 1 = 2 coils.

i.e. 2 coil groups will have 2 coils each.

The remaining (4—2) = 2 coil groups will have coil equal to quotient i.e. 1 coil each.

∴ Ratio of coils for 4 poles/phase = 2 : 1 : 2 : 1

Total elect, degrees = 360° × pair of poles

= 360° × 2

= 720 degrees elect.

Elect. degree/slot $= \frac{720°}{36} = 20$ degrees elect.

No. of slots for 120 degree phase displacement

$= \frac{120°}{20°} = 6$ slots

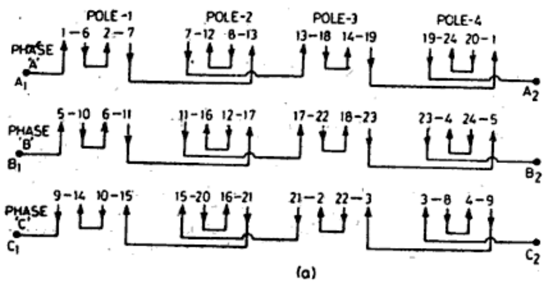



**Fig. Example 18.2 (a) Group connection of winding**

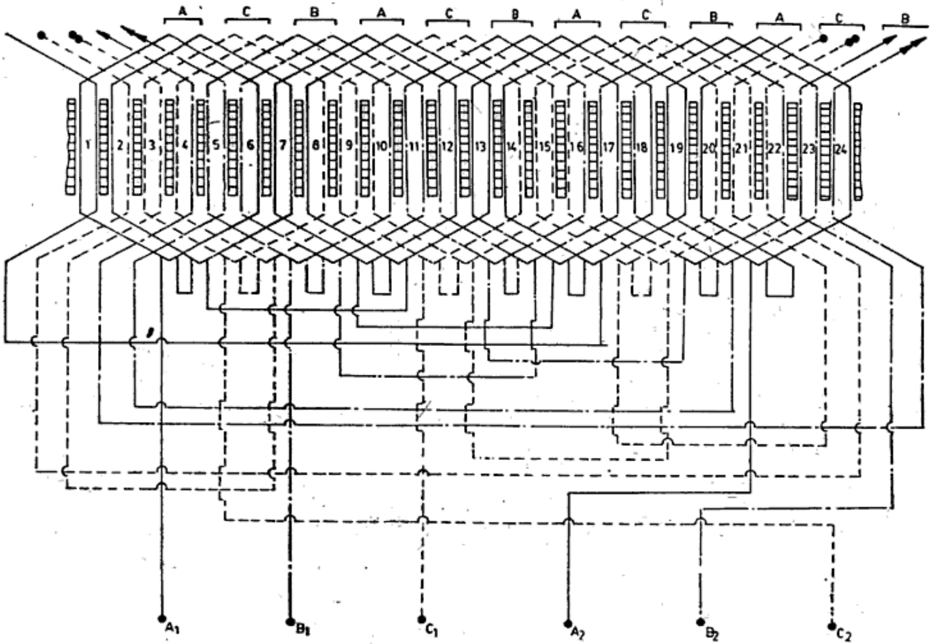



**Fig. Example 18.2 (b) Developed winding diagram of three-phase stator having 24 solts, 24 coils, four poles, double layer, balanced winding Winding pitch=5, coil span=1–6**

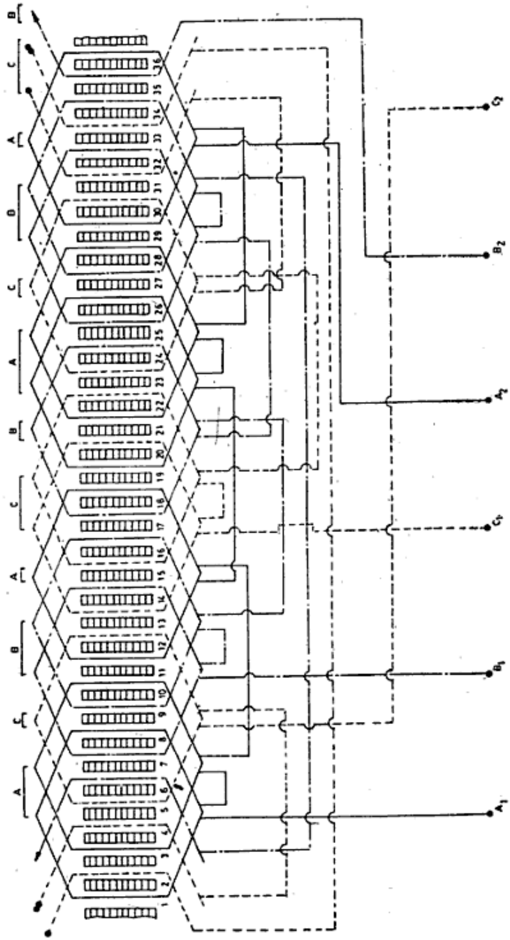



Fig. Example 18.3(b) Developed diagram of three-phase stator winding having 36 slots, 18 coils, four poles single layer, unbalanced basket winding, pitch = 7, coil throw = 1–8

Degree per slot $= \frac{720^\circ}{36} = 20^\circ$ elect.

No. of slots for 120° phase displacement

$$\frac{120^\circ}{20^\circ} = 6 \text{ slots}$$

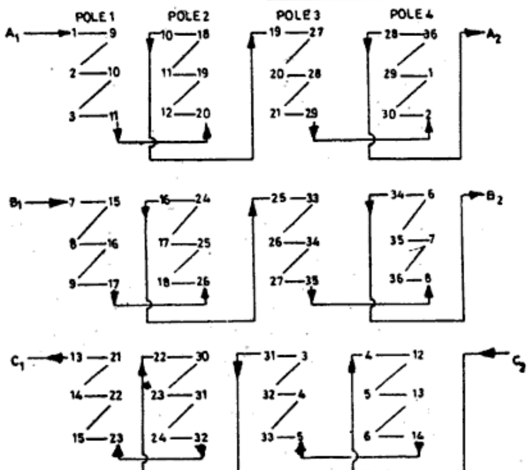
i.e. Lead of phase $A_1$ is from slot No. = 1, Lead of phase $B_1$ from slot no. = (1 + 6) = 7 and lead of phase $C_1$ from slot no. = (7 + 6) = 13.

Coil connection = end-to-start.

Group connection = end-to-end, start-to-start

*Winding Table*

| *Coil No.* | *Phase Connection Lead From* | *Coil Span* | *Phase and Group No.* |
|---|---|---|---|
| 1. | $A_1$ | 1–9 | |
| 2. | | 2–10 | $A_1$ |
| 3. | | 3–11 | |
| 4. | | 4–12 | |
| 5. | | 5–13 | $C_4$ |
| 6. | | 6–14 | |
| 7. | $B_1$ | 7–15 | |
| 8. | | 8–16 | $B_1$ |
| 9. | | 9–17 | |
| 10. | | 10–18 | |
| 11. | | 11–19 | $A_2$ |
| 12. | | 12–20 | |
| 13. | $C_1$ | 13–21 | |
| 14. | | 14–22 | $C_1$ |
| 15. | | 15–23 | |
| 16. | | 16–24 | |
| 17. | | 17–25 | $B_2$ |
| 18. | | 18–26 | |
| 19. | | 19–27 | |
| 20. | | 20–28 | $A_3$ |
| 21. | | 21–29 | |
| 22. | | 22–30 | |
| 23. | | 23–31 | $C_2$ |
| 24. | | 24–32 | |
| 25. | | 25–33 | |
| 26. | | 26–34 | $B_3$ |
| 27. | | 27–35 | |
| 28. | | 28–36 | |
| 29. | | 29–1 | $A_4$ |
| 30. | | 30–2 | |
| 31. | | 31–3 | |
| 32 | | 32–4 | $C_3$ |
| 33. | | 33–5 | |
| 34. | | 34–6 | |
| 35. | | 35–7 | $B_4$ |
| 36. | | 36–8 | |



***Solution*:**

No. of slots = 24

No. of coils = 12 (∵ winding is in single layer)

No. of poles = 4/8

No. of coils/phase $= \frac{12}{3} = 4$

No. of coils/pole for whole coil winding

$$= \frac{4}{4} = 1$$

Pole pitch $= \frac{24}{8} = 3$

Coil throw $= 1-4$

But in the case of four poles,

Pole pitch $= \frac{24}{4} = 6$

But by selecting the pole pitch according to four poles, it becomes a full pitch winding. Moreover with an even number of pitches, single-layer winding is not possible. By considering eight poles, the winding will be short-pitch winding. It should be remembered that pole pitch can be varied upto 50 per cent only in double speed motors. In this case, pole pitch for eight poles is exactly 50 per cent less. Therefore, 3 is the pole pitch which is suitable in this example.

Coil pitch = 3

∴ Coil throw = 1−4

Total elect. degrees = 360° × pair of poles

$$= 360° \times 2$$

$$= 720° \text{ elect.}$$

Elect. degrees/slot $= \frac{720°}{24} = 30°$ elect.

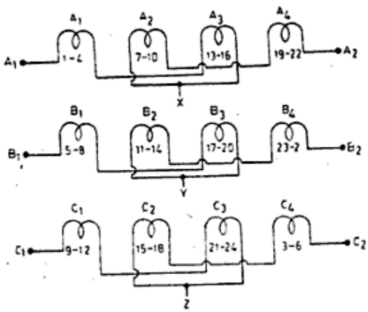



**Fig. 18.17 (a) Group connection of double speed three-phase motor**

No. of slots for 120° elect. phase displacement

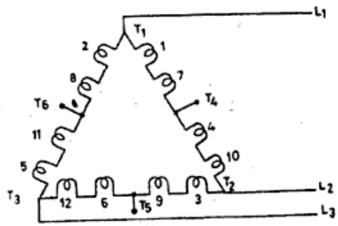
$$= \frac{120°}{30°} = 4 \text{ slots}$$

∴ Lead of phase $A_1$ comes out from slot no. = 1

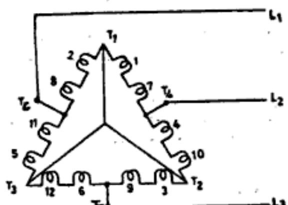
Lead of phase $B_1$ comes out from slot no. $=(1+4) = 5$

Lead of phase $C_1$ comes out from slot no. $(5+4) = 9$

From the above data, the winding table and group connection can be made as given on page 366.




(b)




(c)

**Fig. 18.17 Three-phase connection of a double speed motor**

**(b) 8-poles-low speed series delta connection Line to $T_1$, $T_2$, $T_3$, and insulate properly $T_4$, $T_5$, $T_6$**

**(c) 4-poles-high speed, parallel-star connection Line to $T_4$, $T_5$, $T_6$ and tie together $T_1$, $T_2$, $T_3$ for star connection**

*Winding Table*

| Coil No. | Phase Connection Lead From | Coil Span | Phase and Group No. |
|---|---|---|---|
| 1. | $A_1$ | 1–4 | $A_1$ |
| 2. | | 3–6 | $C_4$ |
| 3. | $B_1$ | 5–8 | $B_1$ |
| 4. | | 7–10 | $A_2$ |
| 5. | $C_1$ | 9–12 | $C_1$ |
| 6. | | 11–14 | $B_2$ |
| 7. | | 13–16 | $A_3$ |
| 8. | | 15–18 | $C_2$ |
| 9. | | 17–20 | $B_3$ |
| 10. | | 19–22 | $A_4$ |
| 11. | | 21–24 | $C_3$ |
| 12. | | 23–2 | $B_4$ |

## 18.10 SINGLE-PHASE MOTOR WINDING

The stator of a single phase motor has two concentric windings which are known as main (or running) winding and auxilary(or starting) winding. The main winding is placed deep in the stator slots while auxilary winding is done at the top of the main winding near the upper portion of the slots. A single-phase winding should fulfil the following conditions.

1. Both the windings should be placed 90° apart from each other.

2. All the coils in a group should have a difference of two slots between them.

3. All the coil groups may or may not have the same number of coils.

4. Usually, the running winding is of thick wire and the starting winding of thin wire. In modern machines, sometimes the same number of wires is used for both windings, keeping more turns in the running winding and less in the starting winding.

5. Each slot may contain one or two coil seats.

6. The expansion of coils outside from slots should be such that side covers should easily be fitted while fixing them on their seats.

7. If a winding is of whole-coil type, it is not essential that the other winding should also be of whole-coil type.

8. While rewinding a coil group, it is always good to make first small inner coil.

9. The running winding is put deep in the slots and starting winding is kept at the top of the running winding.

The following points should be considered and noted before dismantling a single-phase motor:

(*i*) Position of main leads coming out

(*ii*) End space of windings towards side covers

(*iii*) No. of groups in running winding and no. of coils/group in it.

(*iv*) No. of groups in starting winding and no. of coils/group in it

(*v*) Position of leads of running and starting winding

(*vi*) Pitches of both the windings

(*vii*) If any slot is empty in the stator winding, note its position.

The following points should be considered and noted after dismantling a single-phase motor:

(*i*) No. of conductors in parallel, if any, in running or starting winding

(*ii*) Size of wire of running winding and no. of turns/slot in it (or weight of wire/coil group)

(*iii*) Size of wire of starting winding and no. of turns/slot (or weight of wire/coil group)

(*iv*) Total weight of wire of (*a*) running winding and (*b*) starting winding

(*v*) Class of insulation used in (*a*) slot insulation, (*b*) coil insulation, (*c*) lead insulation, and (*d*) phase insulation

(*vi*) Type of winding—if skein winding; measure size of coil, and count number of turns/coil

(*vii*) Make a proper connection diagram of the winding and then remove the old winding from the stator of the machine.

EXAMPLE 18.8 *Draw a developed winding diagram of a single-phase 50 Hz, 1450 rpm, whole-coil induction motor having 24 slots, 12 coils of which eight coils are for running winding and four coils are for starting winding with pitches 5, 3 for running winding and 5 for starting winding.*

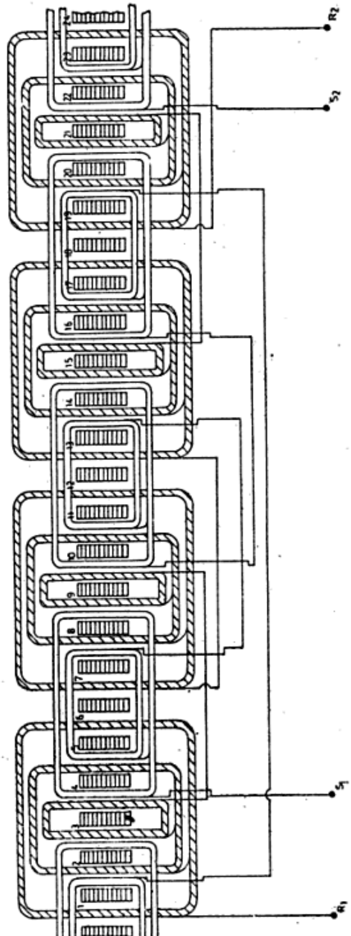
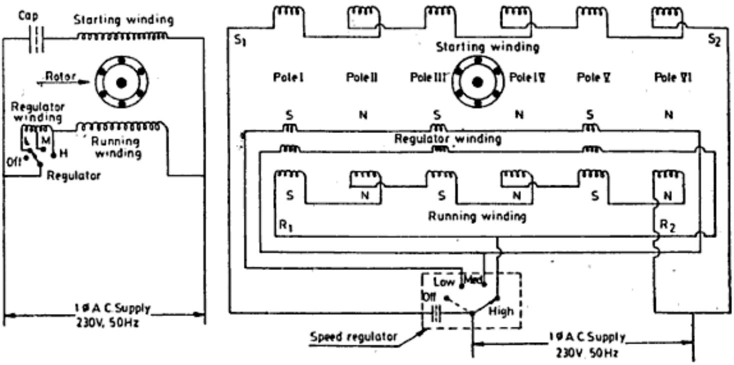



Fig. Example 18.9(b) Developed diagram of single-phase induction motor having 24 slots, 20 coils, four poles, concentric winding




(i) Low speed (ii) High speed

**Fig. Example 18.10(b) Complete connection of fan winding with regulator**
**(i) Connection for low speed, (ii) Connection for high speed**

EXAMPLE 18.11 *Make a winding table for a four-pole shaded pole type table fan motor having four slots, four coils and whole-coil winding.*

***Solution:***

Total coil sides = no. of coils × 2
= 4 × 2 = 8

Coil Sides/Slot $= \dfrac{\text{Total coil sides}}{\text{No of slots}}$

$= \dfrac{8}{4} = 2$

Pole pitch $= \dfrac{\text{No. of slots}}{\text{No. of poles}}$

$= \dfrac{4}{4} = 1$

Coil throw = 1–2

Pole Connection = end-to-end and start-to-start (∵ whole-coil winding)

Group connection of winding is shown in Fig. 18.21

EXAMPLE 18.12 *Make a winding table for a 20 poles shaded pole ceiling fan single phase motor having 20 slots, 10 coils, and half-coil winding.*

***Solution:***

Total coil sides = No. of coils × 2
= 10 × 2 = 20

Coil sides/slot $= \dfrac{\text{total coil sides}}{\text{no. of slots}}$

$= \dfrac{20}{20} = 1$

Pole pitch $= \dfrac{\text{no. of slots}}{\text{no. of poles}}$

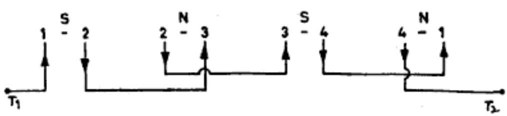



**Fig. Example 18.11 Group connection of 4 poles, single-phase shaded pole fan motor**

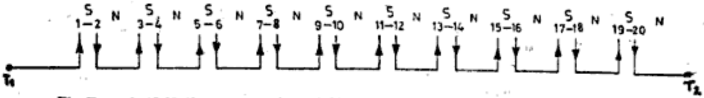



**Fig. Example 18.12** Group connection of 20 poles, single-phase shaded pole fan motor

$$= \frac{20}{20} = 1$$

Coil throw = 1-2

Pole Connection = end-to-start (being half-coil winding)

Group connection of winding is shown in Fig. 18.22.

**Example 18.13** *Develop a winding table for a permanent-capacitor type table fan having four poles, eight slots, eight coils, (i.e. four coils for running and four coils for starting winding). Both windings are whole coil windings.*

***Solution :***

Total coil sides = no. of coils × 2
= 8 × 2 = 16

$$\text{Coil sides/slot} = \frac{\text{total coil sides}}{\text{no. of slots}} = \frac{16}{8} = 2$$

$$\text{Pole pitch} = \frac{\text{no. of slots}}{\text{no. of poles}} = \frac{8}{4} = 2$$

Coil throw = 1-3

Total electrical degrees

$$= 360^\circ \times \frac{4}{2} = 720^\circ \text{ elect.}$$

$$\text{Degree/slot} = \frac{720^\circ}{8} = 90^\circ \text{ elect.}$$

No. of slots for 90-degree phase displacement

$$= \frac{90}{90} = 1 \text{ slot}$$

As both the windings are to be whole coil,

∴ Pole Connection = end-to-end and start-to-start

Group connection is shown in Fig. 18.23

**Example 18.14** *Make a winding table for above table fan having pole pitch = 1.*

***Solution:***

$$\text{Coil sides/slot} = \frac{\text{total coil Sides}}{\text{no. of Slots}} = \frac{8 \times 2}{8} = 2$$

Pole pitch = 1 (given)

Coil throw or span = 1—2

Total elect. degree = 360 × 2 = 720° elect.

$$\text{Degree/slot} = \frac{720}{8} = 90^\circ \text{ elect.}$$

No. of slots for 90° phase displacement

$$= \frac{90}{90} = 1 \text{ slot}$$

Group connection of winding is shown in Fig. Example 18.14.

**Example 18.15** *Develop a winding table for a permanent-capacitor type ceiling fan having 18 poles, 36 slots, 27 coils (i.e. 9 coils for running winding and 18 for starting winding).*

***Solution:***

$$\text{Coil sides/slot} = \frac{\text{Total coil sides}}{\text{No. of slots}} = \frac{18 \times 2}{36} = 1$$

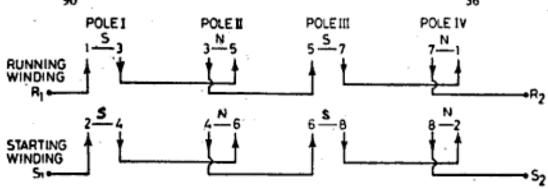



**Fig. Example 18.13** Group connection of a four poles, 8 slots, 8 coils capacitor type table fan motor

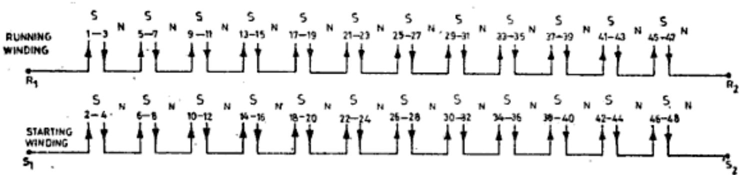



**Fig. Example 18.16 Group connection of a ceiling fan having 48 slots, 24 poles, 24 coils half-coil winding**

## 18.11 TESTING OF AC STATOR WINDING FOR FAULT DETECTION

Before assembling an electric motor after completing rewinding, it is essential to perform some tests to find the common faults such as open circuit, short circuit and leakage or earth fault. These tests can be conducted with the help of either a series test lamp or by meggar. The following are the common tests which must be done before assembling an electric motor:

(*i*) Continuity test
(*ii*) Insulation resistance test between windings
(*iii*) Insulation resistance test between windings and earth

**(i) Continuity Test** The aim of this test is to check the continuity of each winding and if there is any open circuit in the winding, it should be rectified.

When series test lamp is used to check the continuity, it should give dim light on each phase winding provided the lamp is of higher wattage and winding is closed. When this test is conducted with meggar is should indicate zero reading and if it does not show zero, it means there is an open circuit in the winding. Defect should be traced out and removed.

**(ii) Insulation Test between Windings** The purpose of conducting this test is to find out whether there is any short circuit between different windings.

In this test if the two ends of series testing lead are connected across the terminals of different windings one by one and the testing lamp does not glow, it shows winding is perfectly correct. In case the lamp gives full light, it shows that the two windings are touching each other and the winding is fully short circuited. When the lamp lights dim, it means some portion of the two windings is touching each other.

When meggar is used, and its needle rest toward infinity, it shows that winding is correct and there is no short circuit between the windings. If its needle rests on zero, this shows both the winding are touching each other. The defect should be traced and removed.

**(ii) Insulation Test between Windings and Earth** The aim of this test is to check any direct connection between windings and earth. For this, one end of series testing lead is connected to the body of the machine and other to each winding turn by turn. If lamp remains dark, it means winding is correct and if it glows, it shows that the winding is earthed.

In the case of a meggar, its one terminal is connected to the body of the machine and other to the windings. If its needle stands to infinity, winding is sound and there is no connection between the windings and body. The conclusion of the series testing lamp is given on p. 375.

## 18.12 ASSEMBLY OF MOTOR

After testing the stator, the motor is required to be assembled. The following points should be considered before and after assembling a rewound motor:

1. First of all inspect if there is any wedge, insulation or part of the winding protruding from the stator. If so, set them.

Conclusion of series testing lamp:

| Series Testing | Result of Series Testing Lamp | | |
|---|---|---|---|
| | *Lamp remain dark* | *Lamp give full light* | *Lamp remain dim* |
| 1. Continuity Test | Open circuit in winding | Short circuit in winding | Result OK |
| 2. Insulation test between different winding | Result OK | Dead short circuit between coils | Short circuit in certain portions of two windings |
| 3. Insulation test between winding and body | Result OK | Earth fault | Earth leakage in some portion of winding |

2. Examine the condition of bearings and replace if required. Lubricate them properly.
3. Bearing should not be loose in the housing and on the shaft.
4. Do not hammer hard the side covers. Use mallet for this.
5. Rotor should rotate freely without noise after assembling the motor.
6. Put the motor under trial test and measure the per phase current which should be equal for each phase. This test is known as "Balance Test".
7. Remove the side covers and dry out the stator winding from moisture if any at 90°C for at least two to four hours.
8. Dip the winding in the tank of varnish for about half an hour and then bring it out for squeezing the varnish.
9. Bake the winding for 6 to 10 hours at a temperature of 90°C. During this period, the varnish in all the portion of the winding becomes dry.
10. Remove varnish from the sitting collar of side covers in the stator.
11. Assemble the motor and re-test winding for any fault.

## 18.13 METHODS OF DRYING OUT inding WINDING

There are several methods of drying out the winding, and the simple, easy and less costly ones are as given below:

(*i*) Drying by external heaters
(*ii*) Drying by internal heating

**Drying by External Heaters** Apply heat below the winding by means of electric heaters (Do not use oil stoves, coal gas or coke). Then cover the winding with many thickness of clean sacks or wagon cover. Uncover the top of the winding periodically to allow the moisture to escape. Before heating, place a thermometer inside the stator so as to measure the inside temperature during drying out. Temperature should never exceed 90°C.

**Drying by Internal Heating** If a suitable low tension supply is available, the rewound motor, after a satisfactory trial test, may be dried out by sending current about half the full load current of the motor through the winding. The machine may be covered as explained before and in this case the temperature should not exceed 80°C.

## 18.13 DC ARMATURE WINDING—TYPES OF ARMATURE AND TYPES OF WINDINGS AND TERMINOLOGIES USED

**Types of Armature** Dc armatures may be grouped into two classes according to its construction, viz. (*i*) Ring armature and (*ii*) drum armature.

*Ring Armature* In earlier days the winding which was used in dc machines was known as "Ring winding" as it was wound on the core of a ring armature (shown in Fig. 18.10) which may be a ring or hollow cylinder having spider and shaft to hold it. The following are the reasons which made the ring wound armature outdated.

(*i*) In ring winding each turn is to pass through the centre of the ring, making it difficult to wind.

(*ii*) This winding requires more copper as compared to other type of windings for the same output.

| Coil No. | Coil Sides | | | | | Segment No. for individual coil | |
|---|---|---|---|---|---|---|---|
| | Upper Side in Slot No. | | Pitch | | Lower side in Slot No. | From | To |
| 1 | 1 | + | 8 | = | 9 | 1 | 2 |
| 2 | 2 | + | 8 | = | 10 | 2 | 3 |
| 3 | 3 | + | 8 | = | 11 | 3 | 4 |
| 4 | 4 | + | 8 | = | 12 | 4 | 5 |
| 5 | 5 | + | 8 | = | 13 | 5 | 6 |
| 6 | 6 | + | 8 | = | 14 | 6 | 7 |
| 7 | 7 | + | 8 | = | 15 | 7 | 8 |
| 8 | 8 | + | 8 | = | 16 | 8 | 9 |
| 9 | 9 | + | 8 | = | 1 | 9 | 10 |
| 10 | 10 | + | 8 | = | 2 | 10 | 11 |
| 11 | 11 | + | 8 | = | 3 | 11 | 12 |
| 12 | 12 | + | 8 | = | 4 | 12 | 13 |
| 13 | 13 | + | 8 | = | 5 | 13 | 14 |
| 14 | 14 | + | 8 | = | 6 | 14 | 15 |
| 15 | 15 | + | 8 | = | 7 | 15 | 16 |
| 16 | 16 | + | 8 | = | 8 | 16 | 1 |

9 is connected to the upper side 2 of coil 2 kept in slot 2 which is already connected with its lower side 2′–in slot 10. Similarly lower side 2′ is connected to the upper side 3 in slot No. 3 and so on. These junctions formed by connecting 1′ with 2, 2′ with 3 and 3′ with 4 and so on are connected to the commutator segments. Before connecting these junctions with commutator, it must be tested for earth and short circuit between segment otherwise the whole winding will show the fault. For numbering the commutator segment, it should be allotted the same number as that of the upper side of the coil to which it is connected. In this way the whole winding is completed as shown in the table given above

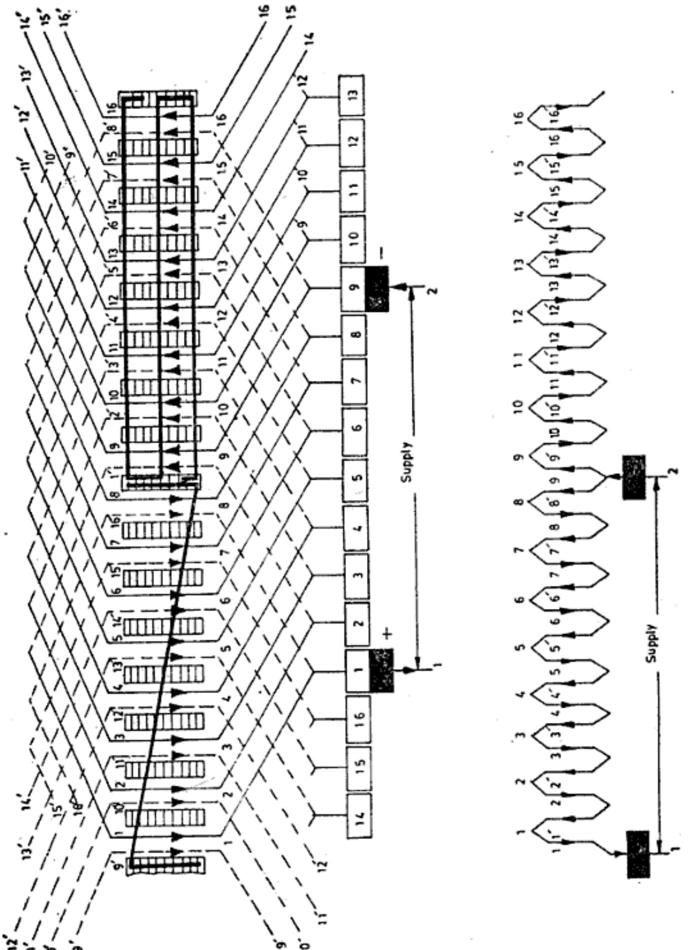
**Method of Determining Brush Location** For determining the location of brush on the commutator, it is essential to first mark the direction of current in the coils. As in this example there are two poles, half the coils from slot 1 to 8 will be kept under North pole and the remaining half from slot 9 to 16 will be under South pole as shown in Fig. 18.35.

Mark the direction of current in the coil sides under North pole as downward and that under South pole upward. Now draw an equivalent ring diagram (which is simply the connection of coils connected in the winding) and mark the direction of current in its coil sides also as marked in the winding. In the ring diagram there are two such points where currents either meet or part. First point is the junction of the coil sides 1 and 16 and the second junction is 8′ and 9. At first junction the currents are coming outward while at second junction these are going inwards. Therefore, in case of generator +ve brush will be placed at first junction and −ve brush at second junction. In case of motor, the positive brush will be at second junction and negative brush at first junction. So in the developed winding diagram, first brush is to be placed at segment No. 1 while second brush at segment 9.

From the ring diagram it is also clear that there are two parallel paths in the winding as the machine is of two poles and emf in each path will be the same.

**Multiple Coil Winding** It is seen in simple lap winding that the number of coils is equal to number of slots (i.e. one coil per slot) which are equal to the number of commutator segments in an armature.

If in an armature, there are two or more than two coils per slot, then the winding is known as multiple-coil winding or multi-coil multi-element winding. In this winding the




Ring diagram

Fig. Example 18.17 Developed diagram of 2-pole, 16-slots 16-segment simple lap winding number of segment is multiple number of slots. Generally the segments are double or triple in number than the number of slots in the armature and a brush makes contact with one segment at a time in this winding.

**Advantages of Multiple Coil Winding** In a dynamo of high output rating the multiple coil windings is done to increase the voltage output of the machine. It is due to the reason that, in this winding the number of coils are connected in series which increases the voltage generated of the machine. The following are the advantages:

(*i*) The average voltage between the adjacent segments should not exceed more than 15V due to danger of flash over. Therefore, the number of segments required in a machine is calculated by the total voltage of the machine. Hence sufficient commutator segments are taken to reduce the flash over voltage.

(*ii*) By placing two or more than two coils per slot, the number of slots are reduced. This increases the cross-sectional area of per slot which results in reducing the cost of winding.

EXAMPLE 18.18 *Draw a developed diagram of multiple coil lap winding having 4 pole, 16 slots, 32 commutator segments, full-pitch symmetrical progressive winding.*

*Solution:*

As the number of commutator segment is equal to double thenumber of slots, so it is a multiple coil lap winding. Therefore there will be 32 coils in the winding and each slot will have four coil side (i.e. two upper and two lower sides),

$$\text{Pole pitch} = \frac{\text{no. of slots}}{\text{no. of poles}}$$

$$= \frac{16}{4} = 4$$

∴ Coil throw = 1—5 (as it is full pitch winding).

Complete the back connection of the winding as described before. As the winding is progressive lap winding, so the commutator pitch is plus one. It means the lower end of first Coil, i.e. 1′ will be joined to the upper end of second coil and second lower end of second coil 2′ will be connected to the upper end of Coil 3 and so on. All such junctions are connected to the commutator segments as in Fig. 18.36.

Now draw an equivalent ring diagram as shown in Fig. for finding the position of the brushes as explained in the last example. From the ring diagram it is quite clear that there are four parallel path in the winding where currents either meet or part and these junctions are:

1. Junction of 32′ and 1
2. Junction of 8 and 9
3. Junction of 16′ and 17
4. Junction of 24′ and 25.

At junction 1 and 3 the currents are coming outward while at 2 and 4 these are going inward. So four brushes are to be used for collecting the current and will be placed at segment No. 1, 9, 17 and 25. The brushes touching the segment 1 and 17 are positive brushes and those touching 9 and 25 are negative brushes. All the positive and negative brushes are separately connected in parallel to form positive and negative groups of brushes. From the ring winding it is again clear that there are four parallel path in the winding and emf in every path is equal.

## 18.15 CONDITIONS FOR WAVE WOUND ARMATURE

In wave winding the finishing end of the first coil is not connected with the starting end of the next coil as in the lap winding but is joined to a coil which is in the same position to this coil.

Consider the case of a four pole wave-wound machine. As there are two North poles, there will be two coils in the similar positions and will be joined in series. In case of a 6 poles machine there will be three coils which will have the same position and will be connected in series to add the emf generated. In wave winding there are always two parallel paths in the armature irrespective of the number of poles. The commutator pitch

$$Y_c = \frac{\text{no. of segments} \pm 1}{\text{pair of poles}}$$

Lap winding is possible in every armature but wave winding is not possible in all armatures. It is only possible in an armature which gives a whole numbered commutator pitch, calculated as

$$Y_c = \frac{\text{no of segments} \pm 1}{\text{pair of poles}}$$

If plus one is taken, the winding is progressive

*Winding Table* Since the commutator pitch ($Y_c$) is equal to 7, therefore the lower end of coil No. 1 (*i.e.* 1) will be connected to upper end of coil No. 1+7=8 and 8+7=15 (i.e. 2, or upper side of coil No. 2) and so on.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| *Junction of coils side* | 1′–8 | 8′–2 | 2′–9 | 9′–3 | 3′–10 | 10′–4 | 4–11′ |
| *Segment No.* | 8 | 2 | 9 | 3 | 10 | 4 | 11 |
| *Junction of coils side* | 11′–5 | 5′–12 | 12′–6 | 6′–13 | 13′–7 | 7′–1 | |
| *Segment No.* | 5 | 12 | 6 | 13 | 7 | 1 | |

In simple lap winding there are as many parallel paths in the winding as the number of poles in the machine. Whenever it is required to increase the number of parallel paths without increasing the number of poles, we use multiplex winding i.e. duplex, triplex (and quadraplex winding which is rarely used) instead of simplex winding.

**Duplex Lap Winding** In this winding there are two electrically insulated windings as shown in Fig. 18.18.

In duplex lap winding the commutator pitch is always two instead of one as in a simple lap winding. In Fig. 18.38 coils 1, 3, 5, 7, 9, 11, 13 and 15 relate to one winding while coils 2, 4, 6, 8, 10, 12, 14, and 16 correspond to the other winding. These windings are joined in parallel by means of brushes which make contact with two segments at a time.

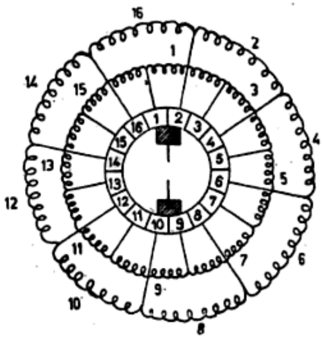



Fig. 18.38 Duplex winding

Therefore a 2 pole duplex lap winding will have 4 parallel paths. Similarly in a 4 pole duplex winding there will be 8 parallel paths and in a 6 pole duplex winding there will be 12 parallel paths in the armature and so on. In short, the number of parallel path in multiplex winding=No. of pole × No. of plex.

*Triplex Lap Winding.* There are three separate electrically insulated windings in a triplex lap winding and the brush touches at least three commutator segments at a time. These three windings are thus connected in parallel which increases the number of parallel paths by three times as that of a simple lap winding. Thus for a four pole triplex lap winding, there will be 12 parallel paths and in a six pole triplex lap winding there will be 18 parallel paths in the winding. In multiplex lap winding the brush makes contact as many segments as the degree of multiplicity of the winding.

*Duplex Wave Winding* This winding has also two electrically insulated separate windings just as the duplex lap winding. These windings may or may not be housed in the same slots but the brush makes contact with at least two commutator segments. The commutator pitch in this winding is given,

$$Y_c = \frac{\text{no. of segments} \pm 2}{\text{pair of poles}}$$

The number of parallel paths for a 4-pole duplex wave winding will be eight.

*Triplex Wave Winding* In this winding there are three electrically insulated separate windings and the brush makes contact with three segments at a time. In a four-pole triplex-wave winding there will be twelve parallel paths.

or short circuit in the winding causes burning of winding until an open circuit exists. (*ii*) Armature winding rubs on some inner part of the machine. (*iii*) Loose pole shoe or fan also damages the winding.

*Open Circuit Test* Keep the armature on growler as in Fig. 18.20 and connect it to single phase ac supply mains. Remove 12 mm insulation from two sides of an insulated piece of wire and place these two ends to the adjacent commutator segments or at a distance according to commutator pitch. Now lift one end of wire from the segment and observe spark. Repeat this testing on all other segments. The segment on which excess sparking is observed, have an open circuit in its coil or at commutator bar.

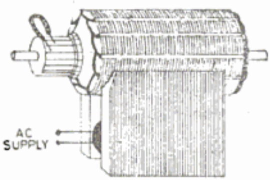



**Fig. 18.20 Open-circuit test with growler (Excessive sparking on segment which has open circuit due to additive emf of all the coils)**

*Armature Testing for Earth Fault* The following are the causes of earth fault which may be at commutator or in the armature winding.

*Causes of Earth Fault on Commutator*

(*i*) Collection of dust, oil or grease behind the riser.

(*ii*) Collection of dust or carbon between the segments causing a leakage of current, results in heat which will cause the mica to blacken and loose its insulating properties.

(*iii*) Bad soldering may allow the solder to run down behind the riser when heated.

*Causes of Earth in Armature Winding*

(*i*) Slot insulation may slide a side during winding.

(*ii*) Varnished not baked properly.

(*iii*) Friction of the field poles with the armature winding.

*Earth Test* Give ac supply to growler after placing the armature on it. When the armature is placed in the 'V' core of the growler as shown in Fig. 18.21, its body is in contact with the body of the growler. Use a millivoltmeter for this test and place its one lead on armature shaft and second on the commutator segment turn by turn and note its deflection. On earthed coil, the needle of the meter will not give any deflection. The armature should be slowly rotated during testing and reading should be noted on each segment.

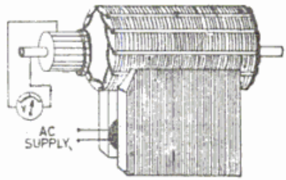



**Fig. 18.21 Earth-test with growler (on earthed segment or coil, the needle of the milli-voltmeter will not deflect)**

*Armature Testing for Reversed Coil* This fault occurs only in a newly rewound armature. Perform this test as previously by placing the ends of a zero centre milli-voltmeter on the adjacent segments. If all the connection of winding are correct, the needle of the meter will give equal deflection in one direction only. If at a particular segment it reverses or deflects more, it means that particular coil is reversed.

**Testing By Voltage Drop Method** This test is generally conducted by a low-range voltmeter, such as milli-voltmeter.

*Short Circuit Test* Put a lamp in series with 220 volts dc supply and place its leads on the commutator at a distance of a pole pitch i.e. where the carbon brushes are placed. This causes equal voltage drop across each coil provided they are having equal resistances. In this test two leads of millivoltmeter is placed to the commutator bars (i.e. according to commutator pitch) in turn. Equal

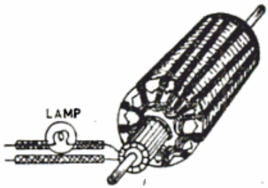



**Fig. 18.24** **Open circuit test with series testing lamp (on open circuit, lamp will give dim light)**

armature and other to each of the commutator segments one by one. If it gives full light, it means that the armature is fully earthed.

*Testing for Reversed Coil* This test is conducted with the help of a magnetic needle. In this test dc supply is given to the commutator through a testing lamp as explained before. A magnetic needle is brought near to each slot and the deflection of its needle noted. If it deflects in one direction on each slot, it shows that connections are correct. But at any slot, deflection in the reversed direction, indicates reversed connection of the coil.

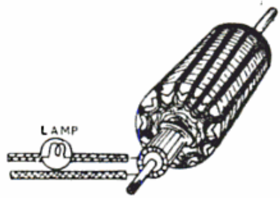



**Fig. 18.25** **Earth-test with series testing lamp (if lamp gives full light, it means the armature is fully earthed)**

## REVIEW QUESTIONS

**18.1** What are the factors used for comparing the insulating properties of an insulating materials? Give the names of six insulating material used in electrical machines for winding and put them in the order of good to bad insulation strength. *(N.C.V.T. 1962 Elect).*

**18.2** Explain in short the tests to be conducted after completing the winding of a three-phase induction motor.

**18.3** What is the difference between a lap and wave winding? Explain it.

**18.4** Describe any one method for testing an armature for faults.

**18.5** Define the following terms used in winding;
(*i*) Active coil side, (*ii*) Half coil winding, (*iii*) Pole pitch, (*iv*) Pitch factor, (*v*) Concentrated winding, (*vi*) Distributed winding, (*vii*) Unbalanced winding.

**18.6** Draw developed diagram of a three-phase stator having 2 poles, 24 slots, 24 coils, double-layer balanced winding.

**18.7** What is growler? What tests, are carried out with the instrument and how? Show by sketches. *(N.C.V.T. 1982 Elect).*

# 19

# Electrical Measuring Instruments

## 19.1 INTRODUCTION

All electrical measurements are done with the help of electrical instruments.

Electrical instruments can be grouped as follows.

(*i*) Indicating instruments
(*ii*) Integrating instruments
(*iii*) Recording instruments.

**Indicating Instruments** Indicating instruments are those which are provided with pointer and scale. The reading is indicated by the pointer on the scale. These instruments indicate reading only for the duration for which they remain connected in the circuit. When they are disconnected from the circuit, the pointer or the needle returns back to zero position on the scale. Such types of instruments do not keep any record of the readings. All types of ammeters, voltmeters and watt-meters are of this category.

**Integrating Instruments** These types of instruments keep a record of the total quantity of electricity (ampere-hour) or total amount of electrical energy (watt-hour) consumed from the time they are connected to the supply, to the time of reading of the instruments. It means these instruments keep a record of the total reading from the time they are connected to the supply. Kilowatt hour and ampere-hour meters are examples of integrating instruments.

**Recording Instruments** Recording instruments are similar to indicating instruments but keep record of the readings on a graph paper which is moved at uniform low speed. The pointer of this type of instrument is provided with a marking deviced (*i.e.* pen or pencil) and moves over the graph paper.

## 19.2 INDICATING TYPE INSTRUMENTS

As discussed earlier, all indicating instruments are provided with a pointer which deflects over a scale. In indicating instruments, three torques are employed.

(*i*) Deflecting torque
(*ii*) Controlling torque
(*iii*) Damping torque

**Deflecting Torque** Each indicating instrument has a pointer which moves over a scale. A force is needed to move the needle over the scale from its zero position. The torque which deflects the pointer on scale is known as deflecting torque. To obtain this torque in instruments, different effects of electric current such as magnetic effect, heating effect, chemical effect and electrostatic effect are employed. How a deflecting torque is developed in an instrument will be explained later while explaining individual instruments.

**Controlling Torque** Deflecting torque acts in an instrument when it is connected in the circuit. If there is no opposing torque, the reading of the instrument will go on increasing. Therefore to obtain a reading on the scale, some opposing torque must be provided in instruments at the time when the pointer moves over the scale. This opposing torque is called as controlling torque.

## 19.3 DIFFERENT METHODS OF CONTROLLING TORQUE

The following two methods are used for providing controlling torque in instruments.

(*i*) Spring control
(*ii*) Gravity control.

*Spring Control* In spring control system one or two springs (fine spirals) made of phosphor bronze material are attached to the moving spindle of the instrument. When one spring is employed, the spring attached to the pointer gets twisted as the needle deflects over the scale. The twisting force is proportional to the deflection of the needle. The spring control system gives a uniform scale.

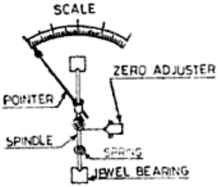



**Fig. 19.1 Spring Control**

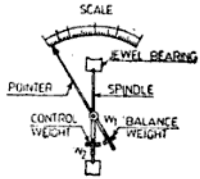



**Fig. 19.2 Gravity Control**

When two springs are used in the instrument, one is attached near the upper jewel bearing and the other near the lower jewel bearing. The two springs are fixed in opposite directions, so that when the needle moves, one gets wound and other unwound. These two springs will produce a force which tends to bring the pointer back to its zero position. The free end of the upper spring is usually kept adjustable and its adjustment can bring the pointer to zero position on the scale. In addition to providing the controlling torque, the springs are used to lead in and lead out the current in the moving system of the instruments. A spring material should be (*i*) non-magnetic, (*ii*) should have low specific resistance and (*iii*) low temperature co-efficient of resistance. However, it should not be subjected to fatigue also.

The phosphor bronze material is best suited for spring material.

*Gravity Control* In this system an adjustable weight is fixed to the moving system of the pointer and this weight keeps the pointer at zero position on the scale when deflecting torque is zero. In this condition, this weight remains vertically downward. When needle moves due to deflecting torque, this weight goes upward and it exerts a force downward. Due to the position of this weight in a direction opposite to that in which the pointer has moved, a force develops which is known as controlling torque.

In practice there are two weights, one weight for controlling torque and the other for counter-balancing the moving system. In Fig. 19.2 $W_1$ is the counterbalancing weight for pointer and $W_2$ is for controlling torque.

When a meter is connected with the supply, the pointer moves on the scale and thus indicates the reading. Since the force of gravity is not uniform, the instrument in which this system is utilized will have cramped scale near its zero position. The advantages of gravity control are that it is (*i*) not subjected to fatigue, (*ii*) cheaper as compared to spring control, and (*iii*) not effected by the change of temperature.

Disadvantages (*i*) instrument has to be kept in vertical position before use and (*ii*) Scale of the gravity control instrument is cramped or crowded in the beginning.

**Damping Torque** It is a torque which is essentially required in an instrument to get a quick reading. If a meter is not having damping device, it will go on oscillating for a long time till it attains its final position.

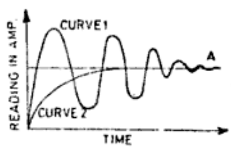



**Fig. 19.3 Shows deflection of pointer**

In Fig. 19.3, the curve No. 1 shows the deflection of the pointer when damping device is not used in the instrument while curve 2 is of the instrument having damping device.

To obtain quick readings, some device will have to be provided in the instrument. This device should develop a force only when the pointer is in motion and the torque developed on it should be in the opposite direction to the motion of the pointer. A good damping device should have the following properties.

(i) It should only produce a damping torque when the needle is in motion.
(ii) It should develop a force in the opposite direction to the deflection of the needle.
(iii) There should be no torque due to this device when the pointer is stationary.
(iv) The damping device should be cheap and simple.
(v) It should not occupy much space.

## 19.4 DAMPING DEVICES

The following damping devices are used in instruments:

(i) Air friction damping device
(ii) Eddy current damping device
(iii) Fluid friction damping device.

*Air friction damping device* An air friction damping device is usually provided with voltmeters and ammeters.

In this device, a light aluminium vane is attached to a spindle as shown in Fig. 19.4 and this vane is free to move in a fixed air chamber known as sector. When the pointer deflects, the vane in the sector also moves. The air in the sector produces friction in the movement of the vane and thus necessary damping torqe is obtained.

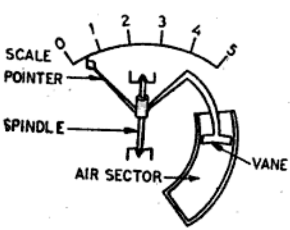



**Fig. 19.4 Air friction damping**

*Eddy Current Damping Device* In this system, a thin aluminium (or copper) disc is fixed with the spindle. With the deflection of the pointer, spindle causes the disc to move under the poles of a permanent magnet as shown in Fig. 19.5.

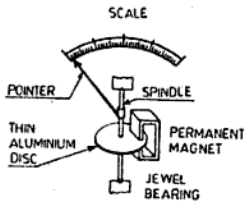



**Fig. 19.5 Eddy current damping system**

When the disc moves under the poles of the magnet, eddy currents are induced in the disc. These currents will exert a force which acts in the opposite direction to the motion of the disc and thus produces essential damping torque in the instrument.

This type of damping is provided in an instrument in which a permanent magnet is used. It is a most effective and efficient system of damping.

*Fluid Friction Damping Device* This type of damping device is employed in instruments which are to be used on the panel boards in verticle position only as insulating oil is put in the damping chamber. Hence this system of damping is not suitable for portable instrument.

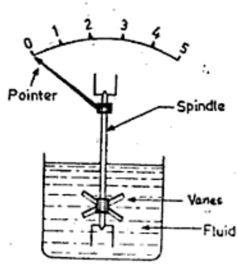



**Fig. 19.6 Fluid friction damping**

Table 19.1

| *S. No.* | *Type of Instrument* | *Suitability for types of measurement* | *Types of control employed* | *Types of damping used* | *Starting torque* | *Scale* | *Cost* |
|---|---|---|---|---|---|---|---|
| 1. | Moving Coil Instrument. | Current, voltage dc only. | Spring control. | Eddy current damping. | High | Uniform | Costly |
| 2. | Moving Iron Instrument | Current, voltage ac/dc | Spring or gravity control. | Air friction damping. | High | Cramped | Cheap |
| 3. | Dynamometer Instrument. | Current voltage, power ac/dc | Spring or gravity control | Eddy current damping. | High | Uniform as a watt meter. Crowded as a voltmeter, ammeter | Costly |
| 4. | Hot Wire Instrument | Current, voltage ac/dc | Spring or gravity control. | Eddy current damping. | High | Cramped | Cheap |
| 5. | Electrostatic Instrument | Voltage ac/dc only. | Spring control | Fluid friction damping. | Low | Crowed | Cheap |
| 6. | Induction meter. | Current, voltage, power ac only. | Spring control | Eddy current. | High | Cramped | Costly |

In this method, damping vanes are fixed to the lower end of the spindle dipped in the oil and are free to move in the oil which opposes the motion and hence necessary damping torque is developed. This system is not usually utilized in practice and can only be used with those instruments which are to be fixed at one place only.

### 19.5 CLASSIFICATION OF ELECTRICAL INDICATING INSTRUMENTS

The classification of electrical indicating instruments is given in Table 19.1.

### 19.6 WORKING PRINCIPLE AND CONSTRUCTION OF MOVING COIL INSTRUMENT

**Working Principle** The working of moving coil instrument is based on the principle that when a current is passed through a coil placed in a magnetic field, a force acts on the coil.

**Construction** A moving coil instrument has a rectangular coil wound on aluminium former, a permanent magnet, a soft iron core, a scale, a pointer, two jewel bearings and spindle with two hair springs as shown in Fig. 19.7.

The rectangular moving coil is wound with a very fine insulated copper wire on a thin light aluminium former and is suspended in a uniform magnetic field. The coil is attached with a spindle resting between the jewel bearings. The two ends of coil are connected to the two phosphor bronze springs fixed one on each side of the coil to lead in and lead out the current. These springs also provide the necessary controlling torque as explained before. The function of keeping the soft iron core in between the moving coil is to decrease the magnetic reluctance between the hollow air gap of the poles and to provide radial magnetic field of uniform intensity.

For damping, no special arrangement is employed but the eddy current developed in the aluminium former produces the necessary damping force. The force which acts on the current carrying moving coil when placed in the magnetic field is determined by

$$F = BIL \quad \text{N}$$

where $B$ = flux density in webers/meter

$I$ = current passing through the moving coil in amperes

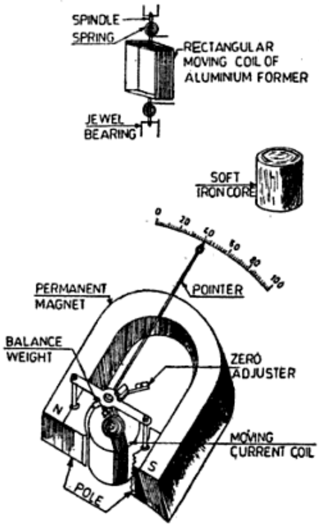



**Fig. 19.7 Moving coil instrument**

$L$ = active length of the conductors in metres.

and $F$ = force developed in the conductors in newtons.

But $B$ and $L$ are constant for a given instrument

$$\therefore \quad F \propto I \qquad (19.1)$$

It is seen from the above that the deflection of the needle is directly proportional to current, and therefore the scale of the moving coil instrument is uniform. The deflection of the pointer depends upon the direction of current flowing through the coil. If such an instrument is connected in reverse polarity, the deflection will be in reverse direction and the pointer will shows reading below the zero position. Therefore, before connecting such an instrument in circuit, polarity must be checked.

**Application** A moving coil instrument can be used on dc supply only. If connected to measure ac, the instrument will produce alternating torque and thus the needle will only vibrate near zero position.

### 19.7 WORKING PRINCIPLE AND CONSTRUCTION OF MOVING IRON TYPE INSTRUMENT

This type of instruments work on the principle of attraction or repulsion between two magnetised iron pieces.

There are two types of moving iron instruments namely:

(*i*) moving iron attraction type and
(*ii*) moving iron repulsion type

### Moving Iron Attraction Type Instrument

*Construction* It consists of a fixed air core coil made of insulated wire and an oval shaped soft iron disc which is fitted with the spindle. kept in between the coil. The spindle is placed between the two jewel bearings. A pointer is attached with its spindle and can freely move. Figure 19.8 shows the parts of an attraction type moving iron instrument.

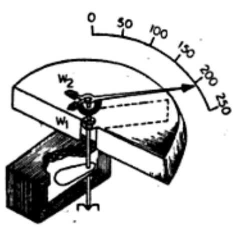



**Fig. 19.8 Moving Iron Instrument (attraction type)**

For controlling torque either gravity control or spring control is used. Gravity control is used for fixed instrument only. In the figure $W_1$ is the weight for balancing and $W_2$ is for gravity control. For damping air friction is provided. The current producing the deflecting torque is to be passed through the coil.

*Working* When the instrument is connected in the circuit, the current through the coil produces a magnetic field which drags the disc inside. When the disc move inside, the coil, the spindle also rotates which causes the pointer to move on the scale. The force of deflection ($F$) exerted by the disc is proportional to the product of magnetising field set up by the coil ($m_1$) and the magnetic power attained by the disc ($m_2$) both of which are proportional to the current through the coil, i.e.

$$F \propto m_1 \times m_2$$

$$\therefore \quad F = \frac{m_1 \times m_2}{d^2}$$

(where "$d$" is the distance between the two fields and is constant)

But $\quad m_1 \propto I \quad$ and $\quad M_2 = I$

$$\therefore \quad F \propto I^2 \quad (19.2)$$

Thus the force of deflection is proportional to the square of the current passing through the coil. The scale of such type of instruments is therefore crowded at the starting and finishing ends.

If the current in the fixed coil changes its direction, the direction of field produced by it also changes and therefore the magnetic field induced in the disc also reverses. Hence the direction of deflecting torque will not change. Such types of instruments can be used on ac as well as on dc and are designed to measure high values of currents.

### Moving Iron Repulsion-Type Instrument

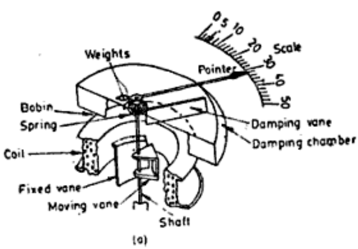
*Principle* These types of instruments work on the principle that two soft iron strips when placed in the same magnetic field are similarly magnetised and experience a force of repulsion between them which tends to move the pointer on the dial. The deflecting torque is proportional to the repulsive force. The Repulsive force is proportional to the square of the current as explained earlier. The scale of such instruments is cramped in the beginning and at the finishing ends.

Figure 19.9 shows the necessary parts of a repulsion type moving iron instrument. There is a hollow cylindrical fixed coil made of insulated copper wire. Inside the coil there are two strips of iron. One iron strip is fixed and is known as fixed iron while the other strip is called as moving iron. The moving iron is attached to the spindle which is free to move between the two jewel bearings. For air friction damping a chamber and a vane are provided. Spring or gravity control is provided in moving iron instruments.

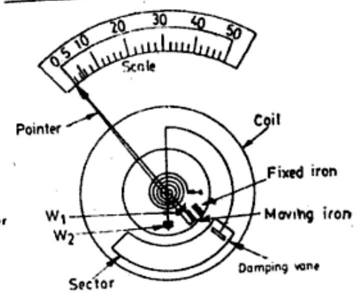
*Application* This type of instrument is suitable for both ac and dc measurements.

## 19.8 COMPARISON OF MOVING COIL AND MOVING IRON INSTRUMENTS

| Sl. No. | Moving Coil Instrument | Moving Iron Instrument |
|---|---|---|
| 1. | More accurate | Less accurate |
| 2. | Costly | Cheaper than moving coil |
| 3. | Delicate | Robust in construction |
| 4. | Uniform scale | Scale cramped at beginning and finishing ends |
| 5. | Very sensitive | Not so sensitive |
| 6. | Eddy current damping | Air friction damping |




(a) Sectionised view




(b) Plan view

Fig. 19.9 Moving Iron Instrument (repulsion type)

∴ Value of multiplier resistance

$$= \left(\frac{V-v}{I}\right) \ \Omega$$

(∵ Same current will pass through multiplier)

**Example 19.2** *A moving coil voltmeter has full-scale deflection of 30 V when its total resistance is 150 Ω. Find the value of multiplier resistance required to be incorporated so that this volt-meter can be used up to a range of 230 V.*

***Solution:***

| | |
|---|---|
| Resistance of voltmeter | = 150 Ω |
| Actual range of voltmeter | = 0–30 V |
| Voltmeter is required to measure | = 230 V |
| Voltage dropped by the multiplier | = V – v |
| | = 230 – 30 |
| | = 200 V |

Current required for full scale deflection of voltmeter,

$$I = \frac{v}{r} = \frac{30}{150}$$

$$= 0.2 \text{ A}$$

∴ Value of multiplier resistance,

$$R = \frac{V-v}{I}$$

$$= \frac{200}{0.2} = 1000 \ \Omega \qquad \textbf{Ans.}$$

**Example 19.3** *A moving coil instrument has a resistance of 10 Ω and requires 60 mA to produce full scale deflection. How would you convert this instrument for use as a voltmeter of range 0–120 V.*

***Solution:***

Current for full scale deflection

$$60 \text{ mA} = 60 \times \frac{1}{1000}$$

$$= 0.06 \text{ A}$$

Instrument is required to read up to 120 V

Resistance of the meter along with multiplier,

$$R = \frac{V}{I} = \frac{120}{0.06} = 2000 \ \Omega$$

∴ Multiplier resistance to be added in series

$$= 2000 - 10 = 1990 \ \Omega \qquad \textbf{Ans.}$$

**Example 19.4** *An ammeter has a resistance of 36 Ω and takes 1 A to produce full scale deflection. How would you use it as*

(*i*) *An ammeter to measure 25 A.*

(*ii*) *A voltmeter to read upto 150 A.*

***Solution:***

**As an ammeter** To convert the meter so as to measure 25 A current only, a shunt resistance is connected across the instrument.

Resistance of ammeter = 36 Ω

Operating current of meter = 1 A

The meter is required to measure a current of 25 A

Current through the shunt,

$$I_s = I - I_A = 25 - 1 = 24 \text{ A}$$

Voltage drop across the instrument

$$= I_A \times r = 1 \times 36 = 36 \text{ V}$$

Value of shunt

$$= \frac{V}{I} = \frac{I_A \cdot r}{I - I_A} = \frac{36}{24} = \frac{3}{2} = 1.5 \ \Omega \qquad \textbf{Ans.}$$

**As a voltmeter** To enable the same meter to measure 150 V, a multiplier resistance must be connected in series with it.

Current for full-scale deflection = 1 A

Voltage drop in the meter

$$Ir = 1 \times 36 = 36 \text{ V}$$

Voltage drop across the multiplier

$$= 150 - 36 = 114 \text{ Volt.}$$

Value of multiplier to be added in series

$$= \frac{V}{I} = \frac{114}{1} = 114 \ \Omega \qquad \textbf{Ans.}$$

## 19.10 DYNAMOMETER INSTRUMENTS

Dynamometer instrument is a modification of moving coil instrument, because it suffers from a disadvantage that it cannot be used on ac supply as the deflecting force developed will be alternating and the pointer will simply vibrate on it initial position. To make the instrument capable of reading alternating quantities, the direction of magnetic field in the air gap must be reversed with the change in direction of current in the moving coil and this principle is used in the dynamometer instrument.

$T$ of the instrument is proportional to the product of the flux produced by fixed coil and the current through the moving coil, i.e. $T \propto \phi I$.

But the flux $\phi$ depends upon the current through the coil

$$\therefore \quad T \propto \times I \times I$$

$$\text{or} \quad T \propto I^2 \quad (19.5)$$

Thus the deflection of the pointer is proportional to the square of the load current and hence the scale is cramped in the beginning and at the end.

When used as a voltmeter, the moving coil is connected in series with the multiplier and they are connected in series with the fixed coil.

But I also depends on terminal voltage $V$.

$$\therefore \text{ Deflecting torque} \quad T \propto V^2 \quad (19.6)$$

Hence the deflection is proportional to the square of the voltage. The scale of the voltmeter is therefore crowded at the lower and at upper ends.

## 19.11 INDUCTION TYPE INSTRUMENT

Just as a dynamometer type instrument can be used as an ammeter, voltmeter and wattmeter, induction type instruments can also be used as an ammeter, voltmeter or wattmeter. In practice, however, it is seldom used as an ammeter or voltmeter. It is generally used as wattmeter only. The deflecting torque is produced by the eddy currents induced in an aluminium or copper disc by the flux of an ac electromagnet. In simple words it can be said that its principle of working is similar to a single phase induction motor.

It consists of a thin circular aluminium or copper disc mounted on a spindle supported between two jewel bearings. A needle is attached with this spindle. The disc can freely move under the effect of the magnetic field produced by the coil placed near and fed from ac supply. This ac supply produces an alternating flux which links with the disc and thus induces current in the disc known as eddy current. The rotating flux of the coil react with the eddy currents and develops a force which causes the disc to revolve in the direction of rotating flux. The deflection of pointer or of disc is controlled by the spring control system. For damping, no special arrangement is provided but eddy currents induced in the disc give sufficient damping torque.

There are two methods of obtaining rotating magnetic flux from a single phase ac supply namely,

(i) By split-phase method
(ii) By using shading poles.

**(i) By Split-phase method** In this system a coil is split into two coils and the two coils are supplied from the same single phase supply. A phase difference of 90° between the currents in the two coils is produced by connecting a reactance in series with one coil and a high resistance in series with the other coil as shown in Fig. 19.14. Consequently, a rotating field is developed which induces eddy currents in the disc which cause it to rotate in the same direction as that of the rotating field with a speed little less than the speed of rotating field. There are two following essential conditions for the rotation of disc viz. (i) The two electromagnets must be placed at right angle to each other, (ii) The currents in the two windings must not be in phase with each other.

**(ii) By using Shading Poles** In this method there is only one electromagnet which produces flux. The half portion of the pole piece of this magnet is surrounded by a copper ring as shown in Fig. 19.15. This ring acts as a short circuited secondary winding of a transformer while the winding of electromagnet coil as a primary winding.

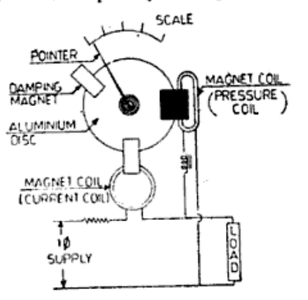



**Fig. 19.14 Developing rotating flux by splitting phase**

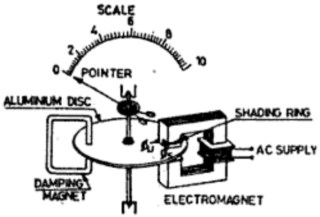



**Fig. 19.15 Developing rotating flux by shading pole**

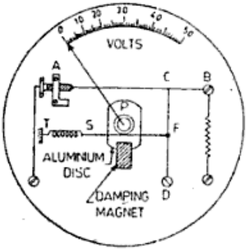



**Fig. 19.16 Hot wire instrument**

When the electromagnet is connected across single phase ac supply it produces a field flux of alternating nature which induces emf in the short circuited shaded ring. This emf causes current to flow in the ring which produces flux. According to Lenz's law, this flux opposes the flux of the electromagnet. Due to this opposition of flux, the maximum value of flux in the shaded portion ($\phi_s$) of the pole lags behind the flux in the unshaded part ($\phi_u$) of the pole. In simple words we can say that flux shifts its position from unshaded part to the shaded part of the pole. Hence this shifting of flux produces the same effect as that of rotating magnetic field in a two phase system and the disc placed in such a field tends to rotate in the direction from the unshaded portion to the shaded portion.

## 19.12 HOT WIRE INSTRUMENT

**Principle** The hot wire instrument works on the principle that when a current is passed through a conductor, some heat is produced. This heat causes increase in length of a wire and thereby causes slackness in a conductor fixed between two points. Reduction in tension of the wire due to increase in length is utilised for creating deflection of the pointer. The increase in length is proportional to the rise of temperature.

The connection and the essential parts of hot wire instrument is shown in Fig. 19.16. In the figure, *ACB* is a platinium iridium resistance wire fixed between two points *A* and *B*. The point *B* of the wire is fixed while the point *A* is adjustable and the tension of the wire can be adjusted with the help of a screw at point *A*. There is another wire of phosphor bronze which is fixed at point *C* in the platinium iridium wire. The other end of the phosphor bronze wire is fixed at *D*. Near the centre of this wire at *F*, a silk thread *S* is attached which after passing over a pulley *P* is attached to tension spring "*T*" which maintains the tension of thread. The pulley "*P*" is fixed with the spindle which carries the needle and an aluminium disc and is freely hung between two jewel bearings.

**Working** When the current is passed through the instrument, the platinium iridium wire expands due to heat developed which is proportional to

$$H \propto I^2 Rt$$

or

$$H \propto I^2$$

Due to expansion, the platinium wire increases in length and creates slackness in phosphor bronze wire. This slackness causes the thread to move towards the left of pulley due to the tension of spring. This moves the pulley in clockwise direction and hence deflection of the pointer is obtained on the scale. The deflection is proportional to the slackness of the wire which is proportional to the square of the current. Therefore the scale of the hot wire instrument is cramped at the lower end. The circular aluminium disc and the magnet develop the damping torque as explained in eddy current damping.

Hot wire instruments are generally used as an ammeter or a voltmeter suitable for both ac and dc. These are cheap, easy to manufacture and are not effected by outside magnetic field. Such types of instruments are not very accurate and need frequent adjustment. These are affected by the surrounding temperature.

The force developed due to eddy current adjusts itself according to the load on the instrument. When a constant load current is passing through the meter, the disc rotates at constant speed and in this case the braking force developed in the disc is just equal and opposite to the motoring force, i.e.

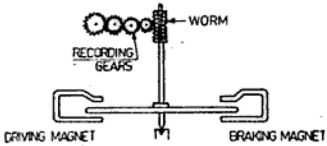



**Fig. 19.18 Braking force**

Speed $N \propto$ load current $I_L$

Emf induced in disc,

$$E \propto \text{speed of disc } (N)$$

$\therefore$ Braking force, $F_b \propto E \times I_L$

or $F_b \propto N \times N$

$$F_b \propto N^2 \tag{19.6}$$

This means, the braking force developed is directly proportional to the square of the speed at which the disc is rotating.

**Recording Device** This proportion of the integrating instrument counts the revolution completed by the disc and hence keeps the record of the energy or quantity of electricity consumed. This part of the instrument consists of a train of wheels each, of which has a pointer fixed to the spindle. All these wheels are attached in such a way that if one wheel completes one revolution, the other moves only 1/10th of a revolution.

Integrating instruments are of the following types;

(i) Ampere-hour mercury motor meter
(ii) Watt-hour commutator motor meter
(iii) Induction motor meter
 (a) Single-phase energy meter
 (b) Three-phase energy meter.

These are explained in the following sections.

## 19.15 AMPERE-HOUR MERCURY MOTOR METER

**Principle** Sometimes it is also known as Ferranti-ampere-hour meter. The operating principle of mercury motor meter depends on the fact that whenever a current fed to a conductor is kept under a magnetic field, a force acts on the conductor which tends to rotate it.

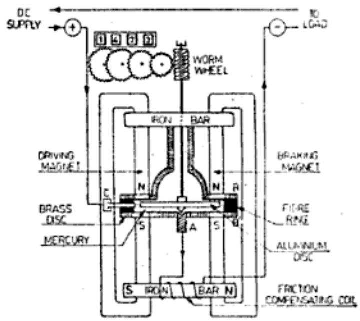



**Fig. 19.19 Ampere-hour mercury motor meter**

**Construction** Figure 19.19 illustrates the main parts and connection of this instrument. It consists of two permanent magnets having north and south poles and an aluminium or copper disc attached to a spindle. This disc is kept under the poles of magnets in an air-tight chamber formed by placing a fiber ring in between to round brass disc $B$ and $B'$. This airtight chamber contains mercury and on its left side a conductor $C$ passes through fiber ring. This conductor makes contact with the mercury. The aluminium disc floats over the mercury and lower end of its spindle rests on an adjustable screw $A$. The mercury in the chamber reduces the friction of the disc at $A$ and it also provides path for the current to flow through the disc. For holding the magnets in position, there are two iron bars in the instrument, one above the chamber and other at the bottom of the chamber. On the lower iron bar, a coil of few turns is wound which is known as a friction compensating coil. A recording device is attached at the upper end of the spindle.

When the instrument is in use, the current is passed in the disc through the conductor $C$ and mercury and from where it goes to the current coil and pressure coil, which interacts with the aluminium disc placed near the coils between bearings. This field induces eddy currents in the disc and hence the disc rotates.

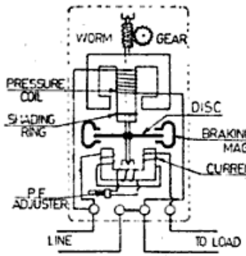



**Fig. 19.21 Single-phase energy meter**

**Construction** Figure 19.21 shows the essential parts of single phase induction type energy meter. It consists of a pressure coil, current coil, an aluminium disc mounted on a spindle which is placed between the two jewel bearings, and a recording arrangement at the top of the spindle. The pressure coil is made of many turns of thin wire and is highly inductive. This coil is connected in parallel with the supply or load and carries current proportional to voltage. The current in this coil lags behind the voltage approximately by 90 degrees. The current coil consists of a few turns of thick wire and is connected in series with the load. It carries full load current which depends upon the angle of lag or lead of the load. Therefore the currents in the pressure coil and current coil have phase difference of nearly 90 degrees. To have better phase displacement between the currents, a shading ring is put on the pressure coil as shown. This ring acts as a short circuited secondary of a transformer. Its inductance is high with respect to its resistance. Hence the induced current in it lags behind the voltage producing it by nearly 90 degrees.

The two field fluxes produced by the pressure coil and current coil act on the aluminium disc, induce eddy currents in the disc, and hence the disc rotates due to the interaction of the two fluxes developed. The speed of the disc is proportional to the product of voltage, current and the number of revolutions of the disc (i.e. time). In other words, the disc speed is proportional to the energy consumed by the load. The number of revolution completed by the disc for one kilowatt-hour is called meter constant which is given on the name plate of the meter, i.e.

One kilowatt-hour

$$= \frac{\text{Rev. travelled by the disc}}{\text{Meter constant}} \qquad (19.7)$$

**Example 19.5** *Calculate the number of revolutions, which would be completed by the disc of a single phase energy meter in 15 minutes when the load on it is 250 watts. Meter constant is 3600 revolution per kWh.*

***Solution:***

$$\text{We know kWh} = \frac{\text{Rev. travelled by the disc}}{\text{meter constant}}$$

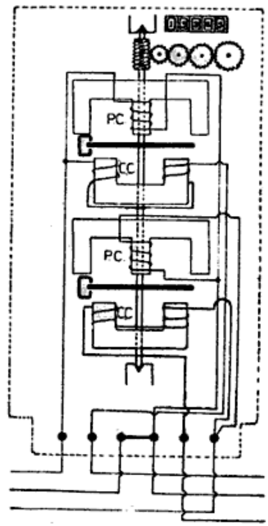



**Fig 19.22 Three-phase three-wire energy meter**

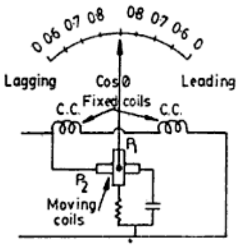



Fig. 19.24 Single phase power factor meter

pressure coil $P_1$ and $P_2$ of many turns of thin wire fixed to a common spindle and are placed at perpendicular to each other. Pressure coil $P_1$ is connected in series with a resistance and carries current in phase with the applied voltage while the current in the other pressure coil $P_2$ is kept out of phase by connecting a choke or condenser in series with it, so that the current in these coils are 90° apart. A pointer is also attached to this spindle which moves over the calibrated scale.

When the power factor of the circuit is unity, the load current $I_L$ is in phase with the voltage. The current $I_1$ of pressure Coil $P_1$ is in phase and current $I_2$ of pressure coil $P_2$ is out of phase by 90°. Now the maximum torque will be exerted by the pressure coil $P_1$ and it sets itself at right angles to the current coils and thus indicates the unity power factor of the circuit.

When the power factor of the load becomes zero due to inductive load, the load current $I_L$ lags behind the voltage by 90 degrees. Under this condition, the current $I_2$ of the pressure coil $P_2$ will be in phase opposition with $I_L$ while $I_1$ will lag behind by 90 degrees. Consequently the pressure coil $P_2$ will adjust itself perpendicular to the field produced by the current coils. For any intermediate value of the load power factor, the pointer takes up a position between zero lagging and zero leading position.

**Three-phase Power Factor Meter** The principle of operation of this instrument is the same as that of the single-phase power-factor meter. Three-phase power factor meter consists of three fixed current coils which are placed at 120 degree apart and are connected in series with the load (see Fig. 19.25). There are

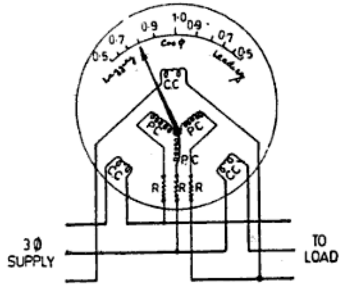



Fig. 19.25 Three-phase power factor meter

three moving coils which function as pressure coils and are fixed to a common spindle which also carries a pointer. These coils are arranged 120 degree apart and their three ends are connected at one junction to form star point while the remaining three ends are joined to the line through the three fixed resistances.

## 19.20 REED-TYPE FREQUENCY METER

In this type of frequency meter, a small soft iron piece is connected to one end of thin steel blade and its other end is fixed to supporting structure of electromagnet forms a reed. In the reed-type frequency meter, there are a number of thin flat reeds, each having a white flag on the free end and are fixed side by side in front of an electromagnet. Each reed is tuned to different frequency.

When the electromagnet is connected across the ac supply, a changing flux is set up which magnetises the soft iron piece of each reed twice in a cycle because the alternating current reaches at its maximum value twice in a cycle. The force of attraction between the soft iron and iron core of magnet is directly proportional to the magnetic power attained by the two i.e. $F \propto M_1 \times M_2$ or $F = I \times I$ or $F \propto I^2$. The reed which is tuned for double the frequency of the applied current, will start vibrating with large white band showing the frequency of the supply.

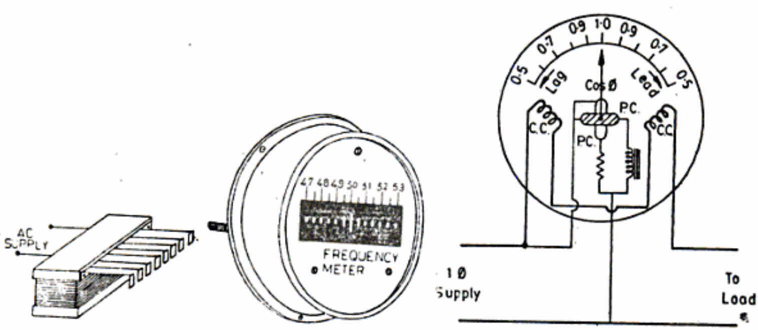



Fig. 19.26 Reed type frequency meter

The frequency meter is always connected across the line (just as a voltmeter) to indicate frequency of the supply on its scale.

## 19.21 OHM METER

It is an instrument which is used for measuring the low value of resistances. In an ohmmeter, there are two coils and a needle having a soft iron piece at its other end. One coil is known as current coil while other is known as pressure coil. Both the coils are placed at perpendicular to each other as shown in Fig. 19.27. A high resistance of $r\ \Omega$ is connected in series with the pressure coil. The current passing through it is proportional to the supply voltage (voltage of the cell connected across it). The current coil is connected in series with the unknown resistance $R\Omega$. The current passing through it is inversally proportional to the value of this resistance. When there is no resistance at the testing terminals of meter (i.e. open circuit), no current will flow through the current coil, but it only flow through the pressure coil. As the pressure coil has greater number of turns, so it will have more flux due to more ampere—turns. This causes in attracting the moving iron towards the pressure coil. Hence pointer rests on infinity on the scale.

When the terminals of the meter are short circuited, maximum current flows through the current coil which helps in developing high flux though the current coil is having few turns. This again brings the needle to be attracted towards the current coil and the pointer stands on zero portion on the scale.

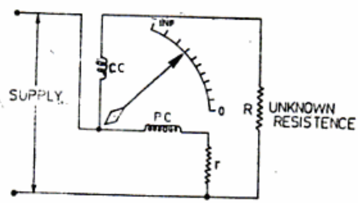



Fig. 19.27 Ohm-meter

When the meter is used for testing unknown resistance, the flux due to the current flowing through the pressure coil produces a torque on the needle in counter clockwise direction while the flux due to the current coil develops a clockwise torque. The magnetic needle is deflected so that counter clockwise deflection is equal to clockwise deflection. The pointer connected to the soft iron piece deflects over the scale giving the value of the reading under test in ohms.

## 19.22 MEGGER

Megger is an instrument which is used for measuring insulation resistance of wiring installation, machines and appliances.

It consists of two main parts, one part is generating part while other is insulation resistance mea:uring part (i.e. ohmmeter). The function of the generating part is to generate the voltage at which the insulation is to be tested. It is a hand driven magneto generator which produces 500 V (for low voltage installation) when its handle is rotated at its normal speed of about 140 to 160 rpm.

The resistance measuring part is an ohmmeter. It consists of two permanent magnet poles in the field of which two coils are fixed to the spindle by placing thtem at right angles to each other. The spindle is free to rotate in the magnetic field and it also carries the needle which moves over the scale ...uated from zero to 1000Ω and then go.. through 20 MΩ to infinity. The two coils are fixed approximately prependicular to each other and one of them carries the load current and is known as current coil. This coil is connected in series to high value of insulation resistance under test. The other coil, called pressure coil, allows a current proportional to the voltage across it. As the two coils are fixed to the spindle, so the deflection of the pointer will depend upon the field or current in the two coils and hence will be proportional to the resistance under test.

Figure 19.28 illustrates the main parts and connection of such a megger. In the figure, $R_1$ and $R_2$ are the two high resistances. Resistances $R_1$ and $R_2$ are connected in series with the pressure coil and current coil respectively and limits the current passing through them.

When the megger terminals are kept open, there is no current in the current coil and the pointer rest on infinity under the effect of pressure coil only. When the megger terminals are short-circuited, full current flows and current in the current coil will be maximum and now the pointer will rest on the scale on zero position under the influence of current coil only. When a resistance is connected in between the above two valves across the terminals of megger, the pointer will rest in between the first two positions due to the resultant magnetic field of the coils.

## 19.23 INSTRUMENT TRANSFORMER

In ac measurement, voltage or current is measured by low or medium voltage instruments. But if these instruments are to be used on high voltage supply, they will have to be modified. Even then their use directly on high voltage is not out of danger. So these instruments are not employed directly on high voltage ac supply. The supply voltage or current is stepped-down and is then given to the instrument for measurement. The transformer which is required to facilitate measurement of high current and high voltage are known as current transformer and potential transformer respectively.

**Current Transformer** Current transformer is an instrument transformer which is used for measuring currents on a high-voltage, ac supply line. Figure 19.29 shows the connection of an ammeter with current transformer.

The primary of current transformer has very less turns (usually one or two turns only) and is connected in series with the line of which the current is to be measured. The secondary of the transformer has greater number of turns and an ammeter is connected across its terminals. The scale of the ammeter is calibrated according to the prima.y line current. As the ampere meters have negligible resistance so the secondary of the transformer is to be considered short-circuited. The flux produced by the primary winding

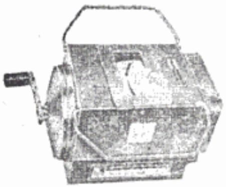
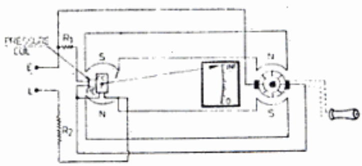


Fig. 19.28 (a) Insulation tester




(b) Connection of insulation testing megger

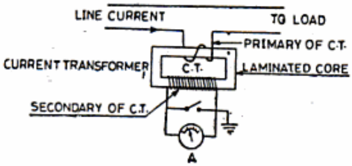



**Fig. 19.29 Connection of current transformer**

depends upon load current. The major portion of it is cancelled by the flux produced by the secondary winding. Hence the resultant flux in the core of the transformer is very small. If the secondary terminals are opened or ammeter is removed, the flux of the secondary will become zero and now the resultant flux in the core of the transformer will be equal to the flux produced by the primary winding. This high value of flux will induce a very high voltage in the secondary winding and the insulation of secondary winding may be punctured and thus the transformer may get damaged. Therefore, the secondary winding of the current transformer is never kept open. Whenever the ammeter is to be taken out, the secondary terminals are short circuited by putting on a switch connected across the ammeter (as shown in Fig. 19.29) before disconnecting the instrument. Generally, one end of the secondary winding is earthed to avoid a danger of shock to operator if by chance any loose connection persists on the secondary of the current transformer. It also reduces the thickness of the insulation required for the winding. The terminals of the current transformers are usually marked for polarity which are to be used on three-phase supply to measure power and energy. This avoids the reversal of current in the current coil of these meters. For moving iron ammeters, there is no need of marking polarity on C.T. because there is no effect of reversing the polarity. The ratio of current transformers are 50 : 5, 75 : 5, 100 : 5, 150 : 5, 200 : 5, 300 : 5, 500 : 5, 1000 : 5 up to 15000 : 5.

The simplest practical application of current transformer is a clip-on meter (Fig. 19.30) which is used for measuring the current flowing in the line without any contact. The live cable is passed through the clip on meter by pressing the lever. The

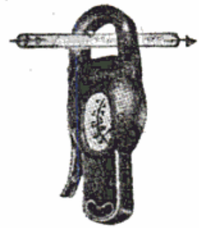


**Fig. 19.30 Clip-on meter**

live cable functions as primary and its flux induces an emf in the secondary which indicates deflection in the ammeter connected.

## 19.24 POTENTIAL TRANSFORMER

These transformers are used to measure high and extra high voltages as it is not practicable to use multipliers as in the case of dc measurement.

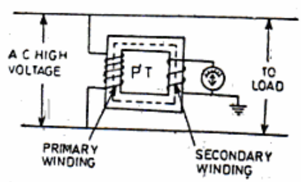
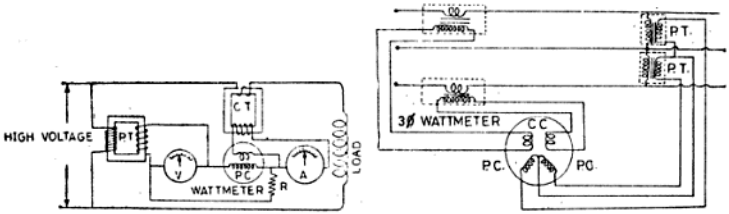



**Fig. 19.31 Connection of potential transformer**

It is a step-down transformer which is used alongwith a voltmeter to measure the voltage. The primary of a potential transformer is designed for high voltage across which it is to be connected. Therefore the primary has greater number of turns of very thin wire and secondary has very less number of turns of slightly thick wire. A 110 V voltmeter is connected across the secondary as it is designed to give an output voltage of 110 V. The scale of the voltmeter is calibrated according to the primary line voltage. The connection of voltmeter with potential transformer is shown in Fig. 19.31. The primary is connected across two phases of high or extra high




(a) (b)

(a) **Single phase wattmeter with instrument transformer**

(b) **Three-phase wattmeter with instrument transformers**

**Fig. 19.32 Illustration of connection of wattmeter with CT and PT**

voltages as the case may be. One end of secondary winding of potential transformer is also earthed to reduce high voltage if a loose connection persists.

The Fig. 19.32 given above shows the connections for a wattmeter with current transformer and potential transformer.

## 19.25 KVAR METERS

KVAR meters are used to measure the wattless component of KVA in a three-phase circuit.

The principle of operation of this instrument is similar to electro-dynamometer three phase power factor meter. It consists of two fixed current coils which provide the field flux. The field produced by these coils is proportional to the line current. The moving coil (known as pressure coil) carries the current proportional to the supply voltage. The pressure coil consists of three coils which are connected in star. The star point is connected to the neutral for correct operation of the instrument. The connection diagram of KVAR meter is shown in Fig. 19.33.

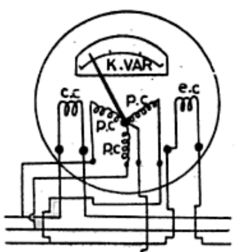



**Fig. 19.33 KVAR meter**

## 19.26 THERMOCOUPLE

When the junction of two dissimilar metals such as copper and iron, is heated up, an emf is generated due to difference of temperature between two dissimilar junction. This emf causes current to flow from the metal which is at higher temperature than the other and this effect of current is known as "thermo-electric effect" and the metals chosen for the production of emf or current is called "thermocouple". In this case copper attains higher temperature, so electronic current starts to flow from copper to iron and conventional current from Iron to copper as shown in Fig. 19.34(a). For this reason the metal which gains higher temperature than the other emits electrons easily at higher rate.

On plotting the graph between the thermal current (emf) and temperature for copper and iron junction, it is seen that the current flows almost a straight line upto a temperature of 300°C, but decreases for greater temperature and reaches to zero for temperature of about 600°C. On further increasing the temperature, the current will start flowing in the opposite direction as shown in the Fig. 19.34(b).

This principle is applied in the construction of thermo-couple ammeter and thermo

## NUMERICAL EXERCISES

19.1 A moving coil galvanometer (i.e. instrument that measure very sensitive current) has a resistance of 29.97 Ω of its moving system and gives full scale deflection when carrying a current of 15 mA. Find the value of shunt required to change the instrument into an ammeter of range 0-15 A (Ans. 0.03 Ω)

19.2 A moving coil instrument has a resistance of 20 Ω and require 50 mA to produce full scale deflection. How would you use this instrument to measure 150 V? (Ans. 2980 Ω)

19.3 A moving coil voltmeter gives full scale deflection of 150 V when current flowing through it is 25 mA. Calculate the value of multiplier resistance required to convert this voltmeter so as to read 200 V. (Ans. 2000 Ω)

19.4 A moving coil voltmeter has full scale deflection of 100 V when its total resistance is 200 Ω. Find the value of the multiplier resistance required to be added so as to enable the meter to read 250 V dc. (Ans. 300 Ω)

19.5 A dc ammeter has total resistance of 18 Ω and produces full scale deflection for a current of 0-5 A. Find the resistancesof the shuntsrequired to give full scale ranges of 15, 30 and 50 A. (Ans. 9 Ω, 3.6 Ω, 2 Ω)

19.6 A moving coil instrument has a resistance of 9 Ω and takes 25 A for full scale deflection. Find the resistances of the shunts required to give full scale deflection ranges to measure 100, 150 and 250 A. (Ans. 3Ω, 1.8Ω, 1Ω)

19.7 A dc voltmeter has total resistance of 18Ω and produce full scale deflection for a current of 500 mA. Find the resistancesof the shunts required to give full scale range of 5, 9.5 and 20.5 A. (Ans. 2Ω, 1Ω, 0.45Ω)

19.8 A milliammeter has a resistance of 20Ω and gives full scale deflection when carrying a current of 25 mA. How would you be able to measure 50, 150 and 250 V ? (Ans. 1980Ω, 5980Ω, 9980Ω)

19.9 A moving coil ammeter has full scale resistance of 20Ω and produce full scale deflection for a current of 10 A. What maximum current can it measure if it is shunted by a shunt of resistance 5Ω. (Ans. 50 A)

19.10 A moving coil ammeter has a resistence of 10 ohms and produce full scale deflection for a current of 150 mA. What maximum current can be measured by it if it is shunted by a shunt resistance of value 0.05Ω? (Ans. 30.15 A)

19.11 A moving coil galvanometer has a resistance of 1Ω and its scale is divided into 250 parts. At a potential difference of 0.6 V, the pointer gives a deflection of 150 parts on the scale. If the meter is required to be converted as an ammeter reading upto 51 A. Find the resistance to be shunted. (Ans. 0.02Ω)

19.12 A moving instrument has a resistance of 10Ω and takes 5 A to give full scale deflection. How this instrument can be used as (i) ammeter to read up to 30 A. (ii) a voltmeter to read up to 250 V. (Ans. 2Ω, 40Ω)

19.13 A moving coil instrument has a resistance of 21.6Ω and takes 500 mA to give full scale deflection. How can this instrument be used as

(i) An ammeter to read up to 25 A
(ii) A voltmeter to read up to 500 V. (Ans. 0.4Ω, 978.4Ω)

19.14 Calculate the number of revolutions, which would be completed by the disc of a single phase energy meter in 40 seconds, when the load on the meter is 4 kW. The meter constant is 3600 revolution for each unit (Ans. 160 Rev.)

19.15 Find the number of revolutions travelled by the disc of a single phase energymeter in 3 minutes, when the load on it is 1.5 kW. The meter constant is 2000 revolutions per unit. (Ans. 150 Rev.)

19.16 Calculate the number of revolutions which would be travelled by the circular disc of a single phase energymeter in 2 minutes, 30 seconds when the load on the meter is 1.6 kW. Take a meter constant of 2400 revolutions/kWh. (Ans. 160 Rev.)

19.17 The disc of a single phase energymeter completes 2 revolutions in 6 seconds. The disc makes 2400 revolutions for each kWh. Calculate the load on the watts meter. (Ans. 500 W)

**19.13** A milliammeter of 3Ω resistance reads a maximum current of 150 mA. How can it be used as:
(i) a voltmeter to read up to 15 V
(ii) an ammeter to read up to 30 A (**Ans.** 97Ω, 0.01508Ω)
(*State level Compet. 1969 Elect.*)

**19.14** Describe with sketches the construction and operation of one of the following
(i) A moving coil voltmeter
(ii) A moving iron voltmeter
State whether each of the above instruments may be used on the following supplies, ac, dc or both
(*All India Skill Compet, 1969 Elect.*)

**19.15** What are the two types of instrument transformers? Explain the difference between the two and their uses. (*NCVT, 1984 W/man*)

**9.16** With the help of diagram explain the working of single phase energy meter. (*NCVT 1987 Elect.*)

# 20

# Illumination

## 20.1 DEFINITION AND MEANING OF TERMS USED IN ILLUMINATION ENGINEERING

**Illumination** It is the quantity of light emitted by a lighting source is known as illumination.

The heating effect of electric current is used in producing illumination. When an electric current is passed through a conductor, some heat is developed which increases the temperature of that conductor. If the temperature is low, (say up to 900°C.), energy consumed is converted into heat only and no light is produced. If the temperature is further increased above 900°C, the substance starts emitting light rays The magnitude of the light emitted depends upon the temperature of the substance. This means, a substance is to operate at high temperature for emitting light rays. Therefore only those substances are to be used for this purpose whose melting point is high, like carbon, tantalum, tungsten, etc.

The illumination power of a lighting source is measured in candle power.

**Candle Power** It is the unit used for measuring the illumination power of a source of light. One candle power is the amount of light given out by a standard candle made of specifiec materials and size.

If this standard candle burns at the rate of 120 grains per hour (or 7.776 g/h), then it emits a unit illumination which is known as one candle power. It is represented by CP.

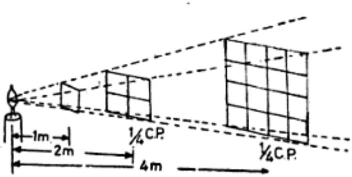



**Fig. 20.1 Variation of intensity of illumination**

**Intensity of Illumination** It is the amount of illumination given out by a unit source of illumination at a unit distance.

It will be seen that the intensity of light varies inversely as the square of distance of an object from the light source. Intensity of light at 2 metres away from a source of light remains only 1/4th of that at 1 m away. Similarly, at 4 m it only remains 1/16th of that at 1 m. Therefore, the measure of intensity of illumination is necessary. The followings are the units of intensity of illumination in different system of measurements.

*Lumen* The unit of volume of light (i.e. total output of light) is "lumen". The lumen per square foot (lm/ft²) is the intensity of light given out by the standard candle over an area of 1 square foot at a distance of 1 foot from the candle. Lumen per square foot is also sometimes known as foot-candle.

*Lux* This is the total output of light. Lumen per square metre (lm/m²) is the intensity of illumination produced on the inner surface of a hollow sphere of radius one metre by a standard candle at the centre. Sometimes this is also known as metre-candle.

## 20.2 FACTORS TO BE VIEWED FOR CORRECT ILLUMINATION

The following are the important factors which should be considered while planning correct and a good illumination:

**Nature of Work** Considering the nature of work, sufficient and suitable lighting should be maintained. For example, a delicate work like radio and TV assembling, etc. requires good illumination to increase the production of work where as for rough work like storage, garrages, etc needs very small illumination.

**Design of Apartment** The design of apartment must be kept in view while planning scheme for illumination. It means that the light emitted by the illumination source should not strike the eyes of the occupants or workers. Correct illumination in a workshop increases production and reduces wastage of material and accident. Therefore suitable reflector and correct size and type of lamps should be used to have good illumination.

**Cost** It is an important factor which should be considered while designing an illumination scheme for a particular purpose.

**Maintenance Factor** While planning illumination, it should also be kept in view the amount of reduction of light due to accumulation of dust or smoke on the source of light and after how much period cleanliness is required. Where there is a possibility of heavy loss of light due to the adherence of smoke, arrangement for extra light is to be made from the very beginning.

## 20.3 PROPERTIES OF GOOD ILLUMINATION

The following properties may be kept in mind while designing an illumination scheme.

An illumination source should have the following properties.

(*i*) It should have sufficient light.
(*ii*) It should not strike the eyes.
(*iii*) It should not producedglareneres in the eyes.
(*iv*) It should be installed at such a place that it gives uniform light.
(*v*) It should be of correct type as needed.
(*vi*) It should have suitable shades and reflectors.

## 20.4 ADVANTAGES OF GOOD ILLUMINATION

The following are the advantages of good illumination. A sufficient and good arrangement of light have the following advantages.

(*i*) It increases production in the workshop.
(*ii*) It reduces the chances of accidents.
(*iii*) It does not strain the eyes.
(*iv*) It reduces the wastage or loss of material.
(*v*) It increases the interior decoration of the building.
(*vi*) It gives compstness to mind.

## 20.5 TYPES OF LIGHT SOURCES

A light source can be classified into three groups as follows.

(*i*) Direct lighting.
(*ii*) Indirect lighting,
(*iii*) Semi-direct lighting

**Direct Lighting** It is the simplest form of lighting and according to the installation point of view is less costly. In this system of lighting, the light comes straight from the source of illumination or from a shade encircling it to the working surface. This type of lighting is generally used in factories or in such places where direct light is required on the job.

**Indirect Lighting** In this system the light does not come direct from the source of light to the job but reflects from ceilings, walls or reflectors. In this system the source of light is totally hidden and the output of light is less. The fittings of such system are costly but give shadowless uniform light. This type of lighting is used for drawing rooms, restaurants, clubs, cinemas, etc.

**Semi Direct Lighting** In this system the light rays neither reflect direct from the source nor from the walls but comes through the shade surrounding it. The shades or reflectors used in such lighting are made of transparent material and are comparatively less costly than indirect lighting. Such lights can also be used in drawing rooms, reception rooms, resistance street light, hospitals, etc.

Suitable values of illumination in lumen/metre$^2$ are given below.

| | | | |
|---|---|---|---|
| 1. | Main roads | — | 5–10 lm/m$^2$ |
| 2. | Corridors | — | 20–30 lm/m$^2$ |
| 3. | Living rooms | — | 50–60 lm/m$^2$ |
| 4. | Offices | — | 100–120 lm/m$^2$ |
| 5. | Billiard tables | — | 200 lm/m$^2$ |
| 6. | Drawing Offices | — | 250–400 lm/m$^2$ |

## 20.6 SOURCES OF LIGHT

The source of light which on supplying electrical power develops light is known as "electric lamp".

The following are the three sources of producing artificial light rays.

(*i*) Incandescent lamp.

(*ii*) Carbon arc lamp

(*iii*) Gas discharge lamp

## 20.7 INCANDESCENT LAMPS

**Incandescent Lamp** There are two types of incandescent lamp in use.

(*i*) Carbon filament lamp

(*ii*) Metal filament lamps ; (a) Metal-filament vacuum lamps, and (b) Metal filament gas-filled lamps.

*Carbon Filament Lamp* This consists of an evacuated glass bulb containing a carbon filament in it, as shown in Fig. 20.2.

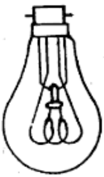


**Fig. 20.2 Carbon filament lamp**

The filament is brought to operating temperature by passing current through it. The operating temperature of carbon filament lamp should not be increased beyond 1800 degree C., because at higher temperature it vaporizes and thus blackens the inside of the bulb. The bulb is evacuated to avoid the burning of filament and to maintain the working temperature of it. Its resistance at working temperature is about 2/5 times that of cold resistances because carbon has negative temperature co-efficient of resistance. The amount of light given out is comparatively less than metal filament lamps and its illumination is light yellow in colour. The efficiency of lamp is about 3.5 W per candle power or 3.6 lumens per watt.

This lamp is best suited for battery charging as the consumption is much higher than other lamps. Its life is about 600 to 800 working hours.

**Metal-Filament Vacuum Lamp** In this lamp tungsten filament is usually used. The melting point of tungsten is about 3400°C. Its operating temperature should not be more than 2000°C, otherwise the metal will evaporate and blacken the bulb. The efficiency of vacuum lamps is low as compared to gas filled lamp and is 8-10 lumens per watt.

**Fig. 20.3 Tungsten filament vacuum lamp**

The life of the lamp is about 750 to 850 working hours.

**Gas-Filled Lamp** The gas-filled lamp is a modification of the vacuum lamp and is commonly used now-a-days. To increase the working temperature and efficiency the lamp is filled with and small percentage of nitrogen gas. Thus the filament can be heated to a higher temperature than that of a vacuum lamp. The working temperature of gas filled lamp is 2500°C while the vacuum lamp it is about 2000°C. The temperature of this lamp can be further increased by using coiled coil filament. The efficiency of this bulb is 10-20 lumens per watt or 0.6 W per C.P. The life of this lamp is about 1000 working hours.

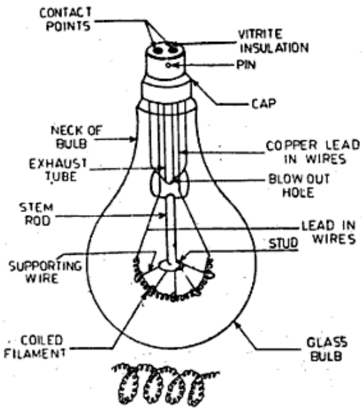



**Fig. 20.4 Parts of a lamp**

In Fig. 20.4 the parts of a gas filled lamp are shown. The filament is specially hung horizontally so that if some material of the filament changes into vapour and deposit in the neck of the bulb and should not interfere with the light given out by the lower half of the bulb.

## 20.8 CARBON ARC LAMP

Two carbon electrodes placed in contact end to end, in which direct current is flowing, and on separating by about 0.6 cm., apart gives out a luminous arc as shown in Fig. 20.5

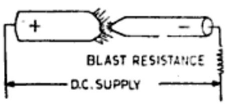



**Fig. 20.5 Carbon arc lamp**

The arc gives path to the flow of current and the separated ends of the carbon emits light rays. The major portion of the light is due to the electrodes and only 5 per cent is given out by the arc. About 85 per cent of light is given out by the positive electrode which has a temperature of 3500°C to 4000°C and only 10 per cent light is emitted by the negative electrode which has a temperature of nearly 2500°C. In the Fig. 20.5 a ballast resistance is also shown because of the negative resistance characteristic of the carbon arc.

The production of heat due to the arc is explained as:

When the carbon electrodes are separated, the electrons flow from negative electrode to positive electrode through the air. When passing through the air they collide with neutral air atom and set the air in ionised (charged) condition. The positive ions move towards the negative electrode colliding with the carbon, there they produce a good amount of heat, which raises the temperature of the negative electrode. Similarly the negative ion will move towards the positive electrode and collide with the electrode producing enough heat to raise the temperature of the electrode about 3500°C to 4000°C.

The heat developed at the positive electrode is greater because the negative ions have less weight than positive ions and so they move with higher velocity after collision.

Due to higher operating temperature, the rate of consumption of positive electrode is nearly double than the negative electrode. Due to this reason the positive electrode is made of twice the cross sectional area to that of the negative electrode. When using arc lamp on ac supply, both electrodes burn away at equal rates and therefore they are made of equal cross-sectional area. The efficiency of the arc lamp is higher than incandescent lamp and is about 0.5 to 0.3W per candle power or 20 lumens per watt.

As the rate of consumption is high due to high operating temperature, it is essential to maintain the air gap between the electrodes to obtain constant and continuous light. For this purpose an electrical and mechanical arrangement is provided in arc lamps. When the carbon becomes short in length, they are replaced. As this lamp needs frequent adjustment and replacement of the carbon rod, so it is not used in general purposes. They are only used in cinemas projectors, search lights. The operating voltage of these lamps varies between 40 to 60 V.

## 20.9 GAS DISCHARGE LAMP

A gas discharge lamp is one in which some inert gas is filled in a glass tube having two electrodes sealed into each end, which on heating allows the flow of electron through it. To obtain a continuous flow of electron, gas is first charged but as the supply is disconnected from the bulb, the gas is discharged. Such a lamp is known as electric Gas Discharge Lamp. Electric gas discharge lamps are of two main types:

(i) Cold cathode lamp

(ii) Hot cathode lamp

In first type no filament is used to heat the electrode for starting but in the second type a filament is provided for heating the main electrode at the time of starting.

The function of both the lamps depend upon the fact that when a current is passed through the gas, it emits light rays. When a voltage is applied across the two ends of the filament contained in a gas filled glass tube, electrons start flowing from one electrode to the other. On the way they strike with neutral gas atoms separating an electron temporarily which when returns gives out light rays. The following are the different types of gas discharge lamps:

**Cold Cathode Lamps** (i) Neon lamp, (ii) neon sign tubes, (iii) sodium vapour lamp.

**Hot Cathode Lamps** (i) mercury vapour lamp (medium pressure), and (ii) fluorescent tube (low pressure mercury vapour lamp)

These are discussed in detail in the following section

## 20.10 TYPES OF GAS DISCHARGE LAMPS

**Neon Lamp** This is a cold cathode lamp as shown in Fig. 20.6. Neon gas at low pressure is used in it.

In this lamp, two flat or spiral electrodes are kept close together in a glass bulb so that the lamp can be operated at low voltage such as 150 V dc or 110 V ac On giving supply to the electrodes, the gas becomes ionised and emits light which is reddish in colour. In usual practice a 2000Ω resistance is also connected in series with the electrodes which is placed in the cap of the lamp. This minimizes the fluctuation of current due to large variation of potential difference.

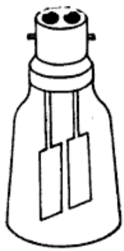


**Fig. 20.6 Neon lamp**

A neon lamp is generally used as an indicator lamp to indicate the presence of supply. It gives a small quantity of light and can also be used as a night lamp A neon lamp of this type is also used in the testing pencil which is of 0.5 W.

## 20.11 NEON SIGN TUBES

These are also cold-cathode neon tubes used for advertising purposes. These glass tubes contain different gases at low pressure for different colours. At the end of the tubes cylinderical electrodes are provided which are made of nickle or iron. As these electrodes are not heated up during operation, they are known as cold cathode tubes. For starting discharge through gas, these tubes require 900 to 1200 V/m. In order to start the discharge, a still higher voltage for a moment is required. The tubes are supplied electric current through a step up transformer from ac mains. A choke coil may be connected in series with the primary winding, which control the current after the discharge takes place. For this purpose a high leakage reactance step up transformer can also be used. A condenser is connected across the transformer (shown in Fig. 20.7) to improve the power factor of the circuit which may be low due to choke coil or high reactance transformer.

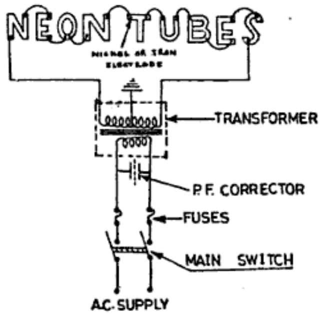



**Fig. 20.7 Neon sign tube**

At the time of starting these tubes draw less current as the resistance of the gas when cooled is high. Thus the starting voltage drop across the tubes will be low. Hence the starting voltage of the transformer thus remains high which is enough to start the arc between the electrodes of the tube. After starting the gas gets heated up and its resistance decreases considerably which further increases the current. Due to this increase of current in the transformer, the high reactance of transformer drops more voltage and hence the tubes get proper operating voltage.

The different colours are obtained by filling the tubes with different gases. The following are the most common gases used.

| *S. No.* | *Gas* | *Colour* |
|---|---|---|
| 1. | Neon | Red |
| 2. | Neon + Argon | Reddish orange |
| 3. | Vapour of mercury | Blue |
| 4. | Neon + Helium | Golden colour |

## 20.12 SODIUM VAPOUR LAMP

A Sodium vapour lamp is also a cold-cathode low-pressure lamp which gives high luminous output about three times higher than other lamps. This lamp is manufactured in the form of long tube into the ends of which two oxide coated electrodes are sealed. This long tube contains a little sodium and neon gas. To reduce the length occupied by the tube they are made of 'U' shaped as shown in Fig. 20.8.

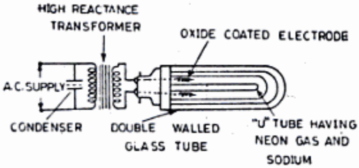



**Fig. 20.8 Sodium vapour lamp**

Since there is great effect of the change of temperature on the light given by the lamp, the "U" shaped tube is enclosed in an outer doubled walled glass tube. Before sealing the lamp, vacuum is created between the double walled glass tubes.

When cold, sodium is in solid state and hence the lamp cannot be started direct as sodium vapour lamp. For this purpose neon gas is inserted in the tube. When connected to the supply it starts as a neon lamp giving reddish light. After 10-15 minutes, the solid sodium turns into vapour giving yellowish light.

For starting the discharge through the lamp, it is essential that the striking voltage should be higher than the normal working voltage of the lamp. This high voltage is taken from a high reactance transformer or auto-transformer which has poor voltage regulation. Thus when discharge in the lamp takes place, the lamp current increases due to decrease in resistance of gas in tube and the output voltage of the transformer falls. The lamp then continues to operate normally. This lamp is usually recommended for street lighting and have practical luminous efficiency of 40 to 50 lumens per watt.

## 20.13 MERCURY VAPOUR LAMP

It is a hot-cathode gas-discharge lamp similar in construction to the sodium vapour lamp and may have low gas pressure in the bulb. As the pressure is low as in the case of sodium lamp, the luminous efficiency of the bulb is very low. To have increased efficiency, medium pressure and high pressure hot cathode mercury lamps are used.

In medium pressure lamps two main electrodes of tungsten coated with barium oxide (material for easy emmission of electrons) are enclosed in a hard glass or quartz tube. There is an auxiliary starting electrode near one of the main electrodes as shown in Fig. 20.9. This tube contains argon gas at low pressure and some mercury. This quartz tube is enclosed in another ordinary glass bulb whose internal surface is coated with flourescent powder as shown in Fig 20.9. The space between the tube and the bulb is evacuated to reduce the heat loss.

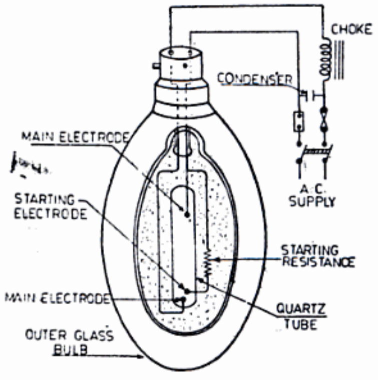



**Fig. 20.9 Mercury vapour lamp**

A choke coil having different tappings is connected in series with the lamp to give high starting voltage for discharge and for controlling the current and voltage across the lamp after discharge. The power factor of the circuit is poor due to choke coil which can be improved by installing a condenser in parallel to the supply line.

Initially when the switch is put on for starting, the current does not flow through the main electrodes due to high resistance of the gas. However the current starts to flow between the main electrode and auxiliary electrode through the argon gas. The heat thus produced vaporizes the mercury which reduces the resistance between the main electrodes and thus discharge takes place between the two main electrodes. This is due to the high voltage induced in the choke coil due to the momentary interruption of current in the auxiliary electrode.

Mercury vapour lamp gives 2.5 times higher light than incandescent lamp for the same power consumption. These lamps are available in different wattages like 80 W, 125 W, 150 W, 250 W, 400 W and 1000 W and give illumination in bluish colour. These lamps are specially used for high way lighting, park lighting, etc. The efficiency of the lamp is 35 to 40 lumens per watt.

*Disadvantages*

(*i*) It takes about 6 minutes to give full brightness.

(*ii*) When moving objects like the chuck of a lathe machine etc. is lighted up by the group of these lamps, it seems that it is rotating in correct direction due to multiple images which may cause accident. This effect of light of mercury vapour lamp is known as stroboscopic effect which may be dangerous. This can be avoided by connecting adjacent lamps on separate phases.

(*iii*) Mercury vapour lamp cannot be used in any standard lamp holder as there are three pins in its cap.

(*iv*) The original colour of an object cannot be judged.

(*v*) It takes 6A approximately on first switching ON and after six minute it falls to 3A.

*Advantages*

(*i*) It produces similar to day light which may help in increasing the production of a concern.

(*ii*) The life of mercury vapour lamp is much higher than incandescent lamp.

## 20.14 FLUORESCENT LAMP

These lamps are hot cathode low pressure mercury vapour lamps and are manufactured in the form of long glass tubes having different wattages and length as 20 W and 0.6 m (2 feet), 40 W and 1.2 m (4 feet), 65 W, 80 W, and 1.5 m (5 feet). There are two tungsten filaments at each end of the fluorescent tube. These are coated with electron emitting material like barium oxide for the easy emission of electron when heated. The tube is coated from inside with fluorescent power and is filled with argon gas at low pressure and some mercury. The gas is added in the tube because at the time of starting the mercury is in the form of normal liquid state, so the lamp starts as conducting with argon gas. When the temperature rises, the liquid mercury changes into vapour form and takes over the conduction of current. A choke coil and a starter is also connected in series with the tube. The function of the choke coil is to provide high impulse voltage of about 1000 volts for starting the tube and after starting it acts as a blast in the circuit to drop the voltage. A glow type starter in the circuit performs the function of a switch.

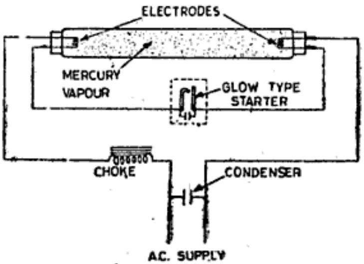



**Fig. 20.10 Fluorescent tube**

The connection of a tube with a glow type starter and a choke coil is shown in the Fig. 20.10. The glow type starter has two bimetallic electrodes enclosed in a small glass tube containing helium gas. These electrodes normally remain open. When the switch is put on, a small current flows from one electrode to the other through the helium gas.

To minimize the radio interference due to make break sound of starter and to increase the life of bi-metallic electrodes a small condenser is connected across the starter.

When the switch is put on, a small current flows through the choke coil, tube filaments and starter. This small current passes from one electrode to the other electrode through the helium gas in the starter. Discharge through the helium gas develops some heat which bends the bi-metallic electrodes and thus they come direct in contact with each other. Now sufficient high current flows directly through the electrodes. After one or two seconds these electrodes cool down. This results in breaking the contact and thus current stops flowing through the filament as well as choke coil. Due to this sudden break, a high voltage of about 4 to 5 times of normal voltage is induced in the choke coil which is applied on the long gas column and thus the discharge starts direct in the tube. After the starting of the tube, the choke coil works as a ballast and drops some voltage across it (due to increased reactance or impedance after starting) and thus the voltage across the tube is less than the supply voltage.

This lamp gives glareless cool day-light and has efficiency of 40 lumens per watt. The average life of the lamp is about 4000 working hours. This is useful for workshops, drawing rooms, offices and for all local and general lighting. When this lamp is required to use on dc supply, a resistance is connected in series with the choke which acts as a ballast in the beginning and later on it drops the voltage and smoothens the current in the circuit.

*Fluorescent Material* The fluorescent material used in side the tube in the form of coating absorbs the ultra violet rays and change them into light rays. Coating of different materials give different colours of light and some of them are given below.

| *Sl. No.* | *Fluorescent Materials* | *Colour* |
|---|---|---|
| 1. | Calcium tungstate | Blue |
| 2. | Magnesium tungstate | Blue-White |
| 3. | Zinc Beryllium silicate | Yellow White |
| 4. | Cadmium silicate | Yellow-Pink |
| 5. | Cadmium borate | Pink |
| 6. | Zinc Silicate | Green |

## REVIEW QUESTIONS

20.1 Describe the principle and construction of a fluorescent tube. Explain the use of starter for lighting the tube and give the wiring diagram. *(NCVT. 1963 Elect, 1970 elect, 1976 W/man, 1980 W/man)*

20.2 (i) What are the various types of lamps available in the market? Describe the construction of any of the two lamps with which you are conversant. (ii) Describe the following:

(i) If the voltage is increased by 5 V in 230 V coiled coil tungsten filament lamp. What would be the percentage increase in the light output?

(ii) State efficiency in lumens output per watt of a tungsten filament coiled coil lamp.

(iii) Life of the lamp. *(NCVT, 1965 Sep. Elect.)*

20.3 Describe briefly the principle of electric discharge lamps. What are the main groups in which they are manufactured. Explain the construction of an HPMV lamp and state the following:

(i) Equipment required for operation of an HPMV lamp.

(ii) Efficiency, i.e. output in lumens per watt.

(iii) Life of the lamp. *(NCVT, 1965, Oct. Elect.)*

20.4 Describe the working of a sodium vapour lamp with the help of a neat sketch explaining the function of each part. *(NCVT, 1976 Elect.)*

20.5 Describe the principle of working of an electric discharge lamp. Explain the construction of a mercury vapour lamp and equipment required for its operation. *(NCVT, 1978 Elect.)*

20.6. (a) What are the different types of lighting devices used in domestic, industrial, cinema hall and road lighting.

(b) Describe in brief the construction and working of a mercury vapour lamp. *(NCVT 1983 W/man)*

20.7 What is the function of a choke coil and a starter in a fluorescent lamp? State where the twin-fitting of these lamps is essentially used. *(NCVT 1986 W/man)*

20.8 Describe with neat sketch the construction and and operation of fluorescent tube light and in what way it is better than incondescent lamp? *NCVT 1988 W/man)*

# 21

# Automobile Electrical System

### 21.1 DIFFERENT CIRCUITS OF AN AUTOMOBILE

In an automobile, electrical energy is supplied to all the electrical circuits from a dynamo or alternator while the vehicle is in normal running condition. But when the vehicle is stationary or running at slow speed, these circuits are supplied electrical energy from a lead acid battery which is usually of 6, 12 or 24 V and 100, 150, 200 Ah capacity. This battery is charged from the dynamo or alternator which gets attached with the engine of the automobile when it attains a predetermined speed. The electrical circuits of an automobile can be grouped into five classes as given below:

(*i*) Lighting circuit
(*ii*) Starting circuit
(*iii*) Ignition circuit
(*iv*) Charging circuit
(*v*) Electrical devices circuit

### 21.2 LIGHTING CIRCUIT

This part of the electrical circuit provides lighting inside and outside of the vehicle for safe operation during night. A lighting circuit comprises the following sub-circuits:

| Head light | Side light | Dome light | Dash Board light | Stop light | Tail light | Door light |
|---|---|---|---|---|---|---|

**Lighting Circuit**

*Headlight Circuit* Headlights are provided in front of the vehicle. The aim of this circuit is to illuminate the objects coming from the opposite side in the night. In headlights, double-filament bulbs of 6 to 24 V and 12 to 36 W are usually used. These lights are separately controlled by a "ON" & "OFF" switch like a two way switch which is fitted on the dash board. This switch puts 'ON' any one of the two filaments in head lights at a time. As the two filaments are of different wattage they give different illumination. When less light is needed, low wattage filament is switched 'ON' and when more light is required, high wattage filament is operated. A dimmer dipper switch is also connected in the circuit which is installed near the foot of the driver. The connection of head light circuit is shown in Fig. 21.1.

*Sidelights* These lights are also known as parking light and are fitted on the front side of the vehicle to indicate the breadth of it. These lights are separately controlled by a common switch (shown in Fig. 21.1). They are left glowing when the vehicle is placed for parking during night. The usual wattage of the bulb is 3 to 6 W.

*Dome light* Dome light is fitted inside the vehicle to illuminate the inner objects. This light should be fitted in such a way that there is no glare of light from the front glass.

*Dash-board Light* This light is fitted on the dash board to illuminate the switch board pannel. This lighting is a type of indirect lighting and a bulb of 1.5 W is generally used for this purpose.

*Stop Lights* (*Danger Lights*) These lights are installed at the back-side of the auto-vehicle on its two sides. The control of these lights is through the brake. When brake is applied, these lights start flickering thus giving an indication to the driver of the rear vehicle. The wattage of the lamp is also 3 W.

*Tail Light* This light is also of 3 W bulb and is fitted on the back side of an automobile. The function of this light is to illuminate the back number plate of the vehicle during

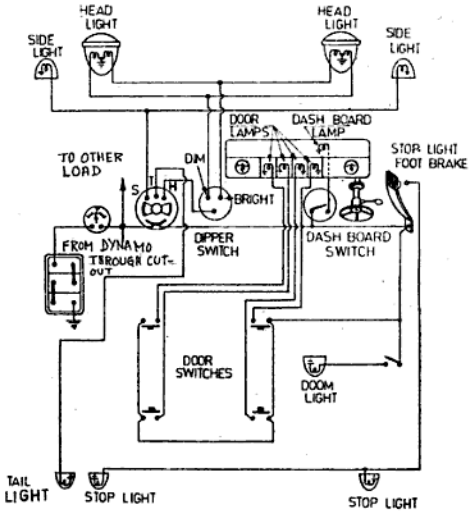



**Fig. 21.1 Lighting circuit**

night. Its control is kept in such a way that it must glow whenever either of head lights or side lights glow.

*Door Lights* The aim of providing these lights is to send indication to the driver whether the doors are open or properly shut. These lamps are fitted at the dash board. Glowing of lamp shows that a particular door is not properly closed.

## 21.3 STARTING CIRCUIT

When a vehicle is stationary and it is required to start the vehicle its engine must be rotated first. For this purpose a self-starter is used which takes current from the battery. This self-starter is a dc series motor, the output of which is about 1 H.P. The working voltage of the starter depends upon the voltage of the lead acid battery which varies from 6 to 24 V. As this motor is to rotate the stationary engine, it takes heavy current for developing high starting torque. This heavy current, of the order of hundred amperes, passes through a thick cable from the battery to the motor. As the vehicle attains speed, this motor is automatically disconnected from the engine by a mechanical gear arrangement provided on the shaft of the motor. As far as possible frequent starting of the self starter should be avoided as it would discharge the battery soon.

The self starter is either a 2 pole or 4 pole dc series motor. Fig. 21.2 (a), (b) shows separate connection of self starter with pedomax switch and solenoid switch.

## 21.4 SPARK PLUG

A spark plug consists of two metal electrodes, shown in Fig. 21.3 separated by a porcelain insulator which can withstand high temperature of combustion engine without loosening

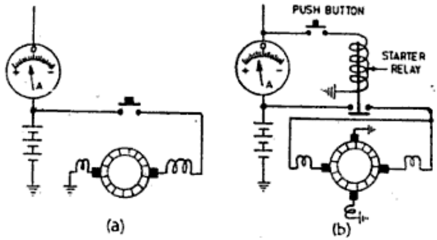



Fig. 21.2 Starting circuit

its insulating properties. The air gap between the two electrodes approximately varies from 0.7 mm to 0.9 mm. A high voltage is applied between the central and ground electrodes of the spark plug. This high voltage causes spark which jumps between the two electrodes thereby igniting the fuel in the combustion chamber.

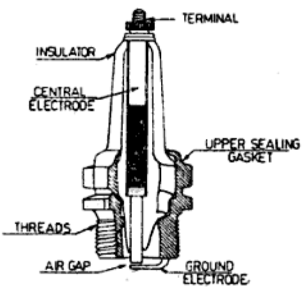



Fig. 21.3 Spark plug

## 21.5 IGNITION CIRCUIT

An ignition circuit consists of an ignition coil, distributor, contact breaker, condenser and spark plug. In petrol engine, a spark is required in a cylinder in a cylinder for starting the engine when the piston is at the end of compression stroke and beginning of working stroke which ignites the fuel. For producing spark in the cylinder it is essential to have high voltage. But in an automobile only low voltage dc supply is available from the lead acid battery. This low voltage is stepped up with the help of ignition coil.

*Ignition Coil* An ignition coil consists of two coils separately insulated from each other as shown in Fig. 21.4.

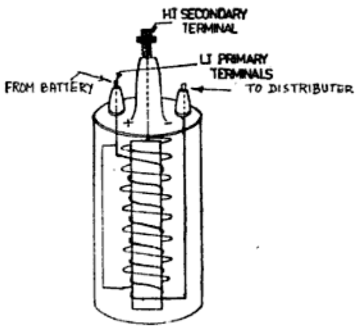



Fig. 21.4 Ignition coil

One coil is having only few hundred turns of thick wire while other coil is having many thousand number of turns of thin wire wound on the same iron core. In fact this coil is a transformer and works on the principle of mutual induction. But for the operation of transformer an alternating current or pulsating current is needed. The current supplied from the battery is a direct current which is changed to pulsating current by passing it through a make break arrangement. This pulsating current is then passed through the primary winding of the ignition coil which sets up a pulsating flux in it and thus a high voltage of nearly 11 to 40 kV is induced in the secondary winding of the coil. This high voltage is applied across the spark plugs and a spark takes place inside the cylinder.

In an auto-vehicle there are generally four, six or eight cylinders depending upon the design of the individual manufacturer and a spark is essentially required in each cylinder just before the working stroke of the piston. It is therefore necessary to distribute the high voltage to the spark plugs in turn. This distribution of current to the spark plugs is done by distributor.

*Distributor* A distributor consists of lower and upper parts. In the lower part of the distributor a make-break arrangement is provided for the current of primary winding of the ignition coil. In the upper part, the distribution of high voltage is given to each cylinder. In the middle of the upper part of distributor, a rotor rotates which can make contact with the stationary points in the upper part of the insulated cap of the distributor. These points are connected to the sparking plugs by high tension wire which are equal in number to the number of cylinders in the engine.

In the lower part of the distributor there is an iron piece having symmetrical sides equal in number to the cylinders of the engine and is known as cam. This iron piece and the rotor rotate with the rotation of the driving shaft of the cam and thus interrupt the current flowing through the primary coil. This results in inducing high voltage in the secondary coil which is applied to the spark plugs.

A condenser is also connected across breaker point of the distributor. Its function is to suppress the spark at the make-break points at the time of opening the contact by retaining charge and give quick discharge at the time of closing these points. These points are usually made of platinum so as to withstand high temperatures. The air gap between the contact breaker point generally varies from 0.038 to 0.457 mm (0.0015 to 0.018"). Figure 21.5 shows the connection for a 4 cylinder vehicle.

The order in which sparking takes place in different cylinders is known as firing order and for a 4 cylinders vehicle this order may be 1, 3 and 4, 2 or 1, 4 and 3, 2, etc. For a six-cylinder automobile, the firing order may be 1, 3, 5, 2 and 4, 6 or 1, 6, 3, 5 and 4, 2 etc.

## 21.6 CHARGING WITH TWO BRUSH DYNAMO

In an auto-vehicle if the current from the battery is taken continuously for all the electrical circuits and no source is provided for its charging, it will be discharged soon. To prevent this, a small shunt dynamo of voltage little higher than the battery voltage is fitted with the engine along with a 3 unit regulator.

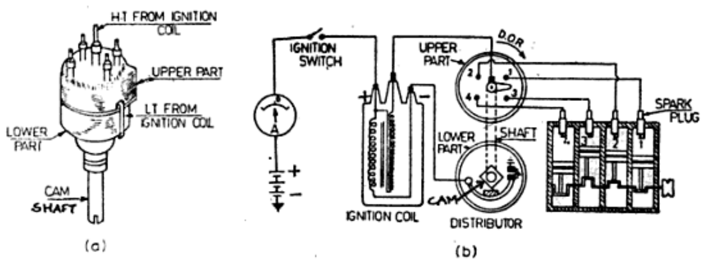



Fig. 21.5 Ignition circuit: (a) Distributor; (b) Ignition coil with distributor

*Electric Horn* The common electric horns in use are of two types viz (i) motor type and (ii) electromagnetic type.

*Electric motor type horn* In this type of horn there is a dc series motor on the shaft of which a circular threaded plate is fixed. Another similar threaded plate is placed making contact with it (as shown in Fig. 21.8) which is attached to a steel diaphram. When the supply is given to the horn motor, it revolves the threaded plate which in turn vibrates the diaphram and thus the necessary sound will be produced.

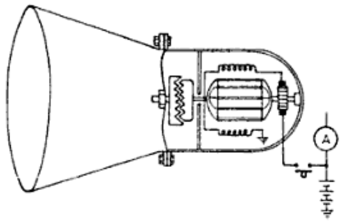



**Fig. 21.8 Electric motor type horn**

*Electromagnetic type electric horn* It consits of a cylindrical hollow coil in the centre of which there is a soft iron plunger. This plunger is attached to a high frequency steel diaphram. Fig. 21.9 shows the connection of this type of horn.

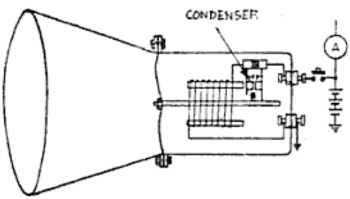



**Fig. 21.9 Electromagnet type horn**

When the horn switch is put on, a current starts flowing through the winding and the plunger is thus magnetised. This plunger now pushes the diaphram inside and then open the contact point and in this way the coil is demagnetised. Due to the tension of the steel diaphragm, the plunger returns to its original condition and thus the contact point is again made. Again current flows, the plunger is magnetised which pulls the diaphragm inside, the contact point breaks and the plunger again comes to its original position. This procedure continue as long as the horn switch is made ON and the diaphragm goes on oscilating producing a sound.

Horn circuit takes large currents of the range of 8 to 12A which may damage the contact point of the ordinary push button. This heavy current will damage the ammeter if installed in the circuit. For this reason supply to the horn circuit is fed direct from the battery through the horn relay.

*Turn signal* Turn signals are used to indicate the side in which the driver wants to take turn. These signals are of two types, namely (i) electromagnetic arm type, and (ii) flasher type.

*Electromagnetic arm type turn signal* Sometimes back these type of side indicating signals were widely in use. But now a days they have been superseded by the flasher types.

This type of turn signal consists of an arm and an electromagnet system as shown in Fig. 21.10. When the current is passed through the electromagnet, it is magnetised and pulls inside the iron plunger attached to an arm. This lifts the arm upwards and thus

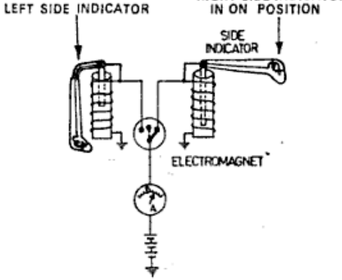



**Fig. 21.10 Electromagnetic turn signal (Arm type)**

showing the tank to be full. When the tank is empty, the float is at the bottom of the tank and thus all the resistance is in series with the current coil. Maximum current will flow through the pressure coil and as this coil has greater number of turns as compared to the current coil, it will have more flux. This will result in attracting the moving iron towards the pressure coil and therefore the needle points towards 'E' on the scale, indicating the tank as empty. When the tank is half-filled, the sliding contact will be midway between the resistance and the magnetic strength of both the coils will be equal and the needle will take its position on 'H' on the dial indicating the tank as half-filled.

*Electric fuel pump* The aim of the fuel pump is to pump the fuel from the tank to the carburetor. Figure 21.13 shows the main connection and working principle of a fuel pump.

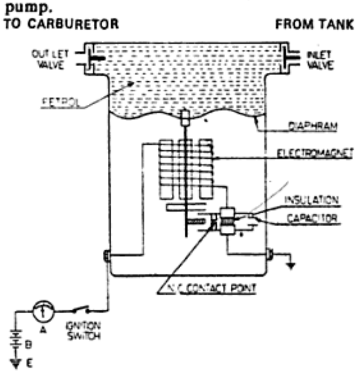



**Fig. 21.13 Electric fuel pump**

A fuel pump has one inlet valve and one outlet valve. The fuel from the fuel tank enters through the inlet valve and goes out to the carburetor through outlet valve. These valves are enclosed in a chamber formed with the help of a diaphram. This diaphram is fixed to a plunger which can move upward and downward by the operation of a solenoid.

When the ignition switch is put 'ON' the solenoid is magnetised and attracts the plunger upward. This plunger pushes the diaphragm upward. Due to increased pressure created in the chamber, the fuel is forced to the carburetor through the outlet valve. During this operation the inlet valve remains closed. But when the plunger gets lifted upward, it opens the contact point of solenoid and in this way it is demagnetised and returns to its original downward position. This results in reducing pressure in the chamber and therefore fuel enters through the inlet valve. As the diaphragm moves to its downward condition, the contact point again touches each other and solenoid is again magnetised and in this manner the whole process is repeated again and again till the ignition switch remains closed.

*Screen Wiper* Its function is to clean the wind glass to enable the driver to see the road clearly. It consists of a small dc series motor having thread on the shaft of its armature which drives other gears as shown in Fig. 21.14. A moveable rubber blade is fixed to this gear which clears the front glass when required.

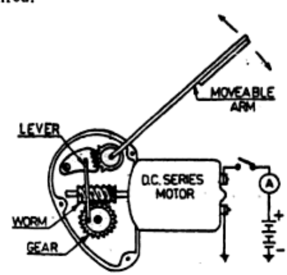



**Fig. 21.14 Electric screen wiper**

When the switch is made 'ON', the motor starts rotating and the threaded portion of the shaft revolves the gear arrangement shown in the figure. The high speed of the motor is reduced to low speed with the help of these gears. A lever is attached to this gear which gives to and fro motion in the wind screen blade which is fixed to the other gear.

| *Troubles* | *Causes* | *Remedies* |
|---|---|---|
| | 4. Loose connection in field winding. | Connect field tightly. |
| | 5. Oily or dirty commutator. | Dip the commutator in petrol and after this clean it with sand-paper. |
| Sparking at the brushes | 1. Worn brushes. | Reset or replace brushes. |
| | 2. Carbonised commutator. | Clean it with sand paper. |
| | 3. Oily Commutator | Dip and wash it in petrol. |
| | 4. Mica above commutator segments. | Commutator to be turned. |
| | 5. Spring tension too low. | Increase spring tension. |
| | 6. Faulty brush contact. | Remove the cause of sticking. |
| Weak sparking in plugpoint. | 1. Weak insulation of ignition coil. | Replace the coil. |
| | 2. Loose connection in primary winding. | Properly tighten its screws. |
| | 3. Wrong adjustment of contact breaker point. | Adjust the gap correctly. |
| | 4. Weak or partial short circuit in condenser. | Change the condenser. |
| | 5. Deposit of carbon on spark plug. | Clean it with sand paper and adjust its gap. |
| No sparking | 1. Short circuit in primary or secondary winding. | Replace the ignition coil. |
| | 2. Burning or carbonizing of contact breaker point. | Clean it with sand paper or change it with new one. |
| | 3. Contact breaker point remains open or short circuited. | Adjust the gap of contact breaker point. |
| | 4. Short circuit in condenser. | Change the condenser. |
| | 5. Burnt ignition switch. | Install new switch. |
| Misfiring at high speed. | 1. Increase in gap of contact breaker point. | Adjust gap as recommended. |
| Misfiring at low speed. | 1. Less gap in contact breaker point. | Adjust the gap properly. |
| | 2. Weak condenser. | Replace condenser. |
| | 3. Incorrect gap of spark plug. | Adjust the air gap. |
| Alternator fails to charge | 1. Loose mounting or belt. | Tighten properly. |
| | 2. Blown fuse. | Change the blown fuse in the regulator. |
| | 3. Open circuit in the rectifier. | Test and remove the fault. |
| | 4. Open circuit in rotating field. | Check the circuit for break and rectify the fault. |
| | 5. Open star of stator winding. | Make the continuity after test. |
| Alternator charging at high rate. | 1. Setting of regulator too high. | Set according to requirement. |
| | 2. Regulator not properly earthed. | Ground it properly. |
| | 3. Regulator contact sticking. | Inspect and remove the fault. |
| Low charging rate. | 1. High resistance due to loose connection of ground wire. | Clean and tighten ground connection rigidly. |
| | 2. Loose battery terminals causes high resistance which reduces charging current. | Tighten battery terminals properly. |
| Sound in Alternator. | 1. Damaged bearing. | Replace bearings. |
| | 2. Foundation Loose. | Tighten foundation properly. |

## REVIEW QUESTIONS

21.1 Describe with the help of a diagram, the electrical part of the ignition system of a four cylinde petrol engine motor car. Explain briefly the working of each component used. *(NCVT, 1971, 1974 Elect.*

21.2 Describe the electrical system of a motor vehicle and give its layout. *(NCVT, 1972 Elect.)*

21.3 What is ignition? How is high voltage generated in the ignition system of an automobile though the battery voltage is only 12 V? Why distributors are used in cars? *(NCVT, 1975 Elect.)*

21.4 What is the function of a distributor in an automobile? Draw the wiring diagram of ignition system. *(NCVT, 1976 Elect.)*

21.5 Draw the connection diagram of a battery charging circuit with 3 unit regulator and explain the function of automatic cut-out.

21.6 Explain the charging system of an automobile using an alternator. State why diodes are used?

21.7 Why does the alternator not require a cut-out relay? Explain the main operating part of alternator.

21.8 Give the connection diagrams of the following auxilary circuit with a brief explanation

(i) Horn

(ii) Fuel gauge

(iii) Side indicator

(iv) Tail light circuit

# 22

# Fundamentals of Electronics

## 22.1 INTRODUCTION

An atom consists of a nucleus (i.e. central part) having protons and neutrons around which electrons revolve in orbits. These revolving electrons are held to the nucleus with an attractive force between the electrons and protons.

Different atoms have different number of electrons in their orbits depending upon the atomic structure. In matter, they revolve in a haphazard manner from atom to atom. In an atom electrons farther from the nucleus have less force of attraction and are known as "free electrons." These free electrons can easily be detached from the atom of conductors by applying suitable electric pressure. An atom which has lost an electron is left with a positive charge and is known as a positive ion and the atom which has gained an electron is negatively charged and is called a negative ion.

## 22.2 ELECTRONICS

Electronics is the science of engineering which deals with the flow of electrons through a vacuum, gas tube or semiconductor. As the flow of electron in one direction is called electric current, it is essential to know the different methods of its emission.

## 22.3 THERMIONIC EMISSION

If a certain thin metal plate or wire is heated in vacuum to a very high temperature, it starts emitting electrons from its surface. The number of emitted electrons depends upon temperature and nature of material. At higher temperatures, more electrons will be emitted. The obtaining of electron emission by heating the surface of a metal is called thermionic emission of electrons.

The most common electron emitters substances are (i) tungsten emitter, and (ii) oxide-coated emitter.

*Tungsten Emitter* It is heated to a very high temperature of about 2500°C and is known as bright emitter. These types of emitters have longer life.

*Oxide-Coated Emitter* In these types of emitters a nickel plate is used which is coated with calcium oxide or barrium oxide and strontium oxides and this enables it to emit electrons at comparatively low temperature at approximately 100°C. At this temperature it is dull red and this require much less power for the emission of electrons.

## 22.4 THERMIONIC VALVE

A thermionic valve allows the current to pass in one direction only. It consists of anode and cathode placed in a glass evacuated bulb. Thermionic valves are of two types, namely (i) directly heated valve and (ii) indirectly heated valve.

*Directly Heated Valve* In such types of valves, there is no cathode. The heating filament itself serves the purpose of cathode. Fig. 22.1 shows a directly heated thermionic valves.

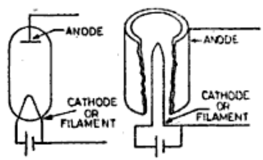



**Fig. 22.1 Directly heated valve**

**Indirectly Heated Valve** In this type of thermionic valve, the electron emitter cathode and heating element have no electrical connection between them as shown in Fig. 22.2.

The heating element is supplied directly either low voltage dc or ac supply.

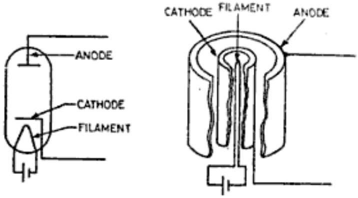



**Fig. 22.2 Indirectly heated valve**

## 22.5 SOME DEFINITIONS

*Plate Resistance* ($r_p$) It is the ratio between the change in plate voltage to the plate current at constant grid voltage.

*Mutual Conductance* ($g_m$) It is the ratio between change in plate current to the change in grid voltage at constant plate voltage.

*Amplification Factor* ($\mu$) It is the change in plate voltage to the change in grid voltage in opposite direction when the plate current remains constant.

*Plate characteristics* The curves that show the relation between the variation of plate current with plate voltage at different grid voltages.

*Mutual Characteristics* The curves that give the relation between the change in plate current with grid voltage at different plate voltages.

## 22.6 DIODE

A diode consists of an anode and a cathode enclosed in a small evacuated glass tube. The working principle of a diode is that when the cathode or the filament is heated to a high temperature, it starts emitting electrons. If the anode is connected to the positive terminal of the supply with respect to the cathode, the electrons will be attracted by the anode. This causes an electric current to flow from anode to cathode as shown in Fig. 22.3

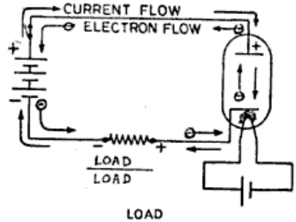



**Fig. 22.3 Flow of current in a diode when anode is at positive potential with respect to cathode**

When the anode is connected to the negative terminal of the supply with respect to the cathode, the emitted electrons will be repelled back and assembled around the hot cathode as shown in Fig. 22.4. The accumulation of electrons between the anode plate and the cathode is known as space charge condition.

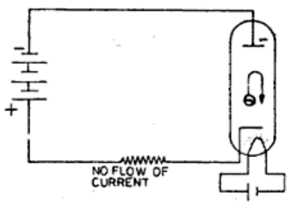



**Fig. 22.4 Current does not flow in a diode when anode is at negative potential**

In this case there is no flow of electrons between cathode and anode. This means, a diode can only permit the electron to pass from cathode to anode only when the anode is positive with respect to the cathode. In other words we can say that a conventional current flows from anode to cathode inside the diode valve. The value of the rectified current in this small tube is very less.

*Diode as a rectifier* A rectifier is a device which is used to allow the current to pass in one direction only. It offers high resistance for the current to pass in the opposite direction. This property enables it to rectify alternating current into direct current.

The practical applications of diode valves are that they can be used as.

(i) Half-wave rectifier, and
(ii) A full-wave rectifier

*Half-wave diode Rectifier* Figure 22.5 (a) shows the circuit diagram of a half wave rectifier. In this rectifier, the ac input to the diode is given through the secondary of a transformer. The cathode or the heating element is supplied ac from a separate low voltage secondary winding of the transformer.

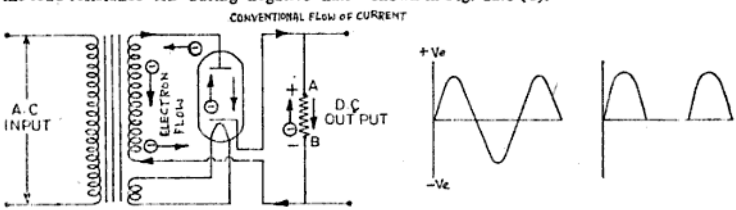
A dc current will flow through the load resistance *AB* when anode is positive as compared to cathode and there will be no flow of current through it when the anode is at a negative potential relative to the cathode. In other words it can be said that only positive half of the cycle will cause the current to flow through the load resistance *AB* from *A* to *B* and there will be no flow of current in the negative half cycle. As only half of the cycle is converted to pulsating dc, this diode is known as half wave diode rectifier. Figure 22.5 (b) and (c) show respectively the curves of the ac input voltage and dc output current through the resistance *AB*.

*Full-wave diode Rectifier* In the half-wave diode rectifier only positive half of the wave is rectified to dc and there is no current in the load resistance *AB* during negative half of the wave. In a full wave rectifier both positive and negative half of cycle is changed to dc.

A full wave diode rectifier has two anodes, *A* and *B* and a common cathode (shown in Fig. 22.6) which is supplied ac through a transformer whose secondary is centre tapped. The two terminals $T_1$ and $T_2$ of the transformer are connected to anodes *A* and *B* respectively. The dc output supply terminals for the load resistance *C* and *D* are taken from the cathode and centre point *E* of the transformer secondary.

During the positive half cycle, if anode *A* is at positive potential as compared to *B*, a current will start flowing through the external load resistance *CD* from *C* to *D* through anode *A* and the common cathode. During the negative half cycle, the anode *B* becomes positive with respect to anode *A*, current will flow from anode *B* to cathode and to load resistance *C* to *D*. Thus there will be pulsating dc through the load resistance from *C* to *D* during both the half cycles and is shown in 22.6 (d).

If a capacitor is placed across the load resistance as shown in Fig. 22.6 (a), it will acquire a charge when voltage is rising in the positive half and discharge into the load resistance *CD* when voltage falls in the same half. Thus current through the load never falls to zero. This current can be further smoothed by providing a filter circuit having inductance and capacitance connected as shown in Fig. 22.6 (b).




(a) (b) (c)

Fig. 22.5 (a) Halfwave diode rectifier (b) Ac input (c) Dc output (Pulsating(

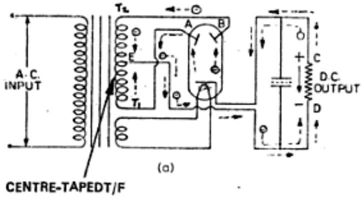



**Fig. 22.6 (a) Full wave diode rectifier (with condenser)**

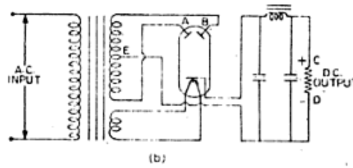
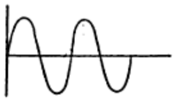
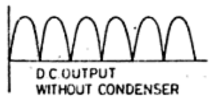



**Fig. 22.6 (b) Full wave rectifier with filter circuit (i.e. choke and condenser)**



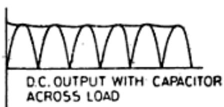
(c)

**Fig. 22.6 (c) AC input**



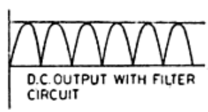

(d)

**Fig. 22.6 (d) DC output without condenser**




(e)

**(e) DC output with capacitor**




(f)

**( f ) DC output with filter circuit**

## 22.7 TRIODE

A triode is a vacuum tube which has three electrodes, viz., anode, cathode and grid.

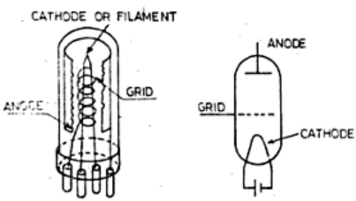



**Fig. 22.7 Triode**

The grid is usually a thin nickel-plated copper wire spiral attached to one or two supporting rods and is placed in between anode and cathode havihg no electrical contact as shown in Fig. 22.7.

This grid controls the anode current if its potential is made positive or negative relative to cathode. The anode current can also be controlled if its potential is kept positive, negative or zero.

If the grid potential is made positive with respect to cathode, the number of electrons emitted from the cathode towards anode is increased and hence the anode current

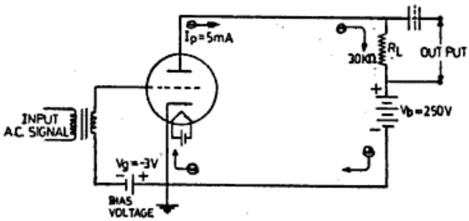



**Fig. 22.8 Triode as an amplifier**

increases. If the grid is made negative with respect to cathode, the electrons emitted from the cathode are repelled back and therefore few electrons are able to reach the anode. By making the grid sufficiently negatively charged, the flow of electrons towards anode can be completely stopped. Similarly when the grid is kept at zero potential with respect to cathode, a triode acts as a diode.

*Practical Application of a Triode Valve* The practical application of a triode is to use it as an amplifier. An amplifier is a device which may be used to magnify the weak signal or a small ac input voltage applied between the grid and cathode and may be amplified in the anode and cathode circuit (i.e. output terminals). Fig. 22.8 shows the connection of a triode when employed as a voltage amplifier.

In Fig. 22.8 load resistance $R_L$ of 30 k Ω is connected between the positive terminal of the battery and the anode. The voltage across the load resistance $R_L$ is known as output voltage and at anode is called anode voltage. In between the cathode and grid a battery of voltage $V_g$ say 3V (bias voltage) is connected in series with the secondary of a transformer whose induced emf is due to the signal voltage applied to the primary and which is to be amplified. The purpose of this battery is to supply a constant negative potential at the grid. $V_b$ is the applied voltage of the anode and is always greater than $V_g$. The grid is never positive with respect to cathode and therefore there is no bias current in it.

Voltage amplification,

$$\mu = \frac{\text{output voltage}}{\text{input voltage}}$$

$$= \frac{\text{Voltage across the load}}{\text{Voltage across grid}} \qquad (22.1)$$

For understanding the amplification of a triode tube, let us consider that the average plate current be 5 mA with − 3V for grid and other values as shown in Fig. 22.8.

Output voltage across 30-k Ω resistance

$$= \text{Plate current}(I_p) \times \text{ load resistance}(R_L)$$

$$= 3000 \times \frac{5}{1000}$$

$$= 150 \text{ V}$$

$$\text{Plate voltage} = V_b - I_p \times R_L$$

$$= 250 - 150 = 100 \text{ V}$$

If the grid signal voltage is varied ± 1 V, the result of amplification will be as given in Table 22.1

**Table 22.1**

| *Grid Signal voltage* (V) | *Plate Current* (m.A.) | *Anode Voltage* (V) | *Output Voltage*$=V_b-I_p\times h_L$ |
|---|---|---|---|
| −3+1=−2 | 6 | 30 k Ω × 6m A=180 | 250−180=70 |
| Average voltage−3 | 5 | 30 k Ω × 5m A=150 | 250−150=100 |
| −3−1=−4 | 4 | 30 k Ω × 4m A=120 | 250−120=130 |

It is clear from the above chart that $\pm 1$ V in grid signal voltage produces an amplification of $\pm$ 30 V at the load. Thus the input signal is amplified by a factor of 30.

## 22.8 SEMI-CONDUCTING MATERIAL AND DEVICES

**Semi-Conducting material** Silicon and germanium in pure form are not good conductors of electricity, but when mixed with impurities they become good conductor of electricity and allows current to pass in one direction only. The following types of Semi-conductors are in use now-a-days in the manufacturing of solid state devices.

*N-type Semiconductor* This type of semi-conductor has excess of electrons, so has the property of donating electrons.

*P-type Semiconductor* This type of semi-conductor has excess of holes in it and has the polarity of accepting the electrons.

*PN Junction* It is a single crystal semiconductor whose one half side is p-type and the other half is N-type. The PN or NP junction is also known as crystal diode or semiconductor. The symbol of crystal diode is shown in Fig. 22.9. The arrow head shows the direction of flow of conventional current.

Fig. 22.9 Shows PN junction (Diode crystal)

*Forward Bias* When a battery is joined to the PN junction in such a way that its positive end is connected to P-side, and negative side to N-side, a large current starts to flow across the junction because it offers little resistance to the conventional flow of current from P to N side. This property of a semi conductor is known as "Forward Bias".

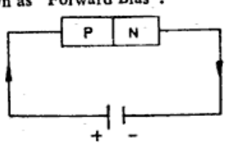



**Fig. 22.10 Forward bias passes the current from the *p* to the *n* junction**

*Reverse Bias* When the battery is connected to the PN junction such that its positive

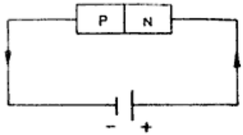



**Fig. 22.11 Reverse bias does not allow current**

end is joined to N-side and negative end to P-side, it offers a very high resistance to the flow of current and thus the current through the junction is practically zero.

## 22.9 SEMICONDUCTOR DIODE

It is a solid state semi-conductor device which allows the current to flow in one direction only as shown in Fig. 22.12. It is made from pure silicon material and is converted into P-type and N-type material. If a layer of P-type material is formed next to a N-type layer, this makes a PN Junction. In such a junction electron can easily pass from N-type to P-type layer when P is at positive potential. Hence this junction may be used as a rectifier which allows the conventional flow of current in the direction from P-type toN-type as shown in Fig. 22.12. The arrow head of the diode shows the conventional flow of current.

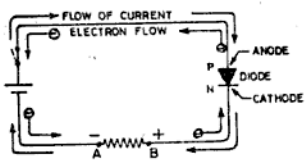



**Fig. 22.12 Flow of current in semi-conductor diode**

## 22.10 TRANSISTOR

A transistor is also a solid semi conductor device which behaves like a triode valve. It is a single crystal of silicon or germanium with three elements known as collector, base and emitter and can be used for amplification and oscilation. The collector acts as an anode, base as grid and emitter like

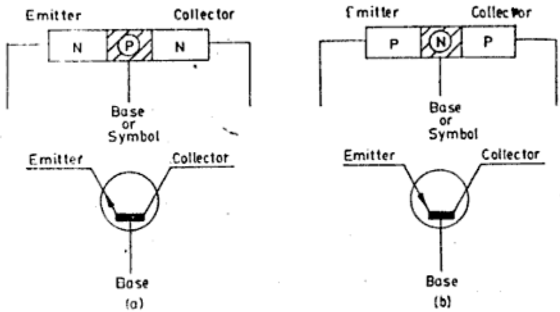



**Fig. 22-13 Transistor**

cathode. Figure 22.13 shows the symbol of a transistor.

In the PNP transistor, there are two P-sections separated by a N-section and in a NPN type transistor there are two N-section aparted by a P-section.

**Collector** It is a section on one side of a transistor and has low conductivity. It collects the electrons emitted by the emitter. It is always' biased in the reverse direction as compared to other section of the transistor.

**Emitter** It is a section on the other side of the transistor and has large conductivity, so supplies a large number of electrons. It is always biased in the forward direction with respect to other section of the transistor.

**Base** It is the thin central part of a transistor and is in between the collector and emitter.

A transistor is a two junction device, one junction is forward biased and other reverse biased and has three ends. One end is made common between input and output circuit. The input is given between the common end and one of the other two ends. The output is taken between the common end and the remaining end.

## REVIEW QUESTIONS

**22.1** Sketch and describe the construction of an indirectly heated cathode.

**22.2** Explain why a diode permits current only in one direction?

**22.3** Draw a sketch and explain the construction of a diode. Sketch the function of each of its parts

**22.4** Explain why the grid is usually kept at negative potential?

**22.5** What do you mean by rectification? Draw the circuit diagram of a half wave diode rectifier and explain its function.

**22.6** What are the advantages of a full-wave rectifier over a half-wave rectifier?

**22.7** State the working of a diode and triode. Mention their uses. *(NCVT, 1976 W/man)*

**22.8** Explain why a large current flows in a forward-biased PN junction.

**22.9** Write Short notes on the following.

(a) N-type semiconductor *(NCTV, 1986 W/man)*

(b) Diode tube *(NCVT, 1968 Elect./1970 W/man)*

# 23

# Conversion of AC to DC

## 23.1 METHODS OF CONVERSION OF AC TO DC

In recent years, generation of ac has gained popularity over dc due to the ease with which it can easily be stepped up or stepped down for economical transmission and distribution of supply. Conversion of ac to dc (or vice versa) is essential because some operation like electroplating, electrolysis, battery charging, relays function, etc. can only be performed on dc supply.

The following are the general methods of converting ac to dc.

(*i*) Motor generator set
(*ii*) Metal plate rectifier
(*iii*) Mercury arc rectifier
(*iv*) Rotary convertor set

## 23.2 MOTOR-GENERATOR SET

In this method an ac motor is mechanically coupled to a dc generator. The motor may be either single phase or three phase. The motor supplied ac drives the dc generator and thus direct current is produced. This method of conversion of ac to dc is generally employed for electric welding, electroplating and battery charging.

*Advantages of Motor-Generator Set*

(*i*) It is easy to start the set.
(*ii*) Dc output voltage can easily be controlled by adjusting the shunt field regulator.
(*iii*) The dc output voltage is practically constant and is not affected by the change of ac voltage as the speed of an induction motor is constant.
(*iv*) It is easy to locate faults in the set.

*Disadvantages of Motor-Generator set*

(*i*) As two different machines are required, its cost is more.
(*ii*) Its maintenance cost is more due to its having two machines.
(*iii*) It requires more floor space.
(*iv*) It has comparatively low efficiency.
(*v*) It is possible to convert ac to dc and not dc to ac.
(*vi*) Overall efficiency of the set is less.

## 23.3 METAL PLATE RECTIFIER

A solid contact metal plate rectifier is based on the principle that the contact of the two different metal offers different resistance to the passage of current through them in different directions. In other words, the resistance offered to the flow of current when passed in one direction is comparatively less than the resistance offered if the direction of current is changed. The difference of resistance depends upon the different metals selected for the purpose.
These rectifiers are of the following types:

(*i*) Copper plate rectifier
(*ii*) Selenium rectifier

**Copper-plate rectifier** These types of rectifiers are suitable for low current output. They are made of copper discs, on one side of which is put a thin layer of cuprous oxide. It is practically seen that this cuprous oxide easily allow the conventional current to pass from copper oxide to copper (or electrons from copper to copper oxide) but offers very high resistance to current in the opposite direction.

This rectifier consists of copper discs having copper on one side, and copper oxide on the other side, soft metal lead washers, cooling fins mounted on an insulated rod and clamped together as shown in Fig. 23.1. The lead washers are used to have good electrical contact with the disc.

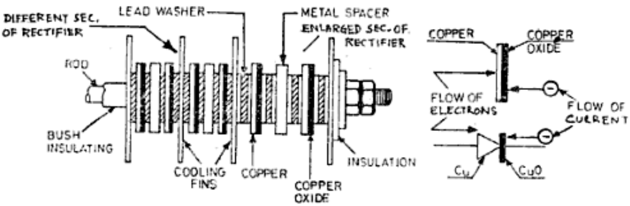



Fig. 23.1 Detail view of copper oxide rectifier

Figure 23.2 shows the connection of a half wave metal plate rectifier. For full wave rectification there are two possible methods of connection as given below·

(*i*) Centre-tapped secondary method
(*ii*) Bridge method

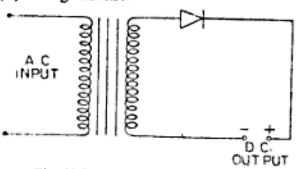



Fig. 23.2 Half-wave metal rectifier

*Centre-Tapped Secondary Method* The operation of a full-wave metal plate rectifier is made through a centre tapped secondary of a transformer. Its two terminals $T_1$ and $T_2$ are connected to two rectifiers $R_1$ and $R_2$ respectively. The common points of the rectifiers and centre tap of the transformer are taken out as terminals for dc output as shown in Fig. 23.3.

When the transformer terminal $T_1$ is positive with respect to $T_2$, a current will flow from rectifier $R_1$ to load, i.e. from *A* to *B* making terminal *A* positive. During the negative half cycle, terminal $T_2$ becomes positive relative to $T_1$. Current again passes from *A* to *B* making terminal *A* positive for the dc output. For smoothing the dc output, a filter circuit is to be employed (not shown in the figure).

*Bridge Method* This method is employed to take large output current. In this method of rectification four metal rectifiers are used

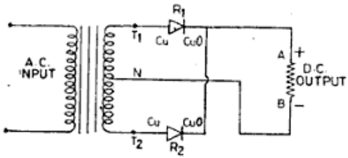



Fig. 23.3 Full-wave rectifier with centre tapped secondary

and are connected in the form of bridge as shown in Fig. 23.4

Suppose during the positive half cycle, terminal $T_1$ of transformer secondary is positive with respect to $T_2$. In this condition dc will flow from $T_1$ to load *LM* through rectifier *AB* and will go back to $T_2$ through rectifier *DC*. When terminal $T_2$ becomes positive during the negative half cycle, the current will pass through rectifier *CB* to load *LM* and back to $T_1$ through rectifier *DA*. The current through the load *LM* remains from *L* to *M* during both the half cycles. Figure 23.4(c) shows the curve for the current through the load resistance *LM*.

Many plate rectifiers are used in series to increase the working voltage of the unit because a single unit of 2 cm dia disc can only operate on 8 V. To increase the current output of the rectifier, many such plates are connected in parallel as shown in Fig. 23.5. Such type of rectifier, are used for electroplating plants in which case they give high output current at low voltage (i.e. 5 to 48 V). This type of rectifier is also suitable for x-ray machine and used with moving coil instrument for measuring alternating current and voltage at low current and very high voltage.

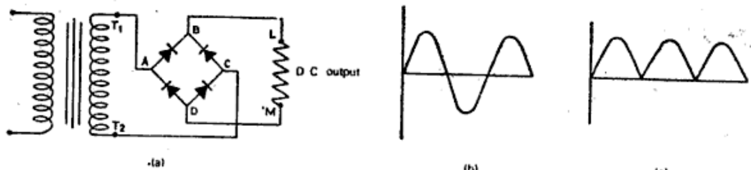



**Fig. 23.4 Full wave metal plate rectifier**

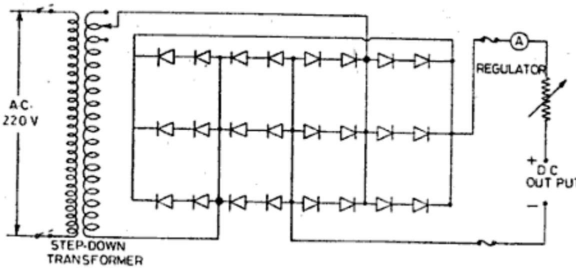



**Fig. 23.5 Full wave metal plate rectifier for high output current**

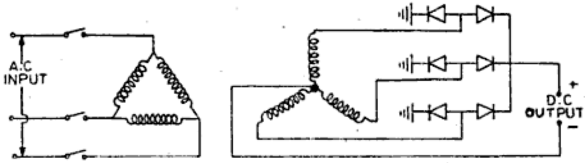



Fig. 23.6 Three-phase full-wave rectification

Figure 23.6 shows the connection of full-wave rectification of a three-phase supply system through a metal plate rectifier.

**Selenium Rectifier** Selenium rectifiers are extensively used nowadays for battery charging, electroplating etc. for output upto 100 kW.

In this rectifier, steel (or aluminium) plates are used. A layer of selenium is deposited on one side of the plate. This contact of steel and selenium has the same property as that of copper and copper oxide.

Germanium and silicon rectifiers may be used for an output of up to 100 MW.

## 23.4 MERCURY ARC RECTIFIER

The function of a mercury arc rectifier depends upon the valve action of the arc developed in a mercury pool. The arc developed in the mercury pool permits the flow of current in one direction only.

It is also a type of thermionic valve which consists of a big evacuated glass bulb having an anode of graphite or iron at the top and a mercury pool at the bottom to act as cathode as shown in Fig. 23.7.

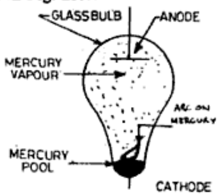



Fig. 23.7 Mercury arc rectifier

This glass bulb also contains some mercury vapours in it. Suppose an arc is created on the surface of the mercury which is operating at a very high temperature about 3000°C. At this very high temperature, the surface of the mercury emits some electrons. If a potential difference is now maintained between anode and cathode with anode at positive potential, these free electrons will be attracted by anode and will travel with high speed towards anode. On the way they will strike with the neutral mercury vapour and break them into positive and negative ions. Thus more electrons are liberated towards anode to make up the deficiency of electrons there. The separated positive ions will move towards cathode and will collide on the surface of pool of mercury to liberate more electrons. These free electrons will again travel towards anode and will strike with neutral mercury vapour and the process continues. The point at which the positive ions hit the mercury cathode attains a very high temperature is known as "Arc cathode point". This point moves on the surface of mercury pool in an irregular manner. The negatively charged electrons also strike the anode but, cannot produce much heat because they are very light in weight.

The continuous movement of negative ions from cathode to anode and positive ions to cathode establish a flow of current through the bulb till the anode is positive. If anode is made negative, the emitted electrons will be repelled back to mercury cathode and thus there will be no flow of current through the rectifier.

It is clear from the above that once the arc is developed, it will continue to exist till the anode is at positive potential.

**Single-Phase Half-Wave Mercury Arc Rectifier** In a single-phase half-wave mercury arc rectifier only one anode at the top of the glass bulb is used and mercury at the bottom serves the function of a cathode. The anode is connected to one end of the secondary winding. The other end of the transformer's secondary and cathode are the terminals of dc output as shown in Fig. 23.8. The function of this rectifier is similar to a thermonic valve. In this rectifier only half of the cycle is rectified as shown in Fig. 23.8(b) and hence is known as half wave mercury arc Rectifier.

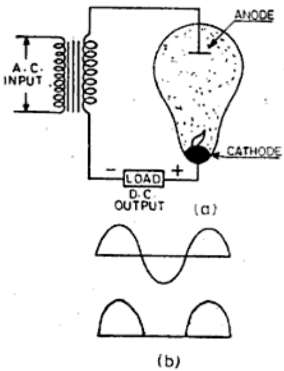



**Fig. 23.8 Single-phase half-wave mercury arc rectifier**

**Single-Phase Full-Wave Mercury Arc Rectifier** In a single-phase full-wave mercury arc rectifier two anodes *a* and *b* at the top of the bulb are provided which are connected with the two terminals $T_1$ and $T_2$ of a centre-tapped secondary of a transformer. The dc output is taken from cathode and the centre tap of secondary of the transformer. Figure 23.9 shows the connection of a full wave mercury arc rectifier.

For starting the arc an ignition anode is placed a little above the mercury pool. For this purpose a potential difference is maintained between ignition anode and cathode which is supplied from an auxiliary secondary of the transformer. An electromagnet is placed below this ignition anode and is magnetised when the push button is pressed. This attracts the ignition anode which makes contact with the mercury and current starts flowing from the ignition anode to the cathode through

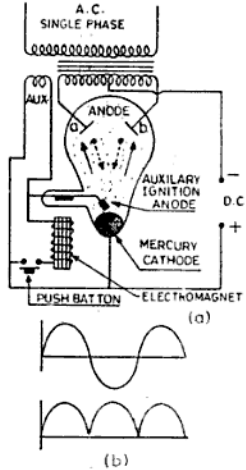



**Fig. 23.9 Single-phase full-wave mercury arc rectifier**

mercury. When the push button is released the ignition anode breaks the contact from the mercury cathode and spark is produced and maintained as explained.

In this rectifier both the halves of a cycle are converted to dc and thus the current is available for whole period. To smoothen the fluctuation of dc output a reactor is used on dc side. Fluctuation on dc side can also be minimized by increasing the number of phases of input supply, say 2, 3 or 6.

**Three-Phase Mercury Arc Rectifier** In a three-phase half wave mercury arc rectifier, there are three anodes placed at equidistance in a circle and at equal distances from the cathode. These anodes are supplied potential from a star connected secondary of a transformer. Figure 23.10 shows the essential connections of a three phase half wave mercury arc rectifier.

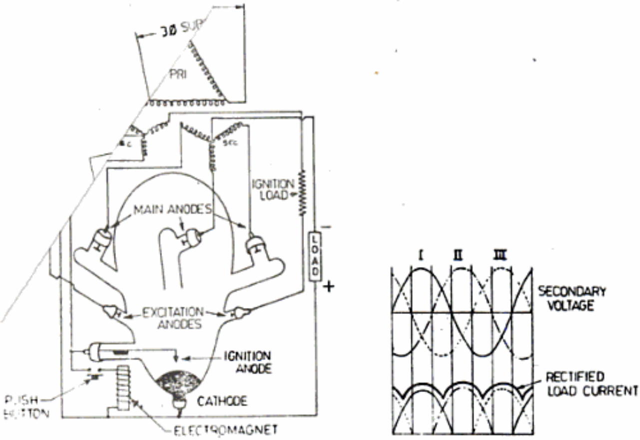



**Fig. 23.10 Three-Phase half-wave mercury arc rectifier**

In such rectifiers each anode carries the arc when it is at higher positive potential with respect to other two anodes for one-third of a cycle and the arc is transferred from one anode to the other in turn. It means, a three phase three anodes mercury arc rectifier is a three-phase half-wave rectifier.

Figure 23.11 shows the connection of a three-phase full-wave arc rectifier. This rectifier has six anodes placed in a glass bulb in the form of a circle and equidistant from each other and from the cathode. These six anodes are supplied potential difference from two secondaries of a transformer which are connected in double star as shown. The neutral point of the secondaries and the cathode are the terminals for dc output. In this rectifier two auxiliary anodes are also provided near the mercury pool to keep the arc alive. These auxiliary anode function as constant load on the rectifier and are supplied from an auxiliary secondary of the transformer. A reactor (i.e. choke coil) is used in the circuit to limit the current in the circuit.

This rectifier is a three phase full-wave mercury arc rectifier. Figure 23.11(b) shows the curve for input ac supply and dc output. From the dc curve it is clear that in this case dc output is better rectified than in the three-anode half-wave rectifier.

**Advantages of a Mercury Arc Rectifier** The following are the advantages and disadvantages of a mercury arc rectifier as compared with other types of rectifiers.

*Advantages*

(*i*) There are less chances of faults as there is no moving part in it.
(*ii*) Maintenance cost is very low due to less wear and tear.
(*iii*) Simple in operation in comparison with other types of ac to dc rectifiers.
(*iv*) Vaporized mercury is not wasted because after cooling it falls down in the mercury pool.
(*v*) It occupies less floor space.
(*vi*) It is lighter in weight and is noiseless.
(*vii*) Its cost is less as compared to rotary convertor.

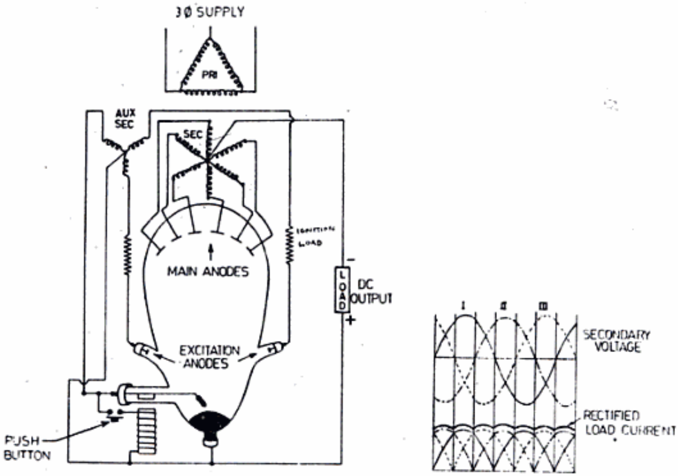



Fig. 23.11 Three-phase full-wave mercury arc rectifier

(*viii*) The efficiency of the mercury arc rectifier is high and is about 95-96%.

(*ix*) It is easy to start and has sufficient overload capacity.

*Disadvantages*

(*i*) As the container of the bulb is made of glass, there are chances of its being broken due to rough handling.

(*ii*) Due to excessive heat developed in the bulb, a cooling arrangement is essential.

(*iii*) It cannot be used as an invertor.

(*iv*) There is always some power loss in the excitation anode circuit when working without load.

EXAMPLE 23.1 *A three-anode mercury arc rectifier supplies a load of 20 kW at 250 V dc. The arc drop is 20 V. Find the kVA of the transformer at this load. Assume a power factor of 0.8.*

*Solution:*

Dc load current, $I = \frac{W}{V}$

$= \frac{20 \times 1000}{250} = 80$ A

Power loss in the rectifier,

$W = V \times I = 20 \times 80 = 1600$ W

Output of transformer $= 20{,}000 + 1600$

$= 21{,}600$ W

$= 21.6$ kW

output of transformer, kVA $= \frac{\text{kW}}{\cos\theta}$

$= \frac{21.6}{0.8}$

$= 27$ kVA Ans.

## 23.5 ROTARY CONVERTOR

In a dc generator voltage generated in the armature is alternating in nature. In the output circuit dc is made available through a brushes and commutator arrangement. If

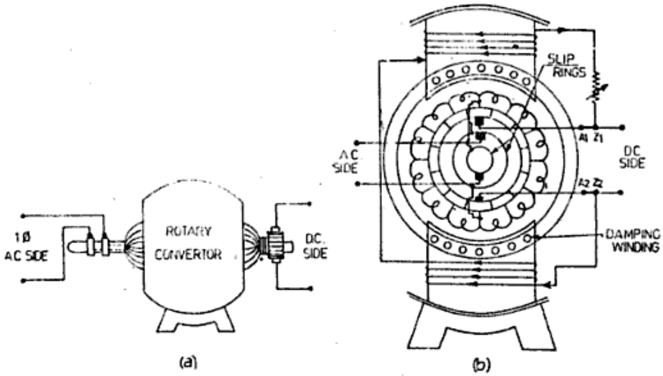



**Fig. 23.12 Single-phase rotary convertor**

tappings from the armature winding are brought out to sliprings mounted on the shaft opposite to the commutator side, alternating current will be available at the sliprings when its armature is rotated.

A rotary convertor is similar in construction to a dc shunt or compound machine with additional sliprings on one side and commutator on the other side. The stator is made of lamination having inter-poles (or commutating poles) and damping windings are also provided in the machine. The damping winding is done on the faces of the pole shoe which is short circuited by rings on both sides. If the machine is supplied with ac, it operates as an auto synchronous motor and delivers dc output. If dc is given to the machine, it acts as a dc shunt or compound motor and gives out ac at the sliprings, (known as "rotary invertor"). If the armature is rotated by a primover, dc will be available at the brushes of the commutator and ac at the brushes of sliprings.

Figure 23.12 shows the essential connection of single phase rotary convertor. A single phase rotary convertor has two sliprings and a three-phase rotary may have three sliprings. Generally a rotary convertor has 6 or 12 sliprings, due to the fact that a 6 or 12 phase rotary convertor is smaller in size as compared to a three-phase rotary convertor for a particular output. For getting 3, 6 or 12 phase supply for rotary, the input supply to the primary of the transformer is usually three-phase and the secondary of the transformer is wound for 3, 6 or 12-phase output.

*Tappings for Wave Winding* In case of wave winding as there are only two parallel paths in the machine irrespective to the number of poles. Therefore in a single phase machine there will be two sliprings, so two tappings will be brought out, one for each slipring at 180° apart. Similarly a three-phase machine has three sliprings, so there will be 3 tappings one for each slipring at 120°. A six phase machine has six slipring, so six tappings are taken out at 60° apart, one for each sliprings and a 12 phase machine has 12 slipring, so 12 tappings are taken out at 30°, one for each slipring.

*Tappings for Lap Winding* In lap wound armature, the number of parallel path is equal to the number of poles. So for any given potential, there will be as many equipotential points in the winding as there are pair of poles.

∴ Total tappings = No. of pair of poles × no. of sliprings

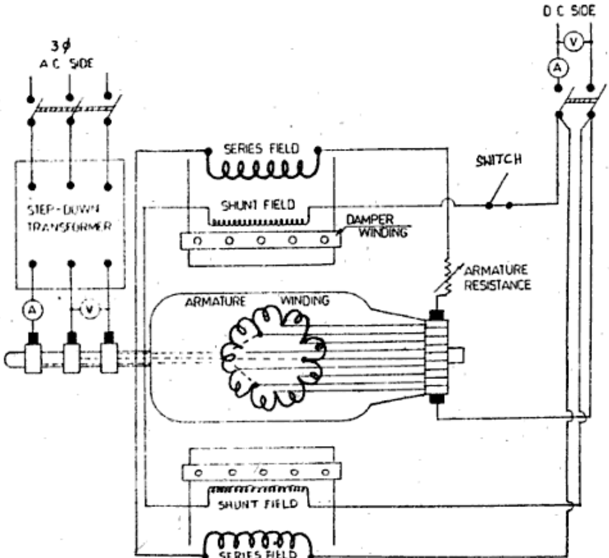



**Fig. 23.13 Three-phase rotary convertor**

For a two pole single-phase machine, there will be two tappings one for each of the two sliprings and in case of a 4 pole single-phase machine, there will be 4 tappings, two for each of the two sliprings. Similarly for a two pole three-phase machine, there will be 3 tappings, one for each of the three sliprings and for a four pole three phase machine, there will be 6 tappings, two for each of the three sliprings. In case of a six poles three-phase machine, there will be 9 tappings, three for each of the three sliprings. Figure 23.13 shows the connection of a three-phase rotary convertor.

*Starting of Rotary Convertor* A rotary convertor can be started either from the dc side, or from ac side.

*Starting of Rotary Convertor from ac Side* Rotary convertors are generally used to convert ac to dc. In all modern power station ac is generated, but for special purposes like battery charging, electro-plating etc., it is required to convert ac to dc. Starting the rotary convertor from dc side may not be required. However, when dc supply is available, ac supply can be obtained by starting the machine from the dc side.

*Starting of Rotary Convertor from ac Side* When starting the rotary convertor from the ac side, the field switch and dc main switch are kept open. The ac main switch is put "ON" and reduced voltage is applied to the sliprings from a step-down transformer. Now, a three-phase current flows through the armature winding and produces rotating magnetic field. This rotating magnetic field cuts the damping windings on the pole faces and thus the rotary starts as inverted-induction motor. When the machine attains normal speed, the field switch is closed. Now the other side of rotary acts as a shunt or compound generator and the motor now pulls into synchronism and runs as a synchronous motor. When the rotary convertor attains synchronous speed, the relative speed of the armature with respect to rotating magnetic field becomes zero and it so seems that the armature field comes from the projected poles and the output current on the brushes of the commutators is a direct current. The rotary convertor is now said to have pulled in step and the polarity of the brushes depends upon the relative position of the armature and field pole at the moment of pulling into step. Therefore, it is possible that the dc output voltage may develop in wrong direction which is indicated by the zero-centre voltmeter. To develop the correct polarity at the commutator, the field switch for an instant is opened and then again it is brought back to its original position. This will cause the armature field to be repelled by the main field and thus dc voltage will develop in correct direction.

At starting the field switch is kept open and is closed when the motor is running at normal speed. This is due to the fact that the rotating magnetic field of the armature cuts the large number of field winding turns on the main poles at synchronous speed. Therefore, a very high voltage is induced in the field winding. To control the induced emf, the field winding is made of sections and kept open as shown in Fig. 23.14. In normal working condition, the armature runs at synchronous speed and the armature field is stationary with respect to rotating magnetic field and no voltage is generated in the field winding. For this reason, the field switch is kept open at the time of starting, for otherwise a heavy circulating current would cause sparking on the commutator.

*Inverted Rotary Convertor* The inverted rotary convertor is also known as an "invertor". An invertor is actually a rotary convertor which is used to convert dc into ac. When working as convertor, it works as a

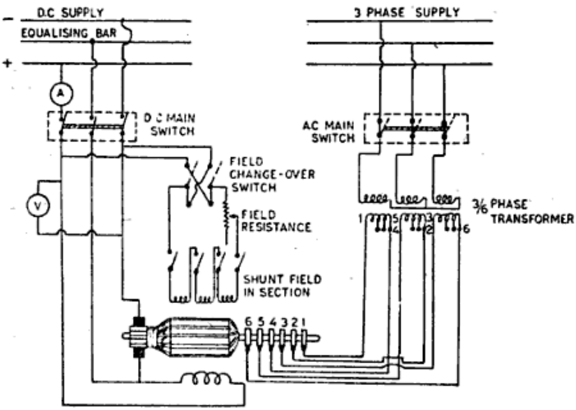



**Fig. 23.14** **Connection of rotary convertor**

synchronous motor on ac side and its speed is constant. But when it operates as an invertor, its dc side will function as a dc shunt or compound motor and in this case the speed is not constant (because the speed depends upon the flux per pole). When the power factor on ac side is lagging, there will be demagnetising effect of the armature current which will reduce the flux of the field poles and hence the speed will increase. If, the power factor becomes very poor, the machine may attain a dangerously high speed like a dc series motor operating without load.

To prevent this, the field system of an invertor is always separately excited from an excitor mounted on the shaft of the machine. This excitor rotates with the same speed as that of the armature and supplies current to the field winding of the invertor.

When the speed of the invertor increases due to demagnetising effect of armature current, the excitor voltage will also increase. This increased voltage will also circulate increased current in the field winding which will increase the field flux and thus neutralize the demagnetising effect.

*Power Factor of Rotary Convertor* Power factor of a rotary convertor depends upon its field excitation. If the excitation is high, the power factor will also be high. This high power factor decreases the current taken by the rotary and thus reduces the losses and increases the efficiency. To improve the power of a rotary convertor it is essential to increase the exciting current.

The rating of the rotary convertor decreases with the decrease of power factor because it increases the losses in the armature. So the improvement of the power factor increases the rating of the convertor which can further be increased by increasing the number of phases. It is only possible if they are designed to operate on poly phase system and should work on or near unity power factor. Therefore single phase rotary convertors are rarely used because its efficiency is comparatively less than poly phase convertors.

TABLE 23.1 COMPARISON BETWEEN MOTOR-GENERATOR SET AND ROTARY CONVERTOR

| S.No. | Motor-Generator Set | S.No. | Rotary Convertor |
|---|---|---|---|
| 1. | It occupies more space as it has two machines. | 1. | It occupy less space because it has only one machine. |
| 2. | Its initial cost is high. | 2. | Less costly. |
| 3. | Its overall efficiency is less. | 3. | Its efficiency is high. |
| 4. | Require frequent maintenance. | 4. | Require less maintenance. |
| 5. | It is very noisy. | 5. | Less noisy |

TABLE 23.2 COMPARISON BETWEEN ROTARY CONVERTOR, METAL PLATE RECTIFIER AND MERCURY ARC RECTIFIER

| Sl. No. | Particular | Rotary Convertor | Metal Plate Rectifier | Mercury Arc Rectifier |
|---|---|---|---|---|
| 1. | Construction | Very difficult to construct | Most easy to construct | Easy to construct as compared with rotary convertor. |
| 2. | Operation | Requires great care at the time of starting | Its starting operation is most easy | Operation easier than that of rotary convertor |
| 3. | Sound and vibration | Produces sound and vibration | Soundless and produces no vibration | No vibration and sound less operation. |

# 24

# Generation, Transmission and Distribution of Electricity

## 24.1 SOURCES OF GENERATION OF ELECTRICITY

Electrical energy in bulk quantity is generated at a big power station from where it is transmitted to the substation and then distributed to the consumers for use. These power stations are of many types and are known according to the energy used to rotate the prime-mover of alternator. These power stations are:

(*i*) Hydro power station
(*ii*) Thermal power station
(*iii*) Diesel power station
(*iv*) Atomic power station

**Hydro Power Stations** In this system the generator is driven by the water turbine. The water for the turbine to rotate is brought down from a high level reservoir through a spiral pipe and is thrown on the blades of the turbine thereby it starts rotating. The generator coupled with the turbine also starts rotating. This system is adopted on such types of rivers where there is no shortage of water throughout the year. Dams are constructed on rivers to water heads. Examples are Bhakra Dam, Hirakund Dam, etc.

The generator used for this system runs at low speed and has more number of poles. The running cost of such type of generating station is comparatively less than the initial commissioning cost.

**Thermal Power Stations** This system is generally used at places where there is a shortage of water. In this system steam is produced in the boiler by burning coal and then it is used to drive the steam turbine. The steam turbine rotates the generator. Such type of stations are of medium capacity and their initial and running costs are high. Badarpur and Indraprastha thermal power stations of Delhi are the examples of this type of generating stations.

**Diesel Power Stations** This system of generation is usually used at such places where there is scarcity of water resources and coal, such as in deserts, hilly areas, war field areas and military camps etc.

In this system diesel engine is used to drive the shaft of the generator. The output rating of such type of stations is very low and requires high initial and runing cost.

**Atomic Power Stations** In this type of stations atomic power is used to produce the steam which drives the steam turbine of a generator. No doubt its commissioning cost is very high but its running cost is comparatively lower than a thermal power station. The output capacity of an atomic power station can be very high. Such type of power stations in India are at Narora Buland Shahar, Trombay, etc.

## 24.2 TRANSMISSION OF ELECTRICITY

The generator used for the production of supply may either be ac or dc. However, these days ac generators are used (usually three phase 11-kV) because the voltage can easily be stepped up and stepped down. The usual generating voltages at the generating stations are 3.3, 6.6 and 11 kV Energy generated at the generating stations is transmitted through the transmission line to the substation from where it is supplied to the consumer through the distribution lines (known as distributor) and supply mains.

Figure 24.1 shows the single line diagram of supply system from generating station to consumer.

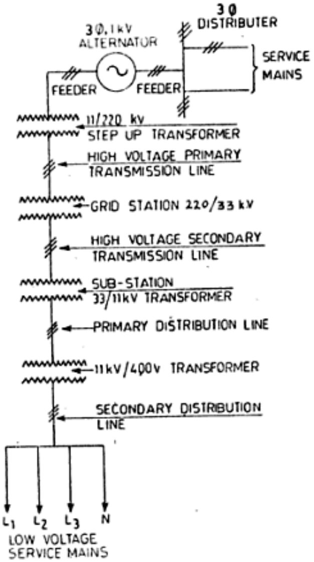



**Fig. 24.1 Single line diagram of complete supply system**

The following terms are used for different sections of supply system.

*Feeder Mains* These are bare or insulated conductors which are used to take current from the generating station and supply to the transmission line.

*Transmission Feeders* These are the supply lines which carry power at high voltage from generating station and supply it to the sub-station.

*Distribution Line* A distribution line is tapped off from the transmission feeder at the substation and supplies energy to the service mains.

*Service Mains* These are the small overhead or underground conductors of the line used to take the energy from the distribution line to the consumer premises.

The standard voltages for transmission lines in India are 220, 132, 110, and 66 kV. Work on 440 kV transmission line is still under consideration for Beas Satluj transmission Link Project. The transmission line of 220 or 132 kV is stepped down to 33 kV in grid stations. This 33 kV transmission line is further stepped-down to 11 kV for distribution and is distributed to different main stations of the city. From these main stations secondary distribution lines are taken for different substations where it is stepped down to three 440 for distribution of supply to the consumer premises.

**Advantages of High-Voltage Transmission**
Transmission of electrical energy at high voltage has the following main advantages.

*Saving in Conductor Material* For a constant power output, if the transmission voltage is increased the current in the transmission line reduces. This reduces the size of the conductor required for transmission line or in other words it decreases the weight of material needed for the line.

For example let 20 kW power be transmitted at 500 V. The line current,

$$I_L = \frac{20 \times 1000}{500} = 40 \text{ A}.$$

If the transmitting voltage is now stepped up upto 1000 V, the current will be

$$= \frac{20 \times 1000}{1000} = 20 \text{ A}$$

For 20 A, the size of the conductor will be only half as that of the first case. Hence it reduces the weight and cost of material.

*Reduction in Power loss of Transmission line* We know power loss, $W = I^2R$. As the current required in the second case of the previous example is only one—half of the first case, the power loss in the line will only be one-fourth as compared to the first case.

*Better Efficiency of Line* Due to decrease of power loss in the transmission line, the efficiency of transmission line is increased.

*Better Voltage Regulation* Transmission at high voltage reduces the voltage drop of the line due to decrease of current and thereby improves the voltage regulation.

*Saving of Material* With the saving of material, the size of the cross arm reduces. The distance between the poles increases which reduces the number of poles required. It also minimizes the cost of labour required for erection etc.

## 24.3 DISTRIBUTION SYSTEM

The following are the distribution systems of supply.

- Radial distribution system
- Ring distribution system
- Grid distribution system

**Radial System** Figure 24.2 shows the connection of a radial system. In radial system each load junction is supplied by an individual feeder which is controlled at the substation. This system is adopted for low voltage and generator is installed in the centre of the city or load. No doubt this system is very simple but suffers from a disadvantage that incase of fault the whole circuit or area is interrupted.

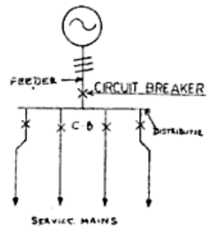



**Fig. 24.2 Radial distribution system**

**Ring System** In this system each load junction is connected to the next and forms a closed ring as shown in Fig. 24.3. It is clear from the figure that each load junction has two supply sources. The main advantages of this system is that the faulty section can easily be disconnected from the circuit without disturbing the others. Moreover it is easy to repair and in case of a break in the feeder line, the load can be supplied from the other side. This system of supply is applied for low and high voltage distribution systems.

**Grid System** This distribution system is also known as "interconnected distribution

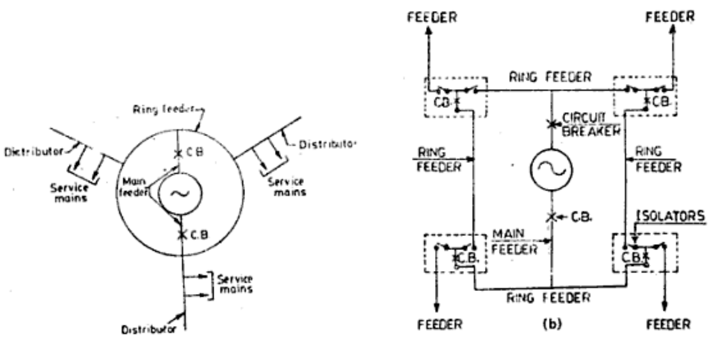



**Fig. 24.3 Ring distribution system**

system". In this system the important generating stations or substations of the country or city are connected together so as to meet the demand during the time of need. In a grid system, the transmitted voltage is stepped down to 33 kV at some convenient point from where it is supplied to ring distribution main.

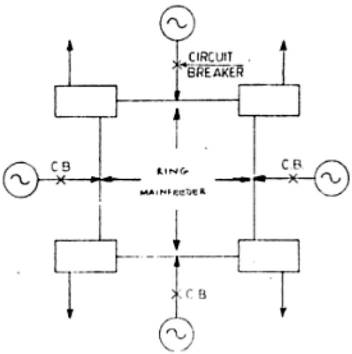



**Fig. 24.4 Grid system**

**Distribution of supply** According to the procedure of construction there are two systems of distribution of electrical energy viz.

(*i*) Overhead system
(*ii*) Underground system.

*Overhead System of Distribution* In this system bare conductors are run on pole or tower which are fastened to the insulators provided on the cross arm. This system of erection is very cheap. It is also easy to take branch line from such system.

*Underground Distribution system* Several methods are employed to bury the armoured cables in the ground. The most common method of burying the cable under the ground is to make a trench about 1 m deep and 0.5 m wide along the road or as required. Before laying a cable in in the trench a layer of sand of about 5 cm thick is spread at the bottom of the trench. After this the cable is rolled over the trench and placed in it. After laying the cable, it is covered with sand to a height of about 15 cm as shown in Fig. 24.5.

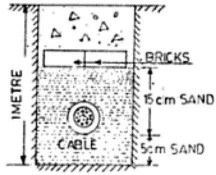



**Fig. 24.5 Laying of cable**

Now a single layer of bricks is spread over the surface of sand which is then coverd with earth. The layer of bricks is given to protect the cable from any mechanical damage (in case another party digs the earth for water mains etc). While laying a cable care should be taken not to fold or twist the cable.

## 24.4 TYPES OF CABLES

As discussed earlier, power from the generating station is transmitted to the substation through cables. These cables are available in single-core, two-core, three-core, four-core and three-and-a-half-core and can be grouped according to the voltage for which they are to operate.

(*i*) Low tension cables (LT cables)—up to 1000 V
(*ii*) High tension cables (HT cables)—up to 11000 V
(*iii*) Super tension cables (ST cables)—from 22 kV up to 33 kV
(*iv*) Extra high tension cable (EHT cables)—from 33 kV to 66 kV
(*v*) Oil filled and gas filled pressurised cables—from 66 kV to 132 kV or above

The main parts of a cable are shown in Fig. 24.6.

*Core* All underground cables consist of single, two, three, four and three-and-a-half cores of stranded aluminium or copper conductors.

together with oil impregnated paper and the empty space between them is filled with jute filling as shown in Fig. 24.6. After the covering of impregnated paper, a layer of lead sheathing is given which is again covered with a layer of impregnated paper, jute bedding, two layers of galvanised steel wire with impregnated fibrous separator, jute serving.

In a paper-insulated oil filled armoured cable, special care should be given to avoid leakage of insulating oil from the cable. For this purpose special sealing boxes (for indoor and outdoor) are used to seal the cable ends at the terminating points where the wires are lead out or joined together along the route of the cable for straight or tee connection. All cable boxes are provided with suitable devices such as brass gland and armoured clamps to give good mechanical protection to the cable, to avoid entry of moisture in the cable and maintain earth continuity. These cables are manufactured in various sizes from 0.007 to 1 sq. inch up to 33 kV.

Oil-filled and gas-filled pressurised cables are used for extra high voltage upto 132 to 220 kV.

*PVC Cable* Nowadays, polyvinyl chloride (PVC) cables are used for low and medium voltage distribution system. The conductors used in these cables are also of stranded aluminium or copper wires which are separately insulated with PVC insulation. After this all the conductors are kept close together and then again a layer of PVC is given all around them. The space between these insulated conductors is filled with jute. On this outer covering of PVC cable, a layer of galvanised steel wire is added which is then covered with a thick layer of PVC insulation.

PVC cables are more flexible, non-draining, and have the following properties.

(*i*) High mechanical strength

(*ii*) High resistance to abrasion

(*iii*) High fire resistance at high temperature

(*iv*) High resistance to acid, oil and chemical fumes

(*v*) High dielectric strength and high insulation resistance even when dipped in water

(*vi*) High ageing property

(*vii*) High corrosion resistance and can be laid directly underground in places where soil is of active nature

## 24.5 MATERIAL FOR OVER HEAD DISTRIBUTION LINE

The following materials are required for the erection of overhead distribution systems.

**Bare Conductors** Bare solid or stranded copper and aluminium conductors are used in overhead distribution lines. In spite of aluminium conductors being cheap they cannot be used for long span due to their low tensile strength. To increase its tensile strength, a steel conductor is placed in the centre of all the aluminium conductors and is known as "aluminium conductor steel reinforced" (ACSR).

**Poles** Figure 24.7 shows the different types of poles used in overhead distribution lines. Poles are used for supporting the conductor above the ground. These are of different types as given below.

(*i*) Wooden poles

(*ii*) Mild Steel poles

(*iii*) Concrete poles

(*iv*) Steel latticed poles or towers

*Wooden Poles* Nowadays these types of poles are rarely used because they have very short life. However, they can be employed for temporary overhead line, electrification of rural areas. Wooden poles are prepared from a well seasoned teak wood. The pole is then dipped in heated creosote oil to prevent it from insects. The approximately life of such type of a pole is 10 years.

*Mild Steel Poles* Mild steel poles are of two types as follows.

(*i*) Tubular type mild steel poles

(*ii*) Rail type mild steel poles

The life of such type of poles is 50 years approximately provided they are painted after every 3 years to prevent it from rust. Their usual height is 9 to 11 m (30 to 34 feet) and are generally used in supporting of lines upto 33 kV.

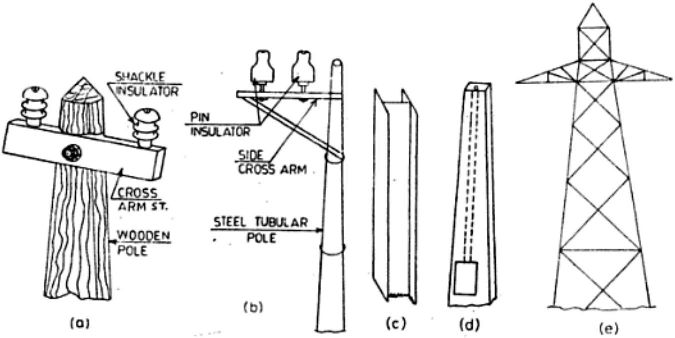



**Fig. 24.7** Types of poles used in overhead distribution system

*Concrete Poles* These poles are known as reinforced cement concrete (RCC) poles and are of the following two types.

(*i*) Hollow type

(*ii*) Solid type

Both these types of poles are used for light and power distribution upto 11 kV. Their life is long as compared to wooden poles.

*Steel Latticed Poles or Tower* Latticed poles are made of steel frame work and are used for high tension transmission lines upto 132 kV.

**Cross Arms** These are also known as insulator supports and are made of either wood or angle iron. Cross arms are installed at the top of the pole for holding the insulator on which conductors are fastened. They are also known according to their position relative to poles. If the cross arm is fixed in the centre of the pole then it is called as a cross arm and if installed on one side of the pole, then it is termed as side cross arm. U shaped cross arms are specially used for three-phase lines.

**Line Insulators** The aim of using the line insulator in an overhead line is to hold the live conductor and to prevent leakage of current from the conductor to the pole. These are made of porcelain clay and are thoroughly glazed to avoid the absorbtion of moisture in the porcelain.

The following are the common types of insulators in use.

(*i*) Pin-type insulator

(*ii*) Shackle insulator

(*iii*) Suspension insulator

(*iv*) Stay insulator

*Pin Insulators* Pin insulators are used for holding the line conductors on straight running of poles. Pin insulators are of three types, i.e. single shed, double shed and triple shed. The single-shed pin insulators are used for telephone lines only. The double shed pin insulators are used for LT lines while the triple shed types are used for over 3000 V. These sheds are used to drip off the rain water.

*Shackle Insulators* Shackle insulators are generally used for terminating or corner poles. These insulators are used for medium voltage line only.

*Suspension Insulators* These insulators are also known as disc or link insulators and are used for high and extra high tension overhead lines. Many discs are connected in series to withstand the high tension supply as a single disc can safely operate on 11 kV.

*Stay Insulator* Stay insulators are also known as strain insulator, and are generally used upto 33 kV line. These insulators should not be fixed below three metres from the ground level. These insulators are also used where the lines are strained.

**Stay Wire** The supporting wire which is used in the opposite direction of tension on the pole due to overhead conductors is known as "stay wire". It prevents the bending of the pole due to tension of the conductor and consists of 4 to 7 strands of GI wire. The correct size to be used depends upon the tension on the pole.

**Stay and Strut** Stay and struts are the different types of supporting wires for the pole. Stays are generally used for angle and terminating poles to prevent its bending where as struts are used where space for stay is very less. Figure 24.9 shows both the stay and strut.

One end of the stay or strut is fixed at the top of the pole and its other end is grouted in the concrete foundation.

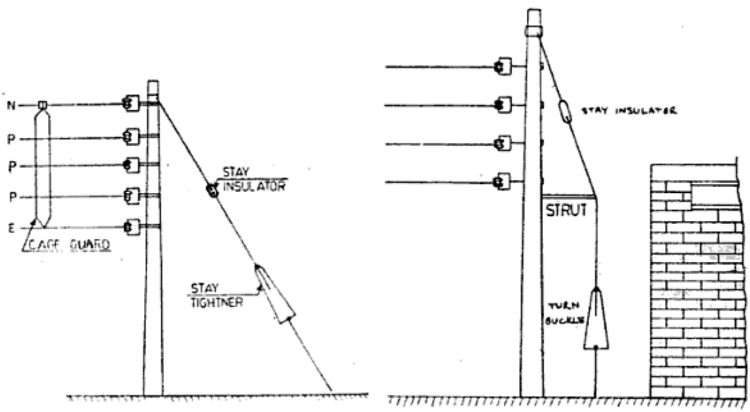
**Guard Wire** A guard wire is a safety cage or craddle wire shown in Fig. 24.9(a) which runs along the distribution line. This wire is properly earthed.

If a live conductor falls down due to storm, it may cause electrical accident. To avoid this, it is necessary to provide guarding to all the conductors of low, medium and high voltage lines. In case of breakage of live conductor, it would first come in contact with the earth wire and thus will trip off the circuit breaker immediately.

## 24.6 ISOLATORS AND CIRCUIT BREAKERS

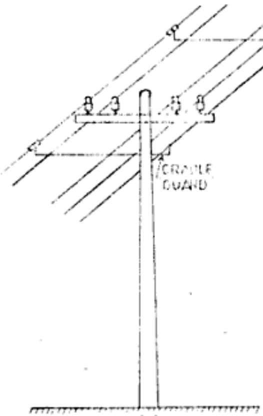
**Isolator** An isolator is a switch which is used for isolating a circuit under no load condition only. If an isolator is switched OFF when a high current is flowing through the circuit, a heavy spark will be produced. This heavy spark may break the supporting insulator of the insolator which may cause a fatal accident to the operator.

**Circuit Breaker** It is a controlling device which is used for switching ON and OFF the circuit quickly, under any load condition.




(a) (b)

**Fig. 24.9(a) Use of stay along with stay insulator** **(b) Illustration of the use of strut**


(c)

(c) Craddle guarding

It is also provided with automatic arrangement to come to OFF position when an abnormal current flows through the circuit due to over load, short circuit or earth fault.

*Types of Circuit Breakers* Circuit breakers are of two types as given below:

(*i*) Oil circuit breaker
(*ii*) Air circuit breaker.

**Oil Circuit Breaker (OCB)** Every circuit breaker has two types of contact.

(*i*) Fixed contact and
(*ii*) Moving contact

These contacts are immersed in insulating oil contained in the tank. The oil in the tank reduces and stops the sparking when O.C.B. is operated. In 50 Hz ac circuit, the current goes through zero value 100 times per second. The oil extinguishes the arc at one of the zero values. For this reason O.C.Bs are employed on ac circuit. However if they are used on dc circuit, the full current has to be switched off which results in heavy sparking on contact points at the time of make and break. Moreover it is difficult to extinguish heavy sparking which remains for longer time and there is a risk of fire. This type of circuit breaker is used for controlling the distribution line. Figure 24.10 shows digram of single-phase and three phase oil circuit breaker in open position, oil circuit breakers are generally used for indoor as a switch gear upto 12 kV.

*Advantages of OCB*

(*i*) Oil in between the contact points serves as an insulator.
(*ii*) Oil in the tank suppresses the arc and thus reduces the heat of the arc.
(*iii*) Oil circuit breakers are cheaper in cost as compared to air break circuit breaker.

*Disadvantage*

(*i*) Danger of fire in the oil of the circuit breaker.
(*ii*) Oil circuit breakers cannot be used on dc circuit.

**Air Circuit Breaker** It is seen that the use of oil in the circuit breaker may cause a fire. So, in all circuit breakers of large capacity, air at high pressure is used which is maximum at the time of quick tripping off the contacts. This reduces the possibility of sparking. This high pressure of air is obtained from a compressor which is attached to the

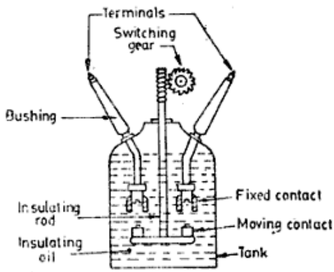



**Fig. 24.10(a) Single-phase oil-circuit breaker**

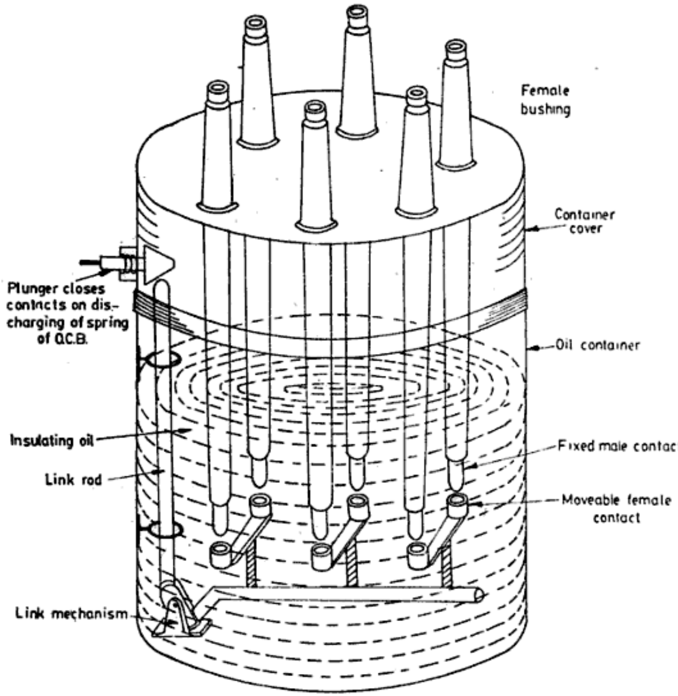
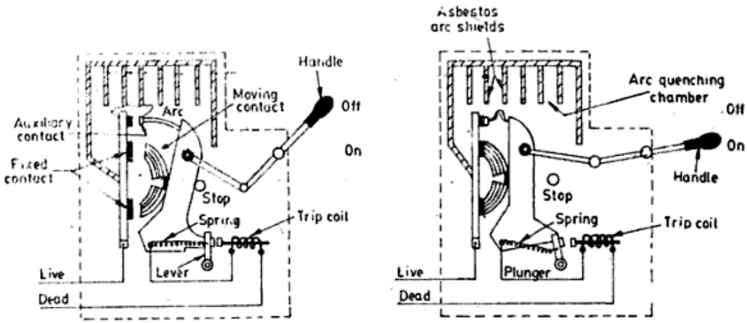



**Fig. 24.10 (b) Three-phase oil-circuit breaker**

circuit breaker. This high pressure may vary from 50 to 60 KG/cm for high and medium capacity circuit breakers. These circuit breakers are used for controlling the high transmission voltage circuit.

It consists of a handle, trip coil, lever with spring, auxiliary, fixed and moveable contacts as shown in Fig. 24.11. The trip coil is either connected in series or in parallel or provided with the auxiliary circuit. It carries the load current and its magnetic attraction is proportional to the load current. When the current reaches the pre-determined maximum value, the power of the tripping coil becomes sufficient enough to attract the lever. This lever causes the handle to come back to its 'off' position. This results in disconnecting the moveable contacts of the breaker from the fixed contacts and thus the maximum sparking takes place at the time of switching 'ON' and OFF. For subsiding the sparking in the circuit breaker, arc shields (i.e. arc-chutes)




(a) OFF position (b) ON position

**Fig. 24.11 Air-circuit breaker**

are made of asbestos and are provided in the arc quenching chamber.

The length of the auxiliary contact point is larger than the main contacts which carry the full load current. For this reason while switching 'ON' it makes contact much earlier than the main contacts. Similarly while switching 'OFF' this contact point breaks the circuit after the main contacts open. These contacts can easily be replaced on damage and thus the main contacts are saved from sparking to provide better performance.

The main advantages of the air circuit breaker is that they are neat in appearance and require less maintenance.

## 24.7 STATIC LIGHTNING DISCHARGE CONTROLLING DEVICES

An electric discharge is produced between the charged clouds (due to friction) and earth or within clouds which may destroy anything in its path. This electric discharge is known as lightning. The device which is used to suppress the arc produced by lightning is known as lightning arrester.

**Purpose of a Lightning Arrester** A lightning arrester is an apparatus or device which is used for providing path to the static electric discharge between the charged clouds and earth.

**Lightning Surge** It is a temporary electrical disturbance in an electric line due to lightning.

For providing path to the lightning surge, a copper or GI wire is run along-with the overhead line and this wire is connected to earth at four points for each 1.609 km (i.e. 1 mile). The atmospheric electric discharge will go to earth through this earth wire and thus save the line and equipment. A lightning arrester should at least have the following properties.

(*i*) It should not allow the flow of current to the earth so far as the voltage across it is the normal working voltage of the apparatus to be protected from lightning.

(*ii*) It must give path to the flow of current when the line voltage reaches to a value about 20 per cent above the highest normal working voltage of the system to be protected.

(*iii*) After discharge it should be ready again for next safe guarding operation.

**Type of Lightning Arresters** The following are the main types of lightning arresters

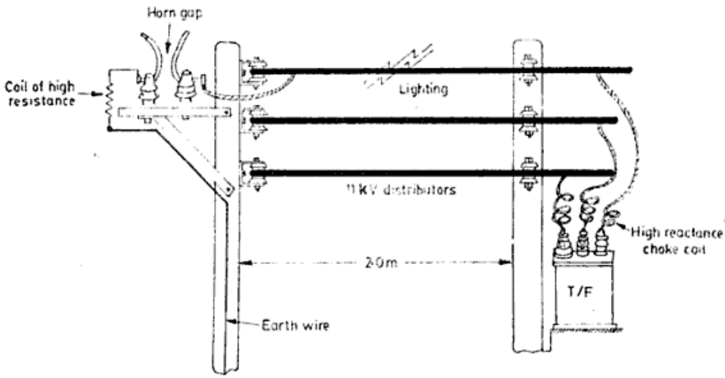



Fig. 24.12 Horn gap lightning arrester

(*i*) Horn gap lightning arrester
(*ii*) Oxide film lightning arrester
(*iii*) Pellet lightning arrester
(*iv*) Thyrite lightning arrester

*Horn Gap Lightning Arrester* This arrester consists of two horn shaped terminals having an air gap between them. One terminal of the horn is connected to the apparatus or line to be protected and other to the earth wire through a series resistance as shown in Fig. 24.12.

Each supply line should have separate lightning arrester at the power stations, sub-stations. An air-core inductive coil is kept in series with the costly apparatus to be protected just ahead of the horn gap arrester This inductive coil consists of copper wire which easily allow the line current to pass to the apparatus at normal frequency. This coil offers increased high opposition (inductance due to high frequency of lightning) when lightning occurs, stops the sudden lightning surge current and forces it to get discharge through the horn gap to the ground.

When the line voltage exceeds about 20 per cent above the highest working voltage of the apparatus, a discharge takes place across the narrowest part of the gap between the horns. To control the discharge current, a resistance is connected in series with the earth wire. The horn gap is so shaped that the heat forces the arc to move upward to wider part and thus lengthens the gap. The arc is thus stopped and the passage of the current to earth is broken. Thus the normal conditions of the system is restored. The length of the gap is directly proportional to the working voltage and is 1.6 mm for 440 V line, 10 mm for 5000 V and 15 mm for 11000 V.

*Oxide Film Lightning Arrester* The oxide film lightning arrester is made of a number of small disc with a gap in series and is connected between line and earth. Each disc consists of two round brass discs (size $2\frac{1}{2}''$ dia and $\frac{1}{2}''$ thick) fitted in between the porcelain tube The space between the discs is filled with lead peroxide (which has low resistance) and varnish which acts as an insulator. The operating voltage of each disc is 300 V approximately. The number of discs required for a system is confirmed from its working voltage.

When lightning voltage sparks over the gap, it develops a small puncture on the insulating coating and give passage to the discharge current to earth through the discs.

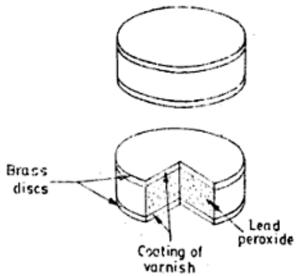



**Fig. 24.13 Oxide film lightning arrester**

This type of arrester is used for indoor and outdoor protection services up to 220 kV system.

*Pellet Lightning Arrester* This type of arrester is a modification of oxide film arrester. In this type of arrester, many small pellets or pills of lead peroxide of diameter ¼" are used. These lead peroxide pills are coated with litharge powder which serves as an insulating film around the pills and are placed in a porcelain tube having metal electrodes at its each end. The litharge film on the pellets functions as a porous spacer and not as a solid insulation.

When a spark occurs over the film due to high surge voltage, it punctures the film

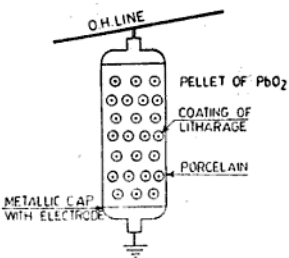



**Fig. 24.14 Pellet lightning arrester**

which again comes to its original condition after the discharge and thus becomes ready for next operation.

Pellet arresters are suitable for outdoor protection service systems of up to 73 kV.

*Thyrite Lightning Arrester* This type of lightning arrester consists of number of discs of inorganic ceramic compound. These discs are placed in a series having some gaps in between them and are sealed in a porcelain tube. This tube has metallic caps and electrodes at its ends.

The compound used for the preparation of the discs serves as an insulator but changes to a good conductor when the voltage across it rises to a certain predetermined value. This lightning arrester is also used up to 240 kV transmitting system.

**Performance of Lightning Arrester** The following conditions must be fulfilled for satisfactory performance of a lightning arrester so as to provide good protection to the electrical machines.

(*i*) The earth resistance of the arrester circuit should be as minimum as possible because it will not function effectively with high ground resistance.

(*ii*) Till the voltage across the arrester is normal, it should not allow the current to the ground.

(*iii*) When the voltage increases predetermined value, lightning arrester must give way to the flow of current to go to earth without any further increase in it.

(*iv*) A lightning arrester should be installed nearest the machine to be protected because it will not provide sufficient protection if installed too far away.

(*v*) The arrester should be selected for the proper voltage.

(*vi*) After the discharge through the arrester, it must close the path for the current to flow to earth.

(*vii*) It should keep itself ready for the second discharge after first discharge.

## 24.8 COMPARISION BETWEEN OVERHEAD AND UNDERGROUND DISTRIBUTION SYSTEM

| Sl. No. | Overhead System | Sl. No. | Underground system |
|---|---|---|---|
| 1. | Supply lines are taken above the ground on poles. | 1. | Armoured cables are run underneath the ground. |
| 2. | As bare conductors are used in overhead system, their cost is comparatively less than armoured cable. | 2. | Armoured cables are used in underground system. This system is very costly. |
| 3. | It is easy to find faults and repair them. | 3. | It is difficult to trace the faults and repair them. |
| 4. | There are more chances of faults in this system as the conductors are open. | 4. | There are less chances of faults. |
| 5. | Maintenance cost is high. | 5. | Its maintenance cost is comparatively less. |
| 6. | Easy to install and requires less cost. | 6. | Difficult to erect and its erection cost is high. |
| 7. | This system is more flexible. | 7. | This system is less flexible than overhead system. |
| 8. | Overhead system does not give nice look. | 8. | Underground system presents neat appearance as cables are not visible. For this reason this system is adopted in modern cities. |
| 9. | Easy to extend the new lines and tapping off service lines. | 9. | New trench is to be made for expansion of lines and is difficult to tap off lines. |
| 10. | Operating voltage of the system can be increased by increasing the distance between the conductors (i.e. insulator). | 10. | New cable of high voltage is required to run for higher operating voltage of the system which is very costly. |
| 11. | This system can be overloaded upto certain extent as the conductors exposed to air dessipate the heat developed. | 11. | Underground system cannot be overloaded as the heat developed is not dessipated in the air. |
| 12. | There are chances of overhead conductors being short circuited in case of storm and may cause fire. | 12. | There are no chances of fire in case of short circuit as the cables are laid in the ground. |
| 13. | Moisture cannot affect the insulation between the conductors to a large extent as the conductors are well spaced. | 13. | Entry of small amount of moisture in the cable can puncture its insulating properties. |
| 14. | It is difficult to erect overhead lines at narrow places. | 14. | Underground cables can be run at narrow places even in zigzag ways. |

## REVIEW QUESTIONS

24.1 What is the difference between a transmission line and distribution line?

24.2 Why ACSR conductors are widely used nowadays for transmission lines?

24.3 What are the advantages of high voltage transmission.

24.4 Explain briefly the different distribution system prevailing in the country and discuss their merits and demerits. *(NCVT, 1970 W/man*

24.5 Describe with neat sketch the construction of 3½ core PILCDSTA medium voltage cable. Describe the method of terminating such cable through a dividing box into TPIC switch. *(NCVT, 1974 Elect.)*

24.6 Differentiate between a switch and a circuit breaker. Explain the working of an oil circuit breaker and an air circuit breaker. Discuss their advantages and disadvantages over each other. *(NCVT, 1974 Elect.)*

24.7 What is a circuit breaker? On what principle does the automatic circuit breaker work and state its advantages. *(NCVT, 1983 Elect.)*

24.8 Describe the procedure of laying underground cables. *(NCVT, 1986 W/man)*

24.9 Write a short note on the horn gap lightning arrester. *(NCVT, 1986 W/man)*

## BASIC ELECTRICAL ENGINEERING

With Numerical Problems

Volume II

The book has been written according to the syllabus prescribed by the Directorate General of Employment and Training for the Craftsman Training Scheme and the Apprenticeship Training Scheme for the Electrical Trades (Electrician, Wireman and Lineman).

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