# GUDLAVALLERU ENGINEERING COLLEGE

**(An Autonomous Institute with Permanent Affiliation to JNTUK, Kakinada)**

**Seshadri Rao Knowledge Village, Gudlavalleru – 521 356.**

## Department of Electrical and Electronics Engineering

# HANDOUT

## on

# ELEMENTS OF ELECTRICAL ENGINEERING

## UNIT – I

# D.C. Machines

**Objectives:**

1. To familiarize the students with the constructional details and working principle of DC machines.
2. To familiarize the students with characteristics of DC machines.
3. To familiarize the students with the speed control methods of dc shunt motor.

**Syllabus:**

Principle of operation of DC Machines- EMF equation – Types of generators –DC Motors – Types of DC Motors – Characteristics of DC motors – 3-point starters for DC shunt motor – Losses and efficiency –Speed control of DC shunt motor – Flux and Armature voltage control methods.

**Learning Outcomes:**

After the completion of this unit, students will be to

1. Explain the function of varies parts of a dc machine.
2. Describe the working of a dc machine for generating and motoring action.
3. Draw the charecteristics of different types of dc machine.
4. Explain the methods of speed control of a dc shunt motor.
5. Determine the efficiency of a dc machine.

## 1.1 Construction of d.c. generator

The d.c. generators and d.c. motors have the same general construction. In fact, when the machine is being assembled, the workmen usually do not know whether it is a d.c. generator or motor. Any d.c. generator can be run as a d.c. motor and vice-versa. All d.c. machines have five principal components viz., (i) field system (ii) armature core (iii) armature winding (iv) commutator (v) brushes [See Fig. 1.1].

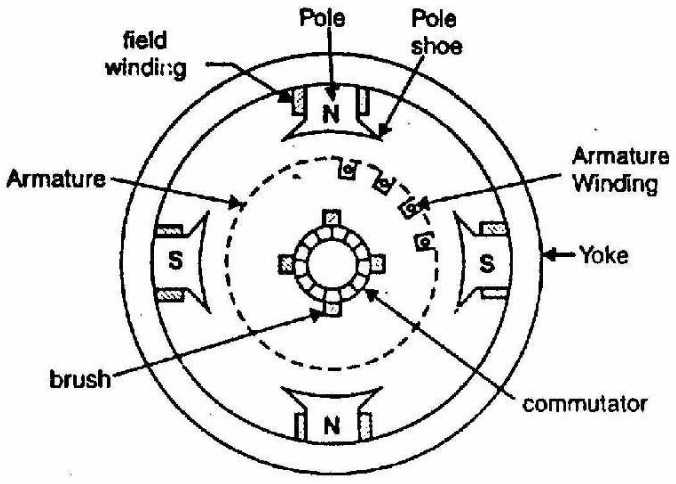


Fig. (1.1)

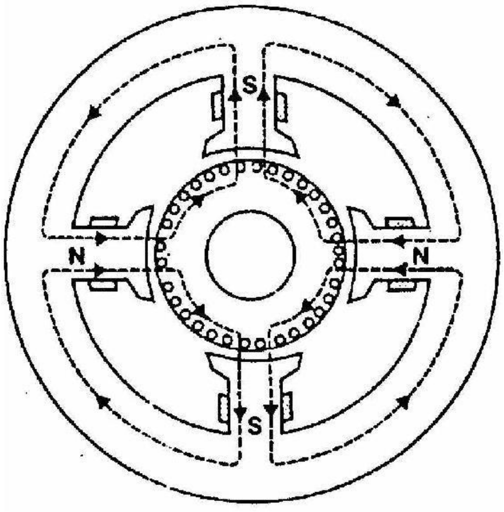


Fig. (1.2)

**(i) Field system**

The function of the field system is to produce uniform magnetic field within which the armature rotates. It consists of a number of salient poles (of course, even number) bolted to the inside of circular frame (generally called yoke). The yoke is usually made of solid cast steel whereas the pole pieces are composed of stacked laminations. Field coils are mounted on the poles and carry the d.c. exciting current. The field coils are connected in such a way that adjacent poles have opposite polarity.

The m.m.f. developed by the field coils produces a magnetic flux that passes through the pole pieces, the air gap, the armature and the frame (See Fig. 1.2). Practical d.c. machines have air gaps ranging from 0.5 mm to 1.5 mm. Since armature and field systems are composed of materials that have high permeability, most of the m.m.f. of field coils is required to set up flux in the air gap. By reducing the length of air gap, we can reduce the size of field coils (i.e. number of turns).

**(ii) Armature core**

The armature core is keyed to the machine shaft and rotates between the field poles. It consists of slotted soft-iron laminations (about 0.4 to 0.6 mm thick) that are stacked to form a cylindrical core as shown in Fig (1.3). The laminations (See Fig. 1.4) are individually coated with a thin insulating film so that they do not come in electrical contact with each other. The purpose of laminating the core is to reduce the eddy current loss. The laminations are slotted to accommodate and provide mechanical security to the armature winding and to give shorter air gap for the flux to cross between the pole face and the armature "teeth".

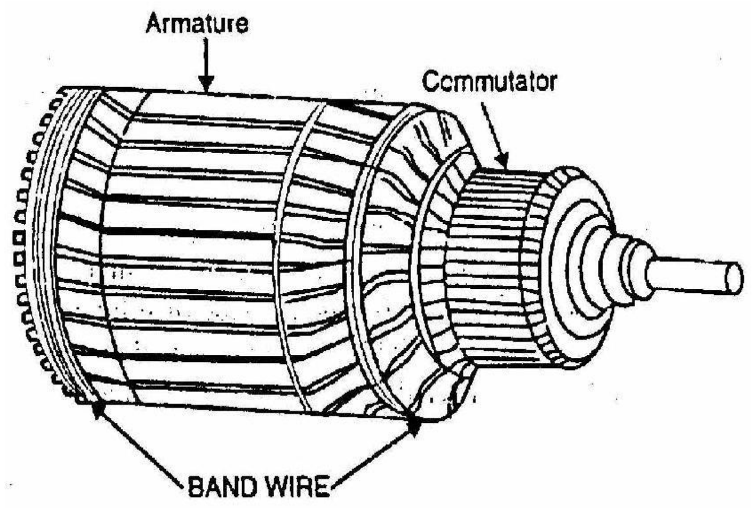


**Fig. (1.3)**

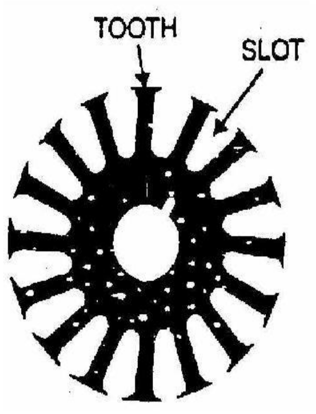


**Fig. (1.4)**

**(iii) Armature winding**

The slots of the armature core hold insulated conductors that are connected in a suitable manner. This is known as armature winding. This is the winding in which "working" e.m.f. is induced. The armature conductors are connected in series-parallel; the conductors being connected in series so as to increase the voltage and in parallel paths so as to increase the current. The armature winding of a d.c. machine is a closed-circuit winding; the conductors being connected in a symmetrical manner forming a closed loop or series of closed loops.

**(iv) Commutator**

A commutator is a mechanical rectifier which converts the alternating voltage generated in the armature winding into direct voltage across the brushes. The commutator is made of copper segments insulated from each other by mica sheets and mounted on the shaft of the machine (See Fig 1.5). The armature conductors are soldered to the commutator segments in a suitable manner to give rise to the armature winding. Depending upon the manner in which the armature conductors are connected to the commutator segments, there are two types of armature winding in a d.c. machine viz., (a) lap winding (b) wave winding. Great care is taken in building the commutator because any eccentricity will cause the brushes to bounce, producing unacceptable sparking. The sparks may bum the brushes and overheat and carbonise the commutator.

**(V) Brushes**

The purpose of brushes is to ensure electrical connections between the rotating commutator and stationary external load circuit. The brushes are made of carbon and rest on the commutator. The brush pressure is adjusted by means of adjustable springs (See Fig. 1.6). If the brush pressure is very large, the friction produces heating of the commutator and the brushes. On the other hand, if it is too weak, the imperfect contact with the commutator may produce sparking.

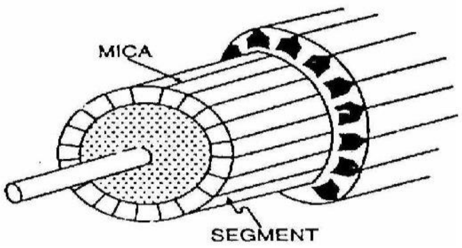


**Fig. (1.5)**

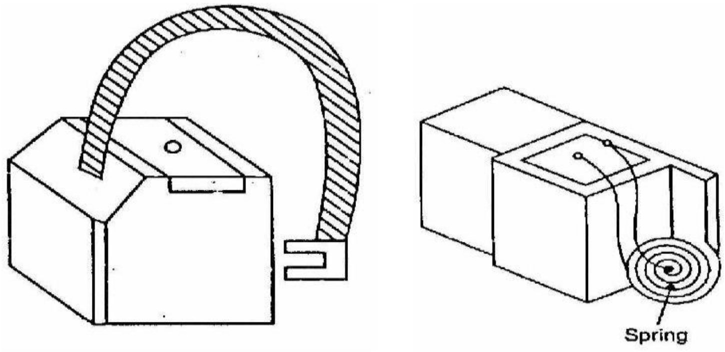


**Fig. (1.6)**

Multi pole machines have as many brushes as they have poles. For example, a 4-pole machine has 4 brushes. As we go round the commutator, the successive brushes have positive and negative polarities. Brushes having the same polarity are connected together so that we have two terminals viz., the +ve terminal and the - ve terminal.

## 1.2 Generator Principle

An electric generator is a machine that converts mechanical energy into electrical energy. An electric generator is based on the principle that whenever flux is cut by a conductor, an e.m.f. is induced which will cause a current to flow if the conductor circuit is closed. The direction of induced e.m.f. (and hence current) is given by Fleming’s right hand rule. Therefore, the essential components of a generator are:

(a) a magnetic field
(b) conductor or a group of conductors
(c) Motion of conductor w.r.t. magnetic field.

## Simple Loop Generator

Consider a single turn loop ABCD rotating clockwise in a uniform magnetic field with a constant speed as shown in Fig.(1.7). As the loop rotates, the flux linking the coil sides AB and CD changes continuously. Hence the e.m.f. induced in these coil sides also changes but the e.m.f. induced in one coil side adds to that induced in the other.

(i) When the loop is in position no. 1 [See Fig. 1.7], the generated e.m.f. is zero because the coil sides (AB and CD) are cutting no flux but are moving parallel to it
(ii) When the loop is in position no. 2, the coil sides are moving at an angle to the flux and,

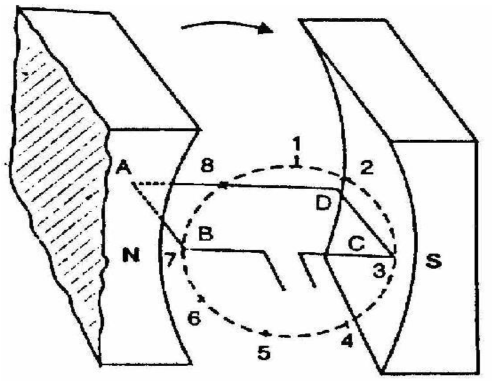
therefore, a low e.m.f. is generated as indicated by point 2 in Fig. (1.8).

(iii) When the loop is in position no. 3, the coil sides (AB and CD) are at right angle to the flux and are, therefore, cutting the flux at a maximum rate. Hence at this instant, the generated e.m.f. is maximum as indicated by point 3 in Fig. (1.8).

(iv) At position 4, the generated e.m.f. is less because the coil sides are cutting the flux at an angle.

(v) At position 5, no magnetic lines are cut and hence induced e.m.f. is zero as indicated by point 5 in Fig. (1.8).

(vi) At position 6, the coil sides move under a pole of opposite polarity and hence the direction of generated e.m.f. is reversed. The maximum e.m.f. in this direction (i.e., reverse direction, See Fig. 1.8) will be when the loop is at position 7 and zero when at position 1. This cycle repeats with each revolution of the coil.



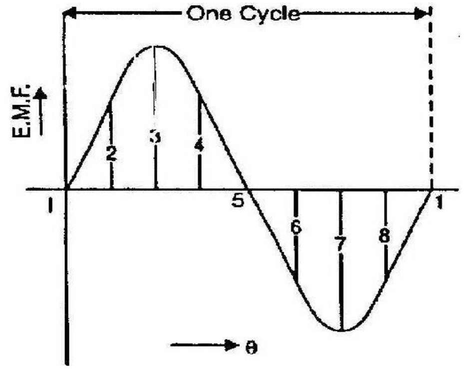


**Fig. (1.7)** **Fig. (1.8)**

Note that e.m.f. generated in the loop is alternating one. It is because any coil side; say AB has e.m.f. in one direction when under the influence of N-pole and in the other direction when under the influence of S-pole. If a load is connected across the ends of the loop, then alternating current will flow through the load. The alternating voltage generated in the loop can be converted into direct voltage by a device called commutator. In fact, a commutator is a mechanical Rectifier.

## 1.3 E.M.F. Equation of a D.C. Generator

We shall now derive an expression for the e.m.f. generated in a d.c. generator.

Let $\emptyset$= flux/pole in Wb

Z = total number of armature conductors P = number of poles

A = number of parallel paths

= 2 ... for wave winding

= P ... for lap winding

N = speed of armature in r.p.m.

$E_g$ = e.m.f. of the generator = e.m.f./parallel path

Flux cut by one conductor in one revolution of the armature, $d\emptyset = P\emptyset$ webers
Time taken to complete one revolution, dt = 60/N second
e.m.f/conductor = $d\emptyset$ / dt = $\frac{\emptyset PN}{60}$
e.m.f. of generator, $E_g$ = e.m.f. per parallel path
= (e.m.f/conductor) * No. of conductors in series per parallel path

$$E_g = \frac{\emptyset PNZ}{60A}$$

## 1.4 Types of D.C. Generators

The magnetic field in a d.c. generator is normally produced by electromagnets rather than permanent magnets. Generators are generally classified according to their methods of field excitation. On this basis, d.c. generators are divided into the following two classes:

(i) Separately excited d.c. generators
(ii) Self-excited d.c. generators

The behaviour of a d.c. generator on load depends upon the method of field excitation adopted.

## 1.5 Separately Excited D.C. Generators

A d.c. generator whose field magnet winding is supplied from an independent external d.c. source (e.g., a battery etc.) is called a separately excited generator. Fig. (1.9) shows the connections of a separately excited generator. The voltage output depends upon the speed of rotation of armature and the field current ($E_g$ = P□ ZN/60 A). The greater the speed and field current, greater is the generated e.m.f. It may be noted that separately excited d.c. generators are rarely used in practice. The d.c. generators are normally of self-excited type.

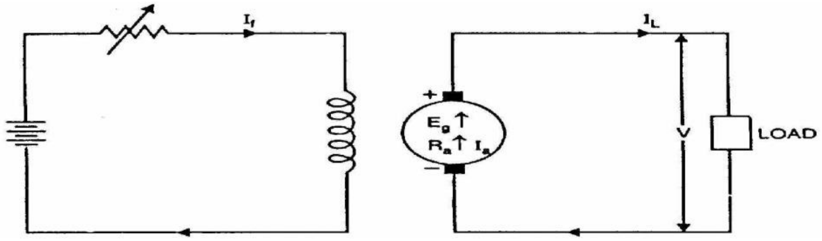


**Fig. (1.9)**

Armature current, $I_a = I_L$
Terminal voltage, $V = E_g - I_aR_a$ Electric
power developed = $E_gI_a$
Power delivered to load = $E_g I_a - I^2_a R_a = I_a (E_g - I_a R_a) = VI_a$

### 1.6 Self-Excited D.C. Generators

A d.c. generator whose field magnet winding is supplied current from the output of the generator itself is called a self-excited generator. There are three types of self-excited generators depending upon the manner in which the field winding is connected to the armature, namely

(i) Series generator
(ii) Shunt generator
(iii) Compound generator

### (i) Series generator

In a series wound generator, the field winding is connected in series with armature winding so that whole armature current flows through the field winding as well as the load. Fig. (1.10) shows the connections of a series wound generator. Since the field winding carries the whole of load current, it has a few turns of thick wire having low resistance. Series generators are rarely used except for special purposes e.g., as boosters.

Armature current, $I_a = I_{se} = I_L = I$(say) Terminal
voltage, $V = E_G - I(R_a + R_{se})$ Power developed in
armature = $E_gI_a$
Power delivered to load=$E_gI_a - I^2{}_a(R_a + R_{se}) =$
$I_a[E_g - I_a(R_a + R_{se}) = VI_a or VI_L$

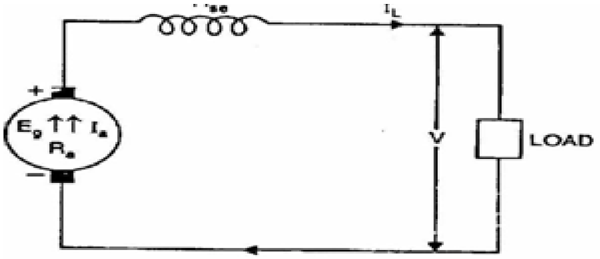


Fig. (1.10)

### (ii) Shunt generator

In a shunt generator, the field winding is connected in parallel with the armature winding so that terminal voltage of the generator is applied across it. The shunt field winding has many turns of fine wire having high resistance. Therefore, only a part of armature current flows through shunt field winding and the rest flows through the load. Fig. (1.11) shows the connections of a shunt-wound generator.

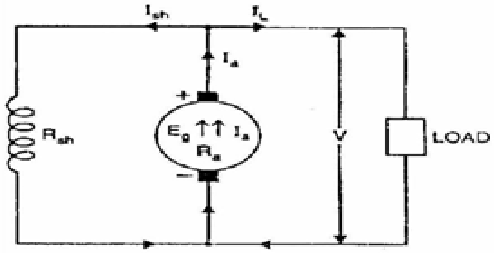


Fig. (1.11)

Shunt field current, $I_{sh} = V/R_{sh}$ Armature
current, $I_a = I_L + I_{sh}$
Terminal voltage, $V = E_g - I_aR_a$
Power developed in armature = $E_gI_a$ Power
delivered to load = $VI_L$

**(iii) Compound generator**

In a compound-wound generator, there are two sets of field windings on each pole one is in series and the other in parallel with the armature. A compound wound generator may be:

(a) Short Shunt in which only shunt field winding is in parallel with the armature winding [See Fig. 1.12(i)].

(b) Long Shunt in which shunt field winding is in parallel with both series field and armature winding [See Fig. 1.12 (ii)].

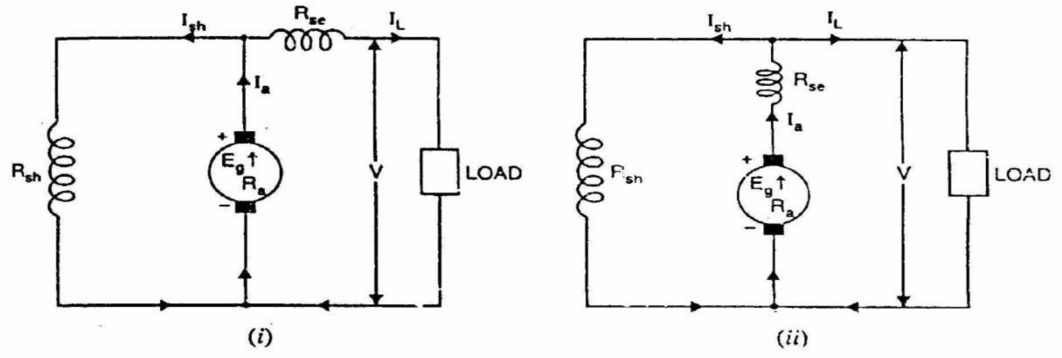


**Fig. (1.12)**

**Short shunt**

Series field current, $I_{se} = I_L$

Shunt field current, $I_{sh} = \dfrac{V + I_{se} R_{se}}{R_{sh}}$

Terminal voltage, $V = E_g - I_a R_a - I_{se} R_{se}$

Power developed in armature = $E_g I_a$

Power delivered to load = $VI_L$

**Long shunt**

Series field current, $I_{se} = I_a = I_L + I_{sh}$

Shunt field current, $I_{sh} = V/R_{sh}$

Terminal voltage, $V = E_g - I_a (R_a + R_{se})$

Power developed in armature = $E_g I_a$

Power delivered to load = $VI_L$

## 1.7 Principle of Operation of dc motor:

DC motor operates on the principle that when a current carrying is placed in a magnetic field, it experiences a mechanical force give n by F = BIL newton. Where ‘B’ = flux density in wb/$m^2$', ‘I’ is the current and ‘L’ is the length of the conductor. The direction of force can be found by Fleming’s left hand rule. Constructionally, there is no difference between a DC generator and DC motor.

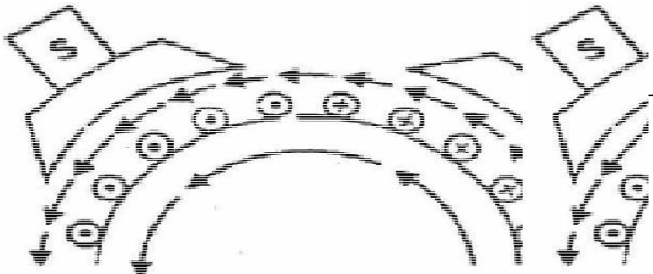


**Figure 1.13**

Figure 1.15 shows a multipolar DC motor. Armature conductors are carrying current downwards under North Pole and upwards under South Pole. When the field coils are excited, with current carrying armature conductors, a force is experienced by each armature conductor whose direction can be found by Fleming's left hand rule. This is shown by arrows on top of the conductors. The collective force produces a driving torque which sets the armature into rotation. The function of a commutator in DC motor is to provide a continuous and unidirectional torque.

In DC generator the work done in overcoming the magnetic drag is converted into electrical energy. Conversion of energy from electrical form to mechanical form by a DC motor takes place by the work done in overcoming the opposition which is called the 'back emf'.

## 1.8 BACK EMF:

Back emf is the dynamically induced emf in the armature conductors of a dc motor when the armature is rotated. The direction of the induced emf as found by Flemings right hand rule is in opposition to the applied voltage. Its value is same as that of the induced emf in a DC
generator i.e. is

$$E_b = \left(\frac{\phi Zn}{60}\right) X \frac{P}{A} \text{volts.}$$

This emf is called as back emf $E_b$'The work done in overcoming this opposition is converted into mechanical energy.

## 1.9 SIGNIFICANCE OF BACK EMF:

Figure 1.16 shows a DC shunt motor. The rotating armature generating the back emf$E_b$' is like a battery of emf $E_b$'connected across a supply voltage of 'V' volts.

From Figure 1.16 $I_a = \frac{V-E_b}{r_a}$ where $r_a = armature\ resistance.$

$$E_b = \frac{\phi ZNP}{60A}\text{Volts.}\ \ E_b \propto N.$$

If $E_b$ is large, armature current will be less and vice versa. Hence $E_b$acts like a governor i.e., it makes the motor self- regulating so that it draws as much current as required by the motor.

## 1.10 VOLTAGE EQUATION OF A MOTOR:

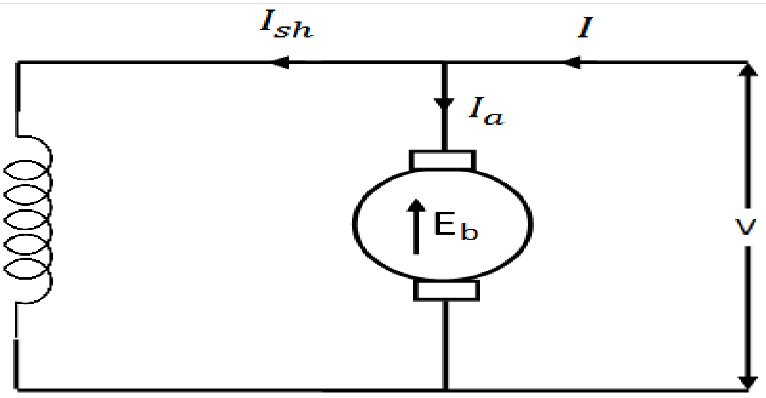


Figure 1.14

The voltage 'V' applied across the motor armature has to

i) Overcome the back emf $E_b$ and
ii) Supply the armature ohmic drop $I_a r_a$

Hence $V = E_b + I_a r_a \ldots..1$ This is known as voltage equation of DC motor.

Multiplying both sides of voltage equation by $I_a$

$VI_a = E_b I_a + I_a^2 r_a \ldots\ldots.2$

$VI_a = electrical\ input\ to\ the\ armature.$

$E_b I_a = P_m =$ $electrical\ equivalent\ of\ mechanical$ $power\ developed\ in\ the\ armature.$

$I_a^2 r_a = armature\ copper\ loss$

## 1.11 CHARACTERISTICS OF DC MOTORS:

**There are three important characteristics.**

1. Armature torque vs Armature current; $T_a$vs $I_a$(Electrical_characteristics)_
2. Speed vs armature current characteristic
3. Speed vs torque N vs $T_a$ (Mechanical characteristics)

## 1.12 CHARACTERISTICS OF SHUNT MOTORS

i) $\frac{T_a}{I_a}$

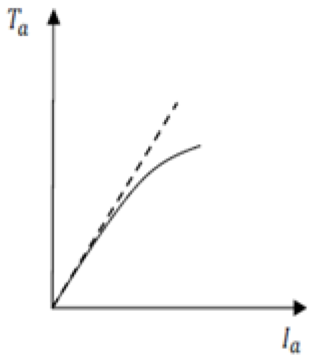


**Fig 1.15**

ii) $\frac{N}{I_a}$

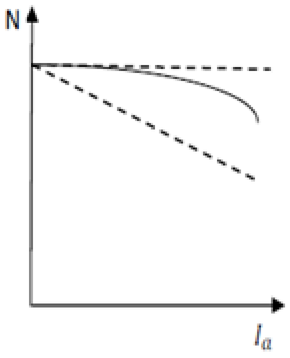


**fig 1.16**

iii) $\frac{N}{T_a}$

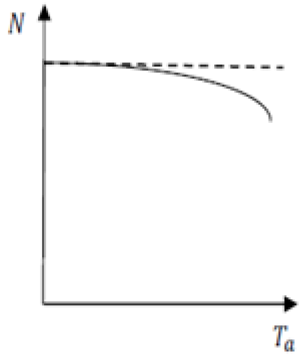


**fig 1.17**

$$N \; \alpha \; \frac{E_b}{\phi} \text{ or } N = K_N\left(\frac{V-I_aR_a}{\phi}\right) \; ; \; N = \frac{K_N V}{\phi} - \frac{K_N I_a r_a}{\phi} \text{------- (a)}$$

$$I_a = \frac{T}{K_T \phi} \text{-------(b)}$$

Substituting (b) in(a)

$$N = \frac{K_N V}{\phi} - \frac{K_N r_a}{K_T \phi^2} T$$

### 1. $T_a$ vs $I_a$ CHARACTERISTICS

For a shunt motor flux $\phi$ can be assumed practically constant (at heavy loads, $\phi$ decreases, due to increased armature reaction)

$T_a \propto \phi \, I_a$

$\phi = constant, T_a \propto I_a$

Therefore electrical characteristic of a shunt motor is a straight line through origin shown by dotted line in Figure 1.17 Armature reaction weakens the flux hence $T_a$ vs $I_a$ characteristic bends as shown by dark line in figure 1.17, Shunt motors should never be started on heavy loads, since it draws heavy current under such condition.

### $2. N\ vs\ I_a$ CHARACTERISTICS

$N \propto E_b$ ;      $E_b$ is practically almost constant.

Hence the speed is constant. However, $E_b$ decreases slightly more than ∅ with increase in load and thus there is slight decrease in speed. This decrease in speed varies from 5 to 15% of full load speed and it depends on armature reaction and saturation. This characteristics is shown in Figure 1.18

### $3. N\ vs\ T_a$ CHARACTERISTICS

This characteristic can be deduced from 1 and 2, shown in figure 1.19

## 1.13 CHARACTERISTICS OF SERIES MOTORS:

### $1. T_a vs\ I_a$ CHARACTERISTICS

$T_a \propto \emptyset\, I_a$

$\emptyset \propto I_a$

$T_a \propto I_a^2$ – upto saturation

$T_a \propto I_a$ – after saturation

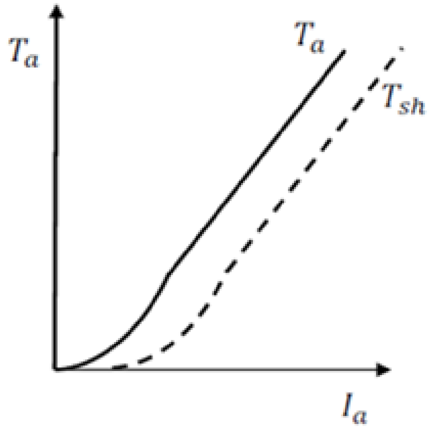


Fig 1.18

At light loads, $I_a$ nd hence is ∅ small. But as $I_a$increases; $T_a$ncreases as the square of the current up to saturation. After saturation ∅ becomes constant, the characteristic becomes a straight line as shown in Figure 1.20. Therefore a series motor develops a torque proportional to the square of the armature current. This characteristic is suited where huge starting torque is required for accelerating heavy masses.

Ex. Hoists, electric trains, etc.

### $2. N\ vs\ I_a$ CHARACTERISTICS

$N \propto \frac{E_b}{\emptyset} E_b \textit{ is approximately constant}$

$N \propto \frac{1}{\emptyset}$.

If $I_a$ increases, $\emptyset$ increases and hence speed decreases.

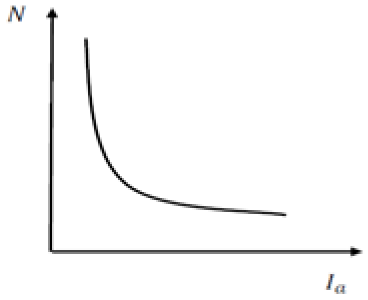


figure 1.19

This characteristic is shown in figure 1.21. Change in $E_b$ for various load currents is small. Hence may be neglected. Therefore the speed is inversely proportional to flux, because $N \propto \frac{E_b}{\emptyset}$ When the load is heavy, $I_a$is large and speed is low. When the load is low, current and hence flux will be small. Therefore speed becomes dangerously high. Hence a series motor should never be started without load on it.

### 3. $N$ $vs$ $T_a$CHARACTERISTICS

$T_a \propto E_b I_a$

$E_b$ *is constant*

Hence, $T_a \propto I_a$. Therefore, N vs $T_a$characteristic

can be deduced from 1 and 2 as shown in Figure

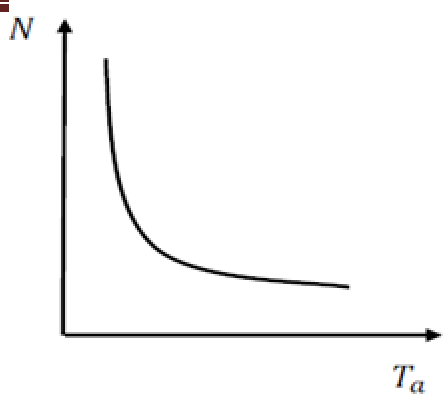


Fig 1.20

**1.14 COMPOUND MOTOR CHARACTERISTICS:**

Cumulative compound motors are used where series characteristics are required and in addition the load is likely to be removed totally such as in some types of coal cutting machines or for driving heavy machine tools which have to take sudden deep cuts quite often. Speed will not become excessively high due to shunt winding and the motor will be able to take heavy loads because of series winding. Differential compound motors: Series field opposes the shunt field; therefore the flux is decreased as the load is applied to the motor. This results in the motor speed remaining almost constant or even increasing with increase in load.

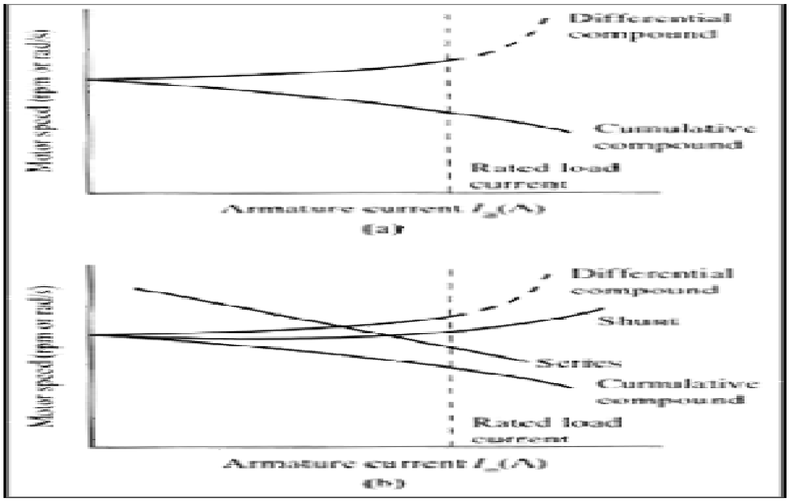


Figure 1.21

## 1.15 Three Point Starter:

It consists of resistances arranged in steps,R1 to R5 connected in series with the armature of the shunt motor. Field winding is connected across the supply through a protective device called ‘NO – Volt Coil’. Another protection given to the motor in this starter is ‘over load release coil’. The arrangement is shown in Figure 1.24

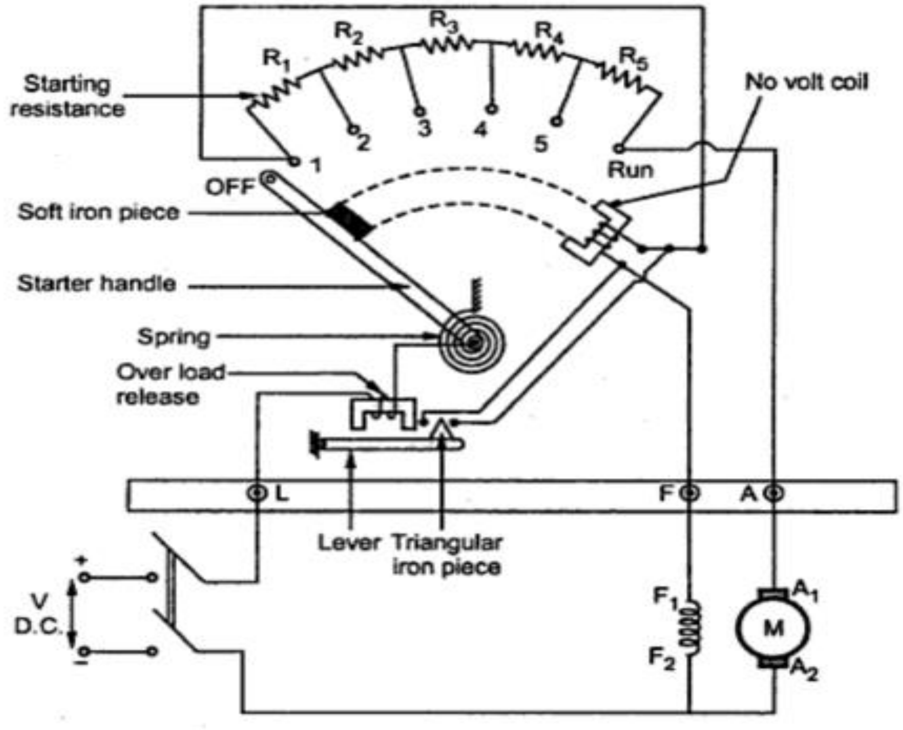


**Figure 1.22 Three Point Starter**

To start the motor the starter handle is moved from OFF position to run position gradually against the tension of a hinged spring. An iron piece is attached to the starter handle which is kept hold by the No-volt coil at Run position. The function of No volt coil is to get deenergised and release the handle when there is failure or disconnection or a break in the field circuit so that on restoration of supply, armature of the motor will not be connected across the lines without starter resistance. If the motor is over loaded beyond a certain predetermined value, then the electromagnet of overload release will exert a force enough to attract the lever which short circuits the electromagnet of No volt coil. Short circuiting of No volt coil results in deenergisation of it and hence the starter handle will be released and return to its off position due to the tension of the spring. In this type of starter, the shunt field current has to flow back through the starter resistance thus decreasing the shunt field current. This can be avoided by placing a brass arc on which the handle moves as shown in Figure 1.25

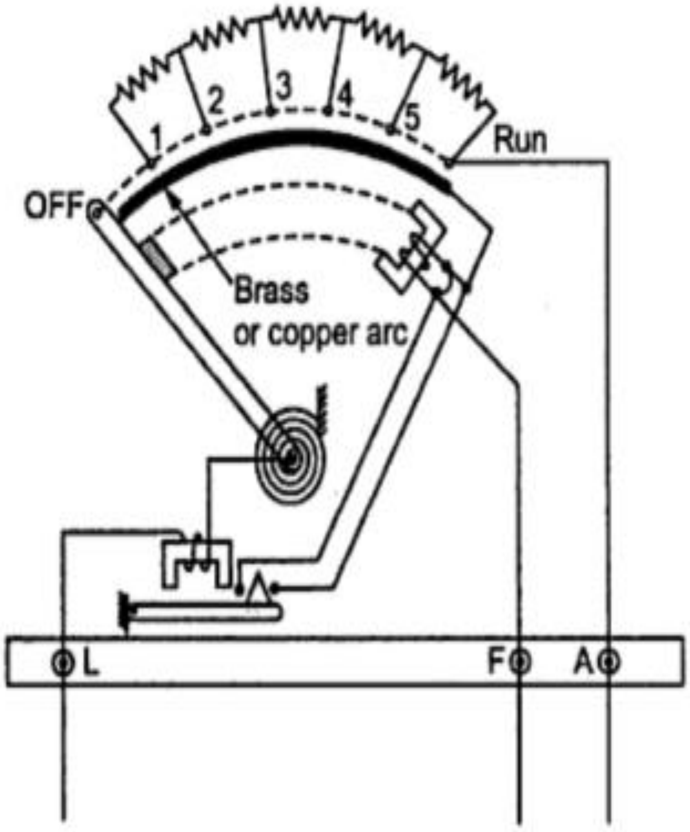


**Figure 1.23**

**Construction of 3 Point Starter**

Construction wise a starter is a variable resistance, integrated into number of sections as shown in the figure beside. The contact points of these sections are called studs and are shown separately as OFF, 1, 2,3,4,5, RUN. Other than that there are 3 main points, referred to as

1. 'L' Line terminal. (Connected to positive of supply.)
2. 'A' Armature terminal. (Connected to the armature winding.)
3. 'F' Field terminal. (Connected to the field winding.)

And from there it gets the name 3 point starter.

Now studying the construction of 3 point starter in further details reveals that, the point 'L' is connected to an electromagnet called overload release (OLR) as shown in the figure. The other end of 'OLR' is connected to the lower end of conducting lever of starter handle where a spring is also attached with it and the starter handle contains also a soft iron piece housed on it. This handle is free to move to the other side RUN against the force of the spring. This spring brings back the handle to its original OFF position under the influence of its own force. Another parallel path is derived from the stud '1', given to the another electromagnet called No Volt Coil (NVC) which is further connected to terminal 'F'. The starting resistance at starting is entirely in series with the armature. The OLR and NVC acts as the two protecting devices of the starter.

## Working of Three Point Starter

Having studied its construction, let us now go into the working of the 3 point starter. To start with the handle is in the OFF position when the supply to the DC motor is switched on. Then handle is slowly moved against the spring force to make a contact with stud No. 1. At this point, field winding of the shunt or the compound motor gets supply through the parallel path provided to starting resistance, through No Voltage Coil. While entire starting resistance comes in series with the armature. The high starting armature current thus gets limited as the current equation at this stage becomes Ia = E/(Ra+Rst). As the handle is moved further, it goes on making contact with studs 2, 3, 4 etc., thus gradually cutting off the series resistance from the armature circuit as the motor gathers speed. Finally when the starter handle is in 'RUN' position, the entire starting resistance is eliminated and the motor runs with normal speed.

This is because back emf is developed consequently with speed to counter the supply voltage and reduce the armature current. So the external electrical resistance is not required anymore, and is removed for optimum operation. The handle is moved manually from OFF to the RUN position with development of speed.

Working of No Voltage Coil of 3 Point Starter

The supply to the field winding is derived through no voltage coil. So when field current flows, the NVC is magnetized. Now when the handle is in the 'RUN' position, soft iron piece connected to the handle and gets attracted by the magnetic force produced by NVC, because of flow of current through it. The NVC is designed in such a way that it holds the handle in 'RUN' position against the force of the spring as long as supply is given to the motor. Thus NVC holds the handle in the 'RUN' position and hence also called hold on coil.

Now when there is any kind of supply failure, the current flow through NVC is affected and it immediately looses its magnetic property and is unable to keep the soft iron piece on the handle, attracted. At this point under the action of the spring force, the handle comes back to OFF position, opening the circuit and thus switching off the motor. So due to the combination of NVC and the spring, the starter handle always comes back to OFF position whenever there is any supply problems. Thus it also acts as a protective device safeguarding the motor from any kind of abnormality.

### Working of over load coil of 3 Point Starter

If any fault occurs on motor or overload, it will draw extreme current from the source. This current raise the ampere turns of OLR coil (over load relay) and pull the armature Coil, in consequence short circuiting the NVR coil (No volt relay coil). The NVR coil gets demagnetized and handle comes to the rest position under the influence of spring. Therefore the motor disconnected from the supply automatically.

### Drawback of three point starter:

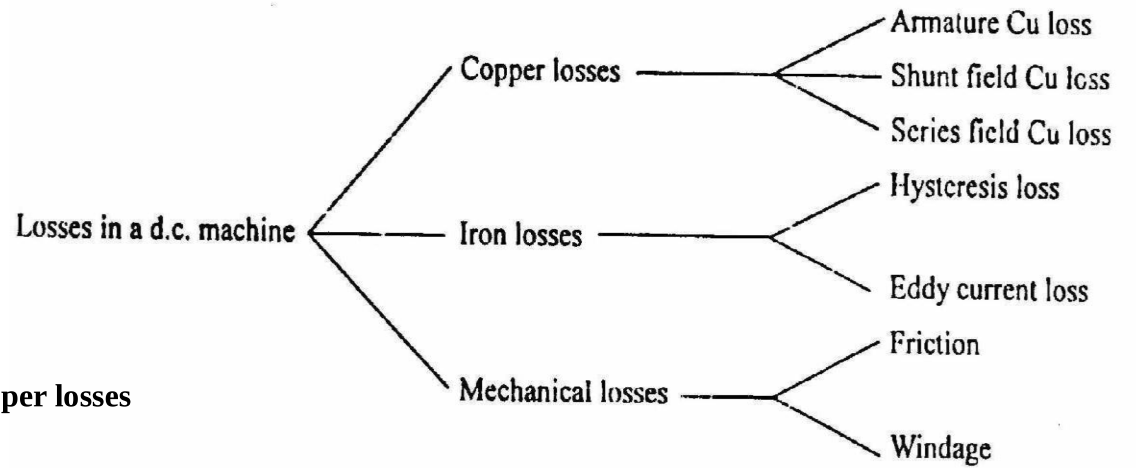
The use of a three point starter presents a problem. The speed of the motor is controlled by means of the field rheostat. To increase the speed of motor necessitates the setting of the field rheostat to higher resistance value. The current through the shunt field is reduced, and so is the current through the coil of the holding electromagnet. The reduced current through the coil weakens the strength of magnet and makes susceptible to line voltage variations. In the weakened condition a slight reduction in line voltage would further weaken the holding magnet, releasing the arm of the starter and thus disconnecting the motor from the line. Unscheduled stoppages of the motor make the three point starter quite unpopular.

## 1.16 Brush Contact Drop

It is the voltage drop over the brush contact resistance when current flows. Obviously, its value will depend upon the amount of current flowing and the value of contact resistance. This drop is generally small

## 1.17 Losses in a D.C. Machine

The losses in a d.c. machine (generator or motor) may be divided into three classes viz (i) copper losses (ii) iron or core losses and (iii) mechanical losses. All these losses appear as heat and thus raise the temperature of the machine. They also lower the efficiency of the machine.



1. **Copper losses**

These losses occur due to currents in the various windings of the machine.

(i) Armature copper loss = $I^2_a R_a$

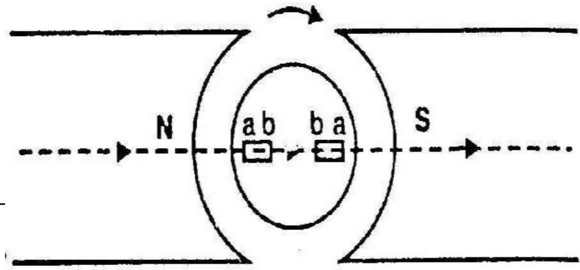
(ii) Shunt field copper loss = $I_{sh}^2 R_{sh}$

(iii) Series field copper loss = $I_{se}^2 R_{se}$

**Note**. There is also brush contact loss due to brush contact resistance (i.e., resistance between the surface of brush and surface of commutator). This loss is generally included in armature copper loss.

2. **Iron or Core losses**

These losses occur in the armature of a d.c. machine and are due to the rotation of armature in the magnetic field of the poles.
They are of two types viz.,



(i) Hysteresis loss (ii) eddy current loss.

(i) **Hysteresis loss**

Hysteresis loss occurs in the armature of the d.c. machine since any given part of the armature is subjected to magnetic field reversals as it passes under successive poles. Fig. (1.26) shows an armature.

Rotating in two-pole machine. Consider a small piece ab of the armature. When the piece ab is under N-pole, the magnetic lines pass from a to b. Half a revolution later, the same piece of iron is under S-pole and magnetic lines pass from b to a so that magnetism in the iron is reversed. In order to reverse continuously the molecular magnets in the armature core, some amount of power has to be spent which is called hysteresis loss. It is given by Steinmetz formula. This formula is

$$\text{Hysteresis loss, } P_h = \eta B^{16}_{max} f V \quad \text{watts}$$

Where

$B_{max}$ = Maximum flux density in armature f =
Frequency of magnetic reversals
= NP/120 where N is in r.p.m. V =
Volume of armature in $m^3$
$\eta$ = Steinmetz hysteresis co-efficient

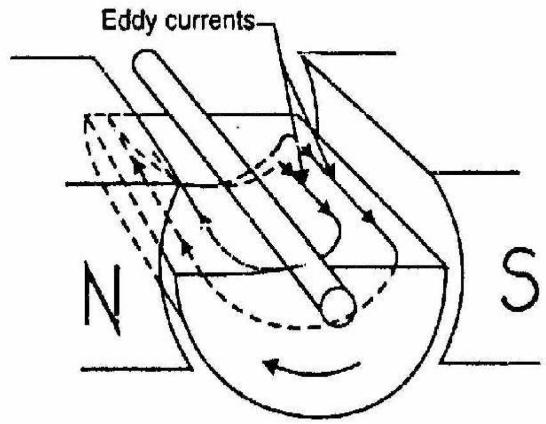
In order to reduce this loss in a d.c. machine, armature core is made of such materials which have a low value of Steinmetz hysteresis co-efficient e.g., silicon steel.

(ii) **Eddy current loss**

In addition to the voltages induced in the armature conductors, there are also voltages induced in the armature core. These voltages produce circulating currents in the armature core as shown in Fig. (1.27). These are called eddy currents and power loss due to their flow is called eddy current loss. The eddy current loss appears as heat which raises the temperature of the machine and lowers its efficiency.

If a continuous solid iron core is used, the resistance to eddy current path will be small due to large cross-sectional area of the core. Consequently, the magnitude of eddy current and hence eddy current loss will be large. The magnitude of eddy current can be reduced by making core resistance as high as practical.

The core resistance can be greatly increased by constructing the core of thin, round iron sheets called laminations [See Fig. 1.28]. The laminations are insulated from each other with a coating of varnish. The insulating coating has a high resistance, so very little current flows from one lamination to the other. Also, because each lamination is very thin, the resistance to current flowing through the width of a lamination is also quite large. Thus laminating a core increases the core resistance which decreases the eddy current and hence the eddy current loss



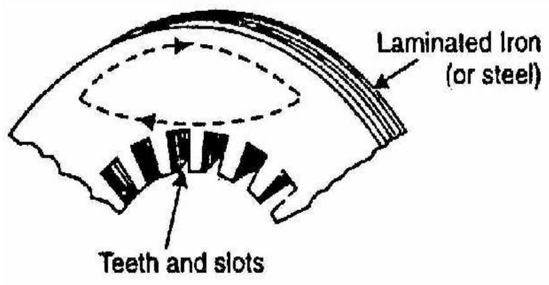


**Fig. (1.24)** **Fig. (1.25)**

$$E_gI_a - I^2{}_a(R_a + R_{se}) = I_a[E_g - I_a(R_a + R_{se}) = VI_a or VI_L$$

$$Eddy\ current\ loss, P_e = K_e f^2 t^2 V\ Watts$$

$K_e$=Constant depending upon the electrical resistance of core and system of units used

$B_{max}$ = Maximum flux density in Wb/m2
f = Frequency of magnetic reversals in Hz
t = Thickness of lamination in m
V = Volume of core in $m^3$

It may be noted that eddy current loss depends upon the square of lamination thickness. For this reason, lamination thickness should be kept as small as possible.

3. **Mechanical losses**

These losses are due to friction and windage.

(i) Friction loss e.g., bearing friction, brushes friction etc.
(ii) Windage loss i.e., air friction of rotating armature.

These losses depend upon the speed of the machine. But for a given speed, they are practically constant.

**Note**. Iron losses and mechanical losses together are called stray losses.

## 1.18 Constant and Variable Losses

The losses in a d.c. generator (or d.c. motor) may be sub-divided into (i) constant losses (ii) variable losses.

(i) **Constant losses**

Those losses in a d.c. generator which remain constant at all loads are known as constant losses. The constant losses in a d.c. generator are:

(a) iron losses

(b) mechanical losses
(c) shunt field losses

**(ii) Variable losses**

Those losses in a d.c. generator which vary with load are called variable losses. The variable losses in a d.c. generator are:

(a) Copper loss in armature winding ( $I^2_a R_a$ )
(b) Copper loss in series field winding ( $I_{se}^2 R_{se}$ )

**Total losses = Constant losses + Variable losses**

**Note**. Field Cu loss is constant for shunt and compound generators.

## 1.19 Power Stages

The various power stages in a d.c. generator are represented diagrammatically in Fig. (1.29).

A - B = Iron and friction losses
B - C = Copper losses

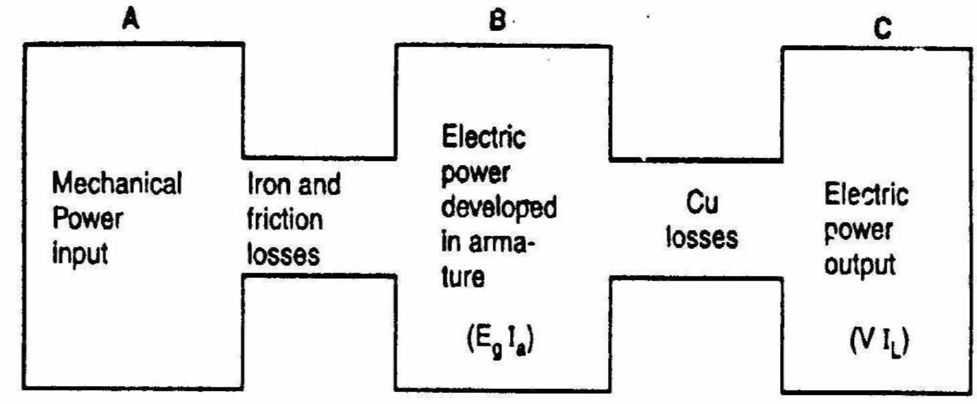


**Fig. (1.26)**

(i) Mechanical efficiency $\eta_m = \frac{C}{A} = \frac{\text{Eg Ia}}{\text{Mechanical power input}}$

(ii) Electrical efficiency $\eta_e = \frac{C}{B} = \frac{VI_L}{E_g I_a}$

Commercial or overall efficiency $\eta_c = \frac{C}{A} = \frac{\text{V IL}}{\text{Mechanical power input}}$

Clearly $\eta_c = \eta_m \times \eta_e$

Unless otherwise stated, commercial efficiency is always understood.

$$\eta_c = \frac{C}{A} = \frac{\text{output}}{\text{input}} = \frac{input - losses}{input}$$

## 1.20 Condition for Maximum Efficiency

The efficiency of a d.c. generator is not constant but varies with load. Consider a shunt generator delivering a load current $I_L$ at a terminal voltage V.

Generator output = $V\ I_L$

Generator input = Output + Losses

$= V\ I_L$ + Variable losses + Constant losses

$= VI_L + I_a^2 R_a + W_C$

$$= VI_L + (I_L + I_{sh})^2 R_a + W_c \qquad (since\ I_a = I_L + I_{sh})$$

The shunt field current $I_{sh}$ is generally small as compared to $I_L$ and therefore, it can be neglected.

∴ Generator input = $VI_L + I^2_L R_a + W_C$

$$\eta = \frac{output}{input} = \frac{VI_L}{VI_L + {I_L}^2 R_a + W_c}$$

$$= \frac{1}{1 + \left[\frac{I_L R_a}{V} + \frac{W_c}{VI_L}\right]}$$

The efficiency will be maximum when the denominator of above Equation is minimum i.e.,

$$\frac{d}{dI_L}\left[\frac{I_L R_a}{V} + \frac{W_c}{VI_L}\right] = 0$$

$$\frac{R_a}{V} + \frac{W_c}{V{I_L}^2} = 0$$

$$or\ \ \frac{R_a}{V} = \frac{W_c}{V{I_L}^2}$$

$$or\ \ {I_L}^2 R_a = W_c$$

Hence Variable loss = Constant loss

$$( I_L \approx I_a)$$

The load current corresponding to maximum efficiency is given by;

$$I_L = \sqrt{\frac{W_c}{R_a}}$$

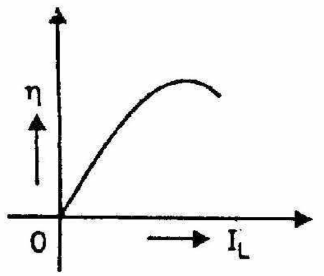


Fig. 1.27

Hence, the efficiency of a d.c. generator will be maximum when the load current is such that variable loss is equal to the constant loss. Fig (1.30) shows the variation of efficiency with load current.

## 1.21 Speed control of dc shunt motor by flux control method

In this method field circuit resistance is varied to control the speed of a d.c shunt motor. Let us rewrite .the basic equation to understand the method.

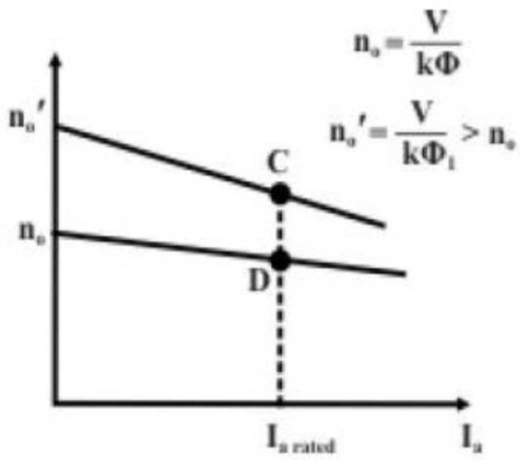
$$n = \frac{V - I_a r_a}{k\phi}$$

If we vary *If*, flux φ will change, hence speed will vary. To change *If* an external resistance is connected in series with the field windings. The field coil produces rated flux when no external resistance is connected and rated voltage is applied across field coil. It should be understood that we can only decrease flux from its rated value by adding external resistance. Thus the speed of the motor will rise as we decrease the field current and speed control above the *base* speed will be achieved. Speed versus armature current characteristic is shown in figure 1.32 for two flux values φ and 1φ. Since 1<φφ, the no load speed *'on* for flux value 1φ is more than the no load speed *no* corresponding to φ. However, this method will not be suitable for constant load torque.

To make this point clear, let us assume that the load torque is constant at rated value. So from the initial steady condition, we have 1=*L ratedea ratedT=TkI*φ. If load torque remains constant and flux is reduced to 1φ, new armature current in the steady state is obtained from 11*aL ratekI=T* φ. Therefore new armature current is

$$I_{a1} = \frac{\phi}{\phi_1} I_{a\ rated}$$

But the fraction,1 1>φ; hence new armature current will be greater than the rated armature current and the motor will be overloaded. This method therefore, will be suitable for a load whose torque demand decreases with the rise in speed keeping the output power constant as shown in figure 1.33 Obviously this method is based on *flux weakening* of the main field. Therefore at higher speed main flux may become so weakened, that armature reaction effect will be more pronounced causing problem in commutation.



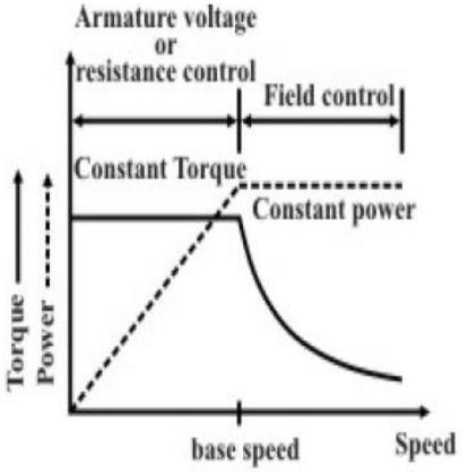
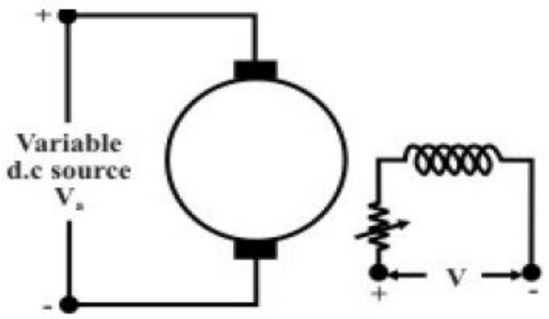
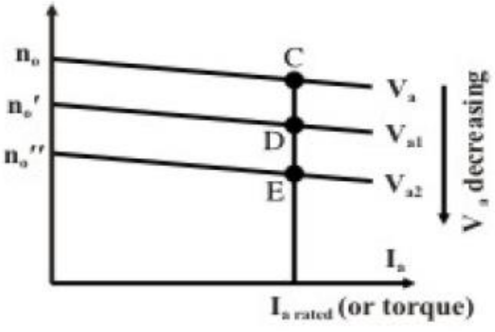


**Fig.1.28 :N v/s Ia Characteristics** **Fig.1.29 : Constant Torque and Power Operation**

## 1.22 Speed control of dc shunt motor by armature voltage control:

In this method of speed control, armature is supplied from a separate variable d.c voltage source, while the field is separately excited with fixed rated voltage as shown in figure 3.5. Here the armature resistance and field current are not varied. Since the no load speed 0=*aVkn*φ, the speed versus *Ia* characteristic will shift parallely as shown in figure for different values of *Va*.





As flux remains constant, this method is suitable for constant torque loads. In a way armature voltage control method is similar to that of armature resistance control method except that the former one is much superior as no extra power loss takes place in the armature circuit. Armature voltage control method is adopted for controlling speed from base speed down to very small speed as one should not apply across the armature a voltage which is higher than the rated Voltage.

# Assignment-Cum-Tutorial Questions

## A. Questions testing the remembering / understanding level of students

### *I) Objective Questions*

1) The armature of a DC machine is laminated to reduce

a) Eddy current Loss b) Hysteresis loss c) Copper loss d) Friction and windage loss

2) The armature mmf wave in a d c machine is

a) Sinusodial b) triangular c) rectangular d) square.

3) The Field winding of a self excited dc generator is excited by

a) DC b) AC c) Either a or b d) its own current.

4) A dc motor is running at its normal speed, suddenly the field winding gets opened, the effect will be

a)motor stops b)heavy sparking c) speed becomes high d) speed decreases slowly

5) A dc series motor is started on no-load, its speed will be

a) zero b) normal c) low d) infinite

6) Which of the following motors gives a high starting torque?

a) series motor b) shunt motor c) compound motor d) none

7) For a given dc motor, the speed depends upon

a) flux only b) applied voltage alone c) back emf alone d) back emf & flux

8) The brushes that carry the current to the load are made of

a) carbon b) graphite c) carbon and graphite d) graphite and lead

9) The type of dc generator used for arc welding purposes is a

a) series generator b) shunt generator

c) cumulatively compound generator d) differentially compound generator

10) the function of a dc motor starter is to

a) start the dc motor b) limit the starting current

c) increase the starting torque d) avoid dips in the supply voltage

11) The armature core of a dc machine is laminated to minimize

a) hysteresis loss b) eddy-current loss

c) mechanical loss d) temperatue rise

12) In dc machines, constant loss is composed of

a) iron loss and mechanical mloss

b) friction, windage and iron loss and field circuit loss

c) iron loss and field circuit loss

d) friction, windage and stray load loss

13) the efficiency of a dc shunt generator is maximum when

a) magnetic loss is equal to the mechanical loss

b) field ohmic loss is equal to the constant loss

c) stray load loss is equal to the armature circuit loss

d) armature circuit loss is equal to the sum of no-load rotational loss and field circuit loss

14) If speed of dc shunt motor is increased above its rated speed, then its counter emf

a) increases b) decreases slightly

c) remains unchanged d) first increases and then decreases

15. State the principle of dc generator.

16. What are the applications of dc compound generator.

17. What is the need of 3-point starter.

## *II) Descriptive Questions*

1) Explain with a neat sketch the constructional details of a DC machine.
2) Explain the basic principle of operation of a dc generator and a dc motor.
3) Develop from first principles an expression for the EMF Equation of a DC machine.
4) What are the different methods of speed control of dc shunt motor. Explain them in detail.

5) Explain the load characteristics of dc shunt, series and compound generators.
6) Explain the classification of dc generators with neat circuit diagrams. Also write the relationships among the currents and voltages.
7) Explain about the different losses that occur in a dc machine. How these are minimized?
8) Explain the operation of 3-point starter with neat sketch. What are the functions of No-Volt & Over-Load release coils?
9) What are the applications of dc generators.
10) What is back emf? Explain the significance of back emf in dc motor?

## B. Question testing the ability of students in applying the concepts.

### *I) Objective Questions*

1) A P pole lap wound dc machine had an armature current I. The conductor current in the armature winding is

a) I    b) I/P    c) PI    d) none of the above.

2) The number of parallel paths for a 4-pole simplex lap winding will be

a) 2    b) 4    c) 6    d) 8

3) A 4 pole generator with 16 coils has a single layer lap winding , pole pitch is

a) 32    b) 16    c) 8    d) 4

4) If the flux per pole is Ø, the approximate value of the flux in the yoke section will be

a) Ø    b) 1.2 Ø    c) 0.5 Ø    d) 1.1 Ø

5) If the applied voltage to a dc machine is 220V, then the back emf for maximum power developed is

a) 110V    b) 200V    c)220V    d)440V

6) A dc shunt motor is running at 1200rpm when excited with 220V dc. Neglecting the losses and saturation, the speed of the motor when connected to a 175V dc supply is

a) 750rpm    b) 900rpm    c) 1050rpm    d) 1200rpm

7) A 4-pole dc generator runs at 1500rpm. The frequency of current in the armature winding is

a) 25Hz    b) 50Hz    c) zero Hz    d) 100 Hz

8) A 230V dc series generator is driven at its rated speed. The no-load voltage across its armature terminals would be

a) 230V    b) some what more than 230V

c) some what less than 230V    d) 6V

9) A dc shunt motor having unsaturated magnetic circuit runs at 1000rpm with rated voltage. If the applied voltage is reduced to half of the rated voltage the motor will be runs at

a) 2000rpm b) 1000rpm c) 750rpm d) 500rpm

10) A dc shunt motor runs at a no-load speed of 1140rpm. At full-load, armature reaction weakens the main flux by 5% where as the armature circuit voltage drops by 10%. The motor full-load speed in rpm is

a) 1080 b)1203 c)1000 d)1200

## II) *Descriptive Questions*

1) Develop the general expression for the speed of a motor in terms of supply voltage, armature resistance and flux per pole.

2) A 6-pole machine has an armature with 90 slots and 8 conductors per slot and runs at 1000rpm, the flux per pole is 0.05wb.Determine the induced emf if winding is (i) Lap connected and (ii) Wave connected.

3) An 8 pole dc shunt generator has 778 wave connected armature conductors running at 500 r.p.m.supplies a load of 12.5Ω resistance at a terminal voltage of 250v. the armature resistance is 0.24Ω and the field resistance is 250Ω .Find out the armature current ,the induced emf and the flux per pole.

4) A short shunt compound generator supplied 7.5Kw at 230V. The shunt fied, series field and armature resistances are 100Ω, 0.3Ω & 0.4Ω respectively. Calculate the induced emf and the load resistance.

5) A 20Kw, 200V shunt generator has an armature resistance of 0.05Ω and a shunt field resistance of 200 Ω. Calculate the power delivered in the armature when it delivers rated output.

6) A 4-pole dc motor has a wave wound armature with 594 conductors. The armature current is 40A and flux per pole is 7.5mwb. Calculate the torque and power delivered when running at 1440rpm.

7) A series motor takes 20A at 400V to drive a fan at 200rpm. Its resistance is 1ohm. If the Torque required to drive the fan varies as the square of the speed ,find the necessary applied Voltage and current to drive the fan at 300 rpm.

8) A 250 V DC shunt motor having an armature resistance of 0.25Ω carries an armature current of 50A.and runs at 750 rpm. if the flux is reduced by 10%, find the speed. Assume that the torque remains the same.

9) The armature resistance of a 220V dc series motor is 0.1 Ω and the series field resistance is 0.05 Ω. When it is running at 500rpm, it draws 70A. Calculate the speed of the motor when it draws 35A. assume the field unsaturated.

10) A shunt generator delivers 100Kw at 250V, when running at 400rpm. The armature resistance is 0.01 ohm and field resistance is 100 ohm . If the same is runs as shunt motor with an input of 100Kw at 250V, calculate the speed of the machine as a motor. Contact drop per brush is 1Volt.

## C. Questions testing the analyzing / evaluating /Creative ability of students

**1.** The following data pertain to the magnetization curve of a dc shunt generator at 1500rpm.

| $I_f$ amps | 0 | 0.4 | 0.8 | 1.2 | 1.6 | 2.0 | 2.4 | 2.8 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|
| $E_a$ volts | 6 | 60 | 120 | 172.5 | 202.5 | 221 | 231 | 237 | 240 |

For this generator obtain

a) The voltage on open circuit to which the machine will buildup (no load emf) for a total shunt field resistance of 100 ohms.

b) The critical value of shunt field resistance at 1500rpm

c) The critical speed for a shunt field resistance of 100 ohm.

**2.** A dc shunt motor takes 50A on full load from 250V mains. Its speed is to be raised by 40% by weakening of the field flux. if the torque at the increased speed is 20% more than that at the initial speed, find the percentage change in field flux. the armature resistance (including brushes) is 0.5 ohms.

**3.** A separately excited dc generator has no-load voltage of 120v at a field current of 2A, when driven at 1500 r.p.m. Assuming that it is operating on the straight line portion of its saturation curve, calculate (i) the generated voltage when the field current is increased to 2.5A,and (ii) the generated voltage when the speed is reduced to 1400 r.p.m.and the field current is increased to 2.84A.

## D.Previous GATE/IES Questions.

**1)** The speed –torque regimes of in a DC motor and the control methods suitable for the same are given, respectively in Group I and Group-II

| Group-I | Group-II |
|---|---|
| P. Field Control | 1. Below base speed |

| | |
|---|---|
| Q.Armature Control | 2.Above base speed |
| | 3. Above base Torque |
| | 4.Below base Torque |

Code:

| | P | Q |
|---|---|---|
| (a) | 1 | 3 |
| **(b)** | 2 | 1 |
| (c) | 2 | 3 |
| (d) | 1 | 4 |

**(GATE -2003)**

2) A DC series motor driving an electric train faces a constant power load .It is running at rated speed and rated voltage .If the speed has to be brought down to 0.25p.u., the supply voltage has to be approximately brought down to [ ]

(a) 0.75 p.u **(b)** 0.5 p.u (c) 0.25pu (d) 0.125pu

**(GATE 2003)**

3) A 250 V dc shunt machine has armature circuit resistance of 0.6Ω and field circuit resistance of125 Ω . The machine is connected to 250 V supply mains. The motor is operated as a generator and then as a motor separately. The line current of the machine in both the cases is 50 A. The ratio of the speed as a generator to the speed as a motor is ____________. Ans:1.27

**(GATE - 2014)**

4) A 500 KW DC shunt motor is loaded to draw rated armature current at any given speed.When driven

(i)at half the rated speed by armature voltage control ,and

(ii) at 1.5 times the rated speed by field control ,the respective output powers delivered by the motors are approximately [ ]

(a) 25KW in (i) and 75 KW in (ii)
(b) 25KW in (i) and 50KW in (ii)
(c) 50KW in (i) and 75KW in (ii)
**(d)** 50KW in (i) and 60KW in (ii) **(GATE -2005)**
Ans:b

5) The DC motor which can provide zero speed regulation at full load with out any controller

(a) series [ ]
(b) shunt
(c) cumulative compound
**(d)** differential compound **(GATE -2007)**

6) A 4-Point starter is used to start and control the speed of [ ]

**(a) DC shunt motor with armature resistance control**
(b) DC shunt motor with fields weakening method
(c) DCseries motor
**(d)** DC compound motor **(GATE-2011)**

7)A 220V ,D shunt motor is operating at a speed of 1440 r.p.m. The armature resistance is 1Ω and armature current is 10A.If the excitation of the machine is reduced by 10% ,the extra resistance to be put in the armature circuit to maintain the same speed and torque will be [ ]

**(a)** 1.79Ω (b)2.1Ω (c)3Ω (d)18.9Ω **(GATE 2011)**

8) A 220 V ,15KW ,1000 r.p.m. shunt motor with armature resistance of 0.25Ω,has rated line current of 68A and a rated field current of 2.2A .The change in field flux required to obtain a speed of 1600 r.p.m while drawing a line current of 52.8 A and field current of 1.8 A [ ]

(a)18.18% increase (b)18.18% decrease (c) 36.36% increase **(d)** 36.36% de crease

**(GATE -2012)**

9) A 4-pole, separately excited, wave wound DC machine with negligible armature resistance is rated for 230 V and 5 kW at a speed of 1200 rpm. If the same armature coils are reconnected to forms a lap winding, what is the rated voltage (in volts) and power (in kW) respectively at 1200 rpm of the reconnected machine if the field circuit is left unchanged? [ ]

(A) 230 and 5 **(B)** 115 and 5 (C) 115 and 2.5 (D) 230 and 2.5 **GATE-2015)**

10) A shunt-connected DC motor operates at its rated terminal voltage. Its no-load speed is 200 radians/second. At its rated torque of 500 Nm, its speed is 180 radian/second. The motor is used to directly drive a load whose load torque TL depends on its rotational speed (in radians/second), such that ω× =T 2.78 . L T Neglecting rotational losses, the steady-state speed (in radian/second) of the

motor, when it drives this load is _________ Ans:179.86

**(GATE-2015)**

# UNIT – II

# TRANSFORMERS

**Objectives:**

4. To familiarize the students with the constructional details and working principle of single phase transformers.
5. To familiarize the students with phase diagram and equivalent circuit of single phase transformer.
6. To familiarize the students with the Predetermination of regulation and efficiency of single phase transformer.

**Syllabus:**

Principle of operation of single phase transformer- Types - Constructional features - Emf equation of Transformer- Equivalent circuit of Single-Phase transformer- Losses & Efficiency- Regulation of Transformer.

**Learning Outcomes:**

After the completion of this unit, students will be to

6. Explain the various types of a single phase transformer.
7. Draw the equivalent circuit and phasor diagram of single phase transformer.
8. Explain the procedure to conduct OC and SC tests on single phase transformer.
9. Predetermine of efficiency and regulation of single phase transformer.

# Learning Material

## 2.1 Introduction

The transformer is probably one of the most useful electrical devices ever invented. It can change the magnitude of alternating voltage or current from one value to another. This useful property of transformer is mainly responsible for the widespread use of alternating currents rather than direct currents i.e., electric power is generated, transmitted and distributed in the form of alternating current. Transformers have no moving parts, rugged and durable in construction, thus requiring very little attention. They also have a very high efficiency—as high as 99%.

A transformer is a static piece of equipment used either for raising or lowering the voltage of an a.c. supply with a corresponding decrease or increase in current. It essentially consists of two windings, the primary and secondary, wound on a common laminated magnetic core as shown in Fig. (1). The winding connected to the a.c. source is called primary winding (or primary) and the one connected to load is called secondary winding (or secondary). The alternating voltage $V_1$ whose magnitude is to be changed is applied to the primary. Depending upon the number of turns of the primary ($N_1$) and secondary ($N_2$), an alternating e.m.f. $E_2$ is induced in the secondary. This induced e.m.f. $E_2$ in the secondary causes a secondary current $I_2$. Consequently, terminal voltage $V_2$ will appear across the load. If $V_2 > V_1$ , it is called a step up-transformer. On the other hand, if $V_2 < V_1$, it is called a step-down transformer.

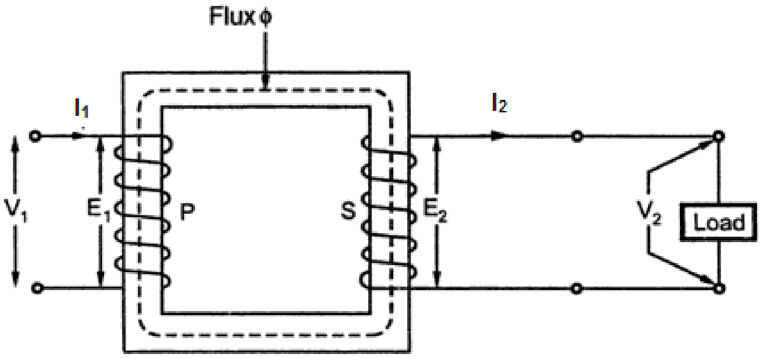


Figure 1

## 2.2 Working Principle of a Transformer

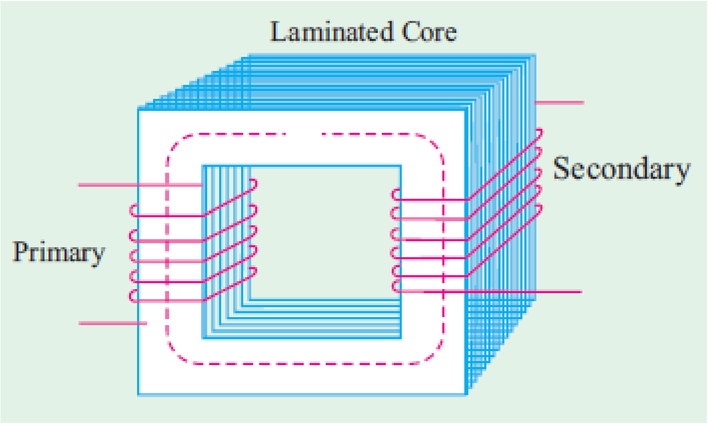


Figure 2

A transformer is a static (or stationary) piece of apparatus by means of which electric power in one circuit is transformed into electric power of the same frequency in another circuit. It can raise or lower the voltage in a circuit but with a corresponding decrease or increase in current. The physical basis of a transformer is **mutual induction** between two circuits linked by a common magnetic flux. In its simplest form, it consists of two inductive coils which are electrically separated but magnetically linked through a path of low reluctance as shown in Fig. 2. The two coils possess high mutual inductance. If one coil is connected to a source of alternating voltage, an alternating flux is set up in the laminated core, most of which is linked with the other coil in which it produces mutually-induced e.m.f. (according to Faraday's Laws of Electromagnetic Induction **e = MdI/dt**). If the second coil circuit is closed, a current flows in it and so electric energy is transferred (entirely magnetically) from the first coil to the second coil. The first coil, in which electric energy is fed from the a.c. supply mains, is called **primary** winding and the other from which energy is drawn out, is called **secondary** winding. In brief, a transformer is a device that

1. transfers electric power from one circuit to another
2. it does so without a change of frequency
3. it accomplishes this by electromagnetic induction and
4. where the two electric circuits are in mutual inductive influence of each other.

When an alternating voltage $V_1$ is applied to the primary, an alternating flux $\emptyset$ is set up in the core. This alternating flux links both the windings and induces e.m.f.s $E_1$ and $E_2$ in them according to Faraday's laws of electromagnetic induction. The e.m.f. $E_1$ is termed as primary e.m.f. and e.m.f. $E_2$ is termed as secondary e.m.f.

**The losses that occur in a transformer are:**

a) Core losses—eddy current and hysteresis losses
b) Copper losses—in the resistance of the windings

In practice, these losses are very small so that output power is nearly equal to the input primary power. In other words, a transformer has very high efficiency.

## (i) Transformer on DC

A transformer cannot be operate on dc supply and never be connected to a dc source. If a rated dc voltage is applied to the primary of a transformer, the flux produce in the transformer core will not vary but remain constant in magnitude and, therefore, no emf will be included in the secondary winding except at the moment of switching on. Thus the transformer is not capable of raising or lowering the dc voltage. Also there will be no self induced emf in the primary winding, which is only possible with varying flux linkage, to oppose the applied voltage and since the resistance of primary winding is quite low, therefore, a heavy current will flow through the primary winding which may result in the burning out of the primary winding. This is reason that dc is never applied to a transformer.

## 2.3 Transformer Construction

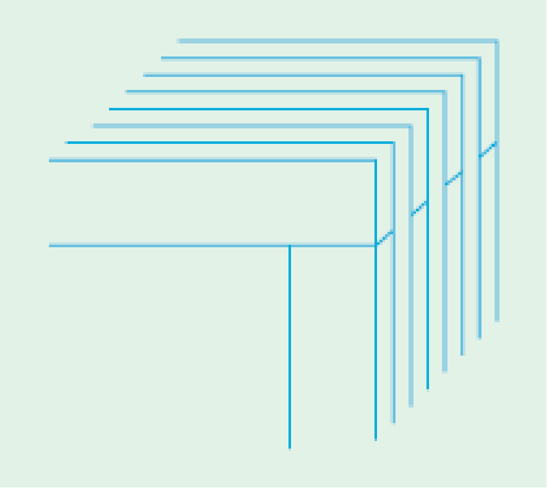


Figure 3

The simple elements of a transformer consist of two coils having mutual inductance and a laminated steel core. The two coils are insulated from each other and the steel core. Other necessary parts are: some suitable container for assembled core and windings; a suitable medium for insulating the core and its windings from its container; suitable bushings (either of porcelain, oil-filled or capacitor-type) for insulating and bringing out the terminals of windings from the tank. In all types of transformers, the core is constructed of transformer sheet steel laminations assembled to provide a continuous magnetic path with a minimum of air-gap included. The steel used is of high silicon content, sometimes heat treated to produce a high permeability and a low hysteresis loss at the usual operating flux densities. The eddy current loss is minimised by laminating the core, the laminations being insulated from each other by a light coat of core-plate varnish or by an oxide layer on the surface. The thickness of laminations varies from 0.35 mm for a frequency of 50 Hz to 0.5 mm for a frequency of 25 Hz. The core laminations (in the form of strips) are joined as shown in Fig. 5.2. It is seen that the joints in the alternate layers are staggered in order to avoid the presence of narrow gaps right through the cross-section of the core. Such staggered joints are said to be 'imbricated'.

## 2.4 Types of Transformers

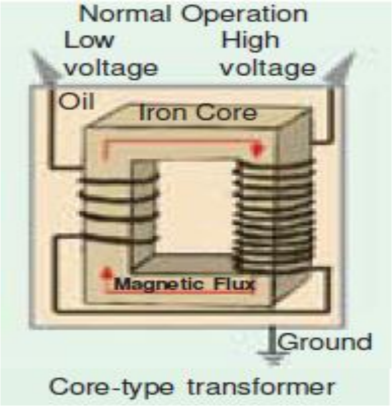


Figure 4

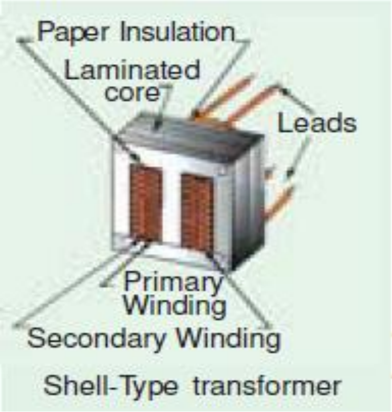


Figure 5

Constructionally, the transformers are of two general types, distinguished from each other merely by the manner in which the primary and secondary coils are placed around the laminated core. The two types are known as

(i) core-type and

(ii) shelltype.

(iii) Another recent development is spiral-core or wound-core type, the trade name being spirakore transformer.

In the so-called core type transformers, the windings surround a considerable part of the core whereas in shell-type transformers, the core surrounds a considerable portion of the windings as shown schematically in Fig. 6.(a) and (b) respectively.

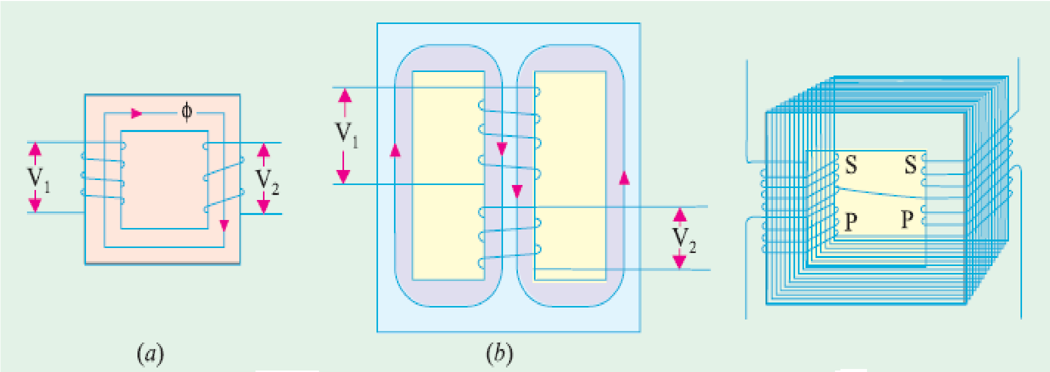


Figure 6

In the simplified diagram for the core type transformers [Fig. 5.4 (*a*)], the primary and secondary winding are shown located on the opposite legs (or limbs) of the core, but in actual construction, these are always interleaved to reduce leakage flux. As shown in Fig. 5.5, half the primary and half the secondary winding have been placed side by side or concentrically on each limb, not primary on one limb (or leg) and the secondary on the other.

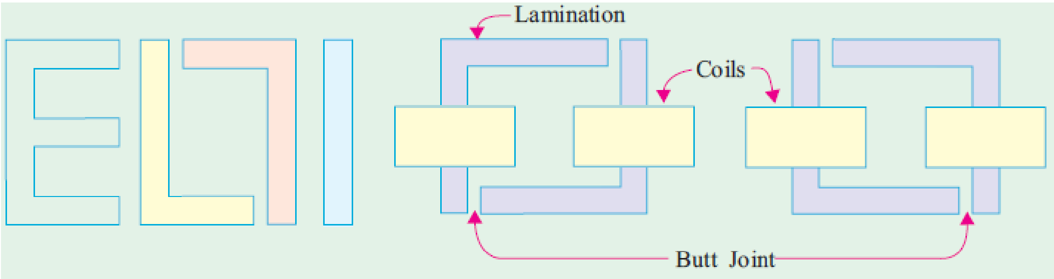


Figure 7

In both core and shell-type transformers, the individual laminations are cut in the form of long strips of L's, E's and I's as shown in Fig. 6. The assembly of the complete core for the two types of transformers is shown in Fig.7 and Fig. 8.

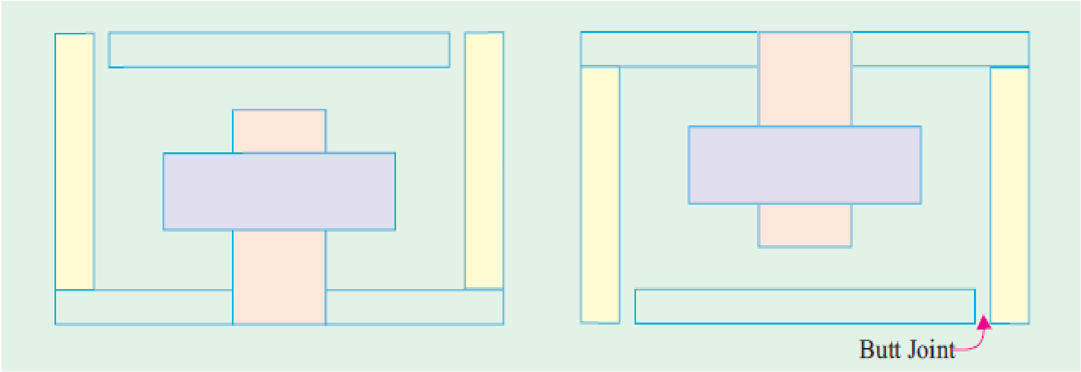


Figure 8

As said above, in order to avoid high reluctance at the joints where the laminations are butted against each other, the alternate layers are stacked differently to eliminate these joints as shown in Fig

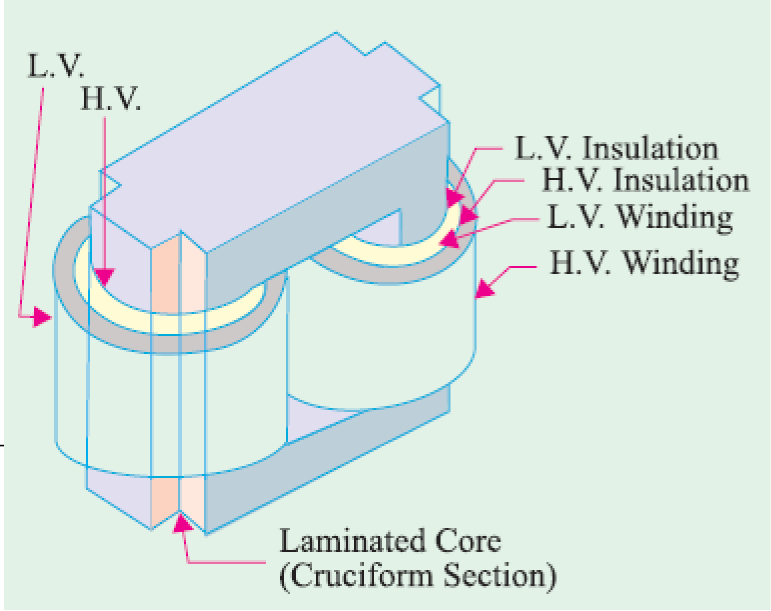
## (i) Core-type Transformers

Figure 9

The coils used are form-wound and are of the cylindrical type. The general form of these coils may be circular or oval or rectangular. In small size core-type transformers, a simple rectangular core is used with cylindrical coils which are either circular or rectangular in form. But for large-size core-type transformers, round or circular cylindrical coils are used which are so wound as to fit over a cruciform core section as shown in Fig. 5.9(a). The circular cylindrical coils are used in most of the core-type transformers because of their mechanical strength. Such cylindrical coils are wound in helical layers with the different layers insulated from each other by paper, cloth, micarta board or cooling ducts.

Fig. 9(c) shows the general arrangement of these coils with respect to the core. Insulating cylinders of fuller board are used to separate the cylindrical windings from the core and from each other. Since the low voltage (LV) winding is easiest to insulate, it is placed nearest to the core (Fig. 5.9).

Because of laminations and insulation, the net or effective core area is reduced, due allowance



for which has to be made (Ex. 5.7). It is found that, in general, the reduction in core sectional area due to the presence of paper, surface oxide etc. is of the order of 10% approximately.

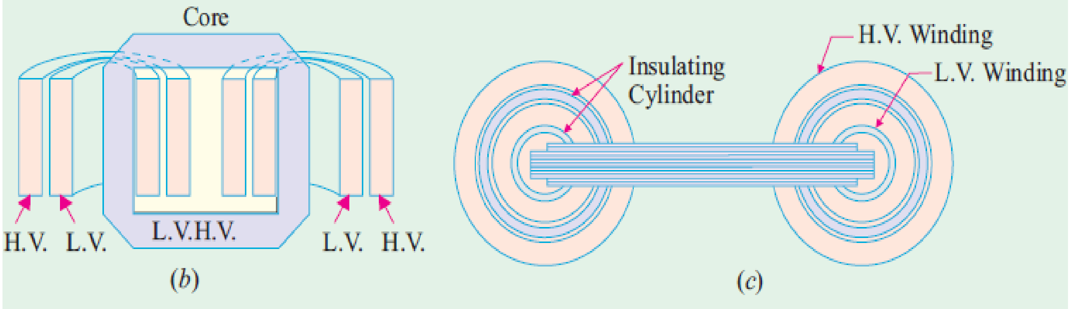


Figure 10

As pointed out above, rectangular cores with rectangular cylindrical coils can be used for small-size core-type transformers as shown in Fig. 10 (a) but for large-sized transformers, it becomes wasteful to use rectangular cylindrical coils and so circular cylindrical coils are preferred. For such purposes, square cores may be used as shown in Fig. 5.10 (b) where circles represent the tubular former carrying the coils. Obviously, a considerable amount of useful space is still wasted.

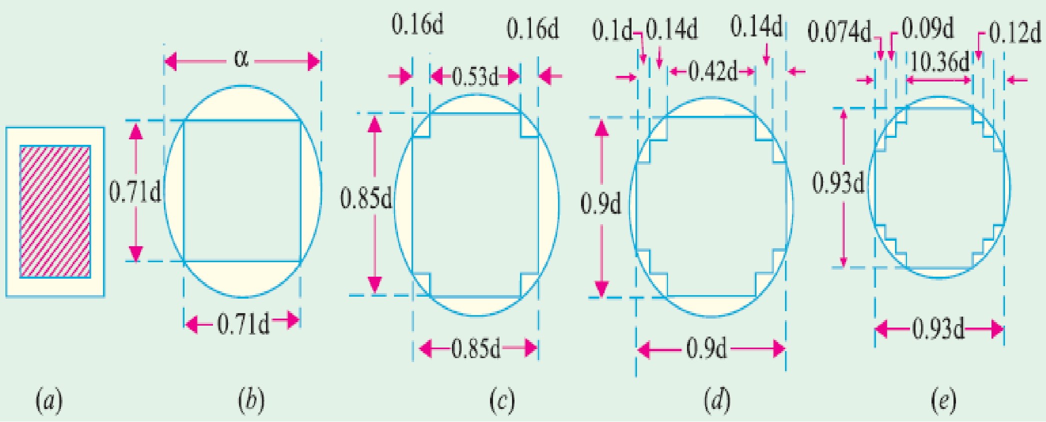


Figure 11

A common improvement on square core is to employ cruciform core as in Fig.11 (c) which demands, at least, two sizes of core strips. For very large transformers, further core-stepping is done as in Fig. 11 (d) where at least three sizes of core plates are necessary. Core-stepping not only gives high space factor but also results in reduced length of the mean turn and the consequent $I^2R$ loss. Three stepped core is the one most commonly used although more steps may be used for very large transformers as in Fig. 5.10 (e). From the geometry of Fig. 5.10, it can be shown that maximum gross core section for Fig. 5.10 (b) is 0.5 d2 and for Fig. 5.10 (c) it is 0.616 d2 where d is the diameter of the cylindrical coil.

### (ii) Shell-type Transformers

In these case also, the coils are form-would but are multi-layer disc type usually wound in the form of pancakes. The different layers of such multi-layer discs are insulated from each other by paper. The complete winding consists of stacked discs with insulation space between the coils–the spaces forming horizontal cooling and insulating ducts. A shell-type transformer may have a simple rectangular form as shown in Fig.11 or it may have distributed form as shown in Fig.12.

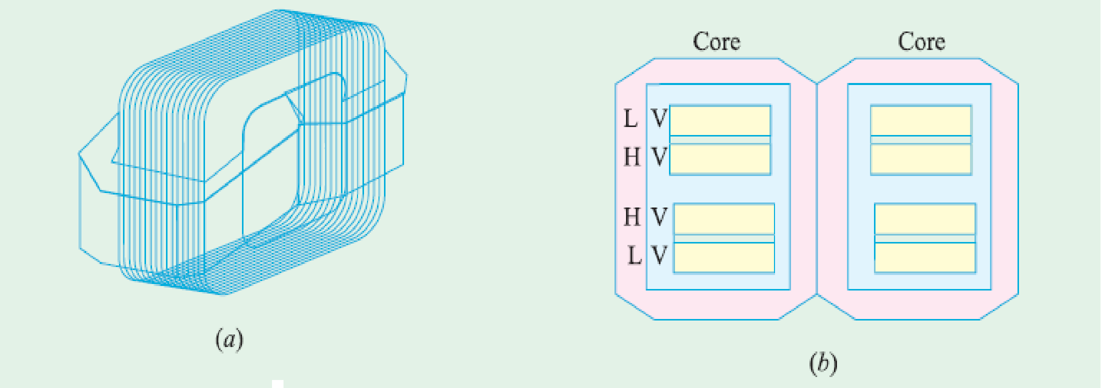


Figure 12

A very commonly-used shell-type transformer is the one known as Berry Transformer–so called after the name of its designer and is cylindrical in form. The transformer core consists of laminations arranged in groups which radiate out from the centre as shown in section in Fig. 5.13.

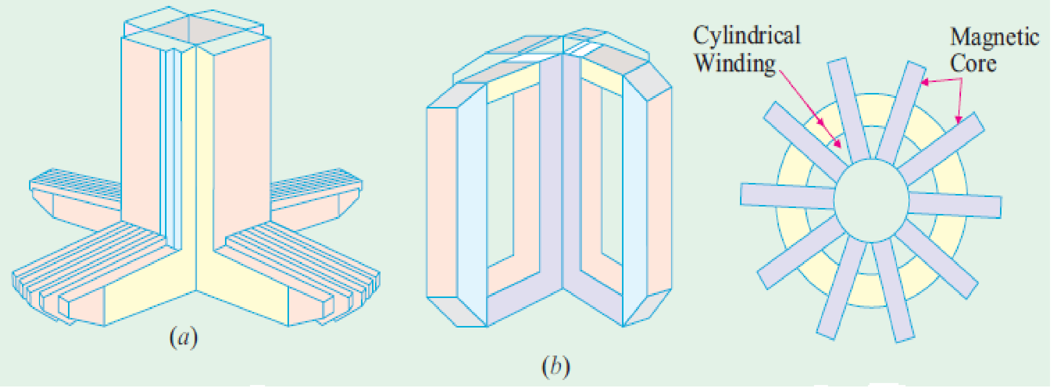


Figure 13

It may be pointed out that cores and coils of transformers must be provided with rigid mechanical bracing in order to prevent movement and possible insulation damage. Good bracing reduces vibration and the objectionable noise–a humming sound–during operation.

The spiral-core transformer employs the newest development in core construction. The core is assembled of a continuous strip or ribbon of transformer steel wound in the form of a circular or elliptical cylinder. Such construction allows the core flux to follow the grain of the iron. Cold-rolled steel of high silicon content enables the designer to use considerably higher operating flux densities with lower loss per kg. The use of higher flux density reduces the weight per kVA. Hence, the advantages of such construction are

i. a relatively more rigid core
ii. lesser weight and size per kVA rating
iii. lower iron losses at higher operating flux densities and
iv. Lower cost of manufacture.

Transformers are generally housed in tightly-fitted sheet-metal; tanks filled with special insulating oil*. This oil has been highly developed and its function is two-fold. By circulation, it not only keeps the coils reasonably cool, but also provides the transformer with additional insulation not obtainable when the transformer is left in the air.

In cases where a smooth tank surface does not provide sufficient cooling area, the sides of the tank are corrugated or provided with radiators mounted on the sides. Good transformer oil should be absolutely free from alkalies, sulphur and particularly from moisture. The presence of even an extremely small percentage of moisture in the oil is highly detrimental from the insulation viewpoint because it lowers the dielectric strength of the oil considerably. The importance of avoiding moisture in the transformer oil is clear from the fact that even an addition of 8 parts of water in 1,000,000 reduces the insulating quality of the oil to a value generally recognized as below standard. Hence, the tanks are sealed air-tight in smaller units. In the case of large-sized transformers where complete air-tight construction is impossible, chambers known as **breathers** are provided to permit the oil inside the tank to expand and contract as its temperature increases or decreases. The atmospheric moisture is entrapped in these breathers and is not allowed to pass on to the oil. Another thing to avoid in the oil is sledging which is simply the decomposition of oil with long and continued use. Sledging is caused principally by exposure to oxygen during heating and results in the formation of large deposits of dark and heavy matter that eventually clogs the cooling ducts in the transformer.

No other feature in the construction of a transformer is given more attention and care than the insulating materials, because the life on the unit almost solely depends on the quality, durability and handling of these materials. All the insulating materials are selected on the basis of their high quality and ability to preserve high quality even after many years of normal use.

All the transformer leads are brought out of their cases through suitable bushings. There are many designs of these, their size and construction depending on the voltage of the leads. For moderate voltages, porcelain bushings are used to insulate the leads as they come out through the tank. In general, they look almost like the insulators used on the transmission lines. In high voltage installations, oil-filled or capacitor type bushings are employed.

The choice of core or shell-type construction is usually determined by cost, because similar characteristics can be obtained with both types. For very high-voltage transformers or for multi winding design, shell type construction is preferred by many manufacturers. In this type, usually the mean length of coil turn is longer than in a comparable core-type design. Both core and shell forms are used and the selection is decided by many factors such as voltage rating, kVA rating, weight, insulation stress, heat distribution etc.

## 2.5 Concept of ideal transformer

An ideal transformer is one which has

1. Its windings have no ohmic resistance and hence which has no $I^2R$ losses.
2. There is no magnetic leakage and hence which has no core losses. In other words, an ideal transformer consists of two purely inductive coils wound on a loss-free core (or Leakage flux is zero i.e. 100% flux produced by primary links with the secondary).
3. Permeability of core is so high that negligible current is required to establish the flux in it.

Although ideal transformer cannot be physically realized, yet its study provides a very powerful tool in the analysis of a practical transformer. In fact, practical transformers have properties that approach very close to an ideal transformer.

## 2.6 E.M.F. Equation of a Transformer

Let $N_1 = \text{No. of turns in primary}$

$N_2 = \text{No. of turns in secondary}$

$\emptyset m = \text{Maximum flux in core in webers}$

$= B_m \times A$

$f = \text{Frequency of a.c. input in Hz}$

As shown in Fig. 5.14, flux increases from its zero value to maximum value $\emptyset m$ in one quarter of the cycle i.e. in $1/4$ f second.

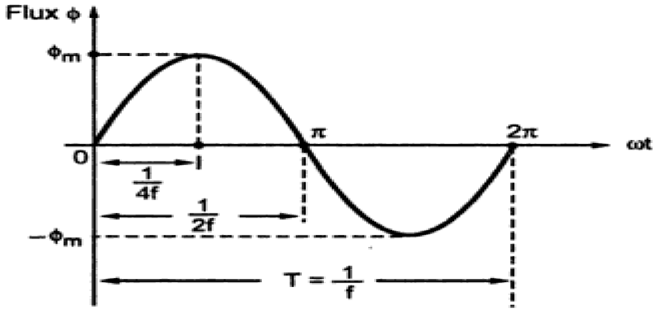


Fig 5.14

$$\therefore \text{ Average rate of change of flux } = \frac{\emptyset m}{1/4f}$$

$$= 4\,f\,\emptyset m \text{ Wb/s or volt}$$

Now, rate of change of flux per turn means induced e.m.f. in volts.

$$\therefore \text{ Average e.m.f./turn } = 4\,f\,\emptyset m \text{ volt}$$

If flux Φ varies sinusoidally, then r.m.s. value of induced e.m.f. is obtained by multiplying the average value with form factor.

$$\text{Form factor } = \frac{\text{r.m.s value}}{\text{average value}} = 1.11$$

$$\therefore \text{ r.m.s. value of e.m.f./ turn} = 1.11 \times 4\,f\,\emptyset m = 4.44\,f\,\emptyset m \text{ volt}$$

Now,

r.m.s. value of the induced e.m.f. in the whole of primary winding = (induced e.m.f/turn) × No. of primary turns

$$E1 = 4.44\,f\,N_1\,\emptyset m = 4.44\,f\,N_1\,B_m A \qquad (1)$$

Similarly, r.m.s. value of the e.m.f. induced in secondary is,

$$E2 = 4.44\, f\, N_2\, \emptyset m = 4.44\, f\, N_2\, B_m A \qquad (2)$$

It is seen from (5.1) and (5.2) that

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44\, f\, \emptyset m$$

It means that e.m.f./turn is the same in both the primary and secondary windings.

In an ideal transformer on no-load, $V_1 = E_1$ and $V_2 = E_2$, where $V_2$ is the terminal voltage.

## Voltage Transformation Ratio (K)

From equations (1) and (2), we get

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = K$$

This constant K is known as voltage transformation ratio.

i. If $N_2 > N_1$ i.e. K > 1, then transformer is called **step-up** transformer.

ii. If $N_2 < N_1$ i.e. K < 1, then transformer is known as **step-down** transformer.

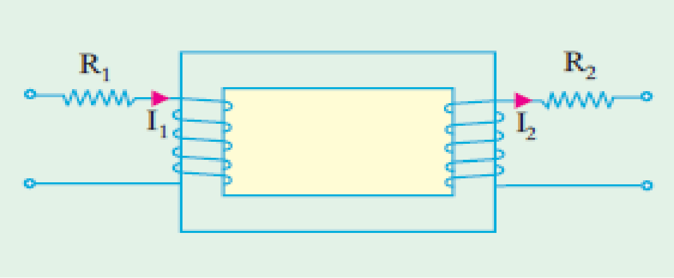
Again, for an ideal transformer, input VA = output VA.

$$V_1 I_1 = V_2 I_2$$

$$\frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{1}{K}$$

Hence, currents are in the inverse ratio of the (voltage) transformation ratio.

## 2.7 Equivalent Resistance



In Fig. 5.19 a transformer is shown whose primary and secondary windings have resistances of $R_1$ and $R_2$ respectively. The resistances have been shown external to the windings. It would now be shown that the resistances of the two windings can be transferred to any one of the two windings.

The advantage of concentrating both the resistances in one winding is that it makes calculations very simple and easy because one has then to work in one winding only. It will be proved that a resistance of $R_2$ in secondary is equivalent to $\frac{R_2}{K^2}$ in primary. The value $\frac{R_2}{K^2}$ will be denoted by $R_2'$ – **the equivalent secondary resistance as referred to primary**.

The copper loss in secondary is $I_2{}^2R_2$. This loss is supplied by primary which takes a current of $I_1$. Hence if $R_2{}'$ is the **equivalent resistance in primary which would have caused the same loss** as $R_2$ in secondary, then

$$I_1{}^2R_2{}' = I_2{}^2R_2$$

$$R_2{}' = \frac{I_2{}^2}{I_1{}^2}R_2 = \frac{R_2}{K^2}$$

$$R_2{}' = \frac{R_2}{K^2}$$

Similarly, equivalent primary resistance as referred to secondary is

$$R_1{}' = K^2R_1$$

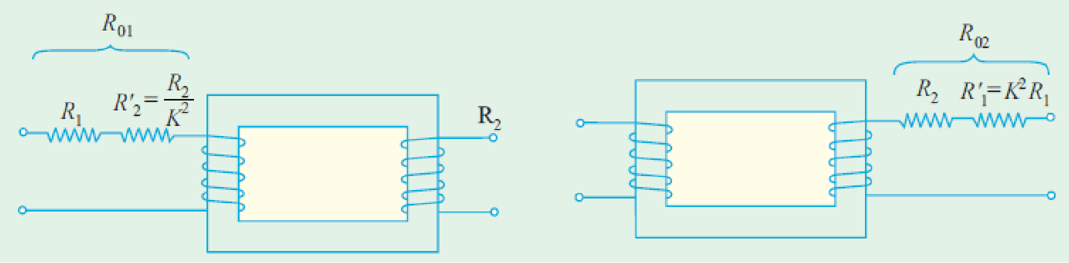
In Fig. 5.20, secondary resistance has been transferred to primary side leaving secondary circuit resistance less. The resistance $R_1 + R_2{}' = R_1 + \frac{R_2}{K^2}$ is known as the **equivalent or effective resistance of the transformer as referred to primary** and may be designated as $R_{01}$.

$$\therefore R_{01} = R_1 + R_2{}' = R_1 + \frac{R_2}{K^2}$$

Similarly, the **equivalent resistance of the transformer as referred to secondary is**

$$\therefore R_{02} = R_2 + R_1{}' = R_2 + K^2R_1$$

This fact is shown in Fig. 5.21 where all the resistances of the transformer has been concentrated in the secondary winding.



It is to be noted that

1. A resistance of $R_1$ in primary is equivalent to $K^2R_1$ in secondary. Hence, it is called **equivalent resistance as referred to secondary** i.e. $R_1{}'$.
2. A resistance of $R_2$in secondary is equivalent to $\frac{R_2}{K^2}$ in primary. Hence, it is called the **equivalent secondary resistance as referred to primary** i.e. $R_2{}'$.
3. Total or effective resistance of the transformer as referred to primary is

$$R_{01} = \text{primary resistance} + \text{equivalent secondary resistance as referred to primary}$$

$$R_{01} = R_1 + R_2{}' = R_1 + \frac{R_2}{K^2}$$

4. Similarly, total transformer resistance as referred to secondary is,

$$R_{02} = \text{secondary resistance} + \text{equivalent primary resistance as referred to secondary}$$

$$R_{02} = R_2 + R_1{}' = R_2 + K^2 R_1$$

**Note:** It is important to remember that

a. When shifting any primary resistance to the secondary, **multiply** it by $K^2$ i.e. $(\text{transformation ratio})^2$.

b. When shifting secondary resistance to the primary, **divide** it by $K^2$.

c. However, when shifting any voltage from one winding to another only K is used.

## (i) Magnetic Leakage

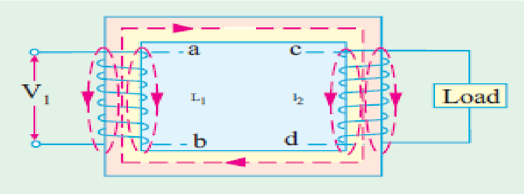
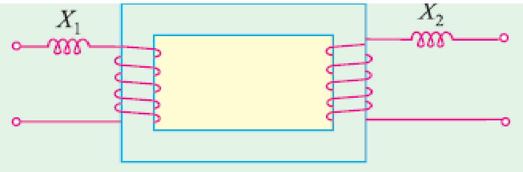


Fig 5.22



In the preceding discussion, it has been assumed that all the flux linked with primary winding also links the secondary winding. But, in practice, it is impossible to realize this condition. It is found, however, that all the flux linked with primary does not link the secondary but part of it i.e. $\emptyset_{L_1}$ completes its 1magnetic circuit by passing through air rather than around the core, as shown in Fig. 5.22. This leakage flux is produced when the m.m.f. due to primary ampere-turns existing between points a and b, acts along the leakage paths.

Hence, this flux is known as **primary leakage flux** and is proportional to the primary ampere-turns alone because the secondary turns do not link the magnetic circuit of $\emptyset_{L_1}$ The flux $\emptyset_{L_1}$ is in time phase with $I_1$. It induces an e.m.f. $E_{L_1}$ in primary but not in secondary.

Similarly, secondary ampere-turns (or m.m.f.) acting across points c and d set up leakage flux $\emptyset_{L_2}$, which is linked with secondary winding alone (and not with primary turns). This flux $\emptyset_{L_2}$ is in time phase with $I_2$ and produces a self-induced e.m.f. $E_{L_2}$ in secondary (but not in primary).

At no load and light loads, the primary and secondary ampere-turns are small, hence leakage fluxes are negligible. But when load is increased, both primary and secondary windings carry huge currents. Hence, large m.m.f.'s are set up which, while acting on leakage paths, increase the leakage flux.

As said earlier, the leakage flux linking with each winding produces a self-induced e.m.f. in that winding. Hence, in effect, it is equivalent to a small choker or inductive coil in series with each winding such that voltage drops in each series coil is equal to that produced by leakage flux. In other words, **a transformer with magnetic leakage is equivalent to an ideal transformer with inductive coils connected in both primary and secondary circuits** as shown in Fig. 5.23 such that the internal e.m.f. in each inductive coil is equal to that due to the corresponding leakage flux in the actual transformer.

$$X_1 = \frac{E_{L1}}{I_1} = \frac{2\pi f L_1 I_1}{I_1} = 2\pi f L_1$$

$$X_2 = \frac{E_{L2}}{I_2} = \frac{2\pi f L_2 I_2}{I_2} = 2\pi f L_2$$

The terms $X_1$ and $X_2$ are known as primary and secondary leakage reactance's respectively.

Following few points should be kept in mind:

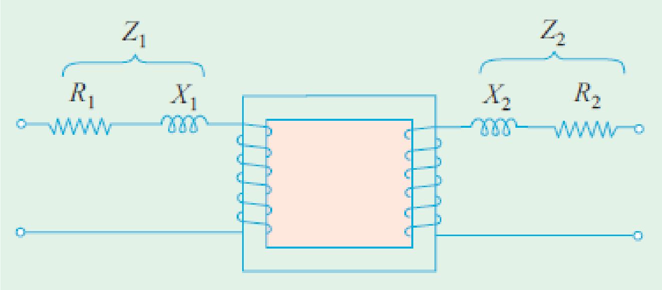
1. The leakage flux links one or the other winding but **not both**, hence it in no way contributes to the transfer of energy from the primary to the secondary winding.
2. The primary voltage $V_1$ will have to supply reactive drop $I_1X_1$ in addition to $I_1R_1$. Similarly $E_2$ will have to supply $I_2R_2$ and $I_2X_2$.
3. In an actual transformer, the primary and secondary windings are not placed on separate legs or limbs as shown in Fig. 5.23 because due to their being widely separated, large primary and secondary leakage fluxes would result. These leakage fluxes are minimized by sectionalizing and interleaving the primary and secondary windings as in Fig. 5.22 or Fig. 5.24.

## 2.8 Transformer with Resistance and Leakage Reactance

In Fig. 5.24 the primary and secondary windings of a transformer with reactances taken out of the windings are shown. The primary impedance is given by

$$Z_1 = \sqrt{R_1{}^2 + X_1{}^2}$$

Similarly, secondary impedance is given by



$$Z_2 = \sqrt{{R_2}^2 + {X_2}^2}$$

The resistance and leakage reactance of each winding is responsible for some voltage drop in each winding. In primary, the leakage reactance drop is $I_1X_1$ (usually 1 or 2% of $V_1$).

Hence

$$V_1 = -E_1 + I_1(R_1 + jX_1)$$

Similarly, there are $I_2R_2$ and $I_2X_2$ drops in secondary which combine with $V_2$ to give $E_2$.

$$E_2 = V_2 + I_2(R_2 + jX_2)$$

The vector diagram for such a transformer for different kinds of loads is shown in Fig. 5.25. In these diagrams, vectors for resistive drops are drawn parallel to current vectors whereas reactive drops are perpendicular to the current vectors. The angle $\phi_1$ between $V_1$ and $I_1$ gives the power factor angle of the transformer.

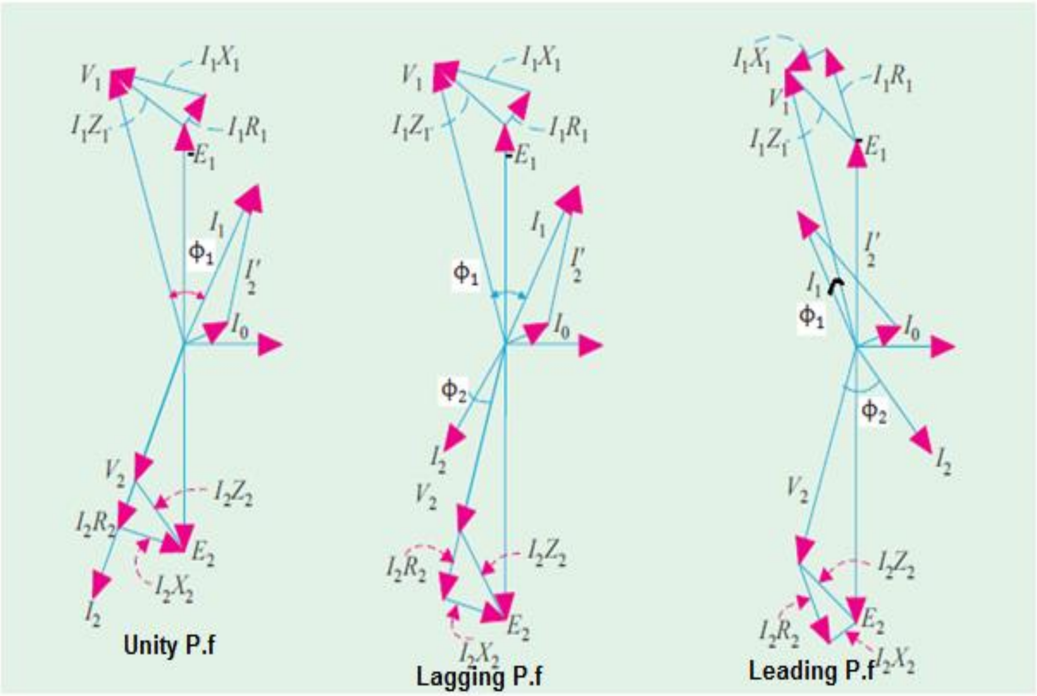
It may be noted that leakage reactances can also be transferred from one winding to the other in the same way as resistance.

$$X_2' = {}^{X_2}/_{K^2}$$

$$X_1' = K^2X_1$$

$$X_{01} = X_1 + X_2' = X_1 + \frac{X_2}{K^2}$$

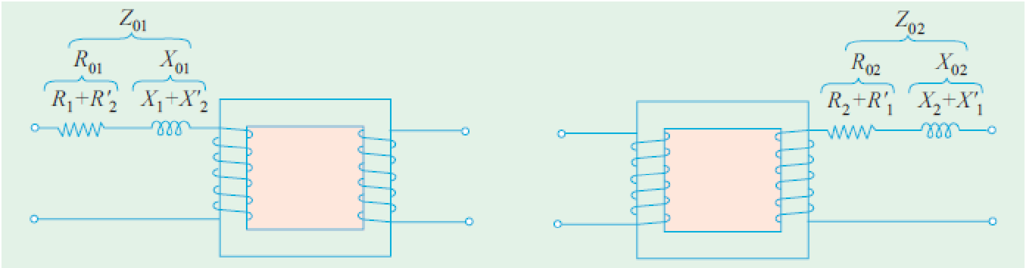
$$X_{02} = X_2 + X_1' = X_2 + K^2X_1$$



Unity P.f

Lagging P.f

Leading P.f



It is obvious that total impedance of the transformer as referred to primary is given by

$$Z_{01} = \sqrt{R_{01}{}^2 + X_{01}{}^2}$$

Similarly, total impedance of the transformer as referred to secondary is given by

$$Z_{02} = \sqrt{R_{02}{}^2 + X_{02}{}^2}$$

## 2.9 Equivalent circuit of a Transformer

The equivalent circuit of any device can be quite helpful in predetermination of the behavior of the device under various conditions of operation and it can be drawn if the equations describing its behavior are known. If any electrical device is to be analysed and investigated further for suitable modifications, its appropriate equivalent circuit is necessary.

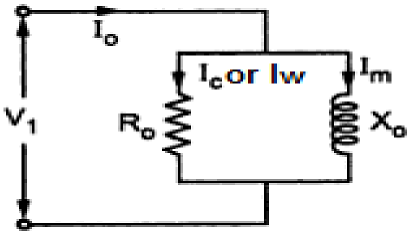


Fig 5.31 No load equivalent circuit

Fig 5.31 shows the equivalent circuit of transformer on No-Load condition. We already known that transformer on No-Load primary current $I_0$ has two components

$$I_W = I_0 \cos\phi_0 = \textbf{active} \text{ or } \textbf{working} \text{ or } \textbf{iron} \text{ loss component}$$

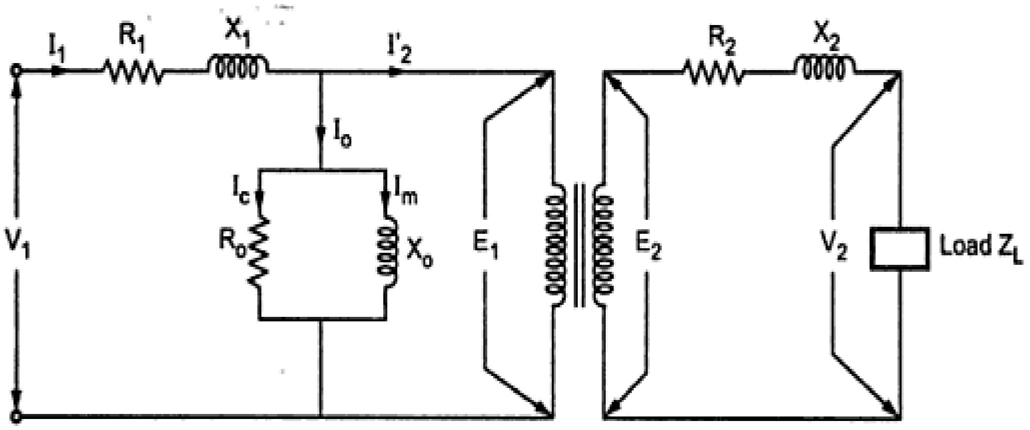
$$I_m = I_0 \sin\phi_0 = \textbf{magnetising} \text{ component}$$

From equivalent circuit we can write,

$$R_o = \frac{V_1}{I_w}$$

$$X_o = \frac{V_1}{I_m}$$

When the load is connected to the transformer then secondary current $I_2$ flows and operation we already discussed. So the equivalent circuit of transformer on loaded condition is given in fig 5.32.



It can be further simplified by transforming all the values to primary or secondary. Fig 5.33 shows the exact equivalent circuit of a transformer referred to primary by using transformation resistances and reactances as already discussed in previous topics.

Transforming secondary parameters to primary as follows,

$$K = \frac{N_2}{N_1}$$

$$R_2' = \frac{R_2}{K^2}$$

$$Z_2' = \frac{Z_2}{K^2}$$

$$X_2' = {}^{X_2}\!/_{K^2}$$

$$I_2' = KI_2$$

$$E_2' = \frac{E_2}{K}$$

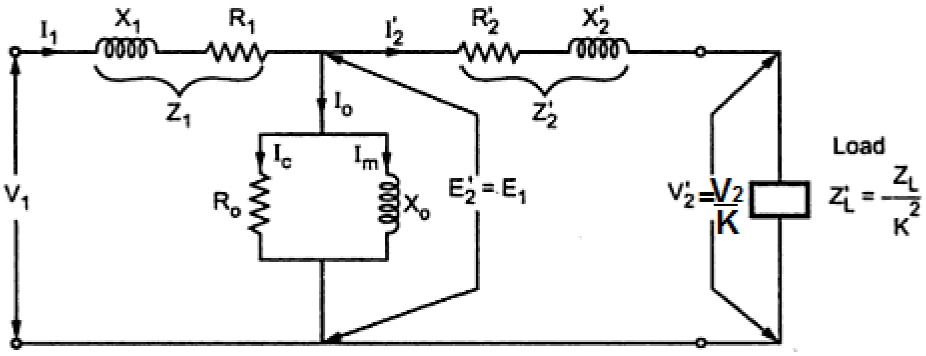


Fig 5.33 Exact equivalent circuit referred to primary

Fig 5.33 shows the exact equivalent circuit of a transformer referred to secondary

Transforming primary parameters to secondary as follows,

$$R_1{}' = K^2R_1$$

$$X_1{}' = K^2X_1$$

$$E_1{}' = KE_1$$

$$Z_1{}' = K^2Z_1$$

$$I_1{}' = \frac{I_1}{K}$$

$$I_0{}' = \frac{I_0}{K}$$

$$R_0{}' = K^2R_0$$

$$X_0{}' = K^2X_0$$

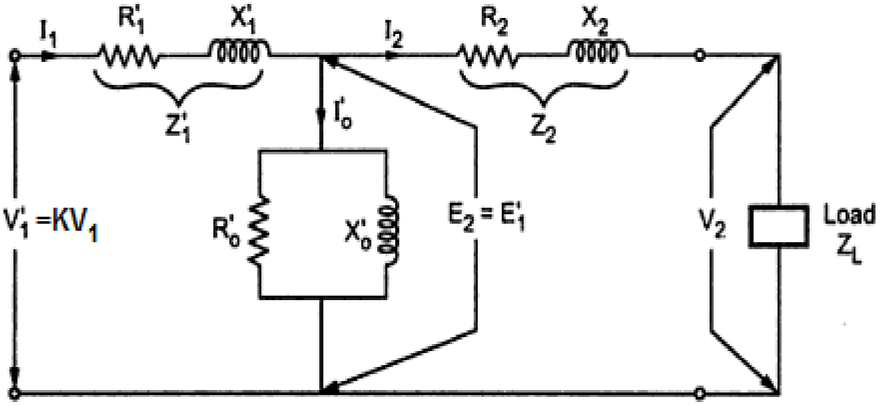


Fig 5.34 Exact equivalent circuit of transformer referred to secondary

## (I) Approximate equivalent circuit

The equivalent circuit is further simplified by transferring $R_0$ and $X_0$ towards left end as shown in fig 5.35. The error introduced by doing do is very small and it is neglected. Hence such an equivalent circuit is called **approximate equivalent circuit.**

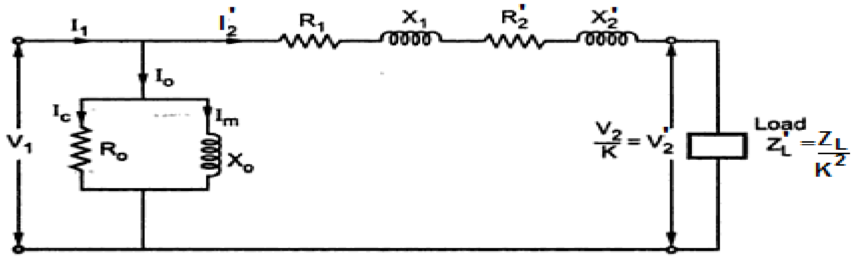
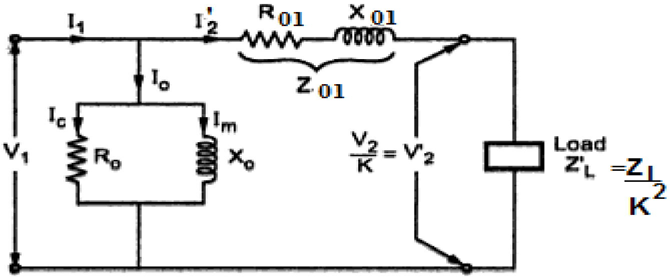


Fig 5.35 Approximate euivalent circuit of a transformer referred to primary



$$R_{01} = R_1 + R_2' = R_1 + \frac{R_2}{K^2}$$

$$X_{01} = X_1 + X_2' = X_1 + \frac{X_2}{K^2}$$

$$Z_{01} = R_{01} + jX_{01}$$

## (II) Total Approximate Voltage Drop in a Transformer

Consider the equivalent circuit referred to secondary as shown in fig 5.37.

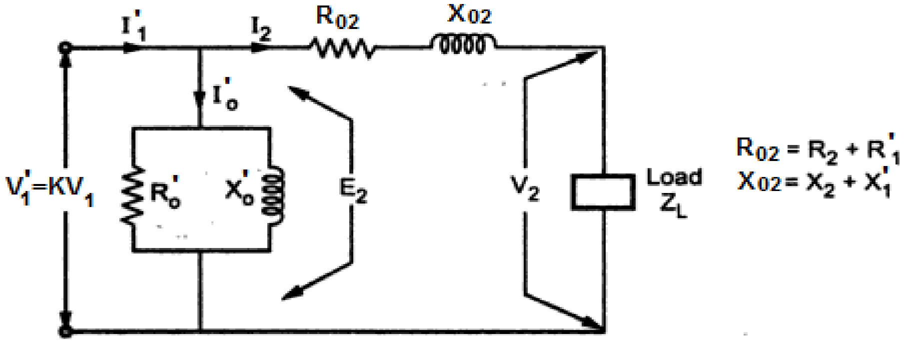
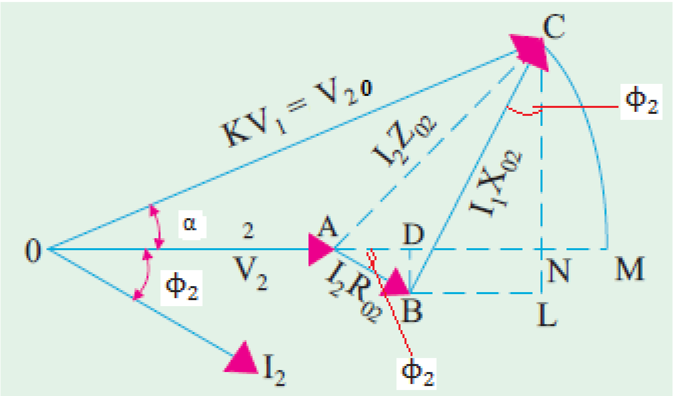


Fig 5.37 Approximate euivalent circuit of a transformer referred to secondary

When the transformer is on no-load, and then $V_1$ is approximately equal to E1. Hence $E_2 = KE_1 = KV_1$. Also, $E_2 = V_{20}$ where $V_{20}$ is secondary terminal voltage on **no load**, hence no-load



secondary terminal voltage is $KV_1$. The secondary voltage on load is $V_2$. The difference between the two is $I_2Z_{02}$ as shown in Fig. 5.38. The approximate voltage drop of the transformer **as referred to secondary** is found from phasor diagram 5.38.

$$V_{20} = \text{No load terminal voltage}$$

$$V_2 = \text{Terminal voltage on load}$$

With O as the centre and radius OC draw an arc cutting OA produced at M. The total voltage drop $I_2Z_{02} = AC = AM$, which is approximately equal to AN. From B draw BD perpendicular on OA produced. Draw CN perpendicular to OM and draw BL parallel to OM.

$$AN = \text{Approximate voltage drop}$$

$$AM = \text{Exact voltage drop}$$

$$\text{Approximate voltage drop} = AN$$

$$= AD + DN$$

$$= AB\cos\phi_2 + BL$$

$$= AB\cos\phi_2 + BC\sin\phi_2$$

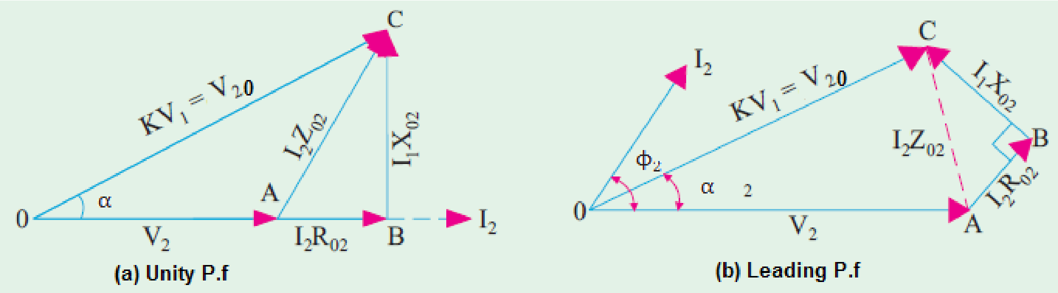
$$= I_2R_{02}\cos\phi_2 + I_2X_{02}\sin\phi_2$$

$$\text{Approximately } \phi_2 = \phi_1 = \phi$$

$$\text{Approximate voltage drop} = I_2R_{02}\cos\phi + I_2X_{02}\sin\phi$$

This is the value of approximate voltage drop for a **lagging** power factor.

The different figures for unity and leading power factors are shown in Fig. 5.39 (*a*) and (*b*) respectively.



(a) Unity P.f

(b) Leading P.f

The approximate voltage drop for **leading** power factor becomes

$$I_2R_{02}\cos\phi - I_2X_{02}\sin\phi$$

Approximate voltage drop=

$$= I_2R_{02}\cos\phi + I_2X_{02}\sin\phi \qquad \text{For lagging P.f}$$

$$= I_2R_{02}\cos\phi - I_2X_{02}\sin\phi \qquad \text{For leading P.f}$$

It may be noted that approximate voltage drop as referred to primary is

$$I_1R_{01}\cos\phi \pm I_1X_{01}\sin\phi$$

$$\%\ \text{Voltage drop in secondary} = \frac{I_2R_{02}\cos\phi \pm I_2X_{02}\sin\phi}{V_{20}} * 100$$

$$= \frac{I_2R_{02}}{V_{20}} * 100 * \cos\phi \pm \frac{I_2X_{02}}{V_{20}} * 100 * \sin\phi$$

$$= V_r * \cos\phi \pm V_x * \sin\phi$$

$$\boxed{\%\ \text{Voltage drop in secondary} = V_r * \cos\phi \pm V_x * \sin\phi}$$

$$V_r = \frac{I_2R_{02}}{V_{20}} * 100 = \text{Percentage resistive drop} = \frac{I_1R_{01}}{V_1} * 100$$

$$V_x = \frac{I_2X_{02}}{V_{20}} * 100 = \text{Percentage reactance drop} = \frac{I_1X_{01}}{V_1} * 100$$

### (III) Exact Voltage Drop

With reference to Fig. 5.38, it is to be noted that exact voltage drop is AM and not AN. If we add the quantity NM to AN, we will get the exact value of the voltage drop.

Considering the right-angled triangle OCN, we get

$$NC^2 = OC^2 - ON^2$$

$$= (OC + ON)(OC - ON)$$

$$= (OC + OC)(OM - ON) \quad (\because OC \approx ON)$$

$$= 2\ OC * NM$$

$$NM = \frac{NC^2}{2\ OC}$$

$$NC = LC - LN = LC - BD$$

$$NC = I_2X_{02}\cos\phi - I_2R_{02}\sin\phi$$

$$NM = \frac{(I_2X_{02}\cos\phi - I_2R_{02}\sin\phi)^2}{2V_{20}}$$

For a **lagging** power factor, exact voltage drop is =AM

$$AM = AN + NM$$

$$= I_2R_{02}\cos\phi + I_2X_{02}\sin\phi + \frac{(I_2X_{02}\cos\phi - I_2R_{02}\sin\phi)^2}{2V_{20}}$$

For a **leading** power factor, exact voltage drop is

$$= I_2R_{02}\cos\phi - I_2X_{02}\sin\phi + \frac{(I_2X_{02}\cos\phi + I_2R_{02}\sin\phi)^2}{2V_{20}}$$

$$\text{Exact Voltage drop} = I_2R_{02}\cos\phi \pm I_2X_{02}\sin\phi + \frac{(I_2X_{02}\cos\phi \mp I_2R_{02}\sin\phi)^2}{2V_{20}}$$

$$\text{Percentage voltage drop} = \frac{(I_2R_{02}\cos\phi \pm I_2X_{02}\sin\phi) * 100}{V_{20}} + \frac{(I_2X_{02}\cos\phi \mp I_2R_{02}\sin\phi)^2 * 100}{2{V_{20}}^2}$$

$$\text{Percentage voltage drop} = V_r\cos\phi \pm V_x\sin\phi + \frac{1}{200}(V_x\cos\phi \mp V_r\sin\phi)^2$$

$$\boxed{\text{Percentage voltage drop} = V_r\cos\phi \pm V_x\sin\phi + \frac{1}{200}(V_x\cos\phi \mp V_r\sin\phi)^2}$$

The upper signs are to be used for a **lagging** power factor and the lower ones for a **leading** power factor.

## 2.10 Voltage Regulation

### Introduction

The voltage regulation can be defined in two ways - Regulation Down and Regulation up. These two definitions differ only in the reference voltage.

### (i) Regulation down:

This is defined as "the change in terminal voltage when a load current at any power factor is applied, expressed as a fraction of the no-load terminal voltage".

Expressed in symbolic form we have,

$$\text{Regulation } = \frac{V_{nl} - V_l}{V_{nl}}$$

$V_{nl}$ and $V_l$ are no-load and load terminal voltages. This is the definition normally used in the case of the transformers, the no-load voltage being the one given by the power supply provider on which the user has no say. Hence no-load voltage is taken as the reference.

### (ii) Regulation up:

Here again the regulation is expressed as the ratio of the change in the terminal voltage when a load at a given power factor is thrown off, and the on load voltage. This definition if expressed in symbolic form results in

$$\text{Regulation } = \frac{V_{nl} - V_l}{V_l}$$

$V_{nl}$ is the no-load terminal voltage. $V_l$is load voltage. Normally full load regulation is of interest as the part load regulation is going to be lower. This definition is more commonly used in the case of alternators and power systems as the user-end voltage is guaranteed by the power supply provider. He has to generate proper no-load voltage at the generating station to provide the user the voltage he has asked for. In the expressions for the regulation, only the numerical differences of the voltages are taken and not vector differences.

In the case of transformers both definitions result in more or less the same value for the regulation as the transformer impedance is very low and the power factor of operation is quite high. The power factor of the load is defined with respect to the terminal voltage on load. Hence a convenient starting point is the load voltage. Also the full load output voltage is taken from the name plate. Hence regulation up has some advantage when it comes to its application.

### (iii) Voltage Regulation of a Transformer

The way in which the secondary terminal voltage varies with the load depends on the load current, the internal impedance and the load power factor. The change in secondary terminal voltage from no-load to full load is termed as inherent regulation. It is usually expressed as a percentage or a fraction of the rated no-load terminal voltage.

$$\text{percentage regulation} = \frac{\text{Terminal voltage on no load} - \text{terminal voltage on load}}{\text{Terminal voltage on no load}} * 100$$

$$= \frac{\text{Voltage drop in transformer at load}}{\text{No} - \text{load rated voltage (secondary)}} * 100$$

We already derived voltage drop in transformer at load. Here we take approximate voltage drop.

For lagging power factor

$$\%\ \text{regulation} = \frac{\mathrm{I_2R_{02}}\cos\phi + \mathrm{I_2X_{02}}\sin\phi}{\text{No} - \text{load rated voltage (secondary)}} * 100$$

For leading power factor

$$\%\ \text{regulation} = \frac{\mathrm{I_2R_{02}}\cos\phi - \mathrm{I_2X_{02}}\sin\phi}{\text{No} - \text{load rated voltage (secondary)}} * 100$$

Voltage regulation of a transformer on an average is about 4 percentage.

### (iv) Condition for zero Regulation

$$\%\ \text{regulation} = \frac{\mathrm{I_2R_{02}}\cos\phi + \mathrm{I_2X_{02}}\sin\phi}{\mathrm{E_2}} * 100$$

Regulation will be zero if the numerator will be equal to zero

$$\mathrm{I_2R_{02}}\cos\phi + \mathrm{I_2X_{02}}\sin\phi = 0$$

$$\tan\phi = \frac{-\mathrm{R_{02}}}{\mathrm{X_{02}}}$$

$$\boxed{\tan\phi = \frac{-\mathrm{R_{02}}}{\mathrm{X_{02}}}}$$

The -ve sign indicates that zero re g power factor.

### (v) Condition for Maximum Regulation

Regulation will be maximum if $\frac{d}{d\phi}(\text{regulation}) = 0$

$$\frac{d}{d\phi}\left(\frac{\mathrm{I_2R_{02}}\cos\phi + \mathrm{I_2X_{02}}\sin\phi}{\mathrm{E_2}}\right) = 0$$

$$-\frac{I_2 R_{02}}{E_2}\sin\phi + \frac{I_2 X_{02}}{E_2}\cos\phi = 0$$

$$\tan\phi = \frac{X_{02}}{R_{02}}$$

$$\boxed{\tan\phi = \frac{X_{02}}{R_{02}}}$$

Maximum regulation will occur at lagging power factor.

## 2.11 Losses

There are two types of power losses occur in a transformer

1. Iron loss
2. Copper loss

1. **Iron Loss:**

   This is the power loss that occurs in the iron part. This loss is due to the alternating frequency of the emf. Iron loss in further classified into two other losses.

   i. Eddy current loss
   ii. Hysteresis loss

   i. **Eddy current loss:** This power loss is due to the alternating flux linking the core, which will induced an emf in the core called the eddy emf, due to which a current called the eddy current is being circulated in the core. As there is some resistance in the core with this eddy current circulation converts into heat called the eddy current power loss. Eddy current loss is proportional to the square of the supply frequency.

$$\text{Eddy current loss} = K_e {B_m}^2 f^2 t^2 \text{ watts/unit volume}$$

$$\boxed{\text{Eddy current loss} = K_e {B_m}^2 f^2 t^2 \text{ watts/unit volume}}$$

Where, $K_e$ = Eddy current constant

$B_m$ = Maximum flux density

$f$ = frequency

$t$ = thickness of the core

   ii. **Hysteresis loss:** This is the loss in the iron core, due to the magnetic reversal of the flux in the core, which results in the form of heat in the core. This loss is directly proportional to the supply frequency.

$$\text{Hysteresis loss} = K_h B_m^{1.67} f\, v \text{ watts}$$

$$\boxed{\text{Hysteresis loss} = K_h B_m^{1.67} f\, v \text{ watts}}$$

Where, $K_h$ = Hysteresis constant

$v$ = Volume of the core

Eddy current loss can be minimized by using the core made of thin sheets of silicon steel material, and each lamination is coated with varnish insulation to suppress the path of the eddy currents.

Hysteresis loss can be minimized by using the core material having high permeability.

2. **Copper loss:**

This is the power loss that occurs in the primary and secondary coils when the transformer is on load. This power is wasted in the form of heat due to the resistance of the coils. This loss is proportional to the sequence of the load hence it is called the Variable loss where as the Iron loss is called as the Constant loss as the supply voltage and frequency are constants.

$$\begin{aligned}\text{Total copper loss} &= {I_1}^2 R_1 + {I_2}^2 R_2 \\ &= {I_1}^2 (R_1 + {R_2}') \\ &= {I_2}^2 ({R_1}' + R_2)\end{aligned}$$

As **voltage is constant** copper losses are proportional to the square of kVA rating of transformer.

$$P_{cu} \propto I^2 \propto (kVA)^2$$

Thus for transformer

$$\begin{aligned}\text{Total losses} &= \text{Iron losses} + \text{Copper losses} \\ &= P_i + P_{cu}\end{aligned}$$

**Volt-Ampere rating (or) Why rating of Transformer in kVA**

It is seen that iron losses depend on the supply voltage while the copper losses depend on the current. The losses are not depending on the phase angle between voltage and current. Hence the rating of transformer is expressed as a product of voltage current and called VA rating of transformer. It is not expressed in watts or kilo watts. Most of the times, rating is expressed in kVA.

## 2.12 Effect of variations of frequency and supply voltage on Iron losses

The iron losses of the transformer includes two types of losses

1. Eddy current loss
2. Hysteresis loss

For given volume and thickness of laminations, these losses depend on the operating frequency, maximum flux density and voltage.

$$P_e = K_e {B_m}^2 f^2 t^2$$

$$P_h = K_h {B_m}^{1.67} f\, v$$

$$P_e \propto {B_m}^2 f^2$$

$$P_h \propto {B_m}^{1.67} f$$

We know that for transformer

$$V = 4.44\, f\, N\, \emptyset m = 4.44\, f\, N\, B_m A$$

$$B_m \propto \frac{V}{f}$$

$$\boxed{\begin{gathered} P_e \propto {B_m}^2 f^2 \\ P_h \propto {B_m}^{1.67} f \\ B_m \propto \frac{V}{f} \end{gathered}}$$

Thus voltage changes flux density changes, both eddy current and hysteresis losses will change.

If the transformer is operated with the frequency and voltage changed in the same proportion, the flux density will remain unchanged and apparently the no-load current will also remain unaffected.

The transformer can be operated safely at frequency less than rated one with correspondingly reduced voltage. In this case iron losses will reduced. But if the transformer is operated with increased voltage and frequency in the same proportion, the core losses may increase to an intolerable level. Increase in frequency with constant supply voltage will cause reduction in hysteresis loss and leave the eddy current losses unaffected. Some increase in voltage could, therefore, be tolerated at higher frequencies, but exactly how much depends on the relative magnitude of the hysteresis and eddy current losses and the grade of iron used in the transformer core.

## 2.13 Efficiency of a Transformer

The efficiency of any device is defined as the ratio of the power output to power input. The efficiency of a transformer at a particular load and power factor is defined as the output divided by the input. It is expressed as η

$$\eta = \frac{\text{Power output}}{\text{Power input}}$$

$$\eta = \frac{\text{Power output}}{\text{Power output} + \text{Total losses}}$$

$$\eta = \frac{\text{Power output}}{\text{Power output} + P_i + P_{cu}}$$

$$\text{Power output} = V_2 I_2 \cos\phi$$

$$\cos\phi = \text{Load power factor}$$

Transformer supplies full load current of $I_2$ and with terminal voltage $V_2$

$$P_{cu} = \text{ copper losses on full load} = {I_2}^2 R_{02}$$

$$\eta = \frac{V_2 I_2 \cos\phi}{V_2 I_2 \cos\phi + P_i + {I_2}^2 R_{02}}$$

$$V_2 I_2 = \text{VA rating of a transformer}$$

$$\%\,\eta = \frac{(\text{VA rating}) * \cos\phi}{(\text{VA rating}) * \cos\phi + P_i + {I_2}^2 R_{02}} * 100$$

$$\boxed{\%\,\eta = \frac{(\text{VA rating}) * \cos\phi}{(\text{VA rating}) * \cos\phi + P_i + {I_2}^2 R_{02}} * 100}$$

This is full load efficiency with, $I_2$ = full load secondary current

But if the transformer is subjected to fractional load then using the appropriate values of various quantities, the efficiency can be obtained.

$$x = \text{Fraction by which load is less than full load} = \frac{\text{Actual load}}{\text{full load}}$$

When load changes, the load current changes by same proportion.

$$\text{new } I_2 = x(I_2)\text{F.L}$$

Similarly the output power also reduces by same fraction.

Similarly as copper losses are proportional to square of current then

$$\text{new } P_{cu} = x^2(P_{cu})F.L$$

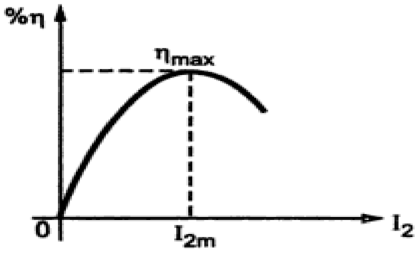
In general for fractional load the efficiency is given by,

$$\%\,\eta = \frac{x(\text{VA rating}) * \cos\phi}{x(\text{VA rating}) * \cos\phi + P_i + x^2(P_{cu})F.L} * 100$$

$$\boxed{\%\,\eta = \frac{x(\text{VA rating}) * \cos\phi}{x(\text{VA rating}) * \cos\phi + P_i + x^2(P_{cu})F.L} * 100}$$

### 2.14 Condition for maximum efficiency:

In general for the efficiency to be maximum for any device the losses must be minimum. Between the iron and copper losses the iron loss is the fixed loss and the copper loss is the variable loss. When these two losses are equal and also minimum the efficiency will be maximum.



Therefore the condition for maximum efficiency in a transformer is

$$\text{Iron loss} = \text{Copper loss}$$

When transformer works on a constant input voltage and frequency then efficiency varies with the load. As load increases, the efficiency increases. At a certain load current, it achieves a maximum value. If the transformer is loaded further the efficiency starts decreasing. The graph of efficiency against load current $I_2$ is shown in fig 5.40.

The load current at which the efficiency attains maximum value is denoted as $I_{2m}$ and maximum efficiency is denoted as $\eta_m$.

So for maximum efficiency

$$\frac{d\eta}{dI_2} = 0$$

$$\eta = \frac{V_2I_2 * \cos\phi_2}{V_2I_2 * \cos\phi_2 + P_i + P_{Cu}}$$

$$\eta = \frac{V_2I_2 * \cos\phi_2}{V_2I_2 * \cos\phi_2 + P_i + I_2{}^2R_{02}}$$

$$\frac{d\eta}{dI_2} = \frac{d}{dI_2}\left[\frac{V_2I_2 \ * \cos\phi_2}{V_2I_2 \ * \cos\phi_2 + P_i + I_2{}^2R_{02}}\right] = 0$$

$$\left(V_2I_2 \ * \cos\phi_2 + P_i + I_2{}^2R_{02}\right)\frac{d}{dI_2}(V_2I_2 \ * \cos\phi_2)$$

$$- (V_2I_2 \ * \cos\phi_2)\frac{d}{dI_2}\left(V_2I_2 \ * \cos\phi_2 + P_i + I_2{}^2R_{02}\right) = 0$$

$$\left(V_2I_2 \ * \cos\phi_2 + P_i + I_2{}^2R_{02}\right)(V_2\cos\phi_2) - (V_2I_2 \ * \cos\phi_2)(V_2\cos\phi_2 + 2I_2 R_{02}) = 0$$

$$(V_2\cos\phi_2)\left[V_2I_2 \ * \cos\phi_2 + P_i + I_2{}^2R_{02} - V_2I_2 \cos\phi_2 - 2I_2{}^2R_{02}\right] = 0$$

$$\left[V_2I_2 \ * \cos\phi_2 + P_i + I_2{}^2R_{02} - V_2I_2 \cos\phi_2 - 2I_2{}^2R_{02}\right] = 0$$

$$P_i - I_2{}^2R_{02} = 0$$

$$P_i = I_2{}^2R_{02} = P_{Cu}$$

$$\boxed{\text{Iron loss} \ = \ \text{Copper loss}}$$

### (i) Load current $I_{2m}$ at maximum efficiency

For $\eta_{max}$, $P_i = I_2{}^2R_{02}$ but $I_2 = I_{2m}$

$$I_{2m}{}^2R_{02} = P_i$$

$$I_{2m} = \sqrt{\frac{P_i}{R_{02}}}$$

$$I_{2\ F.L} = \text{Full load current}$$

$$I_{2m} = \frac{I_{2\ F.L}}{I_{2\ F.L}}\sqrt{\frac{P_i}{R_{02}}}$$

$$I_{2m} = I_{2\ F.L}\sqrt{\frac{P_i}{I_{2\ F.L}{}^2R_{02}}}$$

$$I_{2m} = I_{2\ F.L}\sqrt{\frac{P_i}{P_{Cu\ (F.L)}}}$$

$$\boxed{I_{2m} = I_{2\ F.L}\sqrt{\frac{P_i}{P_{Cu\ (F.L)}}}}$$

This is the load current at $\eta_{max}$ in terms of full load current.

$$\frac{I_{2m}}{I_{2\ F.L}} = \sqrt{\frac{P_i}{P_{Cu\ (F.L)}}} = X$$

$$\boxed{X = \sqrt{\frac{P_i}{P_{Cu\ (F.L)}}}}$$

X is the fraction of load maximum efficiency

**(ii) kVA supplied at maximum efficiency**

For constant $V_2$ the kVA supplied is the function of load current.

$$\text{kVA at } \eta_{max} = I_{2m} V_2 = V_2 I_{2\ F.L} \sqrt{\frac{P_i}{P_{Cu\ (F.L)}}}$$

$$\boxed{\text{kVA at } \eta_{max} = (\text{kVA rating}) * \sqrt{\frac{P_i}{P_{Cu\ (F.L)}}}}$$

Substituting condition for $\eta_{max}$ in the expression of efficiency, we can write expression for $\eta_{max}$ as,

$$\%\ \eta_{max} = \frac{V_2 I_{2m} \cos\phi}{V_2 I_{2m} \cos\phi + 2P_i} * 100 \qquad \text{as } P_i = P_{Cu}$$

$$\%\ \eta_{max} = \frac{\text{kVA for } \eta_{max} \cos\phi}{\text{kVA for } \eta_{max} \cos\phi + 2P_i} * 100$$

$$\boxed{\%\ \eta_{max} = \frac{\text{kVA for } \eta_{max} \cos\phi}{\text{kVA for } \eta_{max} \cos\phi + 2P_i} * 100}$$

# Assignment-Cum-Tutorial Questions

## A. Questions testing the remembering / understanding level of students

### *I) Objective Questions*

1) A Transformer will work on

a) A.C only b) D.C only c) A.C as well as D.C d) None of the above

2) The Primary and Secondary of a transformer are ………… coupled

a)electrically b) magnetically c) electrically and magnetically d) None of the above.

3) A transformer is an efficient device because it ………

a) it is a static device b) uses inductive coupling c) uses capacitive coupling

d) uses electrical coupling.

4) The voltage per turn of the primary of transformer is ……. the voltage per turn of the secondary

a) more than b) less than c) the same as d) None of the above

5) The iron core is used to …….. of the transformer.

a) increase the weight b)provide tight magnetic coupling c)reduce core losses d)None of the above

6) The maximum flux produced in a core of a transformer is…..

a) directly proportional to supply frequency

b) Inversely proportional to supply frequency

c) Inversely proportional to primary voltage d) none of the above

7) When the primary of a transformer is connected to a dc supply, …….

a) primary current draws small current

b) primary leakage reactance is increased

c) core losses are increased d) primary may burn out

8) An ideal transformer is one which……

a) has no losses and leakage reactance b) does n't work c) has same no.of primary and secondary d) none of the above

9) The required thickness of lamination in a transformer decreases when

(a) The applied frequency increases (b) The applied frequency decreases

(c) The applied voltage increases (d) The applied voltage decreases

10) Laminated insulations coated with varnish are normally used in the transformer

(a) To reduce reluctance of magnetic path (b) To reduce the effect of eddy current

(c) To increase the reluctance of magnetic path (d) To reduce the hysteresis effect

11) The size and construction of bushings in a transformer depend upon the

(a) Size of winding (b) Size of tank (c) Current flowing (d)Voltage supplied

12) Transformer humming sound is reduced by the

(a) Proper bracing of transformers assemblies (b) Proper insulation

(c) Proper design (d) Proper design of winding

13) The overload capacity of a transformer depends on

(a) ratio of full load copper losses to its iron losses (b) size of the core

(c) frequency (d) none of the above

14) An air core transformer as compared to iron-core transformer has

(a) Less magnetic core loss (b) More magnetic core loss

(c) No magnetic core loss (d) Less ohmic loss

## *II) Descriptive Questions*

11) Explain the working principle of Single Phase Transformer?
12) Explain the constructional features of different types of single phase transformers?
13) Derive an EMF Equation of a Single Phase Transformer.
14) Explain the operation of a single phase transformer with inductive load by drawing the phasor diagram?
15) What are the different losses occurred in a transformer on load? Explain how each loss varies with load current, supply voltage and frequency? How these losses are minimized?
16) Derive an expression for voltage regulation of a single phase transformer from its equivalent circuit or phasor diagram?
17) Derive the condition for maximum efficiency of a single phase transformer?

## B. Question testing the ability of students in applying the concepts.

### *I) Objective Questions*

1) The low voltage winding of a 400/230 volt, 1-phase, 50Hz transformer is to be connected to a 25Hz supply in order to keep the magnetization current at the same level as that for normal 50Hz supply at 25Hz the voltage should be……

(a) 230V (b) 460V (c) 115V (d) 65V

2) If 90 per cent of norm al voltage and 90 percent of norm al frequency are applied to a transformer, the percent charge in hysteresis losses will be

(a) 20% (b) 4.7% (c) 19% (d) 21%

3) If 110 per cent of norm al voltage and 110 per cent of normal frequency is applied to a transformer, the percentage change of eddy current losses will be

(a) 10% (b) 20% (c) 25% (d) 21%

4) A transformer has two 2,400 V primary coils and two 240 V coils. By proper connection of the windings, the transformation ratio that can be obtained is

(a) 10 (b) 5 (c) 20 (d) 9

5) A single-phase, 2,200/200 V transformer takes 1 A at the HT side or no load at a power factor of 0.385 lagging. The iron losses are

(a)167 W (b) 77 W (c) 88 W (d) 98 W

6) Neglecting resistance, at constant flux density, the power required per kilogram to magnetize the iron core of a transformer is 0.8 W at 25 Hz and 2.04 W at 60 Hz. The power required per kilogram for 100 Hz is

(a)3.8 W (b) 3.63 W (c) 3.4 W (d) 5.2 W

7) The full load copper loss of a transformer is 1600W. At half-load the copper loss will be

(a) 6400W (b)1600W (c) 800W (d) 400W

### *II) Descriptive Questions*

1) A 2000/200v, 20 kVA transformer has 66 turns in the secondary. Calculate (i)primary turns. (ii)Primary and Secondary full load currents. Neglect losses.
2) A single Phase 50hz transformer has 20 primary turns and 273 secondary turns. The net cross sectional area of core is 400cm2. If the primary winding is connected to 230V supply, find (i) peak value of flux density in the core (ii) Voltage induced in the secondary winding.

3) A transformer takes a current of 0.6A and absorbs 64W when primary is connected to its normal supply of 200, 50Hz, the secondary being open circuited. Find the magnetizing and iron loss currents.

4) A Single phase transformer on no-load takes 4.5A at a power factor of 0.25 lagging when connected to a 230v, 50 Hz Supply. The number of turns of the primary winding is 250. Calculate (i) the magnetizing current (ii) the maximum value of flux in the core.

5) In a 50KVA transformer, the iron loss is 500W and full load copper loss is 800KW. Find the efficiency at full load and half full load at 0.8 lagging.

6) A 40KVA t/f has iron loss of 450KW and full load copper loss of 850KW. If the power factor of the load is 0.8 lagging, calculate (i) full laod efficiency (ii) the load at which the maximum efficiency occurs and (iii) the maximum efficiency.

7) A 440/110V transformer has a primary resistance of 0.032 ohms and secondary resistance of 0.02 ohms. Its iron loss at normal inputs of 150W. Determine secondary current at which maximum efficiency will occur and the value of this maximum efficiency at a unity pf load?

8) The primary and secondary windings of a 40KVA, 6600/250 v single phase transformer have a resistances of 10 ohms and 0.02 ohms respectively. The leakage reactance of transformer referred to the primary side is 35 ohms. Calculate the percentage voltage regulation of the transformer when supplying full load current at a p.f of 0.8 lagging.

## C. Questions testing the analyzing / evaluating /Creative ability of students

**4.** A 100KVA transformer has 400 turns on the primary and 80 turns on the secondary. The primary and secondary resistances are 0.3 ohms ans 0.1 ohms respectively and the corresponding reactances are 1.1 and 0.035 ohms respectively. The supply voltage is 220V. Calculate the voltage regulation and secondary terminal voltage for full load having a p.f of (i) 0.8 lagging (ii)0.8 leading .

### D.Previous GATE/IES Questions.

1. In a transformer, zero voltage regulation at full load is **GATE-2010**

(A) not possible (B) possible at unity power factor load

(C) possible at leading power factor load (D) possible at lagging power factor load

2. A single-phase, 50 kVA, 250 V/500 V two winding transformer has an efficiency of 95% at full load, unity power factor. If it is re-configured as a 500 V/750 V auto-transformer, its efficiency at its new rated load at unity power factor will be **GATE-2012**

(A) 95.752% (B) 97.851% (C) 98.276% (D) 99.241%

3. A simple phase transformer has a maximum efficiency of 90% at full load and unity power factor. Efficiency at half load at the same power factor is **GATE-2013**

(A) 86.7% (B) 88.26% (C) 88.9% (D) 87.8%

4. The core flux of a practical transformer with a resistive load **GATE-2014**

(A) is strictly constant with load changes (B) increases linearly with load

(C) increases as the square root of the load (D) decreases with increased load

5. In the protection of transformers, harmonic restraint is used to guard against **GATE-2015**

(A) magnetizing inrush current (B) unbalanced operation

(C) lightning (D) switching over-voltages

# UNIT –III

## Three Phase Induction Motors

Objectives:

7. To familiarize the students with the constructional details and working principle of Three Phase Induction Motors
8. To familiarize the students with Torque –slip Characteristics
9. To familiarize the students with different types of starters like auto transformer starter,DOL starter etc.,

Syllabus:

Principle of operation of three phase induction motors-Slip ring and squirrel cage motors,
Slip-Torque characteristics- Efficiency calculation.

Learning Outcomes:

After the completion of this unit, students will be to

10. Explain the various types of Induction motors.
11. Describe the working of a Three Phase Induction motor.
12. Draw the Torque –slip characteristics.
13. Explain different starting methods of Three phase induction motor.

# Learning Material

## Three Phase Induction Motors

## INTRODUCTION

An **induction motor** (IM) is a type of asynchronous AC motor where power is supplied to the rotating device by means of electromagnetic induction.

The induction motor with a wrapped rotor was invented by Nikola Tesla Nikola Teslain1882inFrancebuttheinitialpatentwasissuedin1888afterTeslahadmovedto theUnitedStates.Inhisscientificwork,Teslalaidthefoundationsforunderstandingthe way the motor operates. The induction motor with a cage was invented by Mikhail Dolivo-DobrovolskyaboutayearlaterinEurope.Technologicaldevelopmentinthefield hasimprovedtowherea100hp(74.6kW)motorfrom1976takesthesamevolumeashp (5.5 kW) motor did in 1897. Currently, the most common induction motor is the cage rotormotor.

An electric motor converts electrical power to mechanical power in its rotor (rotating part). There are several ways to supply power to the rotor. In a DC motor this powerissuppliedtothearmaturedirectlyfromaDCsource,whileinaninductionmotor this power is induced in the rotating device. An induction motor is sometimes called a *rotatingtransformer*becausethestator(stationarypart)isessentiallytheprimarysideof the transformer and the rotor (rotating part) is the secondary side. Induction motors are widely used, especially polyphase induction motors, which are frequently used in industrialdrives.

Induction motors are now the preferred choice for industrial motors due to their rugged construction, absence of brushes(which are required inmost DC motors) and the ability to control the speed of the motor.

**CONSTRUCTION**

A typical motor consists of two parts namely stator and rotor like other type ofmotors.

1. An outside stationary stator having coils supplied with AC current to produce a rotating magnetic field,
2. An inside rotor attached to the output shaft that is given a torque by the rotating field.

## Stator:

Stator of an Induction Machine

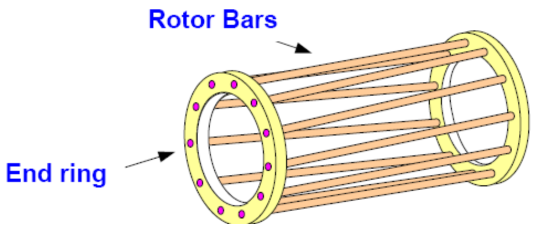
The stator of an induction motor is ,in principle ,the same as that of synchronous motor or generator.It is made up of a number of stampings,which are slotted to receive the windings.The stator carrie s 3-phase winding and is fed from a 3 phase supply.It is wound for a definite number of poles,the exact numbers of poles being determined by the requirements of speed.Greater the number of poles ,lesser the speed and vice-versa.The stator windings ,when supplied with 3-phase currents ,produce a magnetic flux,which is of constant magnitude but which at a speed of synchronous speed. This revolving magnetic flux induces an e.m.f in the rotor by mutual induction.

**Type of rotors**

Rotor is of two different types.

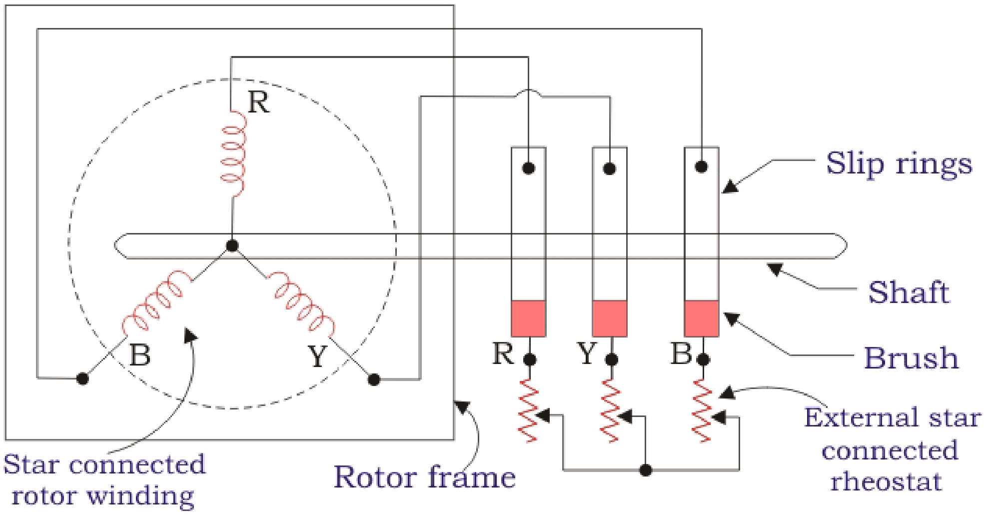
1. Squirrel cagerotor
2. Woundrotor

## 1.Squirrel-Cage Rotor



The rotor of the squirrel cage three phase induction motor is cylindrical in shape and have slots on its periphery. The slots are not made parallel to each other but are bit skewed (skewing is not shown in the figure of squirrel cadge rotor beside) as the skewing prevents magnetic locking of stator and rotor teeth and makes the working of motor more smooth and quieter. The squirrel cage rotor consists of aluminum, brass or copper bars (copper bras rotor is shown in the figure beside). These aluminum, brass or copper bars are called rotor conductors and are placed in the slots on the periphery of the rotor. The rotor conductors are permanently shorted by the copper or aluminum rings called the end rings. In order to provide mechanical strength these rotor conductor are braced to the end ring and hence form a complete closed circuit resembling like a cage and hence got its name as "squirrel cage induction motor". The squirrel cage rotor winding is made symmetrical. As the bars are permanently shorted by end rings, the rotor resistance is very small and it is not possible to add external resistance as the bars are permanently shorted.The absence of slip ring and brushes make the construction of Squirrel cage three phase induction motor very simple and robust and hence widely used three phase induction motor. These motors have the advantage of adapting any number of pole pairs

## 2.Wound Rotor



Slip Ring Three Phase Induction Motor

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In this type of three phase induction motor the rotor is wound for the same number of poles as that of stator but it has less number of slots and has less turns per phase of a heavier conductor.The rotor also carries star or delta winding similar to that of stator winding. The rotor consists of numbers of slots and rotor winding are placed inside these slots. The three end terminals are connected together to form star connection. As its name indicates three phase slip ring induction motor consists of slip rings connected on same shaft as that of rotor. The three ends of three phase windings are permanently connected to these slip rings. The external resistance can be easily connected through the brushes and slip rings and hence used for speed control and improving the starting torque of three phase induction motor. The brushes are used to carry current to and from the rotor winding. These brushes are further connected to three phase star connected resistances. At starting, the resistance are connected in rotor circuit and is gradually cut out as the rotor pick up its speed. When the motor is running the slip ring are shorted by connecting a metal collar, which connect all slip ring together and the brushes are also removed. This reduces wear and tear of the brushes. Due to presence of slip rings and brushes the rotor construction becomes somewhat complicated therefore it is less used as compare to squirrel cage induction motor.

## PRINCIPLE OF OPERATION

- An AC current is applied in the stator armature which generates a flux in the statormagneticcircuit.
- This flux induces an emf in the conducting bars of rotor as they are “cut” by the fluxwhilethemagnetisbeingmoved($E=BVL$(Faraday’sLaw))
- A current flows in the rotor circuit due to the induced emf, which in term producesaforce,($F=BIL$)canbechangedtothetorqueastheoutput.

In a 3-phase induction motor, the three-phase currents $ia$, $ib$ and $ic$, each of equal magnitude, but differing in phase by 120°. Each phase current produces a magnetic flux and there is physical 120 °shift between each flux. The total flux in the machine is the sum of the three fluxes. The summation of the three ac fluxes results in a rotating flux, which turns with constant speed and has constant amplitude. Such a magnetic flux produced by balanced three phase currents flowing in thee-phase windings is called a rotating magnetic flux or rotating magnetic field (RMF).RMF rotates with a constant speed (Synchronous Speed). Existence of a RFM is an essential condition for theoperation of an induction motor.

Ifstatorisenergizedbyanaccurrent,RMFisgeneratedduetotheappliedcurrent to the stator winding. This flux produces magnetic field and the field revolves in the air gap between stator and rotor. So, the magnetic field induces a voltage in the short-circuitedbarsoftherotor.Thisvoltagedrivescurrentthroughthebars.Theinteractionof therotatingfluxandtherotorcurrentgeneratesaforcethatdrivesthemotorandatorque isdevelopedconsequently.Thetorqueisproportionalwiththefluxdensityandtherotor bar current (F=BLI). The motor speed is less than the synchronous speed. The direction of the rotation of the rotor is the same as the direction of the rotation of the revolving magnetic field in the air gap.

However,forthesecurrentstobeinduced,thespeedofthephysicalrotorandthe speed of the rotating magnetic field in the stator must be different, or else the magnetic field will not be moving relative to the rotor conductors and nocurrents will be induced. If by some chance this happens, the rotor typically slows slightly until a current is re- induced and then the rotor continues as before. This difference between the speed of the rotorandspeedoftherotatingmagneticfieldinthestatoriscalled*slip*.Itisunitlessand is the ratio between the relative speed of the magnetic field as seen by the rotor the (*slip speed*) to the speed of the rotating stator field. Due to this an induction motor is sometimesreferredtoasanasynchronousmachine.

## SLIP:

The relationship between the supply frequency, $f$, the number of poles, $p$, and the synchronous speed (speed of rotating field), $n_s$ is given by

$$n_s = \frac{120 f}{p}$$

The stator magnetic field (rotating magnetic field) rotates at a speed, $n_S$, the synchronousspeed.If,n=speedoftherotor,theslip,sforaninductionmotorisdefined asS=Ns-N/Ns

At standstill, rotor does not rotate ,n=0,

So s=1. Atsynchronousspeed,$n=n_S$,s=0

The mechanical speed of the rotor, in terms of slip and synchronous speed is given by,

$$n=(1-s)\, n_S$$

### Frequency of Rotor Current and Voltage

Withtherotoratstand-still,thefrequencyoftheinducedvoltagesandcurrentsisthe sameasthatofthestator(supply)frequency,$f_e$.

If the rotor rotates at speed of n, then the relative speed is the slip speed:

$$n_{slip}=n_S-n$$

$n_{slip}$ is responsible for induction.

Hence,thefrequencyoftheinducedvoltagesandcurrentsintherotoris,$f_r=sf_e$.

### Torque Equation of Three Phase Induction Motor

The torque produced by three phase induction motor depends upon the following three factors: Firstly the magnitude of rotor current, secondly the flux which interact with the rotor of three phase induction motor and is responsible for producing emf in the rotor part of induction motor, lastly the power factor of rotor of the three phase induction motor. Combining all these factors together we get the equation of torque as-

$$T \propto \phi I_2 \cos\theta_2$$

Where, T is the torque produced by induction motor,

φ is flux responsible for producing induced emf,

$I_2$ is rotor current, $\cos\theta_2$ is the power factor of rotor circuit.

The flux φ produced by the stator is proportional to stator emf $E_1$. i.e

$$\varphi \propto E_1$$

We know that transformation ratio K is defined as the ratio of secondary voltage (rotor voltage) to that of primary voltage (stator voltage)

$$K = \frac{E_2}{E_1}$$

$$or,\ K = \frac{E_2}{\phi}$$

$$or,\ E_2 = \phi$$

Rotor current $I_2$ is defined as the ratio of rotor induced emf under running condition , $sE_2$ to total impedance, $Z_2$ of rotor side,

$$i.e\ I_2 = \frac{sE_2}{Z_2}$$

and total impedance $Z_2$ on rotor side is given by ,

$$Z_2 = \sqrt{R_2^2 + (sX_2)^2}$$

Putting this value in above equation we get,

$$I_2 = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

s= slip of Induction motor

We know that power factor is defined as ratio of resistance to that of impedance. The power factor of the rotor circuit is

$$\cos\theta_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Putting the value of flux φ, rotor current $I_2$, power factor $\cos\theta_2$ in the equation of torque we get,

$$T \propto E_2 \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \times \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Combining similar term we get,

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

Removing proportionality constant we get,

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

$$This\ comstant\ K = \frac{3}{2\pi n_s}$$

Where $n_s$ is synchronous speed in r. p. s, $n_s = N_s / 60$. So, finally the equation of torque becomes,

Derivation of K in torque equation.

In case of three phase induction motor, there occur copper losses in rotor. These rotor copper losses are expressed as $P_c = 3I_2^2R^2$We know that rotor current,

Substitute this value of $I_2$ in the equation of rotor copper losses, $P_c$. So, we get

$$P_m = \frac{1}{s} \times \frac{(1-s)3R_2s^2E_2^2}{R_2^2 + (sX_2)^2}$$

On simplifying we get,

$$P_m = \frac{(1-s)3R_2sE_2^2}{R_2^2 + (sX_2)^2}$$

The mechanical power developed $P_m = T\omega$,

$$\omega = \frac{2\pi N}{60}$$

$$or\ P_m = T\frac{2\pi N}{60}$$

Substituting the value of $P_m$

We know that the rotor speed N = $N_s(1 - s)$

Substituting this value of rotor speed in above equation we get,

$$T = \frac{1}{s} \times \frac{(1-s)3R_2 s^2 E_2^2}{R_2^2 + (sX_2)^2} \times \frac{60}{2\pi N_s(1-s)}$$

$N_s$ is speed in revolution per minute (rpm) and $n_s$ is speed in revolution per sec (rps) and the relation between the two is

$$\frac{N_s}{60} = n_s$$

Substitute this value of $N_s$ in above equation and simplifying it we get

$$Toeque,\ T = \frac{s\ E_2^2 R_2}{R_2^2 + (sX_2)^2} \times \frac{3}{2\pi N_s}$$

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

Comparing both the equations, we get, constant K = 3 / $2\pi n_s$

## Equation of Starting Torque of Three Phase Induction Motor

Starting torque is the torque produced by induction motor when it is started. We know that at start the rotor speed, N is zero

$$So,\ slip\ s = \frac{N_s - N}{N_s}\ becomes\ 1$$

So, the equation of starting torque is easily obtained by simply putting the value of s = 1 in the equation of torque of the three phase induction motor,

$$T = \frac{E_2^2 R_2}{R_2^2 + X_2^2} \times \frac{3}{2\pi n_s}\ N-m$$

The starting torque is also known as standstill torque.

## Maximum Torque Condition for Three Phase Induction Motor

In the equation of torque, $$T = \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2} \times \frac{3}{2\pi n_s}$$

he rotor resistance, rotor inductive reactance and synchronous speed of induction motor remains constant . The supply voltage to the three phase induction motor is usually rated and remains constant so the stator emf also remains the constant. The transformation ratio is defined as the ratio of rotor emf to that of stator emf. So if stator emf remains constant then rotor emf also remains constant.

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

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

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

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

negative value of slip we get

$$s^2 = \frac{R_2^2}{X_2^2}$$

So, when slip s = $R_2$ / $X_2$, the torque will be maximum and this slip is called maximum slip Sm and it is defined as the ratio of rotor resistance to that of rotor reactance. NOTE : At starting S = 1, so the maximum starting torque occur when rotor resistance is equal to rotor reactance.

Equation of Maximum Torque

The equation of torque is $$T = \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

The torque will be maximum when slip s = $R_2$ / $X_2$

Substituting the value of this slip in above equation we get the maximum value of torque as,

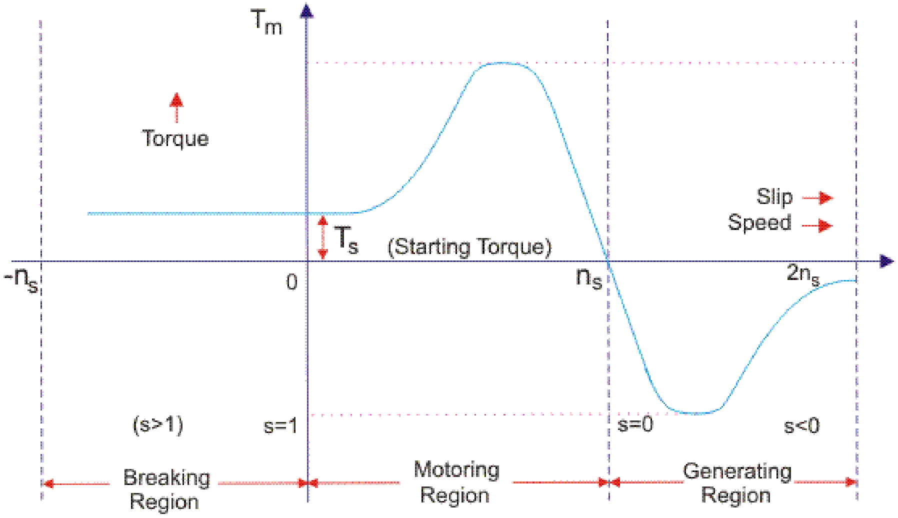
$$T_{max} = K\frac{E_2^2}{2X_2} N - m$$

In order to increase the starting torque, extra resistance should be added to the rotor circuit at start and cut out gradually as motor speeds up.

## Torque Slip Characteristics of Three Phase Induction Motor

The torque slip curve for an induction motor gives us the information about the variation of torque with the slip. The slip is defined as the ratio of difference of synchronous speed and actual rotor speed to the synchronous speed of the machine. The variation of slip can be obtained with the variation of speed that is when speed varies the slip will also vary and the torque corresponding to that speed will also vary.

The curve can be described in three modes of operation-



Torque Slip Curve for Three Phase Induction Motor

Motoring Mode: In this mode of operation, supply is given to the stator sides and the motor always rotates below the synchronous speed. The induction motor torque varies from zero to full load torque as the slip varies. The slip varies from zero to one. It is zero at no load and one at standstill. From the curve it is seen that the torque is directly proportional to the slip. That is, more is the slip, more will be the torque produced and vice-versa. The linear relationship simplifies the calculation of motor parameter to great extent.

Generating Mode: In this mode of operation induction motor runs above the synchronous speed and it should be driven by a prime mover. The stator winding is connected to a three phase supply in which it supplies electrical energy. Actually, in this case, the torque and slip both are negative so the motor receives mechanical energy and delivers electrical energy. Induction motor is not much used as generator because it requires reactive power for its operation. That is, reactive power should be supplied from outside and if it runs below the synchronous speed by any means, it consumes electrical energy rather than giving it at the output. So, as far as possible, induction generators are generally avoided.

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

If load which the motor drives accelerates the motor in the same direction as the motor is rotating, the speed of the motor may increase more than synchronous speed. In this case, it acts as an induction generator which supplies electrical energy to the mains which tends to slow down the motor to its synchronous speed, in this case the motor stops. This type of breaking principle is called dynamic or regenerative breaking.

## Losses and Efficiency of Induction Motor

There are two types of losses occur in three phase induction motor. These losses are,

1. Constant or fixed losses,
2. Variable losses

### 1.Constant or Fixed Losses

Constant losses are those losses which are considered to remain constant over normal working range of induction motor. The fixed losses can be easily obtained by performing no-load test on the three phase induction motor. These losses are further classified as-

1. Iron or core losses,
2. Mechanical losses,
3. Brush friction losses.

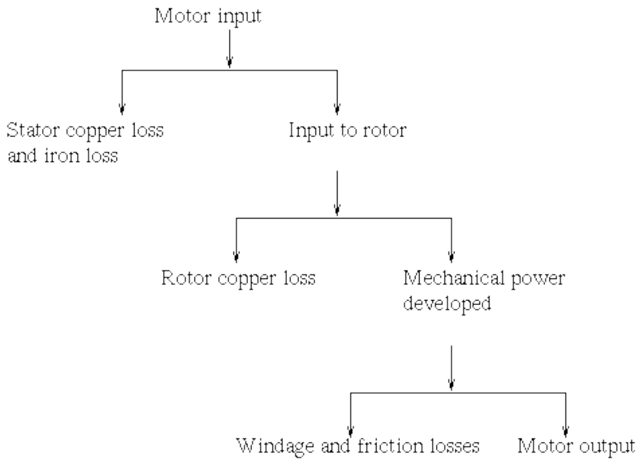
## iron or Core Losses

Iron or core losses are further divided into hysteresis and eddy current losses. Eddy current losses are minimized by using lamination on core. Since by laminating the core, area decreases and hence resistance increases, which results in decrease in eddy currents. Hysteresis losses are minimized by using high grade silicon steel. The core losses depend upon frequency of the supply voltage. The frequency of stator is always supply frequency, f and the frequency of rotor is slip times the supply frequency, (sf) which is always less than the stator frequency. For stator frequency of 50 Hz, rotor frequency is about 1.5 Hz because under normal running condition slip is of the order of 3 %. Hence the rotor core loss is very small as compared to stator core loss and is usually neglected in running conditions.

## Mechanical and Brush Friction Losses

Mechanical losses occur at the bearing and brush friction loss occurs in wound rotor induction motor. These losses are zero at start and with increase in speed these losses increases. In three phase induction motor the speed usually remains constant. Hence these losses almost remains constant.

## Variable Losses



These losses are also called copper losses. These losses occur due to current flowing in stator and rotor windings. As the load changes, the current flowing in rotor and stator winding also changes and hence these losses also changes. Therefore these losses are called variable losses. The copper losses are obtained by performing blocked rotor test on three phase induction motor.

The main function of induction motor is to convert an electrical power into mechanical power. During this conversion of electrical energy into mechanical energy the power flows through different stages. This power flowing through different stages is shown by power flow diagram. As we all know the input to the three phase induction motor is three phase supply. So, the three phase supply is given to the stator of three phase induction motor.

Let, $P_{in}$ = electrical power supplied to the stator of three phase induction motor,

$V_L$ = line voltage supplied to the stator of three phase induction motor,

$I_L$ = line current, Cosφ = power factor of the three phase induction motor.

Electrical power input to the stator,

$$P_{in} = \sqrt{3} V_L I_L \cos\varphi$$

A part of this power input is used to supply stator losses which are stator iron loss and stator copper loss. The remaining power i.e( inputelectrical power – stator losses ) are supplied to rotor as rotor input.

So, rotor input $P_2 = P_{in}$ – stator losses (stator copper loss and stator iron loss).

Now, the rotor has to convert this rotor input into mechanical energy but this complete input cannot be converted into mechanical output as it has to supply rotor losses. As explained earlier the rotor losses are of two types rotor iron loss and rotor copper loss. Since the iron loss depends upon the rotor frequency, which is very small when the rotor rotates, so it is usually neglected. So, the rotor has only rotor copper loss. Therefore the rotor input has to supply these rotor copper losses. After supplying the rotor copper losses, the remaining part of Rotor input, $P_2$ is converted into mechanical power, $P_m$.

Let $P_c$ be the rotor copper loss,

$I_2$ be the rotor current under running condition,

$R_2$ is the rotor resistance,

$P_m$ is the gross mechanical power developed.

$$P_c = 3I_2^2R_2$$
$$P_m = P_2 - P_c$$

Now this mechanical power developed is given to the load by the shaft but there occur some mechanical losses like friction and windage losses. So, the gross mechanical power developed has to be supplied to these losses. Therefore the net output power developed at the shaft, which is finally given to the load is $P_{out}$.

$P_{out} = P_m$ – Mechanical losses (friction and windage losses).

$P_{out}$ is called the shaft power or useful power.

## Efficiency of Three Phase Induction Motor

Efficiency is defined as the ratio of the output to that of input,

$$Efficiency,\ \eta = \frac{output}{input}$$

Rotor efficiency of the three phase induction motor ,

$$= \frac{rotor\ output}{rotor\ input}$$

= Gross mechanical power developed / rotor input

$$= \frac{P_m}{P_2}$$

Three phase induction motor efficiency,

$$= \frac{power\ developed\ at\ shaft}{electrical\ input\ to\ the\ motor}$$

Three phase induction motor efficiency

$$\eta = \frac{P_{out}}{P_{in}}$$

# Assignment-Cum-Tutorial Questions

## A. Questions testing the remembering / understanding level of students

### *I) Objective Questions*

1) The principle of operation of a 3-phase induction motor is most similar to that of a [ ]

a) synchronous motor b)repulsion –start induction motor

c) transformer with shorted secondary d) capacitor start induction motor

2) Regarding skewing of motor bars in squirrel induction motor which statement is false.[ ]

a)it prevents cogging b)it increases starting torque

c)it produces more uniform torque d) it reduces motor hum during its operation

3) The effect of increasing the length of air-gap in an induction motor will be to increase the [ ]

a)Power factor b)speed c) magnetising current d) air-gap flux

4) In a 3-Phase induction motor ,the relative speed of stator flux with respect to …is zero[ ]

a)stator winding b)rotor c) rotor flux d) space

5) In a 3 –Phase induction motor ,the rotor field rotates at synchronous speed with respect to [ ]

a) stator b) rotor c) stator flux d) none of the above

6) Irrespective of the supply frequency,the torque developed by SCIM is the same when ever is the same [ ]

a) supply voltage b) external load c) rotor resistance d) slip speed

7) Which of the following rotor quantity in a SCIM does not depend on its slip? [ ]

a) reactance b) speed c) induced emf d) frequency

8) The efficiency of 3-Phase induction motor is approximately proportional to [ ]

a) (1-s) b) s c) N d) Ns

9)In a 3-Phase slip ring induction motor ,3-Phase balanced supply is given to the rotor and stator winding is short-circuited .The rotor would [ ]

a) not run b) run in the direction of rotating field

c) run against the direction of rotating field d)run at half the synchronous speed

10)squirrel cage induction motor is [ ]

a) low at light loads b) low at heavy loads

c) low at light and heavy loads both d) low at rated load only.

### *II) Descriptive Questions*

11) Explain the principle of operation of 3-phase induction motor
**12)** Explain how the rotating magnetic field is developed in a 3-phase induction Motor
13) Explain the constructional details of a 3-phase Induction motor
14) Derive the torque equation of a three phase induction motor.
15) Derive the condition for maximum torque and starting torque for 3-phase Induction motor
16) Draw and explain the torque –slip characteristics of three phase induction motor
17) List the factors governing the performance of induction motors.?
18) Derive the expression of rotor frequency in terms of main supply frequency and slip.
19) Explain the constructional difference between squirrel cage and slip ring induction motor

## B. Question testing the ability of students in applying the concepts.

### *I) Objective Questions*

1) A induction motor with an open circuited to rotor [ ]

a)runs on no load b) runs at reduced speed c) does not run d) gets damaged.

2) A 6 pole ,50 Hz induction motor can not run at a speed of [ ]

a) 500r.p.m. b) 750 r.p.m c) 950r.p.m d) 1000 r.p.m

3) The speed of rotating field due to rotor current relative to rotor surface is [ ]

a) Ns b) SNs c) N d) none.

4)The synchronous speed of an I-M can be increased by [ ]

a) reducing the friction at the bearings b) increasing the number of poles

c) decreasing the frequency d) increasing the frequency

5)The reactance under running condition is less than its stand still value.this is due to

the reduction in [ ]

a)rotor inductance b) rotor frequency c)mutual flux d)stator flux

6) The air gap between the stator and rotor of a 3 –phase induction motor ranges from [ ]

a)2cm to 4cm b) 0.4mm to 4 mm c) 1cm to 2 cm d) 4cm to 6cm

7) when the rotor of a 3-phase induction motor is blocked ,the slip is ……… [ ]

a)zero b) 0.5 c) 0.1 d) 1

8) A wound rotor is mainly used in applications where …… [ ]

a) high starting torque is required b) speed control is requored

c) less costly motor is not required d) high rotor resistance is required during running.

9) The rotor winding of a 3-phase wound rotor induction motor is generally ….. [ ]

a) star b)delta c) partly star and partly delta d)none.

10) If Ns is the speed of rotating flux and N the speed of the rotor ,then the rate at which the flux cuts the rotor conductors is directly proportional to …… [ ]

a) Ns b)N c)Ns-N d)N-Ns

## *II) Descriptive Questions*

**1.** A 3-phase , 6 pole, 50Hz cage motor is running with a slip of 4%. Find

(a) Speed of rotating field relative to stator winding

(b) Motor speed

(c) slip speed

(d) Frequency of the emf induced in the rotor

(e) Speed of rotation of rotor mmf relative to rotor winding

(f) Speed of rotor of rotor mmf relative to stator winding

2. The power input to the rotor of a 440V, 50Hz, 3-phase, 6-pole induction motor. is 50kW.It is observed that the rotor emf makes 120 complete cycles per minute. Calculate

(i)Slip

(ii) Rotor speed

(iii) Rotor copper losses per phase

(iv)Mechanical power developed

(v)Rotor resistance per phase if the rotor current is 50A

3. A 600Hp three phase,440volts,50Hz induction motor with 6 poles as rotor current frequency of 2Hz. Compute the operating slip and actual speed of the machine

4.A 3-phase, 6 pole, 50Hz induction motor has a slip of 1% at no load and 3% at full load. Find the synchronous speed, no load speed, frequency of rotor current at standstill and frequency of rotor current at full load?

5.A 4 pole ,3 phase induction motor operates from a supply whose frequency is 50Hz ,calculate

(i) the speed at which the magnetic field of the stator is rotating
(ii) the speed of the rotor when the slip is 0.04
(iii) the frequency of the rotor currents when the slip is 0.03
(iv) the frequency of the rotor currents at stand still.

6. A 24 pole ,50 Hz ,star connected induction motor has rotor resistance of 0.016 ohms per phase and rotor reactance of 0.265 ohm per phase at stand still. It is achieving its full load torque at a speed of 247r.p.m.calculte the ratio of i) full load torque to maximum torque ,ii) starting torque to maximum torque.

7. A 3 phase, 4 pole, 50 Hz star connected induction motor running on full load develops a use full torque of 300N-m,The rotor emf is completing 120 cycles per minute. If torque lost in friction is 50Nm Calculate i) slip, ii) Net output power, iii)Rotor copper losses per phase iv)Rotor efficiency v)Rotor resistance per phase if the rotor current is 60 A in running condition.

## C. Questions testing the analyzing / evaluating /Creative ability of students

1. A 400 v ,4 pole, 3 phase ,50 Hz star connected induction motor has a rotor resistance and reactance per phase equal to 0.01ohm and 0.1ohmrespectively.Determine i)starting torque, ii)slip at which maximum torque will occur, iii)speed at which maximum torque will occur iv) Maximum torque,v) full load torque if full load slip is 4%. Assume ratio of stator to rotor turns ratio 4.

2. A 3 phase ,50 Hz, 400V, induction motor has 4 pole star connected stator winding rptor resistance and stands still reactance per pahse are 0.1Ω and 1Ω respectively.The full load slip is 4%.Calculate (a) the total torque developed (b)the horse power developed

   (c) maximum torque developed (d)the speed at maximum torque . Assume that the stator to rotor turns ratio is 2:1

**D.Previous GATE/IES Questions.**

1)The slip of an induction motor normally does not depend on **GATE-2011**

(A) rotor speed (B) synchronous speed (C) shaft torque (D) core-loss component

2) A three-phase 440 V, 6 pole, 50 Hz, squirrel cage induction motor is running at a slip of 5%. The speed of stator magnetic field to rotor magnetic field and speed of rotor with respect of stator magnetic field are

**GATE-2012**

(A) zero, −5 rpm (B) zero, 955 rpm (C) 1000 rpm, −5 rpm (D) 1000 rpm, 955 rpm

3) A 400 V, 50 Hz 30 hp, three-phase induction motor is drawing 50 A current at 0.8 power factor lagging. The stator and rotor copper losses are 1.5 kW and 900 W respectively. The friction and windage losses are 1050 W and the core losses are 1200 W. The air-gap power of the motor will be

**GATE-2012**

(A) 23.06 kW (B) 24.11 Kw (C) 25.01 kW (D) 26.21 kW

4) The speed of rotation of stator magnetic field with respect to rotor structure will be

**GATE-2013**

(A) 90 rpm in the direction of rotation

(B) 90 rpm in the opposite direction of rotation

(C) 1500 rpm in the direction of rotation

(D) 1500 rpm in the opposite direction of rotation

5) A three-phase squirrel cage induction motor has a starting torque of 150% and a maximum torque of 300% with respect to rated torque at rated voltage and rated frequency. Neglect the stator resistance and rotational losses. The value of slip for maximum torque is **GATE-2014**

(A) 13.48% (B) 16.42% (C) 18.92% (D) 26.79%

6) In a single phase induction motor driving a fan load, the reason for having a high resistance rotor is to achieve **GATE-2015**

(A) low starting torque (B) quick acceleration (C) high efficiency (D) reduced size

7) A 3-phase induction motor is driving a constant torque load at rated voltage and frequency. If both voltage and frequency are halved, following statements relate to the new condition if stator resistance, leakage reactance and core loss are ignored 1. The difference between synchronous speed and actual speed remains same 2. The airgap flux remains same 3. The stator current remains same 4. The p.u. slip remains same Among the above, current statements are **GATE-2015**

(A) All (B) 1, 2 and 3 (C) 2, 3 and 4 (D) 1 and 4

8) If a 400 V, 50 Hz, star connected, 3-phase squirrel cage induction motor is operated from a 400 V, 75 Hz supply, the torque that the motor can now provide while drawing rated current from the supply

**GATE-2016**

(A) reduces (B) increases (C) remains the same (D) increases or reduces depending upon the rotor resistance

## UNIT –IV

## Alternators

**Objectives:**

10. To familiarize the students with the constructional details and working principle of alternators.
11. To familiarize the students with the effects of Distribution and Coil factors on emf inducedin an alternator.
12. To familiarize the students with OC and SC tests for predetermining the regulation of an alternator by Synchronous Impedance Method.

**Syllabus:**

Alternators – Constructional features – Principle of operation –Types – EMF equation – Distribution and Coil factors – Predetermination of regulation by Synchronous Impedance Method .

**Learning Outcomes:**

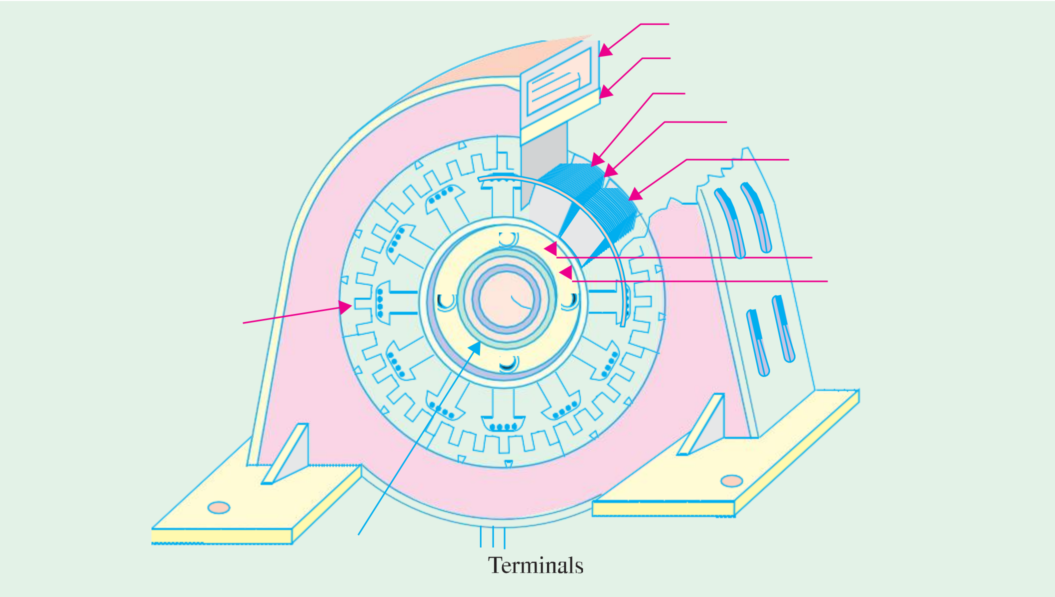
After the completion of this unit, students will be able to

14. Explain the constructional details of various types of alternators.
15. Describe the working principle of an alternator.
16. Explaineffects of Distribution and Coil factors on emf induced in an alternator.
17. Predetermine the regulation of an alternator by Synchronous Impedance Method.

# Alternators

## 4.1 Introduction

A.C. generators or alternators (as they are usually called) operate on the same fundamental principles of electromagnetic induction as d.c. generators. They also consist of an armature winding and a magnetic field. But there is one important difference between the two. Whereas in d.c. generators, the *armature rotates* and the field system is *stationary*, the arrangement in alternators is just the reverse of it. In their case, standard construction consists of armature winding mounted on a stationary element called *stator* and field windings on a rotating element called rotor. The details of construction are shown in Fig.



The stator consists of a cast-iron frame, which supports the armature core, having slots on its inner periphery for housing the armature conductors. The rotor is like a flywheel having alternate *N* and *S* poles fixed to its outer rim. The magnetic poles are excited (or magnetised) from direct current supplied by a d.c. source at 125 to 600 volts. In most cases, necessary exciting (or magnetising) current is obtained from a small d.c. shunt generator which is belted or mounted on the shaft of the alternator itself. Because the field magnets are rotating, this current is supplied through two slip rings. As the exciting voltage is relatively small, the slip-rings and brush gear are of light construction. Recently, brushless excitation systems have been developed in which a 3-phase a.c. exciter and a group of rectifiers supply d.c. to the alternator. Hence, brushes, slip-rings and commutator are eliminated.

When the rotor rotates, the stator conductors (being stationary) are cut by the magnetic flux, hence they have induced e.m.f. produced in them. Because the magnetic poles are alternately *N* and *S*, they induce an e.m.f. and hence current in armature conductors, which first flows in one direction and then in the other. Hence, an alternating e.m.f. is produced in the stator conductors (*i*) whose frequency depends on the number of *N* and *S* poles moving past a conductor in one second and (*ii*) whose direction is given by Fleming's Right-hand rule.

### Advantages of stationary armature

The field winding of an alternator is placed on the rotor and is connected to d.c. supply through two slip rings. The 3-phase armature winding is placed on the stator. This arrangement has the following advantages:

(i) It is easier to insulate stationary winding for high voltages for which the alternators are usually designed. It is because they are not subjected to centrifugal forces and also extra space is available due to the stationary arrangement of the armature.

(ii) The stationary 3-phase armature can be directly connected to load without going through large, unreliable slip rings and brushes.

(iii) Only two slip rings are required for d.c.supply to the field winding on the rotor. Since the exciting current is small, the slip rings and brush gear required are of light construction.

(iv) Due to simple and robust construction of the rotor, higher speed of rotating d.c. field is possible. This increases the output obtainable from a machine of given dimensions.

## 4.2 Construction Details of Alternator

An alternator has 3-phase winding on the stator and a d.c.field winding on the rotor.

### Stator

It is the stationary part of the machine and is built up of sheet-steel laminations having slots on its inner periphery. A 3-phase winding is placed in these slots and serves as the armature winding of the alternator. The armature winding is always connected in star and the neutral is connected to ground.

**Rotor**

The rotor carries a field winding which is supplied with direct current through two slip rings by a separate d.c.source. This d.c.source (called exciter) is generally a small d.c.shunt or compound generator mounted on the shaft of the alternator. Rotor construction is of two types, namely;

(i) Salient (or projecting) pole type
(ii) Non-salient (or cylindrical) pole type

(i) **Salient pole type**

In this type, salient or projecting poles are mounted on a large circular steel frame which is fixed to the shaft of the alternator as shown in Fig. (5.2). The individual field pole windings are connected in series in such a way that when the field winding is energized by the d.c.exciter, adjacent poles have opposite polarities.Low and medium-speed alternators (120-400r.p.m.) such as those driven by diesel engines or water turbines have salient pole type rotors due to the following reasons:

(a) The salient field poles would cause an excessive windage loss if driven at high speed and would tend to produce noise.

(b) Salient-pole construction cannot be made strong enough to with stand the mechanical stresses to which they may be subjected at higher speeds.

Since a frequency of 50Hz is required, we must use a large number of poles on the rotor of slow-speed alternators. Low-speed rotors always possess a large diameter to provide the necessary space for the poles. Consequently, salient-pole type rotors have large diameters and short axial lengths.

(ii) **Non-salient pole type**

In this type, the rotor is made of smooth solid forged-steel radial cylinder having a number of slots along the outer periphery. The field windings are embedded in these slots and are connected in series to the slip rings through which they are energized by the d.c.exciter. The regions forming the poles are usually left un slotted as shown in Fig.(5.3). It is clear that the poles formed are non-salient i.e., they do not project out from the rotor surface. High-speed alternators (1500or3000r.p.m.) are driven by steam turbines and use non-salient type rotors due to the following reasons:

(a) This type of construction has mechanical robustness and gives noiseless operation at high speeds.

(b) The flux distribution around the periphery is nearly a sine wave and hence a better e.m.f. waveform is obtained than in the case of salient-pole type.

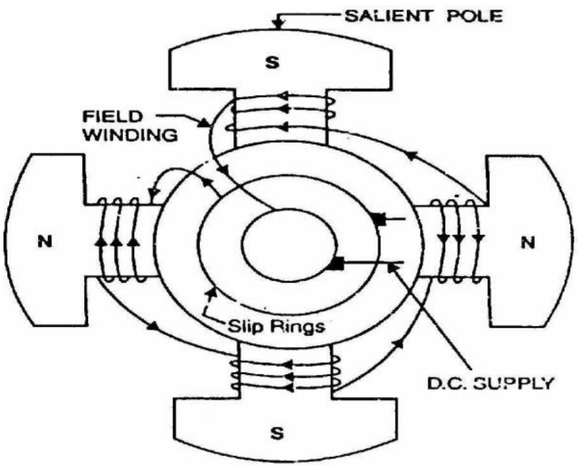


**Fig.(4.2)**

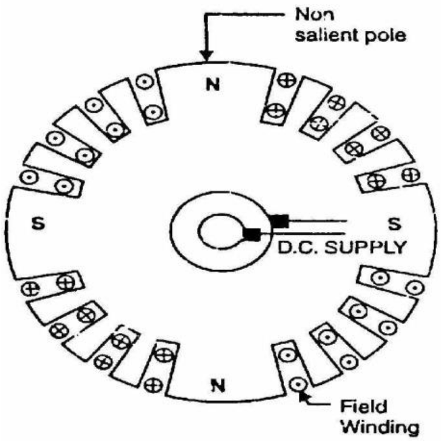


**Fig.(4.3)**

Since steam turbines run at high speed and a frequency of 50Hz is required, we need a small number of poles on the rotor of high-speed alternators (also called turbo alternators). We can use not less than 2 poles and this fixes the highest possible speed. For a frequency of 50Hz, it is 3000 r.p.m. The next lower speed is 1500 r.p.m. for a 4-pole machine. Consequently, turbo alternators possess 2 or 4 poles and have small diameters and very long axial lengths.

## 4.3 Alternator Operation:

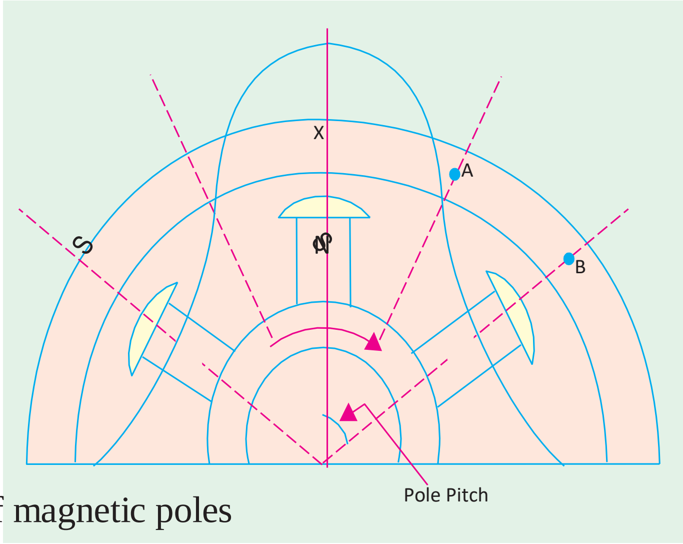
In an alternator, there exists a definite relationship between the rotational speed (*N*) of the rotor, the frequency (*f*) of the generated e.m.f. and the number of poles *P*.

Consider the armature conductor marked *X* in Fig. 37.7 situated at the centre of a *N*-pole rotating in clockwise direction. The conductor being situated at the place of maximum flux density will have maximum e.m.f. induced in it.

The direction of the induced e.m.f. is given by Fleming's right hand rule. But while applying this rule, one should be careful to note that the thumb indicates the direction of the motion of the conductor relative to the field. To an observer stationed on the clockwise revolving poles, the conductor would seem to be rotating anti-clockwise. Hence, thumb should point to the left. The direction of the induced e.m.f. is downwards, in a direction at right angles to the plane of the paper.

When the conductor is in the interpolar gap, as at *A* in Fig. 37.7, it has minimum e.m.f. induced in it, because flux density is minimum there. Again, when it is at the centre of a *S*-pole, it has maxi- mum e.m.f. induced in it, because flux density at *B* is maximum. But the direction of the e.m.f. when conductor is over a *N*-pole is opposite to that when it is over a *S*-pole.

Obviously, one cycle of e.m.f. is induced in a conductor when one pair of poles passes over it. In other words, the e.m.f. in an armature conductor goes through one cycle in angular distance equal to twice the pole-pitch, as shown in Fig.



Let $P$ = total number of magnetic poles

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

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

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

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

$N$ is known as the synchronous speed, because it is the speed at which an alternator must run, in order to generate an e.m.f. of the required frequency. In fact, for a given frequency and given number of poles, the speed is fixed.

## 4.4 Armature Winding of Alternator

With very few exceptions, alternators are 3-phase machines because of the advantages of 3-phase service for generation, transmission and distribution. The windings for an alternator are much simpler than that of a dc. Machine because no commutator is used. Fig.(5.5) shows a 2-pole, 3-phase double-layer, full-pitch, distributed winding for the stator of an alternator. There are 12 slots and each slot contains two coil sides. The coil sides that are placed in adjacent slots belong to the same phase such as a1, a3 or a2, a4 constitute a phase belt. Note that in a 3-phase machine, phase belt is always 60° electrical. Since the winding has double-layer arrangement, one side of a coil, such as a1, is placed at the bottom of a slot and the other side is placed at the top of another slot spaced one pole pitch apart. Note that each coil has a span of a full pole pitch or 180 electrical degrees. Therefore the winding is a full-pitch winding.

Note that there are 12 total coils and each phase has four coils. The four coils in each phase are connected in series so that their voltage said. The three phases then may be connected to form Y or delta-connection. Fig.(5.6) shows how the coils are connected to form a Y-connection.

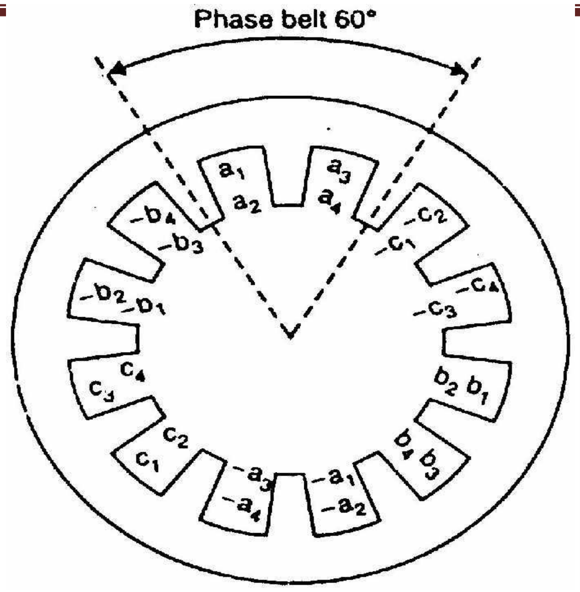


Fig.(4.5)

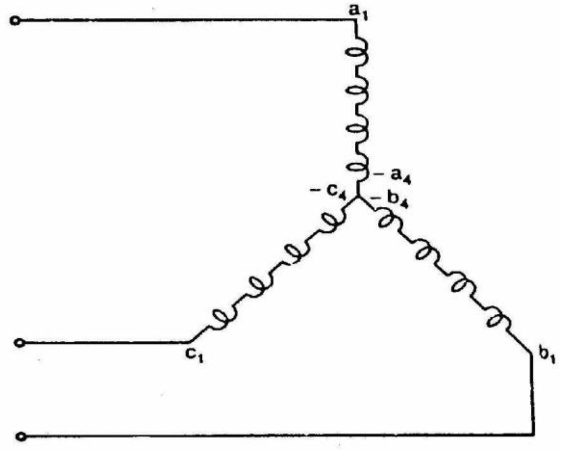


Fig.(4.6)

## Winding Factors

The armature winding of an alternator is distributed over the entire armature. The distributed winding produces nearly a sine wave form and the heating is more uniform. Likewise, the coils of armature winding are not full-pitched i.e., the two sides of a coil are not at corresponding points under adjacent poles. The fractional pitched armature winding requires less copper per coil and at the same time wave form of output voltage is improved. The distribution and pitching of the coils affect the voltages induced in the coils.

We shall discuss two winding factors:

(i) Pitch factor ($K_p$), also known as chord factor($K_c$)
(ii) Distribution factor ($K_d$), also called breadth factor

## Armature windings:

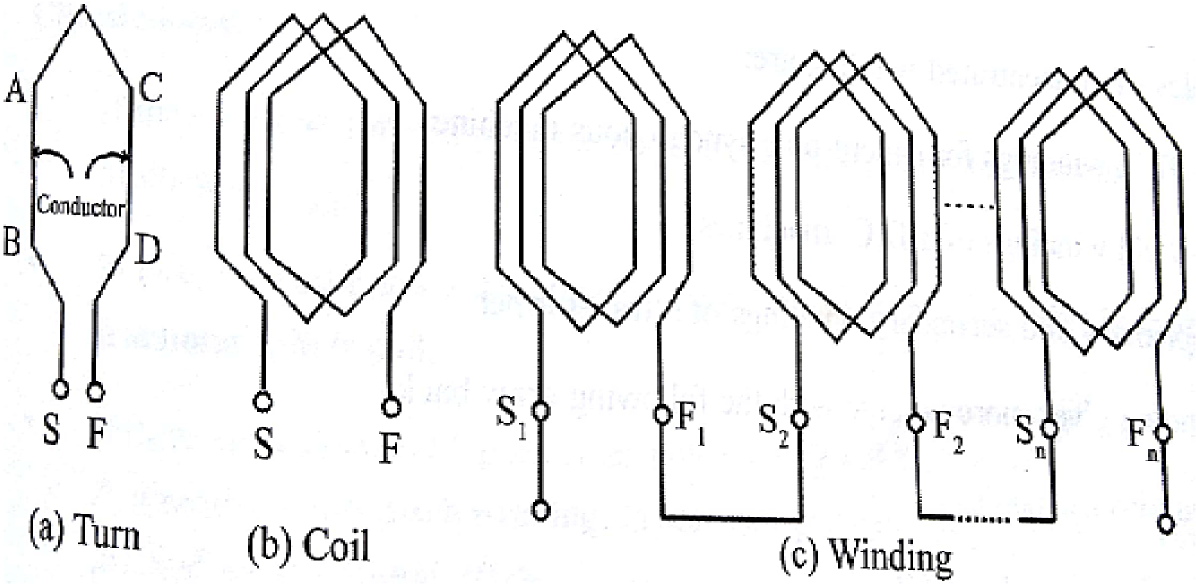
The winding through which a current is passed to produce the main flux is called the field winding. The winding in which voltage is induced is called the armature winding. Some basic terms related to the armature winding are defined as follows.

**(i)** **Conductor:** the length of a wire lying in the magnetic field and in which e.m.f is induced is called a conductor. in fig AB, CD are conductors.

**(ii)** **Turn:** a turn consists of two conductors along with their end connections as shown in fig

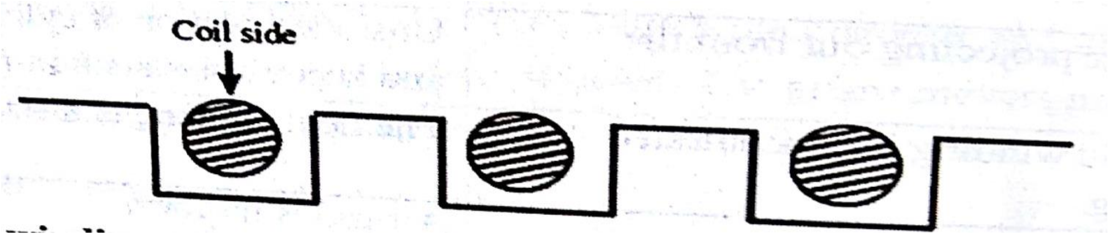
**(iii)** **Coil:** a coil is formed by connecting several turns in series as shown in fig(b).

**(iv)** **Winding:** a winding is formed by connecting several coils in series, as shown in fig (c).

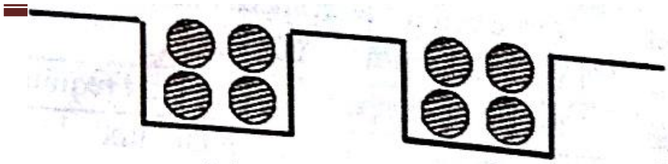


(a) Turn (b) Coil (c) Winding

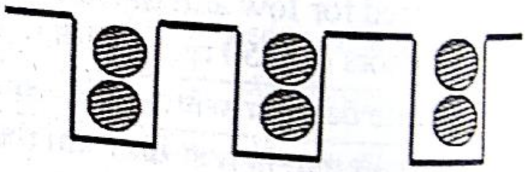
**Single layer winding:** the winding in which one coil side occupies the total slot area, is called single layer winding. Single layer winding is used only in small AC machines.



**(v)** **Double layer winding:** the winding in which even number of coil sides placed in two layers is called double layer winding. Double layer windings are most commonly used.



4 Coil sides / slot



2 Coil sides / slot

The advantages of double layer winding over single layer winding are as follows:

1. Easier to manufacture and lower cost of the coils.
2. Fractional slot winding can be used.
3. Chored-winding is possible.
4. Lower-leackage reactance and therefore, better performance of the machine.
5. Better e.m.f waveform in case of generators.

**vi) Concentrated winding:** in this case all the winding turns are wound together to form one multi-turn coil or in this winding, all the coil sides of any one phase under one pole are bunched in one slot. All the turns have same magnetic axis.

Examples of concentrated winding are:

1. Field windings for salient-pole synchronous machines.
2. Field windings of a D.C machines.
3. Primary and secondary windings of a transformer.

This winding gives more voltage with the following draw backs

1. Contains harmonics
2. Waveform is not smooth

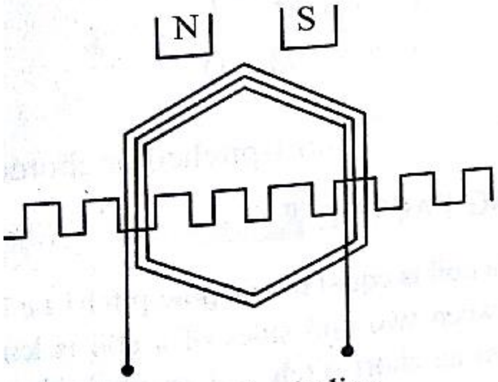
**vii) Distributed winding:** in this case all the winding turns are arranged in several full pitch or fractional pitch coils or in this winding, conductors of a given phase are distributed in various slots around periphery of air gap.

Examples of distributed windings are:

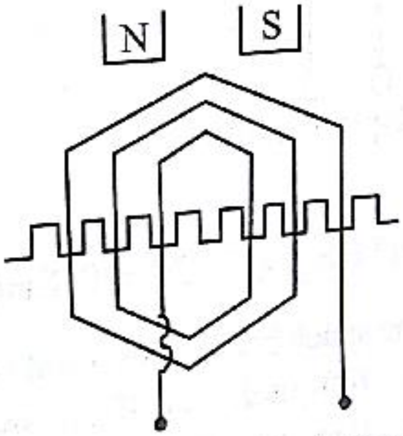
1. Stator and rotor of induction machines
2. The armatures of both synchronous and d.c machines

This winding gives less voltage with the following advantages

1. Harmonics are removed
2. Smooth sine wave



Concentrated winding



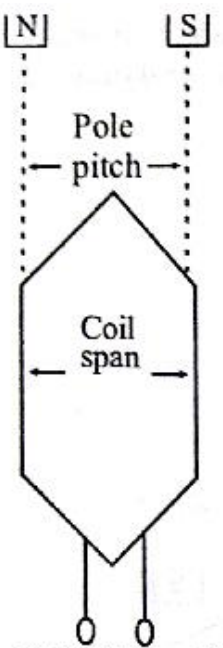
Distributed winding

**ix) Pole-pitch:** a pole pitch is defined as the peripheral distance between identical points on two adjacent poles. Pole pitch is always equal to $180^0$ electrical.

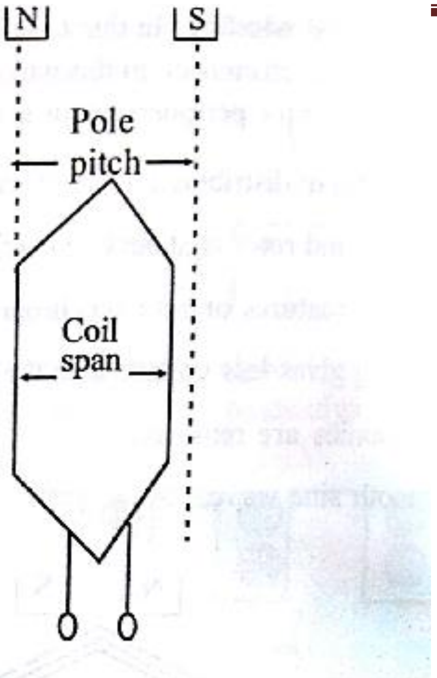
**x) Coil span or coil pitch:** the distance between the two coil sides of a coil is called coil span. It is usually measured in terms of teeth, slots or electrical degrees.

**xi) Chorded-coil**

1. If the coil span is equal to pole pitch, then the coil is termed a full-pitch coil.
2. In case the coil pitch is less than the pole pitch, then it is called, short-pitch or fractional pitch coil.
3. If there are S slots and P poles, then pole pitch Q=S/P slots per pole. If coil-pitch y=S/P, it results in full-pitch winding. In case coil pitch y< S/P, it results in chorded, short pitched or fractional pitch.



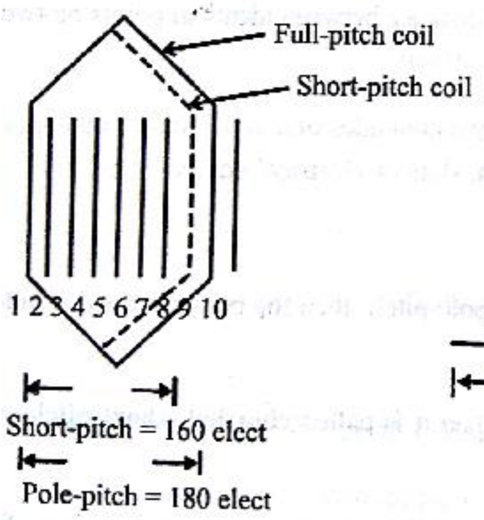
Full-pitch coil



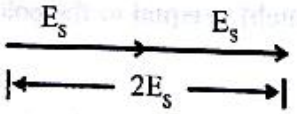
Short-pitched or chorded coil

**Pitch factor or chording factor:**

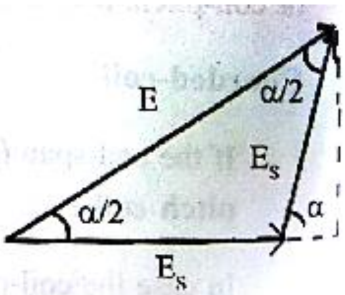
When the space between two coil sides of a coil is equal to one pole pitch it is known as full-pitch coil. If the space between two coil sides of a coil is less than the pole pitch it is known as short pitch coil or chording coil.



(a) Coil which shows full-pitch & short-pitch



(b) EMF's in a full-pitched coil



(c) EMF's induced in a short-pitched coil

Short pitch coils are deliberately used, because of the following advantages

1. Copper can be saved in the end connections.
2. The wave form of generated e.m.f can be improved.
3. Eddy current loss and hysteresis loss can be reduced due to elimination of high frequency harmonics, thereby the efficiency increases.

   The only disadvantage of short-pitched coil is that the net e.m.f induced in the coil is some what reduced, because the e.m.f.'s induced in the two sides of the short pitched coil are slightly out of phase as shown in fig (c).

**Distribution factor ($K_d$)**

A winding with only one slot per pole per phase is called a concentrated winding. In this type of winding, the e.m.f. generated/phase is equal to the arithmetic sum of the individual coil e.m.f.sin that phase. However, if the coils/phase are distributed over several slots in space (distributed winding), the e.m.f.s in the coils are not in phase (i.e., phase difference is not zero) but are displaced from each by the slot angle. (The angular displacement in electrical degrees between the adjacent slots is called slot angle). The e.m.f./phase will be the phasor sum of coil e.m.f.s.

The distribution factor $K_d$ is defined as:

$$K_d = \frac{\text{e. m. f. with distributedwinding}}{\text{e. m. f. withconcentratedwinding}}$$

$$K_d = \frac{\text{phasor sum of coil e. m. f. s/phase}}{\text{arithmetic sum of coil e. m. f. s/phase}}$$

Note that numerator is less than denominator so that $K_d<1$.

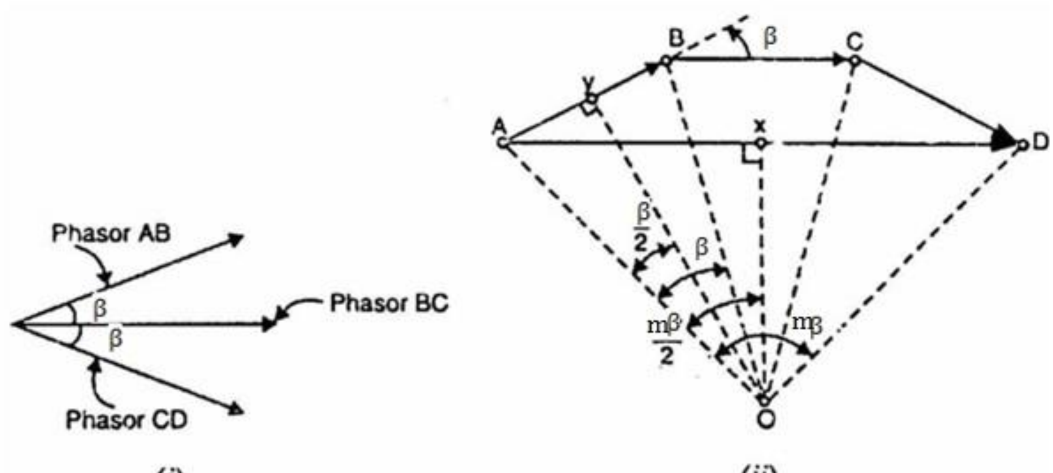
Let β = slot angle $=\frac{180^o electrical}{No.of slots/pole}$ = 180/n

The distribution factor can be determined by constructing a phasor diagram for the coil e.m.f.s. Let m=3. The three coil e.m.f.sare shown as phasors AB, BC and CD [See Fig.5.7(i)] each of which is a chord of circle with centre at O and subtends an angle βat O. The phasor sum of the coil e.m.f.s subtends an angle mβ (Here m=3) at O. Draw perpendicular bisectors of each chord such as Ox, Oy etc [See Fig.5.7(ii)].

$$K_d = \frac{AD}{m \times AB} = \frac{2 \times Ax}{m \times (2Ay)} = \frac{Ax}{m \times Ay}$$

$$K_d = \frac{OA \times \sin(m\beta/2)}{m \times OA \times \sin(\beta/2)}$$

$$K_d = \frac{\sin(m\beta/2)}{m \times sin(\beta/2)}$$



(i) (ii)

**Fig. (4.7)**

## 4.5 E.M.F. Equation of an Alternator

Let Z = No. of conductors or coil sides in series per phase

$\phi$= Flux per pole in Webers

P = Number of rotor poles

N = Rotor speed in r.p.m.

In one revolution (i.e., 60/N second), each stator conductor is cut by P $\phi$ webers i.e.,

$d\phi = P\phi$; $dt = 60/N$

Average e.m.f. induced in one stator conductor

$$= \frac{d\emptyset}{dt} = \frac{P\emptyset}{60/N} = \frac{P\emptyset N}{60} volts$$

Since there are Z conductors in series per phase,

$$\text{Average e.m.f./phase} = \frac{P\emptyset N}{60} \times Z$$

$$= \frac{P\emptyset Z}{60} \times \frac{120f}{P}$$

$=2 f \phi Z$ volts

R.M.S. value of e.m.f./phase = Average value/phase x form factor

$= 2 f \phi Z \times 1.11 = 2.22 f\phi Z$ volts

$E_{r.m.s.}$ / phase = $2.22f\phi Z$ volts (i)

If $K_p$ and $K_d$ are the pitch factor and distribution factor of the armature winding, then,

$E_{r.m.s.}$ / phase = $2.22KpKd f\phi Z$ volts (ii)

Sometimes the turns (T) per phase rather than conductors per phase are specified, in that case, eq. (ii) becomes:

$E_{r.m.s.}$ / phase = $4.44KpKd f \phi T$ volts (iii)

The line voltage will depend upon whether the winding is star or delta connected.

## 4.6 Alternator on Load

Fig. (5.9) shows Y-connected alternator supplying inductive load (lagging p.f.). When the load on the alternator is increased (i.e., armature current Ia is increased), the field excitation and speed being kept constant, the terminal voltage V (phase value) of the alternator decreases. This is due to

(i) Voltage drop IaRa where Ra is the armature resistance per phase.

(ii) Voltage drop IaXL where XL is the armature leakage reactance per phase.

(iii) Voltage drop because of armature reaction.

### (i) Armature Resistance ($R_a$)

The effective resistance of the armature winding is somewhat greater than the conductor resistance, called the dc resistance, as measured by direct current. This is due to additional loss over the purely $I^2R$ loss, inside and sometimes outside the conductor; owing to alternating current. The main source of this additional loss are (i) eddy currents in the surrounding material; (ii) magnetic hysteresis in the surrounding material and (iii) eddy currents or unequal current distribution in the conductor itself.

In many cases it is sufficiently accurate to measure the armature resistance by direct current and increase it to a fictitious value, called the effective resistance, $R_e$ or $R_a$ which is large enough to take care of these additional losses. Effective resistance, $R_e$ or $R_a$ can vary widely from 1.25 to 1.75 or more times the dc resistance, depending upon the design.

### (ii) Armature Leakage Reactance ($X_L$)

When current flows through the armature winding, flux is set up and a part of it does not cross the air-gap and links the coil sides. this leakage flux alternates with current and gives the winding self-inductance. This is called armature leakage reactance. Therefore, there will be $I_aX_L$ drop which is also effective in reducing the terminal voltage.

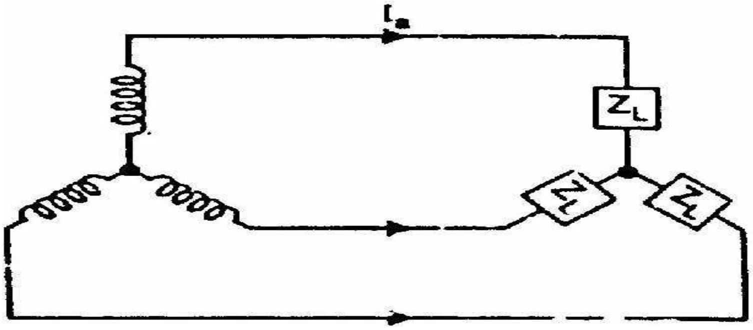


Fig. (4.9)

### (iii) Armature reaction

The load is generally inductive and the effect of armature reaction is to reduce the generated voltage. Since armature reaction results in a voltage effect in a circuit caused by the change in flux produced by current in the same circuit, its effect is of the nature of an inductive reactance. Therefore, armature reaction effect is accounted for by assuming the presence of a fictitious reactance $X_{AR}$ in the armature winding. The quantity $X_{AR}$ is called reactance of armature reaction.

The value of $X_{AR}$ is such that $I_aX_{AR}$ represents the voltage drop due to armature reaction.

## 4.7 Equivalent Circuit

Figure (5.11) shows the equivalent circuit of the loaded alternator for one phase. All the quantities are per phase. Here

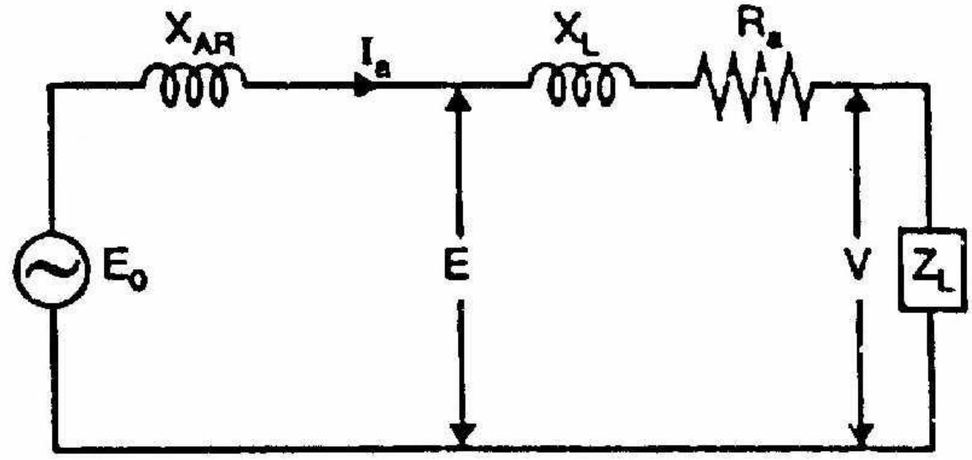


Fig. (4.10)

$E_0$ = No-load e.m.f.

E = Load induced e.m.f. It is the induced e.m.f. after allowing for armature reaction. It is equal to phasor difference of $E_0$ and $IaX_{AR}$.

V = Terminal voltage. It is less than E by voltage drops in $X_L$ and Ra.

$E = V + I(R_a + j X_L)$

$E_0 = E + I_a(jX_{AR})$

**Synchronous Reactance ($X_s$)**

The sum of armature leakage reactance ($X_L$) and reactance of armature reaction ($X_{AR}$) is called synchronous reactance Xs [See Fig. (5.12 (i))]. Note that all quantities are per phase.

$$X_s = X_L + X_{AR}$$

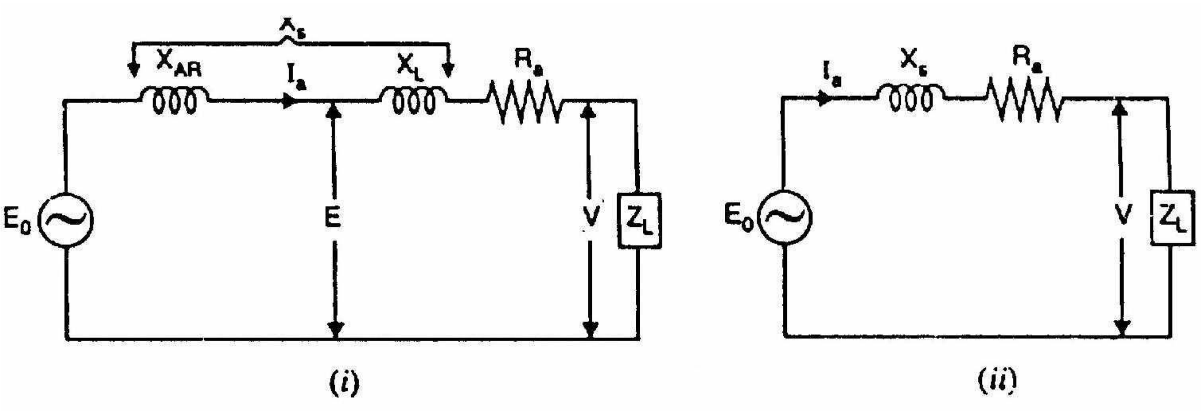


**Fig. (4.11)**

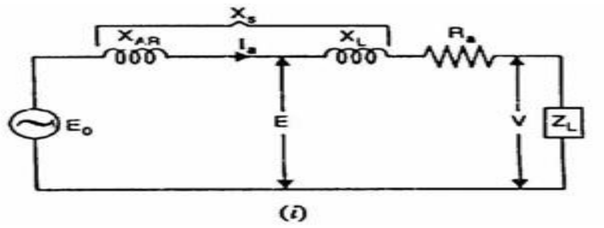
The synchronous reactance is a fictitious reactance employed to account for the voltage effects in the armature circuit produced by the actual armature leakage reactance and the change in the air-gap flux caused by armature reaction. The circuit then reduces to the one shown in Fig. (5.12 (ii)).

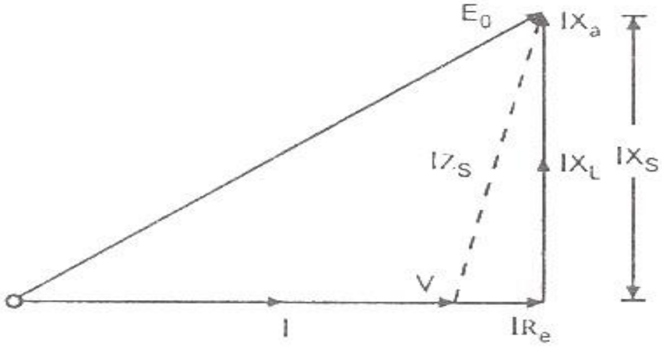
Synchronous impedance, Zs = Ra + j Xs

The synchronous impedance is the fictitious impedance employed to account for the voltage effects in the armature circuit produced by the actual armature resistance, the actual armature leakage reactance and the change in the air-gap flux produced by armature reaction.

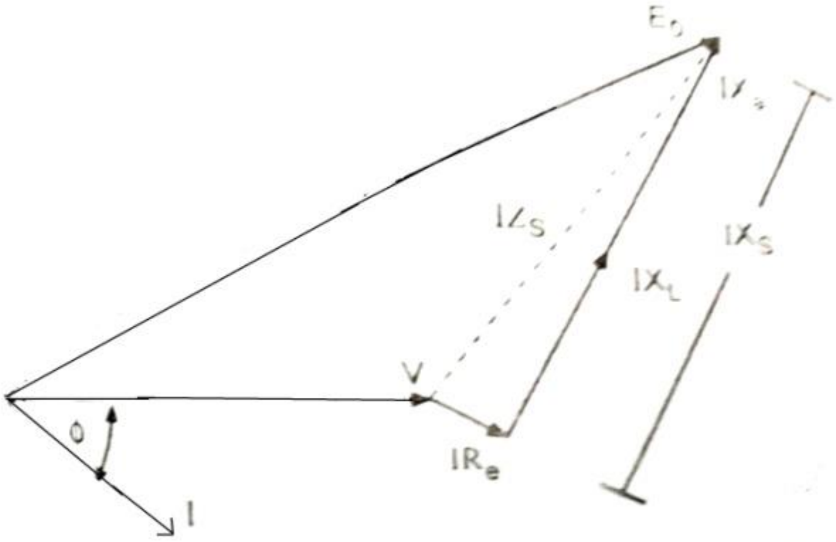
## 4.8 Phasor Diagram of a Loaded Alternator

Consider a Y-connected alternator supplying inductive load, the load p.f. angle being$\phi$. Fig.(5.13 (i)) shows the equivalent circuit of the alternator per phase. All quantities are per phase.

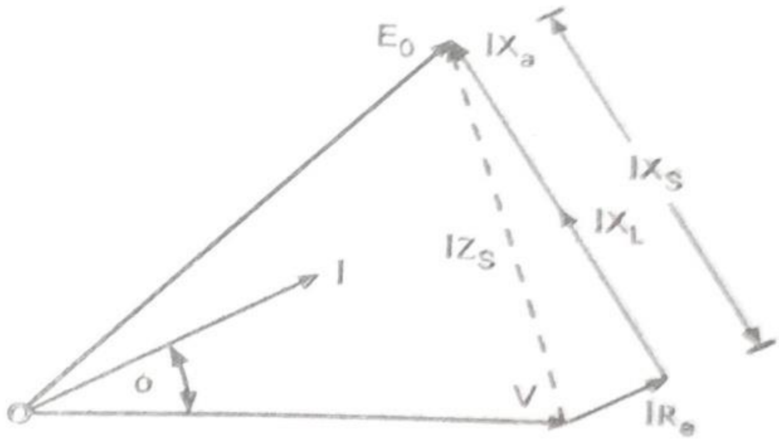




(ii) Unity Pf



(iii) Lagging Pf



(iv) Leading Pf

**Fig.(5.13)**

Fig. (5.13 (ii)) shows the phasor diagram of an alternator for the usual case of inductive load. The armature current $I_a$ lags the terminal voltage V by p.f. angle$\phi$. The phasor sum of V and drops $I_aR_a$ and $I_aX_L$ gives the load induced voltage E. It is the induced e.m.f. after allowing for armature reaction. The phasor sum of E and $I_aX_{AR}$ gives the no-load e.m.f. $E_0$. The phasor diagram for unity and leading p.f. is left as an exercise for the reader. Note that in drawing the phasor diagram either the terminal voltage (V) or armature current (Ia) may be taken as the reference phasor.

### 4.9 Voltage Regulation

The voltage regulation of an alternator is defined as the change in terminal voltage from no-load to full-load (the speed and field excitation being constant) divided by full-load voltage.

$$\%\text{ Voltage regulation} = \frac{\text{No load voltage} - \text{Full load voltage}}{\text{Full load voltage}} \times 100$$

$$= \frac{E_0 - V}{V} \times 100$$

Note that $E_0 - V$ is the arithmetic difference and not the phasor difference. The factors affecting the voltage regulation of an alternator are:

(i) $I_aR_a$ drop in armature winding

(ii) $I_aX_L$ drop in armature winding

(iii) Voltage change due to armature reaction

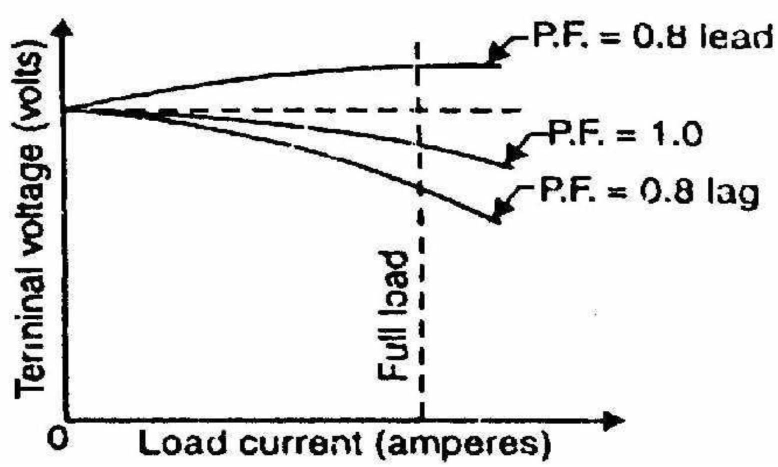


**Fig. (4.12)**

We have seen that change in terminal voltage due to armature reaction depends upon the armature current as well as power-factor of the load. For leading load p.f., the no-load voltage is less than the full-load voltage. Hence voltage regulation is negative in this case. The effects of different load power factors on the change in the terminal voltage with changes of load on the alternator are shown in Fig. (5.14). since the regulation of an alternator depends on the load and the load power factor, it is necessary to mention power factor while expressing regulation.

### 4.10 Determination of Voltage Regulation

The kVA ratings of commercial alternators are very high (e.g. 500 MVA). It is neither convenient nor practicable to determine the voltage regulation by direct loading. There are several indirect methods of determining the voltage regulation of an alternator. These methods require only a small amount of power as compared to the power required for direct loading method.

Three such methods are:

1. Synchronous impedance or E.M.F. method

2. Ampere-turn or M.M.F. method

3. Potier triangle method

For either method, the following data are required:

(i) Armature resistance

(ii) Open-circuit characteristic (O.C.C.)

(iii) Short-Circuit characteristic (S.C.C.)

**(i) Armature resistance**

The armature resistance $R_a$ per phase is determined by using direct current and the voltmeter-ammeter method as shown in fig (5.15). This is the D.C. value. The effective armature resistance (a.c. resistance) is greater than this value due to skin effect. It is a usual practice to take the effective resistance 1.6 times the d.c. value ($R_a = 1.6\ R_{dc}$).

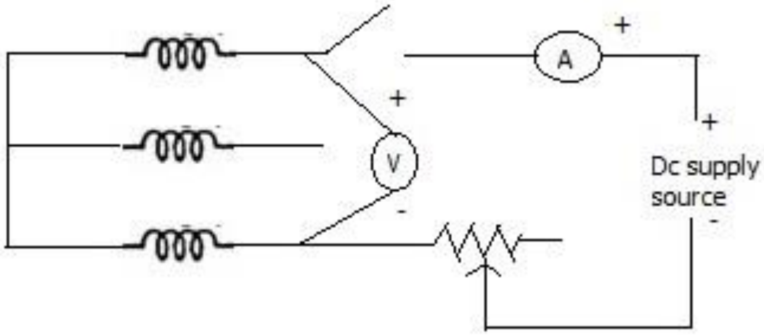


Fig (4.13)

**(ii) Open-circuit characteristic (O.C.C)**

Like the magnetization curve for a d.c. machine, the (Open-circuit characteristic of an alternator is the curve between armature terminal voltage (phase value) on open circuit and the field current when the alternator is running at rated speed. Fig (5.16) shows the circuit for determining the O.C.C. of an alternator. The alternator is run on no-load at the rated speed. The field current If is gradually increased from zero (by adjusting field rheostat) until open-circuit voltage $E_0$ (phase value) is about 50% greater than the rated phase voltage. The graph is drawn between open-circuit voltage values and the corresponding values of $I_f$ as shown in Fig. (5.17).

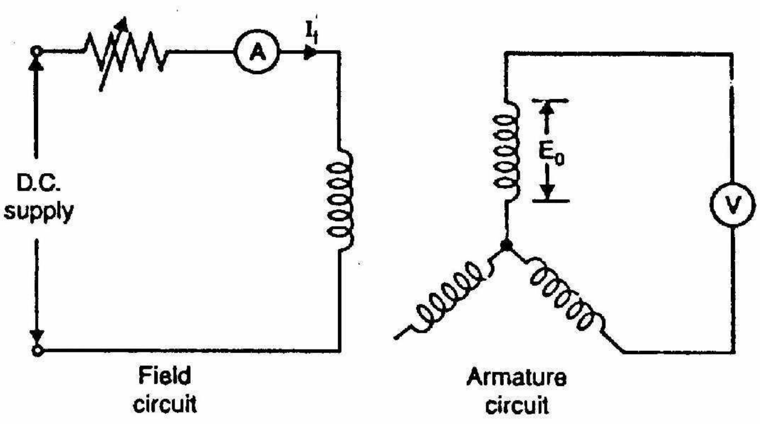


Fig. (4.14)

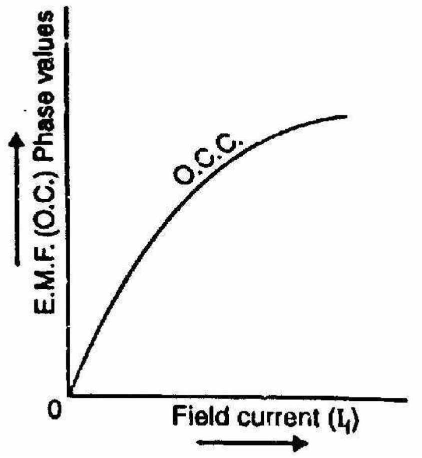


Fig. (4.15)

### (iii) Short-circuit characteristic (S.C.C.)

In a short-circuit test, the alternator is run at rated speed and the armature terminals are short-circuited through identical ammeters [See Fig. (5.18)]. Only one ammeter need be read; but three are used for balance. The field current If is gradually increased from zero until the short-circuit armature current ISC is about twice the rated current. The graph between short-circuit armature current and field current gives the short-circuit characteristic (S.C.C.) as shown in Fig. (5.19).

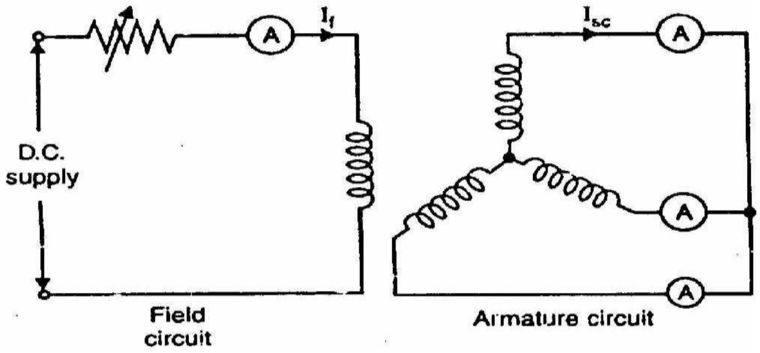


Fig. (4.16)

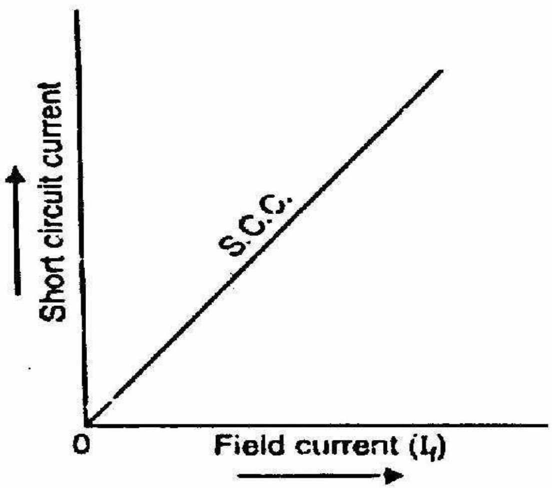


Fig. (4.17)

There is no need to take more than one reading because S.C.C. is a straight line passing through the origin. The reason is simple. Since armature resistance is much smaller than the synchronous reactance, the short-circuit armature current lags the induced voltage by very nearly 90°. Consequently, the armature flux and field flux are in direct opposition and the resultant flux is small. Since the resultant flux is small, the saturation effects will be negligible and the short circuit armature current, therefore, is directly proportional to the field current over the range from zero to well above the rated armature current.

**1. Synchronous Impedance Method**

In this method of finding the voltage regulation of an alternator, we find the synchronous impedance Zs (and hence synchronous reactance Xs) of the alternator from the O.C.C. and S.S.C. For this reason, it is called synchronous impedance method. The method involves the following steps:

(i) Plot the O.C.C. and S.S.C. on the same field current base as shown in Fig. Consider a field current $I_f$. The open-circuit voltage corresponding to this field current is $E_1$. The short-circuit armature current corresponding to field current If is $I_1$. On short-circuit p.d. = 0 and voltage $E_1$ is being used to circulate the snort-circuit armature current $I_1$ against the synchronous impedance Zs. This is illustrated in Fig.

$E_1 = I_1Z_1$ or

$Z_s = E_1$ (open circuit) / $I_1$ (short circuit)

Note that E1 is the phase value and so is $I_1$.

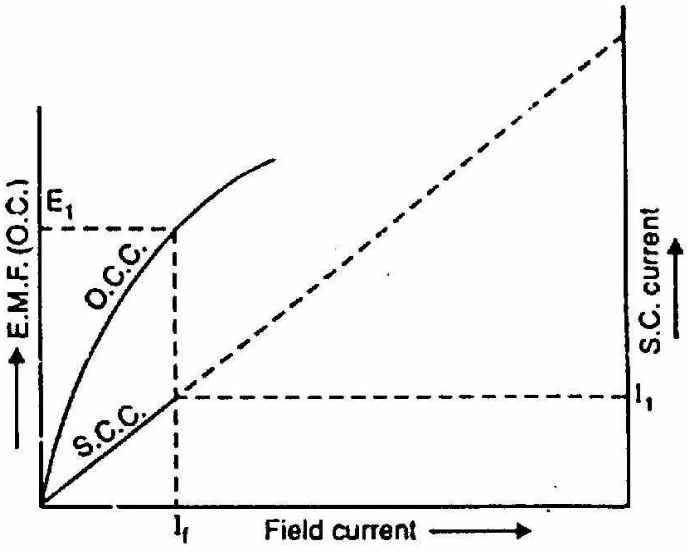


Fig. (4.18)

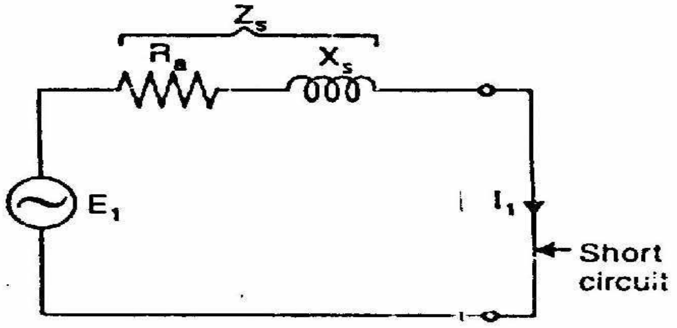


Fig. (4.19)

(ii) The armature resistance can be found as explained earlier.

Synchronous reactance, $X_s = \sqrt{Z_s{}^2 - R_a{}^2}$

(iii) Once we know Ra and Xs, the phasor diagram can be drawn for any load and any p.f. Fig. (5.13) shows the phasor diagram for the usual case of inductive load; the load p.f. being cosϕ lagging. Note that in drawing the phasor diagram, current Ia has been taken as the reference phasor. The $I_aR_a$ drop is in phase with $I_a$ while $I_aX_s$ drop leads $I_a$ by 90°. The phasor sum of V, $I_aR_a$ and $I_aX_s$ gives the no-load e.m.f. $E_0$.

$$E_0 = \sqrt{(OB)^2 + (BC)^2}$$

$$E0 = \sqrt{(V\cos\phi + Ia\ Ra)^2 + (V\sin\phi + Ia\ Xs)^2}$$

$$\%\ \text{Voltage regulation} = \frac{E_0 - V}{V} \times 100$$

**Drawback**

This method if easy but it gives approximate results. The reason is simple. The combined effect of $X_L$ (armature leakage reactance) and $X_{AR}$ (reactance of armature reaction) is measured on short-circuit. Since the current in this condition is almost lagging 90°, the armature reaction will provide its worst demagnetizing effect. It follows that under any normal operation at, say 0.8 or 0.9 lagging power factors will produce error in calculations. This method gives a value higher than the value obtained from an actual load test. For this reason, it is called pessimistic method.

**Solved Problems**

**1.** The coil span for the stator winding of an alternator is 120° (electrical). Find the chording factor of the winding.

**Solution:** chording angle, α = 180 – coil span = 180 -120 = 60

Chording factor, $K_c = \cos(\alpha/2) = \cos(60/2) = 0.866$.

**2.** Calculate the distribution factor for a 36-slot, 4-pole, single layer 3-phase winding.

**Solution:** number of slots per pole , n= 36/4 = 9

Number of slots per pole per phase, m = n/Number of phases = 9/3 = 3

Angular displacement between the slots, β = 180/n = 180/9 =20° (electrical)

Distribution factor, $K_d = \frac{\sin(m\beta/2)}{m\times sin(\beta/2)} = \frac{\sin(3*20/2)}{3\times sin(20/2)} = 0.96$

**3.** A 3-phase, 8-pole, 750 rpm star- connected alternator has 72 slots on the armature. Each slot has 12 conductors and winding is short chorded by 2 slots. Find the induced e.m.f between lines, given the flux per pole is 0.06 wb.

**Solution:** flux per pole, ϕ = 0.06 wb

Frequency, f= PN/120 = 8*750/120 = 50 Hz

Number of conductors connected in series per phase,

$Z_p$ = Number of conductors per slot * number of slots/Number of phases

$Z_p$ = 12*72/3 =288

Number of turns per phase, T =$Z_p$/2 = 288/2 =144

Number of slots per pole, n= 72/8 = 9

Number of slots per pole per phase, m = n/3 = 9/3= 3

Angular displacement between the slots, β = 180/n = 180/9 =20

Distribution factor, $K_d = \frac{\sin(m\beta/2)}{m\times sin(\beta/2)} = \frac{\sin(3*20/2)}{3\times sin(20/2)} = 0.96$

Chording angle, $\alpha = 180 * 2/9 = 40$

Pitch factor, $K_p = \cos(\alpha/2) = \cos 20 = 0.94$

Induced e.m.f between lines, $E_L = \sqrt{3} * 4.44\ K_pK_d\ f\ \phi\ T$ volts

$E_L = \sqrt{3} * 4.44 * 0.96 * 0.94 * 0.06 * 50 * 144 = 2{,}998$ V

**4.** An 8-pole, 3-phase, 60 spread, double layer winding has 72 coils in 72 slots. The coils are short pitched by two slots. Calculate the winding factor for the fundamental and third harmonic.

**Solution:** number of slots per pole, n =72/8 =9

Number of slots per pole per phase, m= n * phase spread / 180 = 9*60/180=3

Angular displacement between the slots, $\beta = 180/n = 180/9 = 20^o$ (electrical)

Coil span = 180 * coil span in terms of slots/ number of slots per pole

$= 180 * (9-2)/9 = 140^o$

Chording angle, $\alpha = 180^o$ – coil span 180 -140 =40

For the fundamental component

Distribution factor, $K_d = \frac{\sin(m\beta/2)}{m \times sin(\beta/2)} = \frac{\sin(3*20/2)}{3 \times sin(20/2)} = 0.96$

Pitch factor, $K_p = \cos(\alpha/2) = \cos(40/2) = 0.94$

Winding factor, $K_w = K_d * K_p = 0.96 * 0.94 = 0.9$

For the third harmonic component (i.e. r =3)

Distribution factor, $K_{d3} = \frac{\sin(rm\beta/2)}{m \times sin(r\beta/2)} = \frac{\sin(3*3*20/2)}{3 \times sin(3*20/2)} = 0.666$

Pitch factor, $K_{p3} = \cos(r\alpha/2) = \cos(3*40/2) = 0.5$

Winding factor, $K_{w3} = K_{d3} * K_{p3} = 0.666 * 0.5 = 0.333$

**5.** Calculate the rms value of the induced emf per phase of a 10-pole, 3-phase, 50 Hz alternator with 2 slots per pole per phase and 4 conductors per slot in two layers. The coil span is $150^o$. The flux per pole has a fundamental component of 0.12 wb and a 20 % third harmonic component.

**Solution:** number of slots/pole/phase, m=2

Number of slots/pole, n = 2 * 3 = 6

Number of slots/phase = 2*10 =20

Number of conductors connected in series, $Z_p = 20 * 4 = 80$

Number of series turns/ phase, $T_{ph} = Z_p/2 = 80/2 = 40$

Angular displacement between adjacent slots, $\beta = 180/n = 180/6 = 30^o$

Distribution factor, $K_d = \frac{\sin(m\beta/2)}{m \times sin(\beta/2)} = \frac{\sin(3*30/2)}{3 \times sin(30/2)} = 0.966$

Coil span factor, $K_p = \cos(\alpha/2) = \cos((180-150)/2) = \cos 15 = 0.966$

Induced emf per phase (fundamental component),

$E_1 = 4.44\ K_{c1}K_{d1}\phi_1 f T_{ph}$
$E_1 = 4.44 * 0.966 * 0.966 * 0.12 * 50 * 40 = 994.4$ V

For third harmonic component of flux

Distribution factor, $K_{d3} = \frac{\sin(mr\beta/2)}{m \times sin(r\beta/2)} = \frac{\sin(2*3*30/2)}{2 \times sin(3*30/2)} = 0.707$

Coil span factor, $K_{p3} = \cos(3\alpha/2) = \cos(3*(180-150)/2) = \cos 45 = 0.707$

Frequency = 3 * 50 = 150
Flux per pole, $\phi_3 = 1/3 * 0.12 * 20/100 = 0.008$ wb

Induced emf per phase (third harmonic component),

$E_3 = 4.44\ K_{p3}K_{d3}\phi_3 f_3 T_{ph}$
$E_1 = 4.44 * 0.707 * 0.707 * 0.008 * 150 * 40 = 106.56$ V

Induced emf per phase, $E_p = \sqrt{(E_{1ph})^2 + (E_{3ph})^2} = \sqrt{(994.4)^2 + (106.56)^2} = 1{,}000V$

**6**. A 3-phase, star connected, 1,000 kva, 11000 v has rated current of 52.5 A. The ac resistance of the winding per phase is 0.45 Ω. The test results are given below:

OC Test: field current = 12.5 A, voltage between lines = 422 V

SC Test: field current = 12.5 A, line current = 52.5 A

Determine the full-load voltage regulation of the alternator (a) 0.8 pf lagging and (b) 0.8 pf leading.

**Solution:** Phase voltage, $V_P = V_L/\sqrt{3} = 11000/\sqrt{3} = 6{,}351$ V

Full-load current, $I_p = I_L = 52.5$ A

Effective resistance per phase, $R_e$ = AC resistance = 0.45 Ω

Synchronous impedance per phase, $Z_s$ = OC phase voltage / SC current per phase

$= 422/(\sqrt{3} * 52.5) = 4.64\ \Omega$

Synchronous reactance, $X_s = \sqrt{Z_s^2 - R_e^2} = \sqrt{4.64^2 - 0.45^2} = 4.62\ \Omega$

**(a)** At 0.8 pf lagging, cos ϕ = 0.8 and sin ϕ = 0.6

Open-circuit phase voltage, $Eop = \sqrt{(V_p \cos\phi + I_p R_e)^2 + (V_p \sin\phi + I_p X_s)^2}$

$$Eop = \sqrt{(6{,}351 * 0.8 + 52.5 * 0.45)^2 + (6{,}351 * 0.6 + 52.5 * 4.62)^2}$$

$E_{op} = 6{,}518$ V

Percentage regulation = $(E_{op} - V_p)/V_p * 100 = (6{,}518 - 6{,}351)/6{,}351 * 100$

$= 2.628\ \%$

**(b)** At 0.8 pf leading cos ϕ = 0.8 and sin ϕ= 0.6

Open-circuit phase voltage, $Eop = \sqrt{(V_p \cos\phi + I_p R_e)^2 + (V_p \sin\phi - I_p X_s)^2}$

$$\text{Eop} = \sqrt{(6{,}351 * 0.8 + 52.5 * 0.45)^2 + (6{,}351 * 0.6 - 52.5 * 4.62)^2}$$

$E_{op}$ = 6,228 V

Percentage regulation = $(E_{op} - V_p)/V_p$ * 100 = (6,228-6,351)/6,351 * 100

= -1.94 %

**7.** The no-load excitation of an alternator required to give rated voltage is 100 A. In a short circuit test with full load current flowing in the armature, the field excitation was 80 A. Determine the approximate excitation that will be required to give full load current at 0.8 pf lag and at the rated terminal voltage.

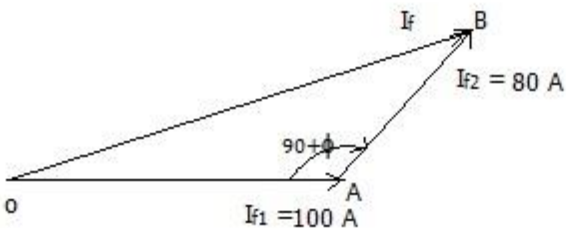
**Solution:** Field current required to give full-load rated voltage on open circuit, $I_{f1}$ = 100 A

Field current required to give full-load current on short circuit in armature, $I_{f2}$=80A

To find the field current, required to give full-load current at 0.8 pf lag and at the rated terminal voltage draw OA equal to 100A, then draw AB equal to 80A making an angle (90+ϕ) with OA where $\phi = \cos^{-1} 0.8$. The required field current will be OB, the phasor sum of OA and AB. The required field current $I_f$to give full-load current at 0.8 pf lag at the rated terminal voltage,

$$\text{OB} = OB = \sqrt{(OA + AC)^2 + CB^2} = \sqrt{(OA + AB\sin\emptyset)^2 + (AB\cos\emptyset)^2}$$

$$= \sqrt{(100 + 80 * 0.6)^2 + (80 * 0.8)^2} = 161.25\ A$$



**8.** A 3-phase star connected salient pole synchronous generator is driven at a speed near synchronous with the field circuit open, and the stator is supplied from a balanced 3-phase supply. Voltmeter connected across the line gave minimum and maximum readings of 2,800 and 2,820 volts. The line current fluctuated between 360 and 275 amperes. Find the direct and quadrature axis synchronous reactances per phase. Neglect armature resistance.

**Solution:** maximum voltage = 2,820 volts

Minimum voltage = 2,800 volts

Maximum current = 360 A

Minimum current = 275 A

Direct axis synchronous reactance between lines = 2,820/275 = 10.25 Ω

Direct axis synchronous reactance per phase, $X_d = 10.25/\sqrt{3} = 5.92\ \Omega$

Quadrature axis synchronous reactance between lines = 2,800/360 = 7.778 Ω

Quadrature axis synchronous reactance per phase, $X_q = 7.778/\sqrt{3} = 4.5\ \Omega$

**9.** A 10 kva, 380 V, star-connected 3-phase salient pole alternator with direct and quadrature axis reactances of 12 Ω and 8 Ω respectively. The armature has a resistance of 1Ω per phase. The generator delivers rated load at 0.8 pf lagging with the terminal voltage being maintained at rated value. If the load angle is 16.15°, determine (i) the direct axis and quadrature axis components of armature current, (ii) excitation voltage of the generator.

**Solution:** Armature resistance, $R_e = 1\Omega$

Direct axis synchronous reactance, $X_d = 12\ \Omega$

Quadrature axis synchronous reactance, $X_q = 8\ \Omega$

Power factor, $\cos \phi = 0.8$

$\phi = \cos^{-1}0.8 = 36.87$

Load angle, $\delta = 16.15$

$\theta = \phi + \delta = 36.87 + 16.15 = 53.02$

Terminal voltage per phase, $V = 380/\sqrt{3} = 219.4$ V

Armature current, I = (KVA * 1000)/ ($\sqrt{3} * V_L$) = (10*1000)/ ($\sqrt{3}$*380) = 15.2A

Direct axis component of armature current, $I_d$ = I sin θ= 15.2 sin53.02=12.14 A

Quadrature axis component of armature current, $I_q$ = I cos θ

= 15.2 * cos 53.02=9.14A

Excitation voltage, $E_o$ = V cos δ+ $I_q$ $R_e$ + $I_dX_d$

= 219.4 cos 16.15 + 9.14 * 1 + 12.14 *12= 365.56 V

Excitation voltage,(line to line) = $\sqrt{3}$ * 365.56 = 633 V

## Assignment-Cum-Tutorial Questions

### A. Questions testing the remembering / understanding level of students

### *I) Objective Questions*

1. The rotor most suitable for turbo alternators which are designed to run at high speed is

   (A) Salient pole type **(B)** Non-salient pole type

   (C) Both (A) and (B) above (D) None of the above

2. Salient poles are generally used on

   (A) high speed prime movers only (B) medium speed prime movers only

   (C) low speed prime movers only **(D)** low and medium speed prime movers

3. Salient pole type rotors as compared to cylindrical pole type are

   (A) smaller in diameter and larger in axial length

   **(B)**larger in diameter and smaller in axial length

   (C) larger in diameter as well as axial length

   (D) small in diameter as well as axial length

4. The advantage of providing damper winding in alternators is

   (A) elimination of harmonic effects

(B) provide a low resistance path for the currents due to unbalancing of voltage

(C) increase stability

**(D)** all of the above

5. The voltage of field system for an alternator is usually

   **(A)**less than 200 V (B) between 200 V and 440 V

   (C) 400 V (D) more than 1 kV

6. The frequency of voltage generated in an alternator depends on

   (A) number of poles **(B)** number of poles and rotative speed

   (C) rotative speed (D) number of poles, rotative speed and type of winding

7. The permissible duration for which a generator of rated frequency 50 Hz can run at 46 Hz is

   (A) zero (B) one cycle **(C)** one second (D) one minute

8. The permissible range in supply frequency is

   **(A)** ± 2 % (B) ± 5 % (C) ± 10 % (D) ± 25 %

9. When a generator designed for operation at 60 Hz is operated at 50 Hz

   **(A)**operating voltage must be derated to (50/60) of its original value

   (B) operating voltage must be derated to $(50/60)^2$ of its original value

   (C) kVA rating can be upgraded to (60/50) of the rated value

   (D) the generator will not take any load

10. In alternators, the distribution factor is defined as the ratio of emfs of

    **(A)**distributed winding to concentrated winding

    (B) full pitch winding to distributed winding

    (C) distributed winding to full pitch winding

    (D) concentrated winding to distributed winding

11. Pitch factor is the ratio of the emfs of

**(A)**short pitch coil to full pitch coil (B) full pitch winding to concentrated winding

(C) full pitch winding to short pitch winding (D) distributed winding to full pitch winding

12. In synchronous alternator, which of the following coils will have emf closer to sine waveform?

(A) concentrated winding in full pitch coils (B) concentrated winding in short pitch coils

(C) distributed winding in full pitch coils **(D)** distributed winding in short pitch coils

13. In an alternator if the armature reaction produces demagnetisation of the main field, the power factor should be

**(A)** Zero, lagging load(B) Zero, leading load (C) Unity (D) None

14. In an alternator if the armature reaction produces magnetisation of the main field the power factor should be

(A) Zero, lagging load**(B)** Zero, leading load (C) Unity (D) None

15. For an alternator when the power factor of the load is unity

(A) the armature flux will have square waveform

(B) the armature flux will be demagnetising

**(C)**the armature flux will be cross-magnetising

(D) the armature flux will reduce to zero

16. The effect of cross magnetization in an alternator field is to make the output

(A) true sinusoidal **(B)** non-sinusoidal (C) harmonic free (D) none of the above

17. A three phase alternator has a phase sequence of RYB for its three output voltages. In case the field current is reversed, the phase sequence will become

(A) RBY **(B)** RYB (C) YRB (D) none of the above

18. One of the advantages of distributing the winding in alternator is to

(A) reduce noise (B) save on copper

**(C)**improve voltage waveform (D) reduce harmonics

19. The advantage of a short pitch winding is

(A) low noise (B) increased inductance

**(C)**suppression of harmonics (D) reduced eddy currents

20. In case of a uniformly distributed winding, the value of distribution factor is

**(A)** 0.995 (B) 0.80 (C) 0.75 (D) 0.50

21. For alternator having fractional pitch of 5/6 the coil span is

(A)90° (B)120° **(C)**150° (D)180°

22. The regulation of an alternator is likely to be negative in case of

(A) high speed alternators (B) slow speed alternators

(C) lagging power factor of the load **(D)** leading power factor of the load

23. A magnetisation curve represents the relationship between

(A) reactive and non-reactive components of voltage

**(B)**exciting currents and terminal voltage

(C) power factor and terminal voltage

(D) magnetic flux and armature current

24. Which of the following method is likely to give the voltage regulation more than the actual value?(*pessimistic method)*

**(A)** Synchronous reactance method (B) MMF method

(C) Zero power factor method (D) None of the above

25. Which of the following method is likely to give the voltage regulation less than the actual value?(*optimistic method*)

(A) Synchronous reactance method **(B)** MMF method

(C) Zero power factor method (D) None of the above

### *II) Descriptive Questions*

1. Explain the construction details of an alternator.
2. Explain the comparison of different types alternators based on rotor construction.
3. Explain the principle of operation of an alternator.
4. Explain about pitch factor for an alternator. Derive the expression for pitch factor.
5. Explain about distribution factor for an alternator. Derive the expression for distribution factor.
6. State the advantages and disadvantages of using short pitched winding and distributed winding in an alternator.
7. What are effects of harmonics on pitch and distribution factors?
8. Derive the expression for emf induced in an alternator.
9. Explain the procedure to conduct OC and SC tests for determining the regulation of an alternator.
10. Explain the synchronous impedance method (pessimistic method) for determining the regulation of an alternator.

## B. Question testing the ability of students in applying the concepts.

### *I) Objective Questions*

1. The frequency of voltage generated by an alternator having 8 poles and rotating at 250 rpm is

   (A) 60 Hz (B) 50 Hz (C) 25 Hz **(D)** 16 2/3 Hz

2. An alternator is generating power at 210 V per phase while running at 1500 rpm. If the need of the alternator drops to 1000 rpm, the generated voltage per phase will be

   (A) 180 V (B) 150 V **(C)** 140 V (D) 105 V

3. The number of electrical degrees passed through in one revolution of a six pole synchronous alternator is

   (A) 360 (B) 720 **(C)** 1080 (D) 2160

4. For 50 Hz system the maximum speed of an alternator can be

   (A) Approximately 3600 rpm (B) Approximately 3000 rpm

(C) 3600 rpm **(D)** 3000 rpm

5. The effective voltage in one phase of an alternator having 240 turns per phase, frequency of 60 Hz and flux per pole of $2.08 \times 10^6$ lines will be

(A) 332.5 V (B) 665 V **(C)** 1330 V (D) 2660 V

6. In an alternator if the winding is short pitched by 50 electrical degrees, its pitch factor will be

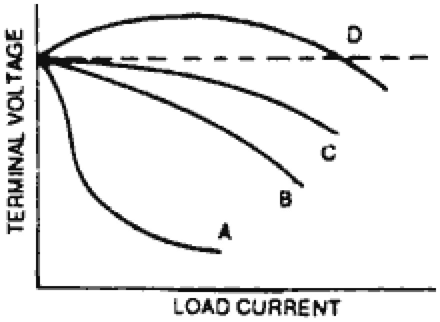
(A) 1.0 **(B)** 0.866 (C) 0.75 (D) 0.50

7. Fractional pitch to eliminate 7th harmonic from alternator emf is

(A) 7/6 **(B)** 6/7 (C) 6/5 (D) 3/5

**Questions 8 and9 refer to the following data:**

Voltage characteristic of an alternator is shown in figure.



8. Which curve represents the characteristics for leading power factor?

(A) A (B) B (C) C **(D)** D

9. The characteristic for unity power factor is represented by the curve marked

(A) A (B) B **(C)** C (D) D

10. An alternator has full load regulation of 4% when the power factor of the load is 0.8 lagging while alternator runs at 1500 rpm. The full load regulation of 1400 rpm for 0.8 pf lagging load will be

(A) 15/14 x 4 percent (B) 14/15 x 4 percent
**(C)** 4 percent (D) Depends on other factors also

11. The power output of an alternators is 100 kW. In order that the tangent of pf angle may be 0.8 lagging, the KVAR rating must be

i(A) 80 cosφ KVAR (B) 80 sin φ KVAR **(C)** 80 KVAR (D) -80 KVAR

***II) Descriptive Questions***

1. A 3 phase 16 pole alternator has a star connected winding with 144 slots and 10 conductors per slot. The flux per pole is 0.03Wb and the speed is 375 RPM. Find the frequency of generated voltage, the magnitude of phase voltage and line voltage. Assume full-pitched coil.
2. Find the value of Kd for an alternator with 9 slots per pole for the following cases:
   i. One winding in all the slots
   ii. One winding using only the first 2/3 of the slots /pole
   iii. Three equal windings placed sequentially in $60^0$group.
3. Calculate the voltage induced per phase in a 3-phase, 50 Hz, alternator having a flux per pole of 0.15wb. The numbers of conductors in series are 360. Assume full pitch coil with a distribution factor of 0.96?
4. A 4-pole, 50 Hz star-connected alternator has a flux per pole of 0.12 Wb. It has 4 slots per pole per phase, conductors per slot being 4. If the winding coil span is $150^0$, find the induced emf.
5. A 6-pole, 3-phase, 50 Hz alternator has 12 slots per pole and four conductors per slot. The winding is five-sixths pitch. The flux per pole is 1.5wb, the armature coils are all connected in series. The winding is star connected. Calculate the speed and induced e.m.f per phase.
6. A 3-phase, 6 pole, star connected alternator revolves at 1000 rpm. The stator has 90 slots and 8 conductors per slot. The flux per pole is 0.05Wb. Calculate the voltagegenerated by the machine if the winding factor is 0.96.
7. A 3-phase, 10 pole alternator has 2 slots per pole per phase on its stator with 10conductors per slot. The air gap flux is sinusoidally distributed and equals to 0.05wb. The stator has a coil span of $150^0$ electrical degrees. If the alternator isrunning at 600 r. p. m., calculate the
   emf generated per phase at no load.

8. An alternator on open circuit generates 360V at 60Hz when the field current is 3.6A. Neglecting saturation, determine the open circuit e.m.f. when the frequency is 40Hz and the field current is 2.4A.

9. A 120KVA, 300V, single phase alternator has the following parameters:
   armatureresistance = 0.5Ω
   synchronous reactance = 10Ω
   Calculate the percentage voltage regulation at full load at
   (a) unity power factor (b) 0.8 power factor lagging

10. A 1500 kVA, 6.6 kV, three phase, star connected alternator has a resistance of 0.5Ω/phase and a synchronous reactance of 5Ω/phase. Find its voltage regulation for (a) Unity power factor(b) 0.8 power factor lagging (c) 0.8 power factor leading

**C. Questions testing the analyzing / evaluating /Creative ability of students**

1. The stator of a 3-Phase, 50Hz, 8 pole alternator driven at 750 rpm has 72 slots. Thewinding has been made with 36 coils having 10 turns per coil. Calculate the rms value ofinduced emf per phase if the flux per pole is 0.15 mwb and is sinusoidally distributed.Assume full pitch coils have been used on the stator.

2. A 200 kVA, 480 V, 50 Hz ,Y-connected Synchronous Generator with a ratedfield current of 5 A was tested, and the following data were obtained:
   Open circuit terminal voltage: 540 V (line-to-line).
   Short Circuit current : 300A
   When a DC voltage of 10 V was applied to two of its terminals, a current of 25A was
   measured. Find the value of Synchronous Reactance.

3. From the following test results, determine the voltage regulation of a 2000 V single phase alternator delivering a current of 100 A. at 0.8 p.f lag.
   **Test results:** Full load current of 100 A is produced on short circuit by a field excitation of 2.5A. An emf of 500V is produced on open circuit by the same excitation the armature resistance is 0.8 ohms.

4. Find the synchronous impedance and reactance of an alternator in which a given field current produces an armature current of 200 A on short circuit and a generated e.m.f. of 50V on open circuit. The armature resistance is 0.1 ohm.
To what induced voltage must the alternator be excited if it is to deliver a load of 100 A at a pf of 0.8 lagging, with a terminal voltage of 200 V.

5. A 220 V, 50 Hz, 6 pole, star connected alternator with ohmicresistane of 0.06 ohm per phase, gave the following data for open circuit , short circuit characteristics:

| S.No. | Field current, $I_f$ (A) | Open circuit voltage, $E_f$ (V) | Short circuit current, $I_{SC}$ (A) |
|---|---|---|---|
| 1 | 0.2 | 29 | 6.6 |
| 2 | 0.4 | 58 | 13.2 |
| 3 | 0.6 | 87 | 20.0 |
| 4 | 0.8 | 116 | 26.5 |
| 5 | 1.0 | 146 | 32.4 |
| 6 | 1.2 | 172 | 40.0 |
| 7 | 1.4 | 194 | 46.3 |
| 8 | 1.8 | 232 | 59.0 |
| 9 | 2.2 | 262 | --- |
| 10 | 2.6 | 284 | --- |
| 11 | 3.0 | 300 | --- |
| 12 | 3.4 | 310 | --- |

Find the percentage voltage regulation at full load current of 40 A at power factor of 0.8 lag by emf method.

**PREVIOUS GATE/IES QUESTIONS:**

**1.** A three phase, salient pole synchronous motor is connected to an infinite bus. It is operated at no load a normal excitation. The field excitation of the motor is first reduced to zero and then increased in reverse direction gradually. Then the armature current. **GATE-2011**

(A) Increases continuously

(B) First increases and then decreases steeply
(C) First decreases and then increases steeply
(D) Remains constant

2. Distributed winding and short chording employed in AC machines will result in **GATE-2011**

(A) increase in emf and reduction in harmonics
(B) reduction in emf and increase in harmonics
(C) increase in both emf and harmonics
(D) reduction in both emf and harmonics

3. A synchronous motor is connected to an infinite bus at 1.0 pu voltage and draws 0.6 pu current at unity power factor. Its synchronous reactance is 1.0 pu resistance is negligible. MCQ 4.39 The excitation voltage (E) and load angle δ will respectively be **GATE-2012**

(A) 0.8 pu and 36.86c lag (B) 0.8 pu and 36.86c lead
(C) 1.17 pu and 30.96c lead (D) 1.17 pu and 30.96c lag

4. Keeping the excitation voltage same, the load on the motor is increased such that the motor current increases by 20%. The operating power factor will become **GATE-2012**

(A) 0.995 lagging (B) 0.995 leading (C) 0.791 lagging (D) 0.848 leading

5. A three-phase synchronous motor connected to ac mains is running at full load and unity power factor. If its shaft load is reduced by half, with field current held constant, its new power factor will be **GATE-2013**

(A) unity (B) leading (C) lagging (D) dependent on machine parameters

6.. A synchronous generator is feeding a zero power factor (lagging) load at rated current. The armature reaction is

**GATE-2013**

(A) magnetizing (B) demagnetizing
(C) cross-magnetizing (D) ineffective

7. A 3-phase, 400 V, 5 kW, star connected synchronous motor having an internal reactance of 10 Ω is operating at 50% load, unity p.f. Now, the excitation is increased by 1%. What will be the new load in percent, if the power factor is to be kept same ? Neglect all losses and consider linear magnetic circuit.

**GATE-2014**

(A) 67.9% B) 56.9% (C) 51% (D) 50%

8. In relation to the synchronous machines, which on of the following statements is false ? **GATE-2014**

(A) In salient pole machines, the direct-axis synchronous reactance is greater than the quadrature-axis synchronous reactance.

(B) The damper bars help the synchronous motor self start.

(C) Short circuit ratio is the ratio of the field current required to produces the rated voltage on open circuit to the rated armature current.

(D) The V-cure of a synchronous motor represents the variation in the armature current with field excitation, at a given output power.

9. A 400 V, 50 kVA, 0.8 p.f. leading 3-connected, 50 Hz synchronous machine has a synchronous reactance of 2 Ω and negligible armature resistance. The friction and windage losses are 2 kW and the core loss is 0.8 kW. The shaft is supplying 9 kW load at a power factor of 0.8 leading. The line current drawn is

**GATE-2015**

(A) 12.29 A (B) 16.24 A (C) 21.29 A (D) 36.88 A

10. A 500 MW, 3-phase, Y-connected synchronous generator has a rated voltage of 21.5 kV at 0.85 p.f. The line current when operating at full load rated conditions will be **GATE-2016**

(A) 13.43 kA (B) 15.79 kA (C) 23.25 kA (D) 27.36 Ka

11. A stand alone engine driven synchronous generator is feeding a partly inductive load. A capacitor is now connected across the load to completely nullify the inductive current. For this operating condition. **GATE-2016**

(A) the field current and fuel input have to be reduced

(B) the field current and fuel input have to be increased

(C) the field current has to be increased and fuel input left unaltered
(D) the field current has to be reduced and fuel input left unaltered

# UNIT-V

# SINGLE-PHASE INDUCTION MOTORS

## 5.1 INTRODUCTION:

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

## 5.2 TYPES OF SINGLE-PHASE MOTOR:

The Single phase motors may be of the following types:

1. **Single-phase Induction Motors:**
    A. Split-phase motors
        (i) Resistance-start motor

- (ii) Capacitor-start motor
  - (iii) Permanent-split (single-value) capacitor motor
  - (iv) Two-value capacitor motor.
- B. Shaded-pole induction motor.
- C. Reluctance-start induction motor.
- D. Repulsion-start induction motor.

## 5.3 SINGLE-PHASE INDUCTION MOTORS

**Applications:**

- Single phase induction motors are in very wide use in industry especially in fractional horse-power field.
- They are extensively used for electrical drive for low power constant speed apparatus such as machine tools, domestic apparatus and agricultural machinery in circumstances where a three-phase supply is not readily available.
- There is a large demand for single-phase induction motors in sizes ranging from a fraction of horse-power up to about 5 H.P.

## 5.4 CONSTRUCTION OF SINGLE PHASE INDUCTION MOTOR:

Single phase induction motor is very simple and robust in construction. The stator carries a distributed winding in the slots cut around the inner periphery. The stator conductors have low resistance and they are winding called Starting winding is also mounted on the stator. This winding has high resistance and its embedded deep inside the stator slots, so that they have considerable inductance. The rotor is invariably of the squirrel cage type. In practice, in order to convert temporarily the single phase motor into two-phase motor, auxiliary conductors are placed in the upper layers of stator slots. The auxiliary winding has a centrifugal switch in series with it. The function of the switch is to cut off the starting winding, when the rotor has accelerated to about 75% of its rated speed. In capacitor-0start motors, an electrolytic capacitor of suitable capacitance value is also incorporated in the starting winding circuit.

The main stator winding and auxiliary (or starting) winding are joined in parallel, and there is an arrangement by which the polarity of only the starting winding can be reversed. This is necessary for changing the direction of rotation of the rotor.

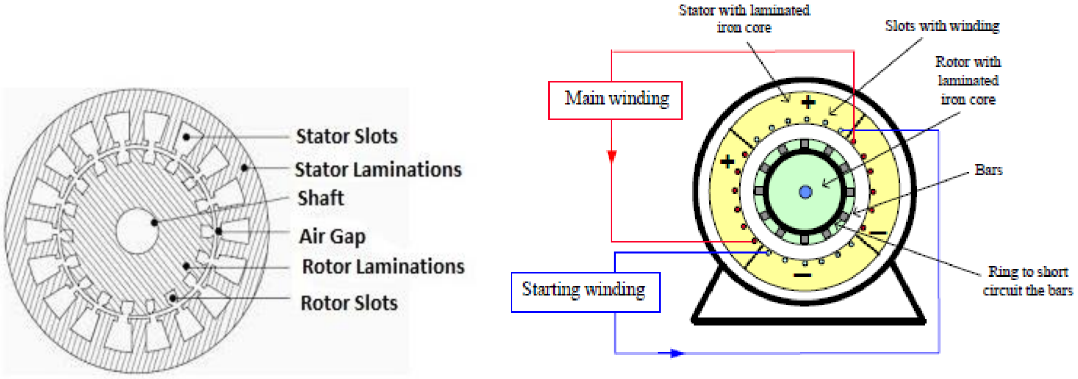


**Fig**: 5.1

A 1-phase induction motor is similar to a 3-phase squirrel cage induction motor in physical appearance. The rotor is same as that employed in 3-phase squirrel cage induction motor. There is uniform air gap between stator and rotor but no electrical connection between them. A 1-phase motor can be wound for any even number of poles.

The stator windings are distinctively different in two aspects.

i. First, 1-phase motors are usually provided with concentric coils as shown in figure: 4.2

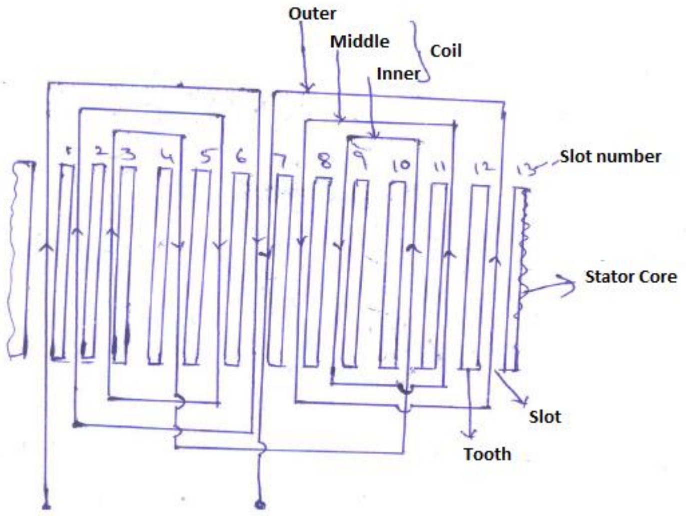


**Fig**: 5.2

In this diagram the coils appear to have only one turn of wire, but in practice each coil has many turns. With concentric coils, the number of turns per coil can be adjusted to provide an approximately sinusoidal distribution of m.m.f along the air gap.

ii. Second, 1-phase cage motors normally have two stator windings, which are in space quadrature with respect to each other. In motors that operate with both windings energized, the winding with the heaviest wire is known as the main winding and the other is called the auxiliary winding. In most of the motors the main winding is placed at the bottom of the slots and the starting winding on top but shifted $90^0$ from the running winding.

Although single phase induction motor is more simple in construction and is cheaper than a 3-phase induction motor of the same frame size, it is less efficient and it operates at lower power factor.

### 5.5 WORKING OF SINGLE-PHASE INDUCTION MOTOR:

That a single phase induction motor is inherently not self-staring can be shown easily.

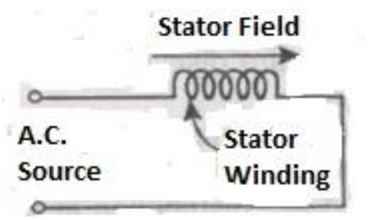


**Fig**: 5.3

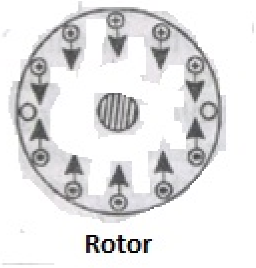


**Fig**:5.4

Consider a single phase induction motor whose rotor is at rest. Let a single phase a.c. source be connected to the stator winding (it is assumed that there is no starting winding). Let the stator be wound for two poles.

When power supply for the stator is switched on, an alternating current flows through the stator winding. This sets up an alternating flux. This flux crosses the air gap and links with the rotor conductors. By electromagnetic induction e.m.f.'s are induced in the rotor conductors. Since the rotor forms a closed circuit, currents are induced in the rotor bars. Due to interaction between the rotor induced currents and the stator flux, a torque is produced. It is readily seen that if all rotor conductors in the upper half come under a stator N pole, all rotor conductors in the lower half come under a stator S pole. Hence the upper half of the rotor is subjected to a torque which tends to rotate it in one direction and the lower half of the rotor is acted upon by an equal torque which tends to rotate it in the opposite direction. The two equal and opposite torques cancel out, with the result that the net driving torque is zero. Hence the rotor remains stationary. Thus the single phase motor fails to develop starting torque.

This argument holds good irrespective of the number of stator poles and the polarity of the stator winding. The net torque acting on the rotor at standstill is zero.

If, however, the rotor is in motion in any direction when supply for the stator is switched on, it can be shown that the rotor develops more torque in that direction. The net torque then, would have non-zero value, and under its impact the rotor would speed up in its direction.

The analysis of the single phase motor can be made on the basis of two theories:

i. Double revolving field theory, and
**ii.** Cross field theory.

### 5.5.1 DOUBLE REVOLVING FIELD THEORY:

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

As shown in figure: (a) let the alternating flux have a maximum value of $\phi_m$. Its component fluxes A and B will each equal to $\phi_m/2$ revolving in anti-clockwise and clockwise directions respectively.

After some time, when A and B would have rotated through angle +ϴ and – ϴ, as in figure: (b), the resultant flux would be

$$= 2*\frac{\phi_m}{2}\cos\frac{2\theta}{2} = \phi_m \cos\theta$$

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

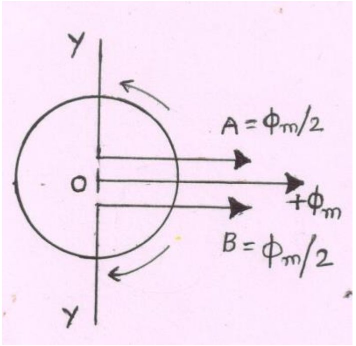


**Fig**: 5.5(a)

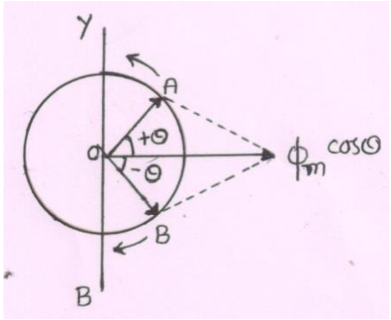


**Fig**: 5.5(b)

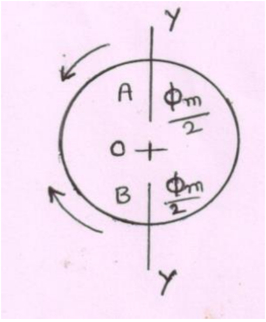


**Fig**:5.5 (c)

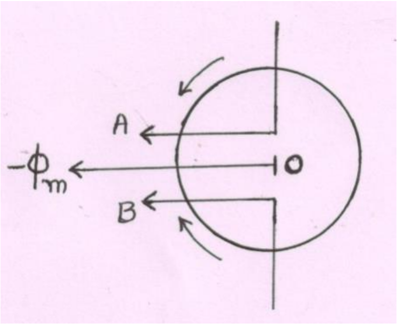


**Fig**: 5.5 (d)

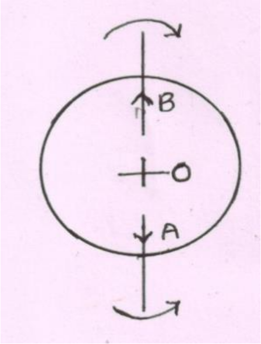


**Fig**: 5.5 (e)

After half a cycle, fluxes A and B will have a resultant of $-2*\frac{\phi_m}{2} = -\phi_m$. After three quarters of a cycle, again the resultant is zero, as shown in figure: (e) and so on. If we plot the values of resultant flux against $\Theta$ between limits $\Theta=0^0$ to $\Theta=360^0$, then a curve similar to the one shown in figure: (f) is obtained. That is why an alternating flux can be looked upon as composed of two revolving fluxes, each of half the value and revolving synchronously in opposite directions.

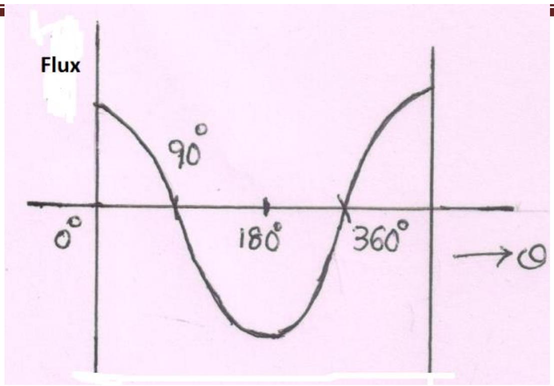


**Fig**: 5.5 (f)

It may be noted that if the slip of the rotor is S with respect to the forward rotating flux (i.e. one which rotates in the same direction as rotor) then its slip with respect to the backward rotating flux is (2-S).

Each of the two component fluxes, while revolving round the stator, cuts the rotor, induces an e.m.f. and this produces its own torque. Obviously, the two torques (called forward and backward torques ) are oppositely-directed, so that the net or resultant torques is equal to their difference as shown in fig: 5.5(g)

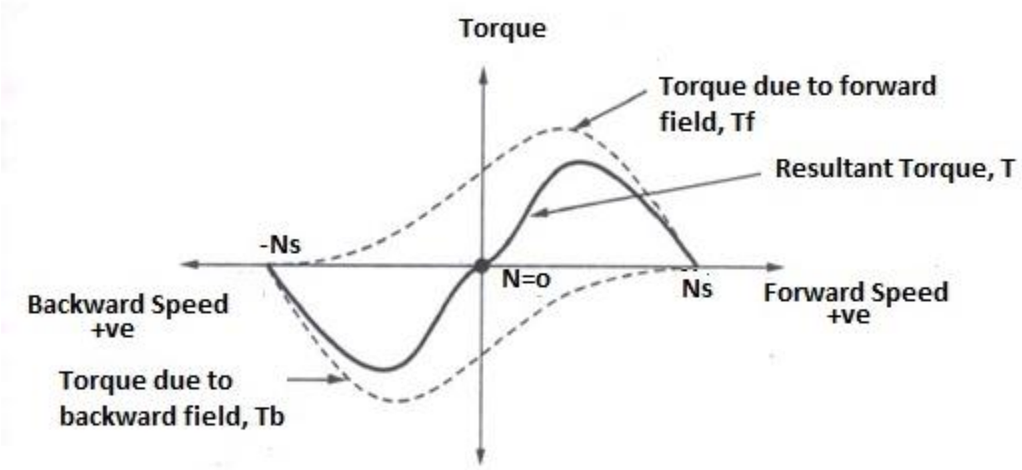


**Fig**: 5.5(g) Torque-Speed characteristics

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

If N is the rotor r.p.s., then torque is given by , $T_g = \frac{1}{2\Pi N}\left(\frac{1-S}{S}\right) I_2^2 R_2$

Now, $N = N_s\,(1-S)$

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

Hence, the forward and backward torques are given by

$$T_f = k\,\frac{I_2^2\,R_2}{S} \qquad \text{and} \qquad T_b = -k\,\frac{I_2^2\,R_2}{(2-S)}$$

or $$T_f = \frac{I_2^2\,R_2}{S}\ \text{synch. Watt} \qquad \text{and} \qquad T_b = -\,\frac{I_2^2\,R_2}{(2-S)}\ \text{synch. Watt}$$

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

Fig: 4.5(g) shows both torques and the resultant torque for slips between zero and +2. At standstill, S=1 and (2-S) =1. Hence, $T_f$ and $T_b$ are numerically equal but, being oppositely directed, produce no resultant torque. That explains why there is no starting torque in a single-phase induction motor.

However, if the rotor is started somehow, say, in the clockwise direction, the clockwise torque starts increasing and, at the same time, the anticlockwise torque starts decreasing. Hence, there is a certain amount of net torque in the clockwise direction which accelerates the motor to full speed.

## 5.6 EQUIVALENT CIRCUIT:

The equivalent circuit of a single phase induction motor can be developed on the basis of two revolving field theory. To develop the equivalent circuit it is necessary to consider standstill or blocked rotor conditions.

The motor with a blocked rotor merely acts like a transformer with its secondary short circuited and its equivalent circuit will be as shown in fig: 4.6 (a), $E_m$ being e.m.f. induced in the stator.

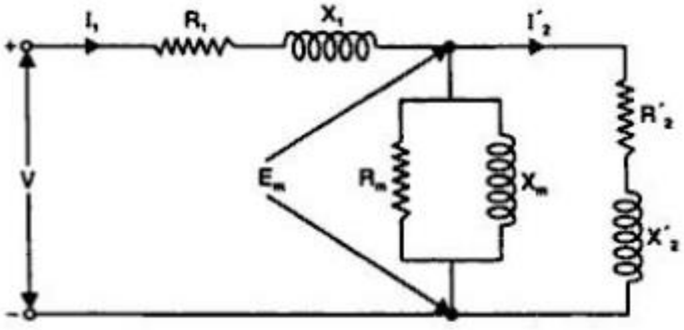


**Fig**:5.6 (a) Equivalent Circuit of a Single Phase Induction Motor

The motor may now be viewed from the point of view of the two revolving field theory. The two flux components induce e.m.f. $E_{mf}$ and $E_{mb}$ in the respective stator winding. Since at standstill the two oppositely rotating fields are of same strength, the magnetizing and rotor impedances are divided into two equals halves connected in series as shown in figure:5.6(b)

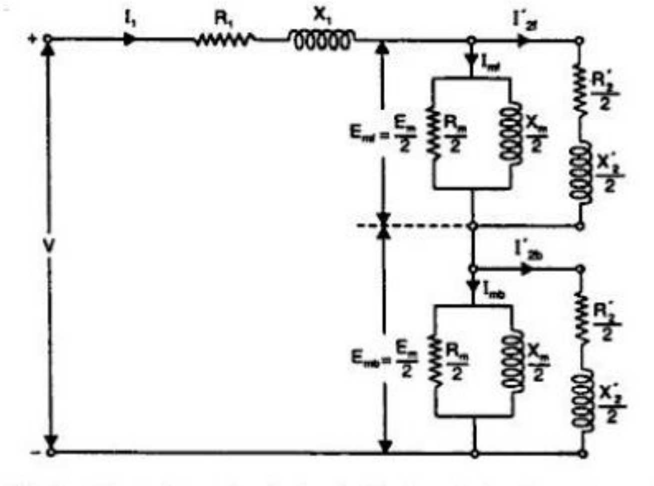


**Fig**:5.6 (b) Equivalent Circuit of Single Phase Induction Motor at Standstill on the basis of Two Revolving Field Theory

When the rotor runs at speed N with respect to forward field, the slip is S w.r.t. forward field and (2-S) w.r.t. backward field and the equivalent circuit is as shown in fig:5.6(c)

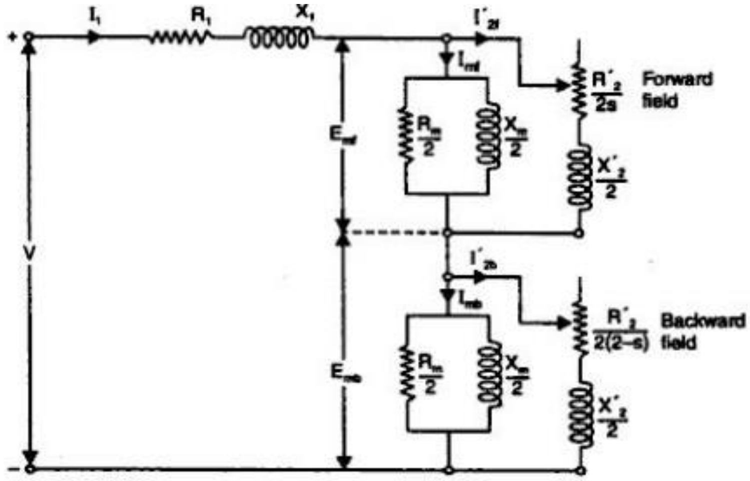


**Fig**:5.6 (c) Equivalent Circuit of a Single Phase Induction Motor Under Normal Operating Conditions

If the core losses are neglected the equivalent circuit is modified as shown in fig:5.6(d). The core losses, here, are handled as rotational losses and subtracted from the power converted into mechanical power; the amount of error thus introduced is relatively small.

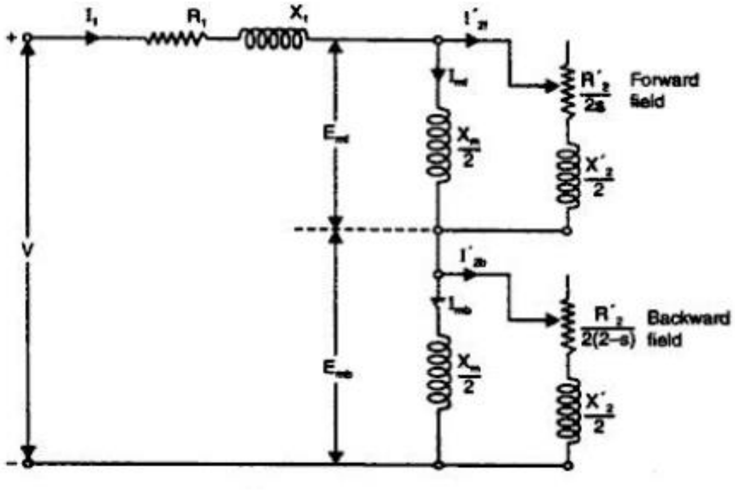


**Fig**:5.6 (d) Approximate Equivalent Circuit of a Single Phase Induction Motor Under Normal Operating Conditions

## 5.7 STARTING METHODS OF SINGLE-PHASE INDUCTION MOTORS:

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

a) Split-phase starting.
b) Shaded-pole starting.
c) Repulsion-motor starting and
d) Reluctance starting.

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

(i) Torque-speed characteristic of load from standstill to the normal operating speed.
(ii) The duty cycle and
(iii)The starting and running line-current limitations as imposed by the supply authorities.

## 5.7 (a) SPLIT-PHASE STARTING:

Single-phase induction motors employing this method of starting are called Split-phase motors. All the split-phase motors have two stator windings, a main (or running) winding and an auxiliary (or starting) winding. Both these windings are connected in parallel but their magnetic axes are space displaced by $90^0$ electrical.

It is known that when two windings spaced $90^0$ apart on the stator, are excited by two alternating e.m.f. that are $90^0$ displaced in time phase, a rotating magnetic field is produced. If two windings so placed are connected in parallel to a single phase source, the field produced will alternate but will not revolve since the two windings are equivalent to one single phase winding. If impedance is connected in series with one of these windings, the currents may be made to differ in time phase, thereby producing a rotating field. This is the principle of phase splitting. Split phase motors are of following types.

1. Resistor-split phase motors
2. Capacitor split-phase motors
3. Capacitor start and run motors
4. Capacitor-run motors

## 5.7.1 RESISTOR SPLIT-PHASE MOTORS:

The stator of a split-phase induction motor is provided with an auxiliary or starting winding S in addition to the main or running winding M. The starting winding is located 90° electrical from the main winding [See figure: 5.8(a)] and operates only during the brief period when the motor starts up. The two windings are so designed that the starting winding S has a high resistance and relatively small reactance while the main winding M has relatively low resistance and large reactance as shown in the schematic connections in figure: 5.8(b). Consequently, the currents flowing in the two windings have reasonable phase difference (25° to 30°) as shown in the phasor diagram in figure: 4.8(c).

**Operation**

(i) When the two stator windings are energized from a single-phase supply, the main winding carries current $I_m$ while the starting winding carries current $I_s$

(ii) Since main winding is made highly inductive while the starting winding highly resistive, the currents $I_m$ and $I_s$ have a reasonable phase angle a (25° to 30°) between them as shown in figure. Consequently, a weak revolving field approximating to that of a 2-phase machine is produced which starts the motor. The starting torque is given by;

$$Ts = k\, I_m\, I_s \sin\phi$$

where k is a constant whose magnitude depends upon the design of the motor.

When the motor reaches about 75% of synchronous speed, the centrifugal switch opens the circuit of the starting winding. The motor then operates as a single-phase induction motor and continues to accelerate till it reaches the normal speed. The normal speed of the motor is below the synchronous speed and depends upon the load on the motor.

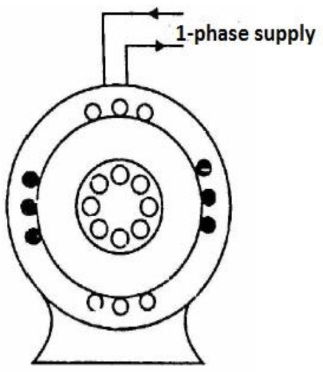
**Characteristics:**

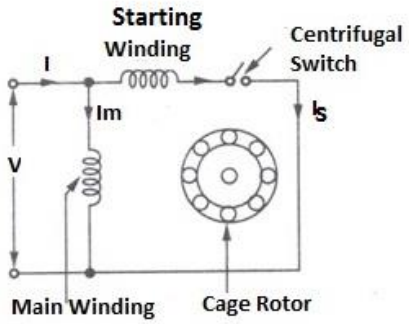
(i) The sinning torque is 15 to 2 times the full-loud torque mid (starting current is 6 to 8 times the full-load current.

(ii) Due to their low cost, split-phase induction motors are most popular single phase motors in the market.

(iii) Since the starting winding is made of fine wire, the current density is high and the winding heats up quickly. If the starting period exceeds 5 seconds, the winding may burn out unless the motor is protected by built-in-thermal relay. This motor is, therefore, suitable where starting periods are not frequent.

(iv) An important characteristic of these motors is that they are essentially constant-speed motors. The speed variation is 2-5% from no-load to full-load.





Schematic Diagram of Resistor-split phase motor

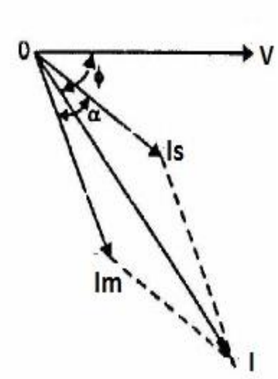


**Fig: 5.7(a)** **Fig: 5.7(b)** **Fig: 5.7(c)**

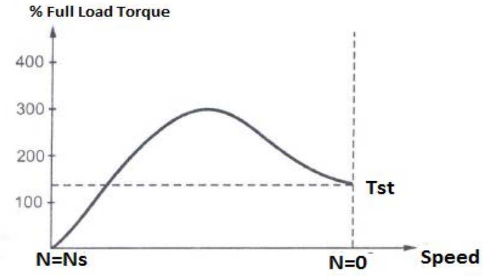


Fig: 5.7(d)

**Applications:**

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

a. Fans
b. washing machines
c. oil burners
d. Small machine tools etc.

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

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

The capacitor split-phase motor is identical to a resistor split-phase motor except that the starting winding has as many turns as the main winding. Moreover, a capacitor C is connected in series with the starting winding as shown in figure: 4.9(a).The value of capacitor is so chosen that $I_s$ leads $I_m$ by about 80° (i.e., ϕ ~ 80°) which is considerably greater than 25° found in resistor split-phase motor [See figure: 4.9(b).Consequently, starting torque ($T_s = k\ I_m\ I_s \sin\phi$) is much more than that of a split-phase motor Again, the starting winding is opened by the centrifugal switch when the motor attains about 75% of synchronous speed. The motor then operates as a single-phase induction motor and continues to accelerate till it reaches the normal speed.

## Characteristics

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

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

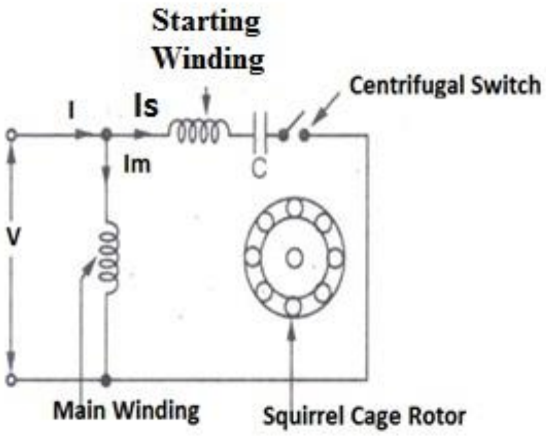


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**Fig:** 5.8(a)

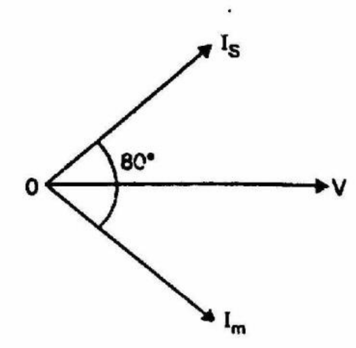


**Fig**: 5.8(b)

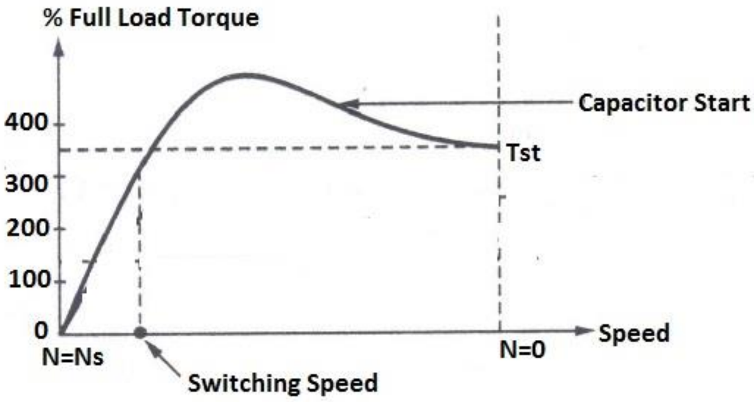


**Fig**: 5.8(c)

**Applications:**

Since the motors possess high-starting torque, these motors are used for

a. Refrigerators
b. Air-conditioners
c. Compressors
d. Reciprocating pumps
e. Other loads requiring high-starting torques.

The power rating of such motors lies between 120 W and 750W.

### 5.7.3 Capacitor-Start and Capacitor-Run motors:

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

(i) In one design, a single capacitor C is used for both starting and running as shown in fig: 4.10(a).This design eliminates the need of a centrifugal switch and at the same time improves the power factor and efficiency of the motor.

(ii) In the other design, two capacitors C1 and C2 are used in the starting winding as shown in fig: 4.10(b). The smaller capacitor C1 required for optimum running conditions is permanently connected in series with the starting winding. The much larger capacitor C2 is connected in parallel with C1 for optimum starting and remains in the circuit during starting. The starting capacitor C1 is disconnected when the motor approaches about 75% of synchronous speed. The motor then runs as a single-phase induction motor.

**Characteristics**

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

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

**Applications:**

a. Hospitals

b. Studios and

c. Other places where silence is important.

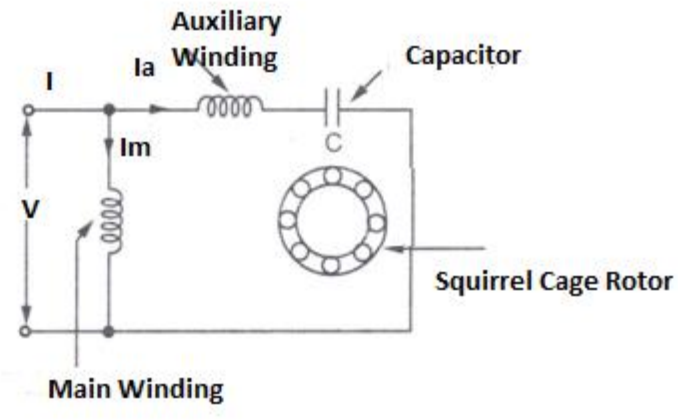


**Fig:** 5.9(a)

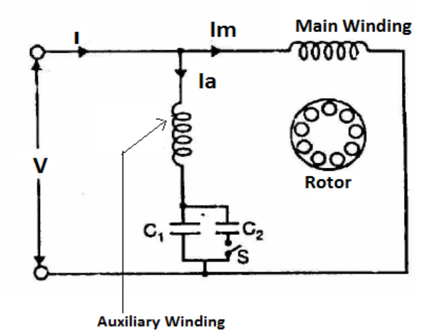


**Fig**: 5.9 (b)

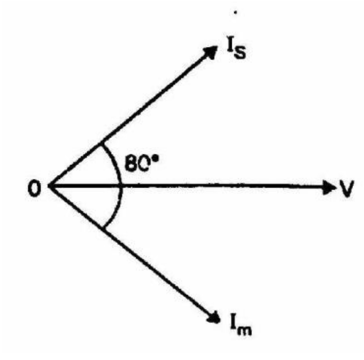


**Fig:** 5.9 (c)

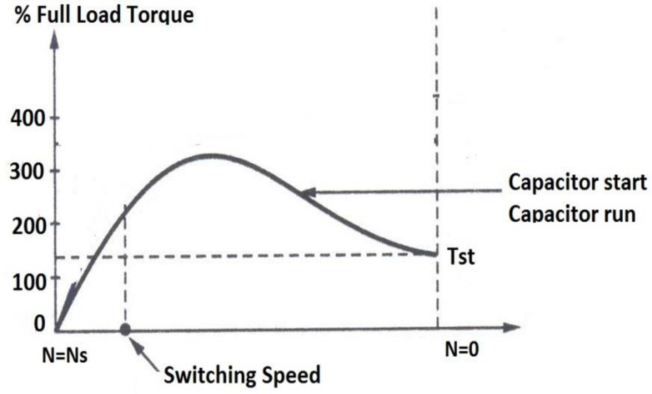


**Fig:** 5.9 (d)

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

### 5.7.4 Capacitor-run motors:

This motor is also called permanent split capacitor motor. The same capacitor is kept permanently in series with auxiliary winding both at starting and under running conditions as illustrated in figure: 4.10 (a). There is no centrifugal switch. At a particular desired load, the capacitor and auxiliary winding can be so designed as to result in $90^0$ time-phase displacement between the two winding currents. In such a case, the motor would operate as a balanced two phase induction motor, backward rotating flux would, therefore, be absent and the motor would have improved efficiency and better operating power factor. Since backward rotating field can be reduced to zero, the pulsating torque due to interaction between forward and backward rotating fields is absent and this results in a quiet motor.

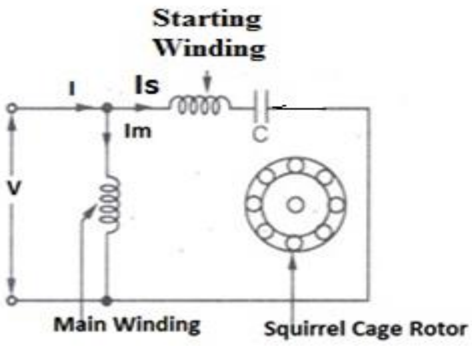


**Fig:** 5.10 (a)

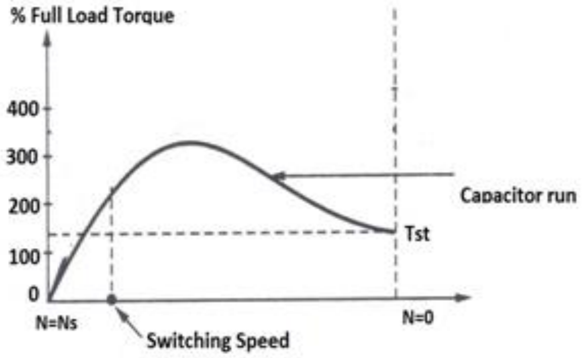


**Fig**: 5.10 (b)

In these motors, the value of permanent capacitor is so chosen as to obtain a compromise between the best starting and running conditions. A typical torque-speed characteristic is shown in fig: 5.10 (b)

These motors are used where quiet operation is essential as in

a. Offices
b. Class rooms
c. Theaters
d. Ceiling fans, in which the value of capacitance varies from 2 to 3µF.

## 5.8 Shaded-Pole Motor:

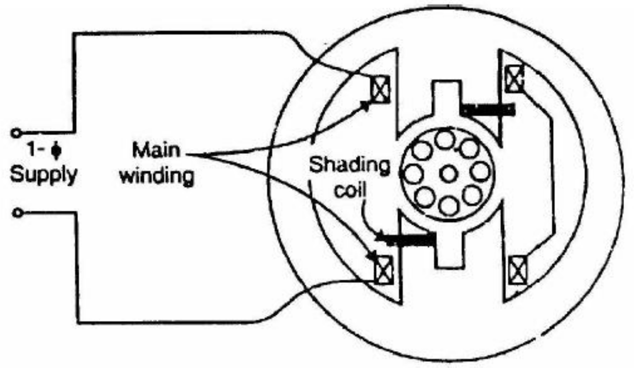


**Fig:** 5.11(a)

The shaded-pole motor is very popular for ratings below 0.05 H.P. (~40 W) because of its extremely simple construction. It has salient poles on the stator excited by single-phase supply and a squirrel cage rotor as shown in figure: 5.11(a). A portion of each pole is surrounded by a short-circuited turn of copper strip called shading coil.

The operation of the motor can be understood by referring to figure: 5.111(b) which shows one pole of the motor with a shading coil.

(i) During the portion OA of the alternating-current cycle [See figure: 5.11(b)(i)], the flux begins to increase and an e.m.f. is induced in the shading coil. The resulting current in the shading coil will be in such a direction (Lenz's law) so as to oppose the change in flux. Thus the flux in the shaded portion of the pole is weakened while that in the unshaded portion is strengthened as shown in figure:

(ii) During the portion AB of the alternating-current cycle, the flux has reached almost maximum value and is not changing. Consequently, the flux distribution across the pole is uniform [See figure: 5.11(b)(iii)] since no current is flowing in the shading coil. As the flux decreases (portion BC of the alternating current cycle), current is induced in the shading coil so as to oppose the decrease in current. Thus the flux in the shaded portion of the pole is strengthened while that in the unshaded portion is weakened as shown in figure: 5.11(b)(iv)

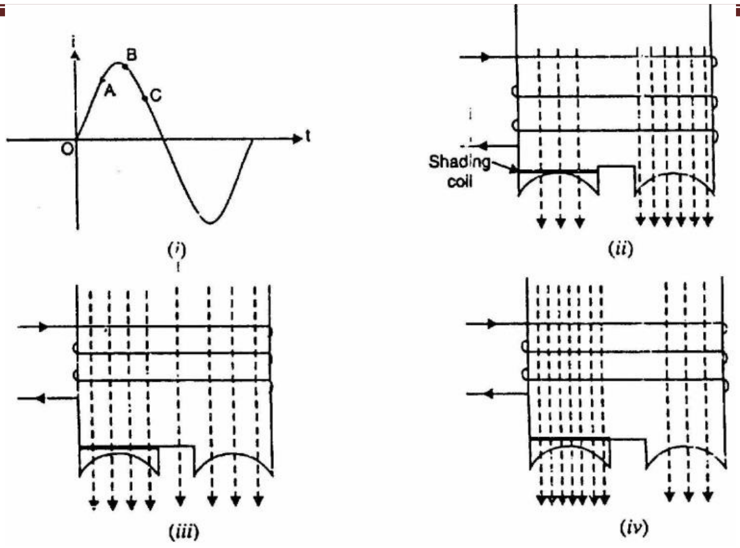


**Fig:** 5.11(b)

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

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

**Characteristics**

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

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

**Applications:**

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

a. small fans
b. Toys
c. Hair driers
d. Desk fans etc.

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

### 5.9 AC Servomotor

Servomotors are special electromechanical devices that produce precise degrees of rotation. A servo motor is a DC or AC or brushless DC motor combined with a position sensing device. Servomotors are also called control motors as they are involved in controlling a mechanical system. The servomotors are used in a closed-loop servo system as shown in Figure 4.14. A reference input is sent to the servo amplifier, which controls the speed of the servomotor. A feedback device is mounted on the machine, which is either an encoder or resolver. This device changes mechanical motion into electrical signals and is used as a feedback. This feedback is sent to the error detector, which compares the actual operation with that of the reference input. If there is an error, that error is fed directly to the amplifier, which will be used to make necessary corrections in control action. In many servo systems, both velocity and position are monitored. Servomotors provide accurate speed, torque, and have ability of direction control.

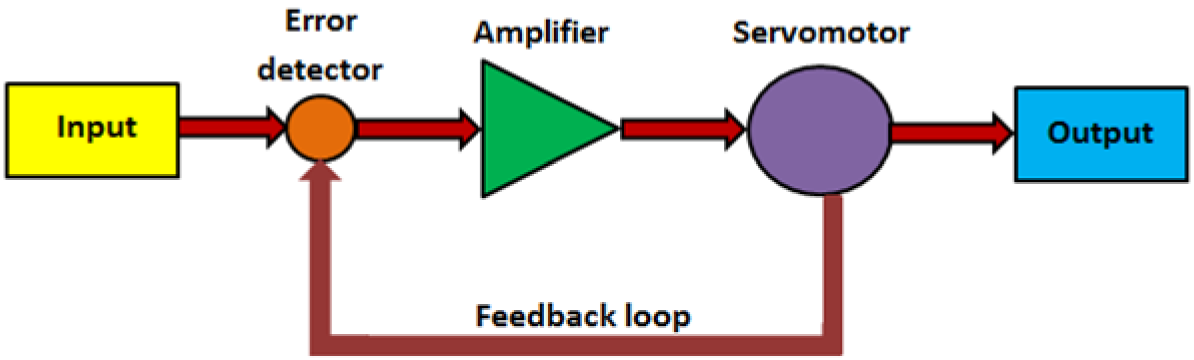


**Fig. 5.12 Servo system block diagram**

### 5.9.1 Advantages of servo motors

- Provides high intermittent torque, high torque to inertia ratio, and high speeds
- Work well for velocity control
- Available in all sizes
- Quiet in operation

- Smoother rotation at lower speeds

### 5.9.2 Disadvantages of servo motors

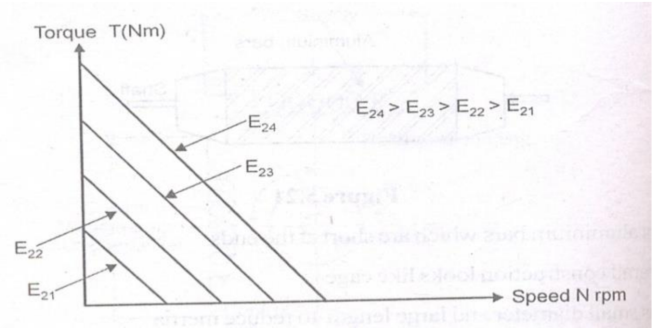
- More expensive than stepper motors
- Require tuning of control loop parameters
- Not suitable for hazardous environments or in vacuum
- Excessive current can result in partial demagnetization of DC type servo motor

### 5.9.3 Uses of AC Servo Motor:

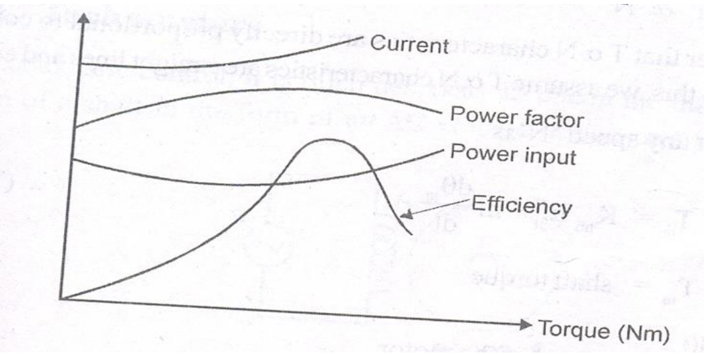
- Low power applications
- Robotics
- Instrument servos
- Self balancing recorders
- Process controllers

### 5.9.4 Characteristics:

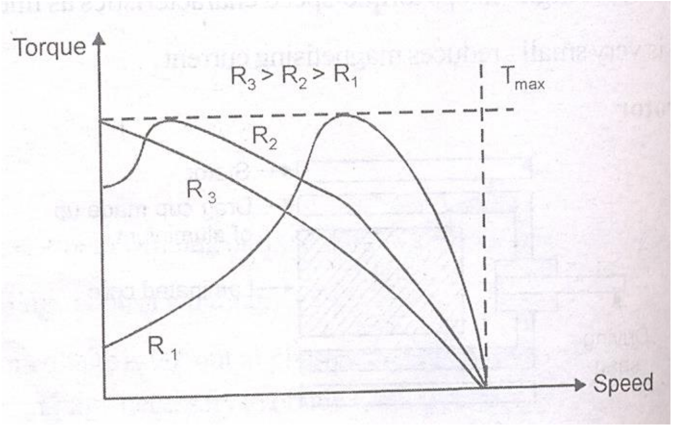
#### a) Torque - slip Characteristics:



#### b) Performance Characteristics:



**c) Effect of increasing resistance**



## 5.10 Stepper motor

A stepper motor is a pulse-driven motor that changes the angular position of the rotor in steps. Due to this nature of a stepper motor, it is widely used in low cost, open loop position control systems.

Types of stepper motors:

- Permanent Magnet stepper motors
- Variable Reluctance motor
- Hybrid stepper motor

### 5.10.1 Variable Reluctance Motor

Figure 4.17 shows the construction of Variable Reluctance motor. The cylindrical rotor is made of soft steel and has four poles as shown in Fig.4.17. It has four rotor teeth, $90^0$ apart and six stator poles, $60^0$ apart. Electromagnetic field is produced by activating the stator coils in sequence. It attracts the metal rotor. When the windings are energized in a reoccurring sequence of 2, 3, 1, and so on, the motor will rotate in a $30^0$ step angle. In the non-energized condition, there is no magnetic flux in the air gap, as the stator is an electromagnet and the rotor is a piece of soft iron; hence, there is no detent torque. This type of stepper motor is called a variable reluctance stepper.

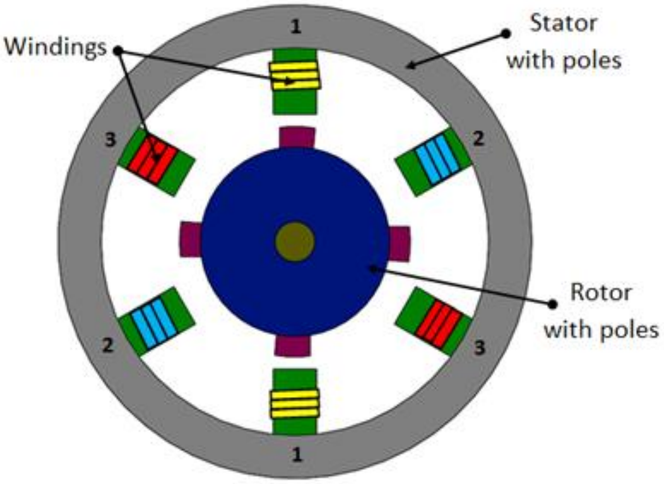


**Fig.5.13 Variable reluctance stepper motor**

### 5.10.2 Permanent magnet (PM) stepper motor

In this type of motor, the rotor is a permanent magnet. Unlike the other stepping motors, the PM motor rotor has no teeth and is designed to be magnetized at a right angle to its axis. Figure 4.18 shows a simple, $90^0$ PM motor with four phases (A-D). Applying current to each phase in sequence will cause the rotor to rotate by adjusting to the changing magnetic fields. Although it operates at fairly low speed, the PM motor has a relatively high torque characteristic. These are low cost motors with typical step angle ranging between $7.5^0$ to $15^0$ .

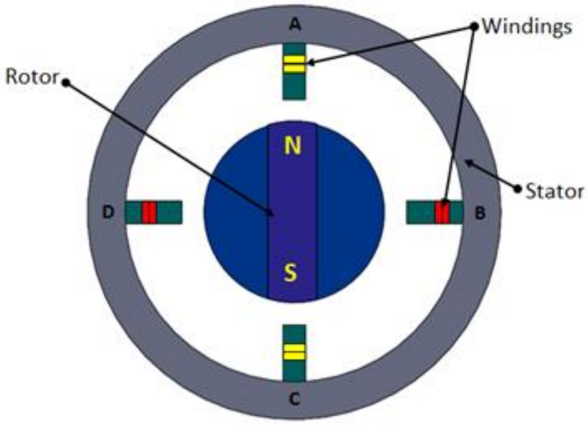


**Fig.5.14 Permanent magnet stepper**

### 5.10..3 Hybrid stepper motor

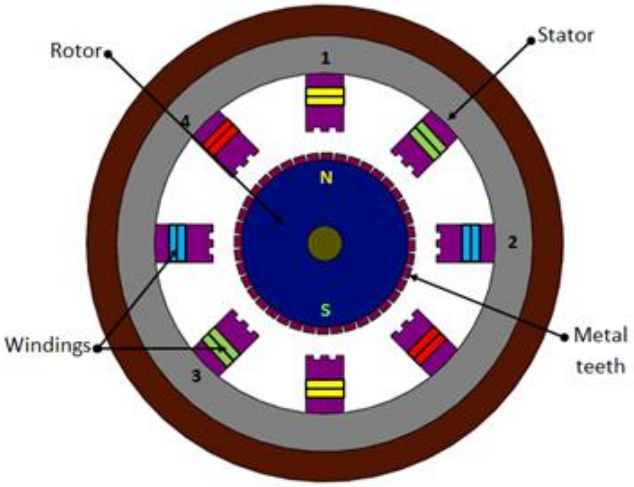


**Fig. 5.15 Hybrid stepper**

Hybrid stepping motors combine a permanent magnet and a rotor with metal teeth to provide features of the variable reluctance and permanent magnet motors together. The number of rotor pole pairs is equal to the number of teeth on one of the rotor's parts. The hybrid motor stator has teeth creating more poles than the main poles windings (Fig. 4.19).

Rotation of a hybrid stepping motor is produced in the similar fashion as a permanent magnet stepping motor, by energizing individual windings in a positive or negative direction. When a winding is energized, north and south poles are created, depending on the polarity of the current flowing. These generated poles attract the permanent poles of the rotor and also the finer metal teeth present on rotor. The rotor moves one step to align the offset magnetized rotor teeth to the corresponding energized windings. Hybrid motors are more expensive than motors with permanent magnets, but they use smaller steps, have greater torque and maximum speed.

Step angle of a stepper motor is given by,

$$\text{Step angle} = \frac{360^\circ}{\text{Number of poles}}$$

**<u>Advantages of stepper motors :</u>**

- Low cost
- Ruggedness

- Simplicity of construction
- Low maintenance
- Less likely to stall or slip
- Will work in any environment
- Excellent start-stop and reversing responses

**Disadvantages of stepper motors :**

- Low torque capacity compared to DC motors
- Limited speed
- During overloading, the synchronization will be broken. Vibration and noise occur when running at high speed.

## SOLVED PROBLEMS

1. The resistance and inductive reactance of each winding of a 50Hz single phase capacitor induction motor are 80 ohms and 237.58 ohms respectively. Additional resistance "R" and a capacitor "C" are in series with one winding in order to achieve a phase difference of 90 degrees while both windings carry equal current. Calculate the values of R and C.

Sol: Given f=50 Hz, R=80Ω, $X_L$=237.5 Ω

The windings are shown in the figure:

$$Z=80+j237.5\ \Omega$$

$$=250.611\angle 71.38^0$$

$$V=V\angle 0^0$$

$$I_m=\frac{V}{Z}=\frac{V\angle 0^0}{250.611\angle 71.38^0}$$

$$=\left|\frac{V}{250.611}\right|\angle -71.38^0\ \text{A}$$

Thus the angle of $I_a'$ is $18.62^0$ with respect to voltage such that there exists $90^0$ phase difference between the two currents.

The magnitude of two currents is equal.

$$Z' = Z + R - jX_C$$

$$= (80 + R) - j(X_C - 237.5)$$

$$X_C > 237.5 \text{ as } I_a' \text{ leads V}$$

$\phi_a' = -18.62^0$ negative as leading

$$= \tan^{-1}\left\{\frac{-(X_C-237.5)}{(80+R)}\right\} \ldots\ldots\ldots\ldots\ldots\ldots.. (1)$$

While $|Z'| = |Z|$ as $|I_m| = |I_a'|$

$$\sqrt{(80+R)^2+(X_C-237.5)^2} = 250.611 \ \ldots\ldots\ldots\ldots\ldots (2)$$

From equation (1), $\tan(-18.62) = \frac{-(X_C-237.5)}{80+R}$

$$(X_C - 237.5) = 0.3369(80+R) \ \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Using in equation (2),

$$(80+R)^2 + [0.3369(80+R)]^2 = (250.611)^2$$

$$80+R= \frac{250.611}{\sqrt{1.1135}} = 273.495\ , \quad R=157.495\,\Omega$$

Using in equation (3), $X_C = 317.512\Omega$ i.e., $C = \frac{1}{2\Pi*50*317.512} = 10\mu F$

2.The following test results were obtained in case of a 220V single phase induction motor:

Free running test: 220V, 5.8A, 310W , Blocked rotor test: 120V, 13.8A, 530 W

Stator winding resistance=1.4Ω. Determine the approximate equivalent circuit of a motor.

Sol: From blocked rotor test,

$V_{sc} = 120V, I_{sc} = 13.8A, P_{sc} = 530W$

$$Z_{eq} = \frac{V_{sc}}{I_{sc}} = \frac{120}{13.8} = 8.6956\Omega$$

$$R_{eq} = \frac{P_{sc}}{I_{sc}^2} = \frac{530}{(13.8)^2} = 2.783\Omega$$

$$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2} = 8.2382\Omega$$

$$X_1 = X_2 = \frac{X_{eq}}{2} = 4.1191\Omega$$

$$R_1 + R_2' = R_{eq} \text{ and } R_1 = 1.4\Omega$$

$$1.4 + R_2' = 2.783 \text{ i.e. } R_2' = 1.383\Omega$$

From no load test, $V_0 = 220V, I_0 = 5.8A, P_0 = 310W$

$$\cos\emptyset_0 = \frac{P_0}{V_0 I_0} = \frac{310}{220*5.8} = 0.2429$$

$$\emptyset_0 = 75.93^0$$

$$I_0 = 5.8\angle -75.93^0 A$$

$$V_0 = 220\angle 0^0 V$$

The equivalent circuit on no load is as shown

$$r_2 = \frac{R_2'}{2} = \frac{1.383}{2} = 0.6915\Omega$$

$$x_2 = \frac{X_2}{2} = \frac{4.1191}{2} = 2.0595\Omega$$

$$V_{AB} = \bar{V}_0 - \bar{I}_0\left[\left(R_1 + \frac{r_2}{2}\right) + j(X_1 + X_2)\right]$$

$$V_{AB} = 220\angle 0^0 - 5.8\angle - 75.93^0[(1.4 + 0.6915)] + j(4.1191 + 2.0595)]$$

$$= 220\angle 0^0 - (5.8\angle - 75.93^0)[6.523\angle 71.29^0$$

$$= 220\angle 0^0 - (37.833\angle - 4.64^0) = 220 + j0 - [37.709 - j3.06]$$

$$= 182.291 + j3.06 = 182.3166\angle 0.916^0 V$$

$|V_{AB}| = |I_0|\, X_0$ i.e., $X_0 = \frac{|V_{AB}|}{|I_0|} = \frac{182.3166}{5.8} = 31.433\ \Omega$, $X_m = 2X_0 = 2 * 31.433 = 62.867\Omega$

# Assignment-Cum-Tutorial Questions

## A. Questions testing the remembering / understanding level of students

### *I) Objective Questions*

1. Single phase motors are commercially manufactured up to

(A) 1H.P. **(B)** 2 H.P. (C) 5 H.P. (D) 10 H.P.

2. If a single phase motor runs slow, the probable case may be

(A) overload (B) low frequency (C) low voltage **(D)** any of the above

3. The starting torque of a single phase induction motor is

(A) uniform (B) high (C) low **(D)** zero

4. The capacitance of a small single phase motor will be of the order of

(A) Kilo farads (B) Few hundred farads (C) Farads **(D)** Micro or pico farads

5. The starting capacitor of a single phase motor is

**(A)** Electrolytic capacitor (B) Ceramic capacitor

(C) Paper capacitor (D) None of the above

6. The starting torque of a capacitor start motor is

(A) zero **(B)** low (C) same as rated torque (D) more than rated torque

7. A single phase capacitor start motor will take starting current nearly

(A) same as full load current **(B)** twice the full load current

(C) three times the full load current (D) four to six times the full load current

8. A capacitor start, capacitor run single phase induction motor is basically a

(A) ac series motor (B) dc series motor

**(C)** 2 phase induction motor (D) 3 phase induction motor

9. After the starting winding of a single- phase induction motor is disconnected from supply, it continues to run only on ............winding.

(A) rotor (B) compensating (C) field **(D)** running

10. Which of the following is the most economical method of starting a single phase motor?

(A) Resistance start method (B) Inductance start method

**(C)** Capacitance start method (D) Split-phase method

11. In a shaded pole motor, the direction of rotation is from

**(A)**main pole to shaded pole (B) shaded pole to main pole

(C) depends on supply line polarity (D) None of the above

12. In a shaded pole motor, shading coils are used to

(A) reducewindage losses (B) reduce friction losses

**(C)** produce rotating magnetic field (D) to protect against sparking

13. The main drawback of a shaded pole motor is

(A) Low efficiency (B) Low starting torque

(C) Very little overload capacity **(D)** All of these

14. The torque developed by a split phase motor is proportional to

**(A)** Sine of angle between $l_m$ and $l_s$ (B) Cosine of angle between $l_m$ and $I_s$

(C) Main winding current, $I_m$ (D) Auxiliary winding current,$I_s$

15. If the ceiling fan, when switched on, runs at slow speed in the reverse direction, it can be concluded that

(A) winding has burnt out (B) bearings are worn out

**(C)**capacitor is ineffective (D) none of the above

16. Which of the following single phase motors will operate at high power factor ?

(A) shaded pole motor
**(B)** capacitor run motor
(C) split phase motor
(D) capacitor start motor

17. A motor generally used in toys is

(A) Hysteresis motor
**(B)** Shaded pole motor
(C) Two value capacitor motor
(D) Reluctance motor

18. A single phase motor generally used for small air compressor is

**(A)** Capacitor start capacitor run motor
(B) reluctance motor
(C) Universal motor
(D) shaded pole motor

19. Out of the following motors, which will give the highest starting torque ?

(A) Universal motor
**(B)** Capacitor start motor
(C) Shaded pole motor
(D) All have zero starting torque

20. The motor used in household refrigerators is

(A) dc series motor
(B) dc shunt motor
(C) universal motor
**(D)** single phase induction motor

21. For ceiling fans generally the single phase motor used is

(A) split phase type
(B) capacitor start type
(C) capacitor start and run type
**(D)** permanent capacitor type

22. Which of the following is a reversible motor?

(A) Universal motor
(B) Capacitor start split phase motor
**(C)** Both (A) and (B) above
(D) None of the above.

23. Which of the following is non-reversible motor?

(A) Universal motor
(B) Capacitor start split phase motor
**(C)** Resistance start split phase motor
(D) Permanent split capacitor motor

24. One of the basic requirements of a servomotor is that it must produce high torque at all

(A) loads
(B) frequencies
**(C)** speeds
(D) voltages

25. The most common two-phase ac servomotor differs from the standard ac induction motor because it has

**(A)** higher rotor resistance
(B) higher power rating
(C) motor stator windings
(D) greater inertia.

26. Tachometer is employed to measure

**(A)** Rotational speed (B) Displacement

(C) Torque developed (D) Driven shaft speed

27. An a.c. tachometer is just a ________with one phase excited from the carrier frequency.

(A) Two-phase A.C. servomotor (B) Two-phase induction motor

(C) A.C. operated universal motor **(D)** Hybrid stepper motor.

28. A stepper motor may be considered as a .................. converter.

(A) dc to dc (B) ac to ac (C) dc to ac **(D)** digital-to-analogue

### *II) Descriptive Questions*

1. Explain the Operating Principle of a single phase induction motor with the help of
   a) Double Revolving Field Theory b) Cross Field Theory.
2. Explain why single phase induction motor is not self starting?
3. Explain the operation of Capacitor-Start Induction motor?
4. Explain the operation of Capacitor- Start Capacitor Run Induction motor?
5. Explain the operation of Shaded pole motors with a neat diagram?
6. Explain the operation of Split Phase induction motor with a neat diagram?
7. Explain the working of an AC Servo Motor. Also list the applications of AC Servo motors?
8. What is a Tachometer? Explain the operation of AC Tachometer. Discuss its Applications?
9. What is a Stepper motor? List different types of stepper motors. What are their applications?
10. Explain the construction and working of a Stepper motor?
11. Draw and explain the characteristics of a) stepper motor b) Shaded pole motor c) Capacitor motor.
12. What are the applications of single phase induction motors?

## B. Question testing the ability of students in applying the concepts.

### *I) Objective Questions*

1. All single phase ac motors are designed to operate usually on

(A) 220 V only (B)220V + 10V (C) 220 ± 0 V **(D)** 220 ± 10% volts

2. All single phase ac motors are designed usually to operate on the frequency

(A) 50 Hz (B) 50 ± 0.5 Hz (C) 50 ±1 Hz **(D)** 50 ± 5 Hz

3. A capacitor start single phase induction motor will usually have a power factor of

   (A) unity (B) 0.8 leading (C) 0.6 leading **(D)** 0.6 lagging

4. In case of split phase motors the phase shift is usually limited to

   **(A)** 3 degrees (B) 60 degrees (C) 90 degrees (D) 150 degrees

5. In a split phase motor, the ratio of number of turns for starting winding to that for running winding is

   (A) 2.0 (B) more than 1 (C) 1.0 **(D)** less than 1

6. The number of turns in the starting winding of a capacitor start motor as compared to that for split phase motor is

   (A) same **(B)** more (C) less (D) none of the above

7. A capacitor motor of 1/4 HP needs a condenser of 8 μ F. A similar motor of 3/4 HP will need a condenser of

   **(A)** 24μF (B) 16μF (C) 8μF (D) 2 μF

8. A single phase capacitor run motor will have starting torque as

   (A) 1/2 of full load torque (B) same as full load torque

   (C) 1 1/2 times full load torque (D) 2 times full load torque

9. For how many poles is a split-phase motor wound if it operates at 1750 rpm at full load from a 60 Hz source?

   (A) 2 poles **(B)** 4 poles (C) 6 poles (D) 12 poles

10. Consider the following single-phase motors :

    I. Capacitor start motor II. Capacitor start and run motor

    III. Permanent split capacitor motor IV. Shaded pole motor.

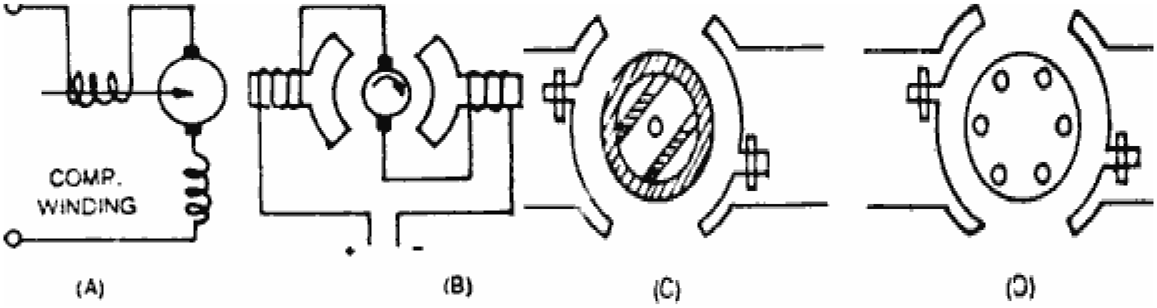
    The correct sequence of the increasing order of their costs is

    **(A)** IV, III, II, I (B) IV, III, I, II (C) III, IV, II, I (D) III, IV, I, II

11. A capacitor start single phase induction motor is switched on the supply with its capacitor replaced by an inductor of equivalent reactance value. It will

    **(A)**not start (B) start and run (C) start and then stall (D) none of the above

**Questions 12 to 20 refer to the Figure given below. Single phase configurations are shown in the Figure.**



12. Which figure represents a shaded pole motor?

(A) figure A (B) figure B (C) figure C **(D)** figure D

13. Which figure represents a universal motor?

(A) figure A **(B)** figure B (C) figure C (D) figure D

14. Which figure represents anAC seriesmotor?

**(A)** figure A (B) figure B (C) figure C (D) figure D

15. Which figure represents a hysteresis motor?

(A) figure A (B) figure B **(C)** figure C (D) figure D

16. A stepper motor having a resolution of 300 steps/rev and running at 2400 rpm has a pulse rate of— pps.
(A) 4000 (B) 8000 **(C)** 6000 (D) 10,000

17. In a three-stack 12/8-pole VR motor, the rotor pole pitch is
(A) 15° (B) 30° **(C)** 45° (D) 60°

18. A three-stack VR stepper motor has a step angle of 10°. What is the number of rotor teeth in each stack?
(A) 36 (B) 24 (C) 18 **(D)** 12

19. If a hybrid stepper motor has a rotor pitch of 36° and a step angle of 9°, the number of its phases must be
**(A)** 4 (B) 2 (C) 3 (D) 6

20. What is the step angle of a permanent-magnet stepper motor having 8 stator poles and 4 rotor poles?
(A) 60° **(B)** 45° (C) 30° (D) 15°

## *II) Descriptive Questions*

1. Discuss the revolving field theory of single-phase induction motors. Find the mechanical power output at a slip of 0.05 of the 185-W, 4-pole, 110-V, 60-Hz single-phase induction motor, whose constants are given below:

| | |
|---|---|
| Resistance of the stator main winding | $R_1 = 1.86$ ohm |
| Reactance of the stator main winding | $X_1 = 2.56$ ohm |
| Magnetizing reactance of the stator main winding | $X_m = 53.5$ ohm |
| Rotor resistance at standstill | $R_2 = 3.56$ ohm , |
| Rotor reactance at standstill | $X_2 = 2.56$ ohm |

2. Find the mechanical power output of 185-W, 4 pole, 110-V, 50-Hz single-phase induction motor, whose constants are given below at a slip of 0.05. $R_1 = 1.86$ ohm $X_1 = 2.56$ ohm $X_\phi = 53.5$ ohm $R_2 = 3.56$ ohm $X_2 = 2.56$ ohm,Core loss = 3.5 W,

   Friction and windage loss = 13.5 W.

3. A 250- W, 230-V, 50-Hzcapacitor-start motor has the following constants for the main and auxiliary windings: Main winding, $Z_m = (4.5 + j\,3.7)$ ohm. Auxiliary winding $Z_a = (9.5 + j\,3.5)$ ohm. Determine the value of the starting capacitor that will place the main and auxiliary winding currents in quadrature at starting.

4. At starting, the windings of a 230v, 50 Hz split phase motor have the following parameter:

   Main winding: R = 6 ohm, $X_L = 8$ ohm

   Starting winding: R = 8 ohm, $X_L = 6$ ohm

   Find (a) Current $I_m$ in the main winding (b) Current Is in the starting winding

   (c) Phase angle between $I_S$ and $I_m$ (d) line current (e) Power factor of the motor

5. A 230v, 50 Hz Capacitor – Start motor has the following winding constants:

   Main winding: R = 4 ohm, $X_L = 3$ ohm

   Starting winding: R = 8 ohm, $X_L = 4$ ohm

   Find the values of starting capacitance that will result in the maximum torque.

6. A small motor has an output of 0.25N-m and a speed of 100rad/sec. if the input current is 0.6A at 230V and 0.6 lagging pf. find (a) Output Power (b) Efficiency.

7. A 1/3 hp,110V, 50Hz Capacitor start motor has the following constant for the main and auxiliary windings.

Main winding = (4+j3) ohms, Starting winding = (8+j2.5)ohms.

Calculate the value of the starting capacitance that will place the main and auxiliary winding currents in phase quadrature at the time of starting.

**PREVIOUS GATE/IES QUESTIONS:**

1. The slip of an induction motor normally does not depend on **GATE-2011**

(A) rotor speed (B) synchronous speed (C) shaft torque (D) core-loss component

2. A 230 V, 50 Hz, 4-pole, single-phase induction motor is rotating in the clockwise (forward) direction at a speed of 1425 rpm. If the rotor resistance at standstill is 7.8 Ω, then the effective rotor resistance in the backward branch of the equivalent circuit will be **GATE-2012**

(A) 2 Ω (B) 4 Ω (C) 78 Ω (D) 156 Ω

3. For a single phase capacitor start induction motor which of the following statements is valid ? **GATE-2012**

(A) The capacitor is used for power factor improvement

(B) The direction of rotation can be changed by reversing the main winding terminals

(C) The direction of rotation cannot be changed

(D) The direction of rotation can be changed by interchanging the supply terminals

4. In a single phase induction motor driving a fan load, the reason for having a high resistance rotor is to achieve **GATE-2013**

(A) low starting torque (B) quick acceleration

(C) high efficiency (D) reduced size

5. For a given stepper motor, the following torque has the highest numerical value **GATE-2013**

(A) Detent torque (B) Pull-in torque `

(C) Pull-out torque (D) Holding torque

6. The following motor definitely has a permanent magnet rotor **GATE-2013**

(A) DC commutator motor (B) Brushless dc motor

(C) Stepper motor (D) Reluctance motor

7. The type of single-phase induction motor having the highest power factor at full load is

**GATE-2014**

(A) shaded pole type (B) split-phase type

(C) capacitor-start type (D) capacitor-run type

8. A single-phase, 230 V, 50 Hz 4-pole, capacitor-start induction motor had the following stand-still impedances Main winding Z j m = + 6.0 4.0 Ω Auxiliary winding Z j a = + 8.0 6.0 Ω The value of the starting capacitor required to produce 90c phase difference between the currents in the main and auxiliary windings will be **GATE-2014**

(A) 176.84 Mf (B) 187.24 µF (C) 265.26 µF (D) 280.86 µF

9. For a 1.8c, 2-phase bipolar stepper motor, the stepping rate is 100 steps/second. The rotational speed of the motor in rpm is **GATE-2015**

(A) 15 (B) 30 (C) 60 (D) 90

10. A single-phase induction motor with only the main winding excited would exhibit the following response at synchronous speed **GATE-2015** (A) Rotor current is zero

(B) Rotor current is non-zero and is at slip frequency

(C) Forward and backward rotaling fields are equal

(D) Forward rotating field is more than the backward rotating field

11. The locked rotor current in a 3-phase, star connected 15 , kW 4 , pole 230 V, 50 Hz induction motor at rated conditions is 50 A. Neglecting losses and magnetizing current, the approximate locked rotor line current drawn when the motor is connected to a 236 , V 57 Hz supply is

**GATE-16**

(A) 58.5 A B) 45.0 A (C) 42.7 A D) 55.6 A

**GUDLAVALLERU ENGINEERING COLLEGE**

**(An Autonomous Institute with Permanent Affiliation to JNTUK, Kakinada)**

**Seshadri Rao Knowledge Village, Gudlavalleru – 521 356.**

## Department of Electrical and Electronics Engineering

# HANDOUT

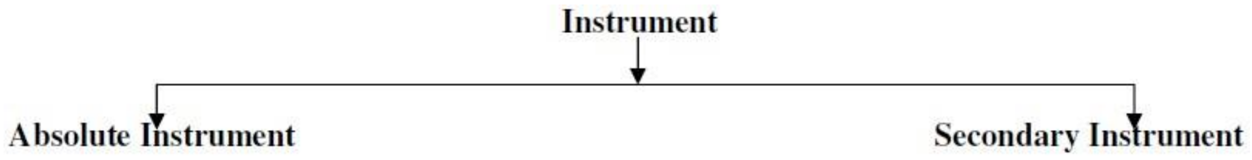
# on

# ELECTRICAL TECHNOLOGY

# MEASURING INSTRUMENTS

## 6.1Definition of instruments:

An instrument is a device in which we can determine the magnitude or value of the quantity to be measured. The measuring quantity can be voltage, current, power and energy etc. Generally instruments are classified in to two categories.

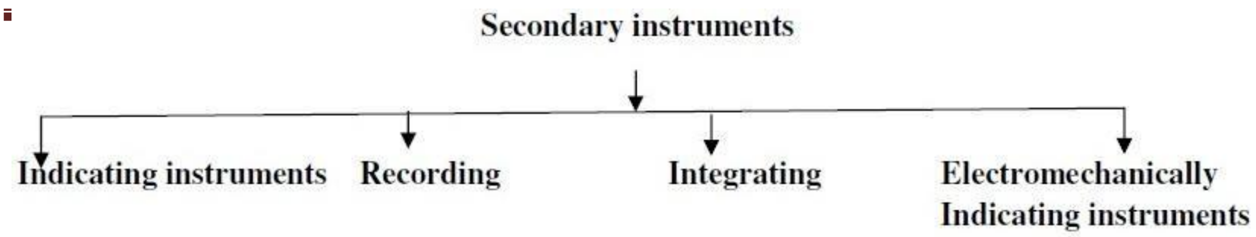


## 6.2 Absolute instrument:

An absolute instrument determines the magnitude of the quantity to be measured in terms of the instrument parameter. This instrument is really used, because each time the value of the measuring quantities varies. So we have to calculate the magnitude of the measuring quantity, analytically which is time consuming. These types of instruments are suitable for laboratory use. Example: Tangent galvanometer

## 6.3 Secondary instrument:

This instrument determines the value of the quantity to be measured directly. Generally these instruments are calibrated by comparing with another standard secondary instrument. Examples of such instruments are voltmeter, ammeter and wattmeter etc. Practically secondary instruments are suitable for measurement.



### 6.3.1 Indicating instrument:

This instrument uses a dial and pointer to determine the value of measuring quantity. The pointer

Indication gives the magnitude of measuring quantity.

### 6.3.2 Recording instrument:

This type of instruments records the magnitude of the quantity to be measured continuously over a specified period of time.

### 6.3.3 Integrating instrument:

This type of instrument gives the total amount of the quantity to be measured over a specified

Period of time

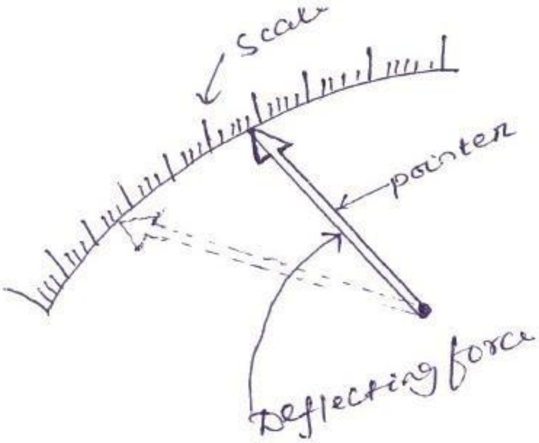
### 6.3.4 Electromechanical indicating instrument:

For satisfactory operation electromechanical indicating instrument, three forces are necessary. They are

(a) Deflecting force
(b) Controlling force
(c)Damping force

### 6.4 Deflecting force:

When there is no input signal to the instrument, the pointer will be at its zero position. To deflect the pointer from its zero position, a force is necessary which is known as deflecting force. A system which produces the deflecting force is known as a deflecting system. Generally a deflecting system converts an electrical signal to a mechanical force.



## 6.5 Controlling force:

To make the measurement indicated by the pointer definite (constant) a force is necessary which will be acting in the opposite direction to the deflecting force. This force is known as controlling force. A system which produces this force is known as a controlled system. When the external signal to be measured by the instrument is removed, the pointer should return back to the zero position. This is possibly due to the controlling force and the pointer will be indicating a steady value when the deflecting torque is equal to controlling torque.

$$T_d = T_c$$

### 6.5.1 Spring control:

Two springs are attached on either end of spindle (Fig. 6.5).The spindle is placed in jeweled bearing, so that the frictional force between the pivot and spindle will be minimum. Two springs are provided in opposite direction to compensate the temperature error. The spring is made of phosphorous bronze.

$$T_C \propto \theta$$

The deflecting torque produced Td proportional to ‘I’. When $T_C$ = Td the pointer will come to a steady position. Therefore

$$\theta \propto I$$

Since, θ and I are directly proportional to the scale of such instrument which uses spring controlled is uniform

### 6.6 Damping force:

The deflection torque and controlling torque produced by systems are electro mechanical. Due to inertia produced by this system, the pointer oscillates about it final steady position before coming to rest. The time required to take the measurement is more. To damp out the oscillations quickly, a damping force is necessary. This force is produced by different systems.

(a) Air friction damping

(b) Fluid friction damping

(c) Eddy current damping

### 6.6.1 Air friction damping:

The piston is mechanically connected to a spindle through the connecting rod (Fig. 6.6). The pointer is fixed to the spindle moves over a calibrated dial. When the pointer oscillates in clockwise direction, the piston goes inside and the cylinder gets compressed. The air pushes the piston upwards and the pointer tends to move in anticlockwise direction

If the pointer oscillates in anticlockwise direction the piston moves away and the pressure of the air inside cylinder gets reduced. The external pressure is more than that of the internal pressure. Therefore the piston moves down wards. The pointer tends to move in clock wise direction.

### 6.6.2 Eddy current damping:

An aluminum circular disc is fixed to the spindle (Fig. 6.6). This disc is made to move in the magnetic field produced by a permanent magnet.

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**Fig. 6.6 Disc type**

When the disc oscillates it cuts the magnetic flux produced by damping magnet. An emf is induced in the circular disc by faradays law. Eddy currents are established in the disc since it has several closed paths. By Lenz’s law, the current carrying disc produced a force in a direction opposite to oscillating force. The damping force can be varied by varying the projection of the magnet over the circular disc.

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**Fig. 6.6 Rectangular type**

## 6.7 Permanent Magnet Moving Coil (PMMC) instrument:

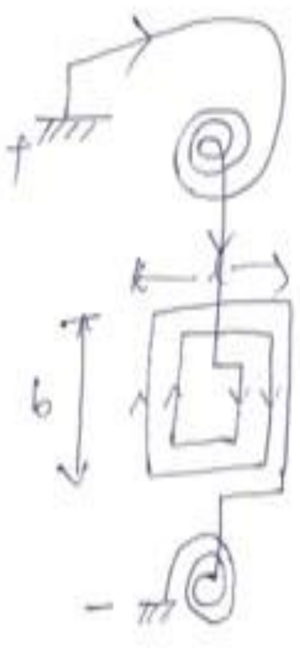
One of the most accurate type of instrument used for D.C. measurements is PMMC instrument.

**Construction:** A permanent magnet is used in this type instrument. Aluminum former is provided in the cylindrical in between two poles of the permanent magnet (Fig. 1.7). Coils are wound on the aluminum former which is connected with the spindle. This spindle is supported with jeweled bearing. Two springs are attached on either end of the spindle. The terminals of the moving coils are connected to the spring. Therefore the current flows through spring 1, moving coil and spring 2.

Damping: Eddy current damping is used. This is produced by aluminum former.
Control: Spring control is used.

**Principle of operation:**

When D.C. supply is given to the moving coil, D.C. current flows through it. When the current carrying coil is kept in the magnetic field, it experiences a force. This force produces a torque and the former rotates. The pointer is attached with the spindle. When the former rotates, the pointer moves over the calibrated scale. When the polarity is reversed a torque is produced in the opposite direction. The mechanical stopper does not allow the deflection in the opposite direction. Therefore the polarity should be maintained with PMMC instrument.



If A.C. is supplied, a reversing torque is produced. This cannot produce a continuous deflection. Therefore this instrument cannot be used in A.C.

**Torque developed by PMMC:**

Let *Td* =deflecting torque

*TC* = controlling torque q = angle of deflection

K=spring constant

b=width of the coil

l=height of the coil or length of coil

N=No. of
turns
I=current
B=Flux
density

A=area of the coil

The force produced in the coil is given by F = BIL sinθ

When θ = 90º

For N turns, F = NBIL

Torque produced Td = F* perpendicular distance

$T_d$ =NBIL* b

=BINA

$T_d$ =BANI

$T_d \alpha I$

**Advantages:**

Torque/weight is high

Power consumption is less

Scale is uniform

Damping is very effective

Since operating field is very strong, the effect of stray field is negligible

Range of instrument can be extended

**Disadvantages:**

Use only for D.C.

Cost is high

Error is produced due to ageing effect of PMMC

Friction and temperature error are present

## 6.8 Moving Iron (MI) instruments:

One of the most accurate instruments used for both AC and DC measurement is moving iron instrument. There are two types of moving iron instrument.

- Attraction type
- Repulsion type

### 6.8.1 Attraction type M.I. instrument

**Construction:** The moving iron fixed to the spindle is kept near the hollow fixed coil (Fig. 1.10).The pointer and balance weight are attached to the spindle, which is supported with jeweled bearing. Here air friction damping is used.

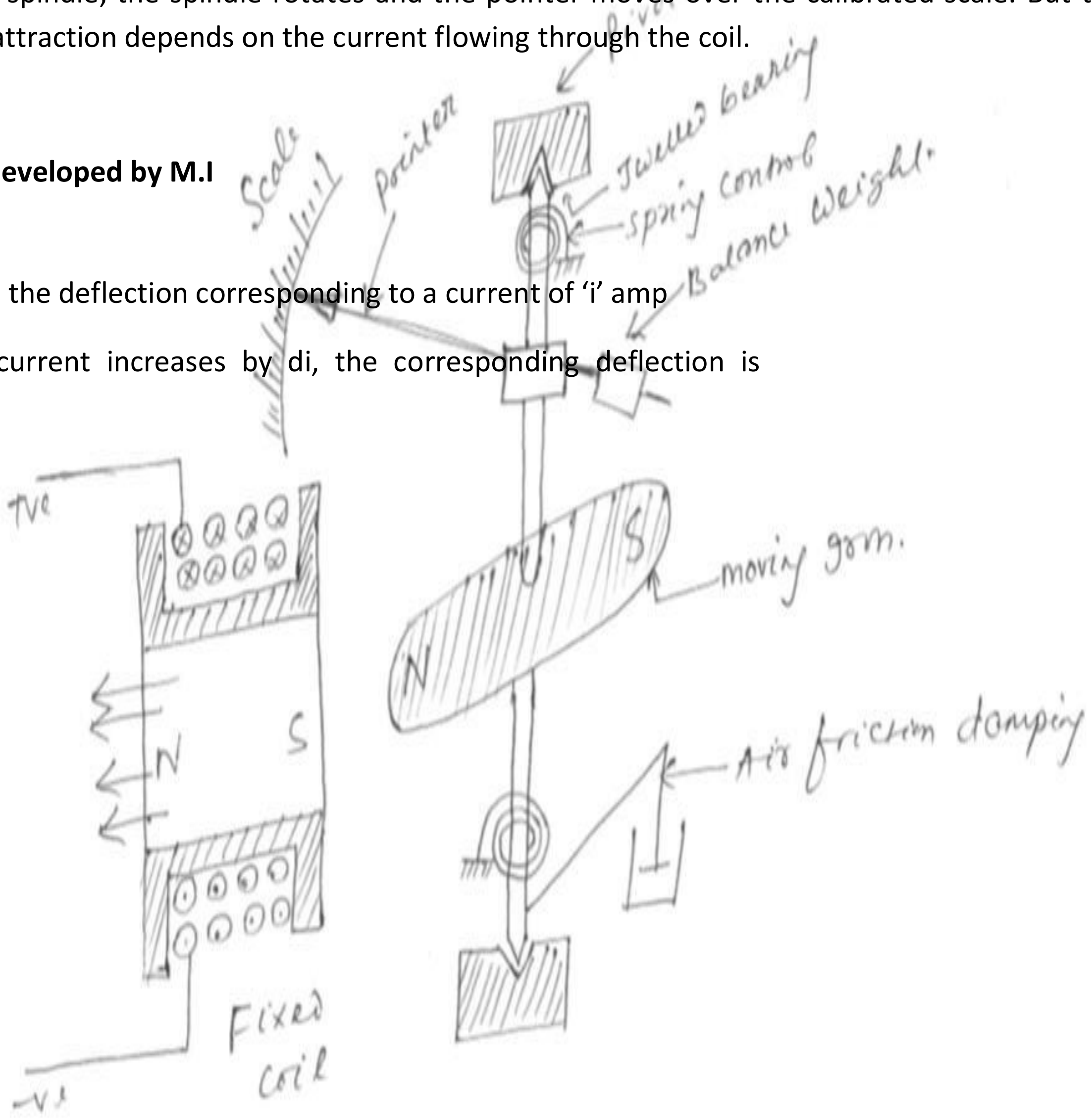
**Principle of operation:**

The current to be measured is passed through the fixed coil. As the current is flow through the fixed coil, a magnetic field is produced. By magnetic induction the moving iron gets magnetized. The north pole of moving coil is attracted by the south pole of fixed coil. Thus the deflecting force is produced due to force of attraction. Since the moving iron is attached with the spindle, the spindle rotates and the pointer moves over the calibrated scale. But the force of attraction depends on the current flowing through the coil.

**Torque developed by M.I**

Let ‘θ’ be the deflection corresponding to a current of ‘i’ amp

Let the current increases by di, the corresponding deflection is ‘θ+dθ



(Fig. 6 .10)

(Fig. 6 .10)

There is change in inductance since the position of moving iron change w.r.t the fixed electromagnets.

Let the new inductance value be ‘L+dL’. The current change by ‘di’ is dt seconds. Let the emf induced in the coil be ‘e’ volt

It gives the energy is used in to two forms. Part of energy is stored in the inductance. Remaining energy is converted in to mechanical energy which produces deflection

(Fig. 6.11)

Mechanical work to move the pointer by $d\theta$

$=Td\ d\theta$

By law of conservation of energy, Electrical energy supplied=Increase in stored energy+ mechanical work done

Electrical energy supplied =Increase in stored energy+ mechanical work done

Input energy = Energy stored + Mechanical energy

$$T_d = \frac{1}{2} i^2 \frac{dL}{d\theta}$$

At steady state condition $T_d = T_C$

$$\frac{1}{2} i^2 \frac{dL}{d\theta} = K\theta$$

$$\theta = \frac{1}{2K} i^2 \frac{dL}{d\theta}$$

$$\theta \propto i^2$$

When the instruments measure AC, $\theta \propto i^2_{rms}$

Scale of the instrument is non uniform.

**Advantages:**

MI can be used in AC and DC

It is cheap

Supply is given to a fixed coil, not in moving coil.

Simple construction

Less friction error.

**Disadvantages**:

It suffers from eddy current and hysteresis error.

Scale is not uniform

It consumed more power

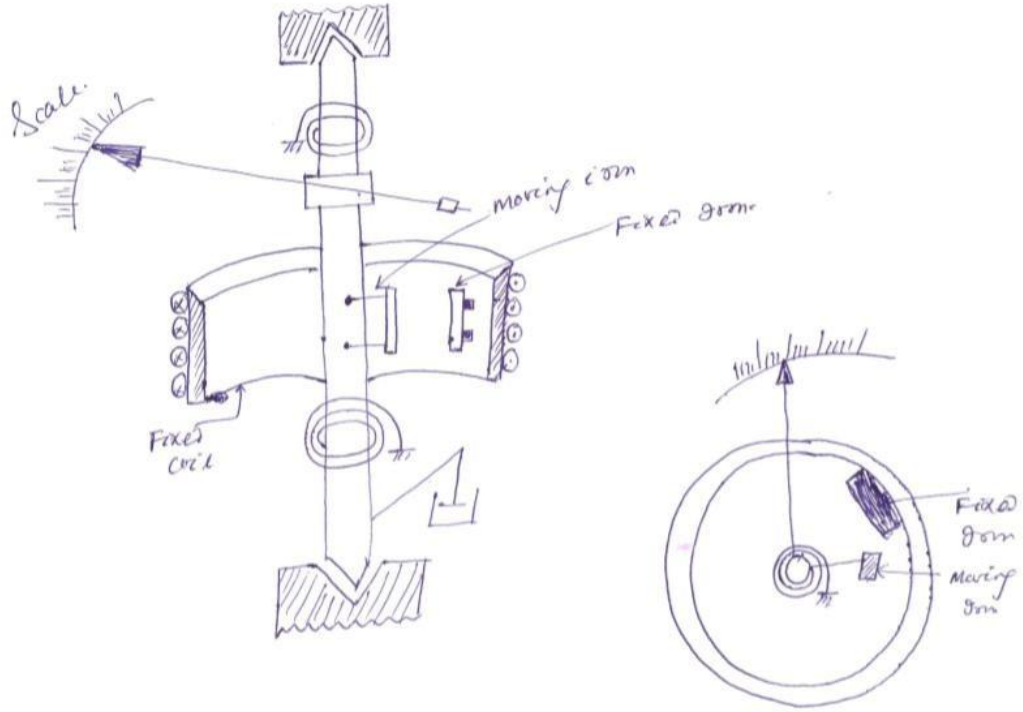
Calibration is different for AC and DC operation

### 6.8.2 Repulsion type moving iron instrument:

**Construction:** The repulsion type instrument has a hollow fixed iron attached to it (Fig. 6.12). The moving iron is connected to the spindle. The pointer is also attached to the spindle in supported with jeweled bearing.

**Principle of operation:** When the current flows through the coil, a magnetic field is produced by it. So both fixed iron and moving iron are magnetized with the same polarity, since they are kept in the same magnetic field. Similar poles of fixed and moving iron get repelled. Thus the deflecting torque is produced due to magnetic repulsion. Since moving iron is attached to spindle, the spindle will move. So that pointer moves over the calibrated scale.

Damping: Air friction damping is used to reduce the oscillation.
Control: Spring control is used.


Scale.
Moving iron
Fixed iron
Fixed coil
Fixed iron
Moving iron

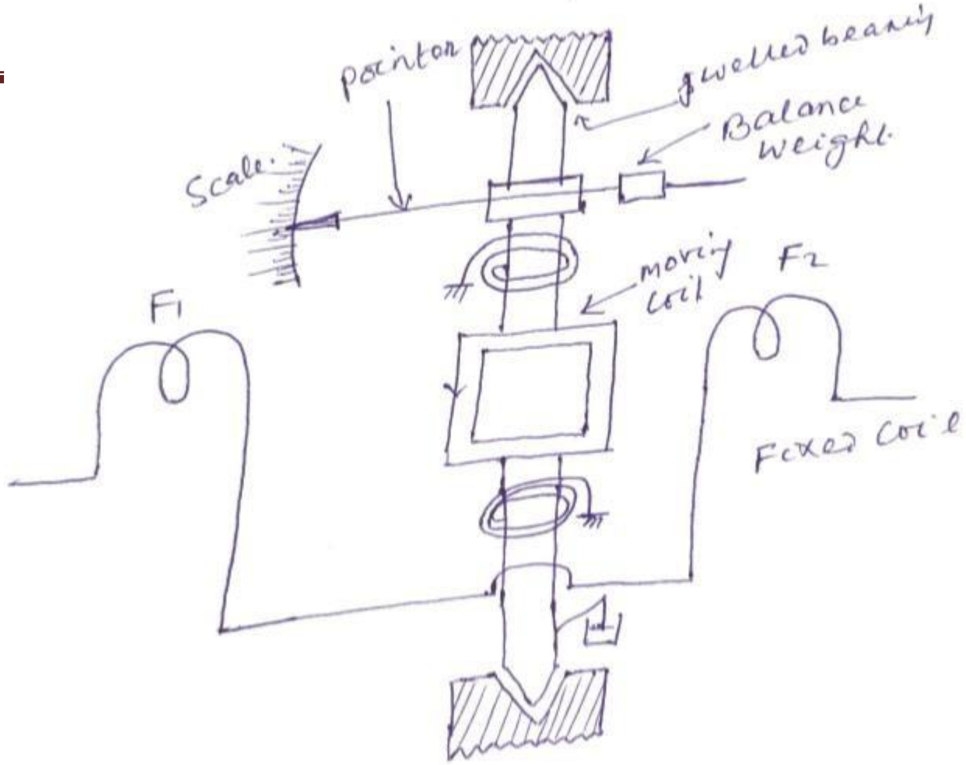
(Fig. 6.12)

### 6.9 Dynamometer (or) Electromagnetic moving coil instrument (EMMC):

This instrument can be used for the measurement of voltage, current and power. The difference between the PMMC and dynamometer type instrument is that the permanent magnet is replaced by an electromagnet.

**Construction:** A fixed coil is divided in to two equal half. The moving coil is placed between the two half of the fixed coil. Both the fixed and moving coils are air cored. So that the hysteresis Effect will be zero. The pointer is attached with the spindle. In a non metallic former the moving Coil is wounded.

Control: Spring control is used.
Damping: Air friction damping is used

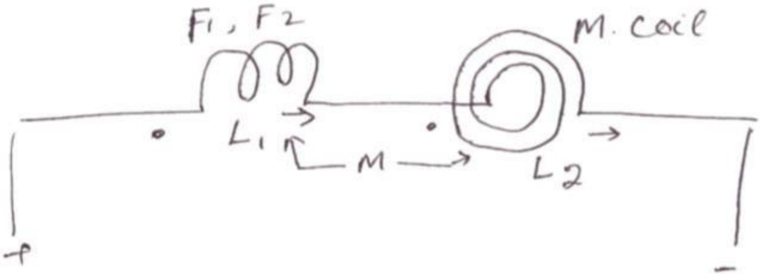


(Fig. 6 .13)

**Principle of operation:**

When the current flows through the fixed coil, it produced a magnetic field, whose flux density is Proportional to the current through the fixed coil. The moving coil is kept in between the fixed coil. When the current passes through the moving coil, a magnetic field is produced by this coil. The magnetic poles are produced in such a way that the torque produced on the moving coil deflects the pointer over the calibrated scale. This instrument works on AC and DC. When AC voltage is applied, alternating current flows through the fixed coil and moving coil. When the current in the fixed coil reverses, the current in the moving coil also reverses. Torque remains in the same direction. Since the current i1 and i2 reverse simultaneously. This is because the fixed and moving coils are either connected in series or parallel.

**Torque developed by EMMC:**



(Fig. 1.14)

Let

L1=Self inductance of fixed coil

L2= Self inductance of moving coil

M=mutual inductance between fixed coil and moving coil i1=current through fixed coil

i2=current through moving coil

Total inductance of system

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Hence the deflection of pointer is proportional to the current passing through fixed coil and

moving coil

## Errors in PMMC:

The permanent magnet produced error due to ageing effect. By heat treatment, this error can be eliminated.

The spring produces error due to ageing effect. By heat treating the spring the error can be eliminated.

When the temperature changes, the resistance of the coil vary and the spring also produces error in deflection. This error can be minimized by using a spring whose temperature co-efficient is very low.

***I)***

## Assignment-Cum-Tutorial Questions

**A. Questions testing the remembering / understanding level of students**

***I) Objective Questions***

1. Which of the following instruments can be used to measure AC current only?
(a) Permanent Magnet Type ammeter
(b) Induction type ammeter
(c) Moving iron voltmeter
(d) Moving iron ammeter
Answers:
1. D only
**2.** B only
3. A, B, D
4. B and D only

2. The error of an instrument is normally given as a percentage of
(a) measured value
**(b)** full-scale value
(c) mean value
(d) rms value

3. Which of the following are integrating instruments ?
(a) Ammeters (b) Voltmeters
(c) Wattmeters **(d)** Ampere-hour and watt-hour meters

4. Resistances can be measured with the help of
(a) wattmeters (b) voltmeters (c) ammeters

**(d)** ohmmeters and resistance bridges (e) all of the above

5. Which of the following essential features is possessed by an indicating instrument ?
(a) Deflecting device (b) Controlling device
(c) Damping device **(d)** All of the above

6. A _____ device prevents the oscillation of the moving system and enables the latter to reach its final position quickly
(a) deflecting (b) controlling **(c)** damping (d) any of the above

7. The spring material used in a spring control device should have the following property.
(a) Should be non-magnetic (b) Most be of low temperature co-efficient
(c) Should have low specific resistance (d) Should not be subjected to fatigue
**(e)** All of the above

8. Which of the following properties a damping oil must possess ?
(a) Must be a good insulator (b) Should be non-evaporating

(c) Should not have corrosive action upon the metal of the vane (d) The viscosity of the oil should not change with the temperature **(e)** All of the above

9. A moving-coil permanent-magnet instrument can be used as _____ by using a low resistance shunt.
   **(a)** ammeter (b) voltmeter (c) flux-meter (d) ballistic galvanometer

10. Which of the following devices may be used for extending the range of instruments ?
    (a) Shunts (b) Multipliers (c) Current transformers
    (d) Potential transformers **(e)** All of the above

## *II) Descriptive Questions*

1. What is the need of Deflecting and Damping torques in indicating instruments?
2. Write a short note on deflecting torque
3. What are the types of torques associated for the working of measuring instrument.
4. What are advantages & disadvantages of PMMC instrument?
5. . Explain the working of a PMMC type instruments. Derive the expression for torque produced
6. Explain the construction and operation of Moving Iron instruments.
7. What are advantages & disadvantages of Moving iron instrument.
8. *Classify different types of instruments and explain.*

## B. Question testing the ability of students in applying the concepts.

## *I) Objective Questions*

1. Induction type single phase energy meters measure electric energy in
   (a) kW (b) Wh **(c)** kWh (d) VAR (e) None of the above

2. Most common form of A.C. meters met with in every day domestic and industrial installations are
   (a) mercury motor meters (b) commutator motor meters
   **(c)** induction type single phase energy meters (d) all of the above

3. The pointer of an indicating instrument should be
   **(a)** very light (b) very heavy (c) either (a) or (b) (d) neither (a) nor (b)

4. In majority of instruments damping is provided by

(a) fluid friction (b) spring **(c)** eddy currents (d) all of the above

5. An ammeter is a

**(a)** secondary instrument (b) absolute instrument

(c) recording instrument (d) integrating instrument

6. In a portable instrument, the controlling torque is provided by

(a) spring (b) gravity (c) eddy currents (d) all of the above

7. The function of shunt in an ammeter is to

**(a)** by pass the current (b) increase the sensitivity of the ammeter

(c) increase the resistance of ammeter (d) none of the above

8. The multiplier and the meter coil in a voltmeter are in

**(a)** series (b) parallel (c) series-parallel (d) none of the

9. A moving iron instrument can be used for

(a) D.C. only (b) A.C. only **(c)** both D.C. and A.C.

10. An ohmmeter is a

(a) moving iron instrument **(b)** moving coil instrument
(c) dynamometer instrument (d) none of the above

## II) *Descriptive Questions*

1. With neat diagram explain about Moving Iron repulsion instrument.

2.Explain the principle of operation of moving coil instrument.

3. The inductance of a moving iron ammeter with a full scale deflection of $90^0$ at 1.5A, is given by the expression $L=200+40ɵ-4ɵ^2 - ɵ^3$ µh, where ɵ is the deflection in radian from the zero position. Estimate the angular deflection of the pointer for a current of 1A.

4.Explain the working of a moving iron type instruments. Derive the expression for torque produced.

5.Explain how following torque are produced in pmmc instrument and attracted type moving iron

instruments
1. Deflecting torque
2. Control torque
3. Damping torque

6.A moving coil instrument gives a full scale detection of 20ma. When a potential difference of 50mv is applied. Calculate the series resistance to measure 500V on scale?

7.The inductance of a moving iron instrument is given by $L=10+4ɵ-ɵ^2$ µh where ɵ is the deflection in radian from the zero position.the spring constant is $12*10^{-6}$ N-m/rad. Estimate the deflection for a

current of 5A.

8.Explain the working of a PMMC type instruments. Derive the expression for torque produced

10.A moving coil instrument has the following data: number of turns=100, width of coil= 20mm, depth of coil= 30mm, flux density in the gap=0.1 tesla. Calculate the deflection torque when carrying a current of 10ma. Also calculate the deflection in the moving coil voltmeter.

## C. Questions testing the analyzing / evaluating /Creative ability of students

1. Design a series type ohmmeter. The movement to be used requires 0.5mA for full scale deflection and has an internal resistance of 50ohm. The internal battery has a voltage of 3V. the desired value of half scale resistance is 3000ohm. Calculate a) the values of series and parallel resistances $R_1$ and $R_2$ b) the range of values of $R_{2,}$ if the battery voltage may vary from 2.7V to 3.1V. use the value of $R_1$calculated in (a).

**PREVIOUS GATE/IES QUESTIONS:**

1. An analog voltmeter uses external multiplier settings. With a multiplier setting of 20 kΩ, it reads 440 V and with a multiplier setting of 80 kΩ, it reads 352 V. For a multiplier setting of 40 kΩ, the voltmeter reads
   (A) 371 V (B) 383 V (C) 394 V (D) 406 V

2. An ammeter has a current range of 0-5 A, and its internal resistance is 0.2 Ω. In order to

change the range to 0-

25 A, we need to add a resistance of

(A) 0.8 Ω in series with the meter (B) 1.0 Ω in series with the meter

(C) 0.04 Ω in parallel with the meter (D) 0.05 Ω in parallel with the meter

3. The pressure coil of a dynamometer type wattmeter is

(A) Highly inductive (B) Highly resistive (C) Purely resistive (D) Purely inductive

4. A current of −+ + 86 ( ) 2 30 sinωt % A is passed through three meters. They are a centre zero
PMMC meter, a true rms meter and a moving iron instrument. The respective reading (in A) will be

(A) 8, 6, 10 (B) 8, 6, 8 (C) −8,10,10 (D) −8,2,2

5. A variable w is related to three other variables x ,y ,z as w xy z = / . The variables are measured with meters of accuracy !0 5. % reading, !1% of full scale value and !1 5. % reading. The actual readings of the three meters are 80, 20 and 50 with 100 being the full scale value for all three. The maximum uncertainty in the measurement of w will be
(A) !0 5. % rdg (B) !5 5. % rdg (C) !6 7. Rdg (D) !7 0. Rdg

6. A DC ammeter has a resistance of 0.1 Ω and its current range is 0-100 A. If the range is to be
extended to 0-500 A, then meter required the following shunt resistance

(A) 0.010 Ω (B) 0.011 Ω (C) 0.025 Ω (D) 1.0 Ω

7. A moving coil of a meter has 100 turns, and a length and depth of 10 mm and 20 mm respectively. It is positioned in a uniform radial flux density of 200 mT. The coil carries a current of 50 mA. The torque on the coil is

(A) 200 µNm (B) 100 µNm (C) 2 µNm (D) 1 µNm

8. A dc A-h meter is rated for 15 A, 250 V. The meter constant is 14.4 A-sec/ rev. The meter

constant at rated voltage may be expressed as

(A) 3750 rev/kWh (B) 3600 rev/kWh (C) 1000 rev/kWh (D) 960 rev/kWh

9. A Manganin swap resistance is connected in series with a moving coil ammeter consisting of a milli-ammeter and a suitable shunt in order to

(A) minimise the effect of temperature variation (B) obtain large deflecting torque (C) reduce the size of the meter (D) minimise the effect of stray magnetic fields

10. The effect of stray magnetic field on the actuating torque of a portable instrument is maximum when the operating field of the instrument and the stray fields are

(A) perpendicular (B) parallel (C) inclined at 60% (D) inclined at 30

11. A 100 µA ammeter has an internal resistance of 100 Ω. For extending its range to measure 500 µA, the shunt required is of resistance in Ω

(A) 20.0 (B) 22.22 (C) 25.0 (D) 50.0