LECTURE NOTES

On

Energy Conversion - I

On

4th Semester of Electrical Engineering Branch

Prepared by

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D.C Generator

An electrical Generator is a machine which converts mechanical energy (or power) into electrical energy (or power). The generator operates on the principle of the production of dynamically induced emf i.e., whenever flux is cut by the conductor, dynamically induced emf is produced in it according to the laws of electromagnetic induction, which will cause a flow of current in the conductor if the circuit is closed.

Hence, the basic essential parts of an electric generator are:

► A magnetic field and

► A conductor or conductors which can so move as to cut the flux

In dc generators the field is produced by the field magnets which are stationary. Permanent magnets are used for very small capacity machines and electromagnets are used for large machines to create magnetic flux. The conductors are situated on the periphery of the armature being rotated by the prime-mover.
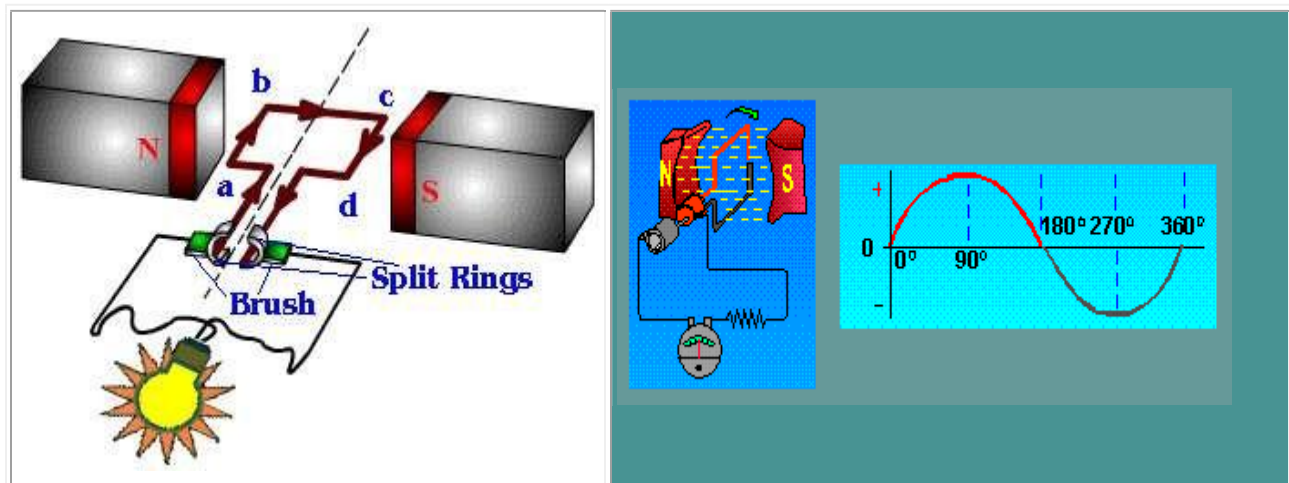

Fig. 1.1 Basics of dc generators

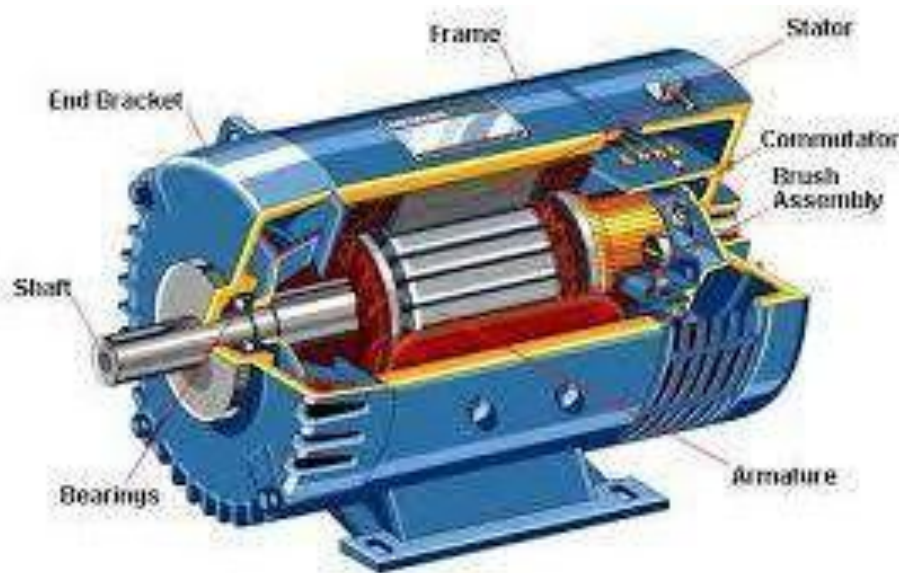1.1   Practical DC generator construction

Fig. 1.2 Cut-away view of dc practical generators

The actual DC generator consists of the following essential parts:

- Magnetic frame or Yoke

- Pole Cores and Pole Shoes

- Pole Coils or Field Coils

- Armature Core

- Armature Windings or Conductors

- Commutator

- Brushes and Bearings

a)   Magnetic frame or Yoke

Purpose of Yoke is

1. It act as a protecting cover for whole machine

2. It provides mechanical support for poles

3. It carries the magnetic flux produced by poles

b)   Pole Cores and Pole Shoes

The field magnets consist of pole cores and pole shoes. The Pole shoes serve two purposes:

1. They spread out the flux in the air gap

2. They support the exciting coils

c)   Armature

When current is passed through field coils, they electro-magnetize the poles which produce the necessary flux.

The Armature serves two purposes:

1.   Armature houses the armature conductors or coils

2.   It provides low reluctance path for flux

It is drum shaped and is built up of laminations made sheet steel to reduce eddy current loss. Slots are punched on the outer periphery of the disc. The Armature windings or conductors are wound in the form of flat rectangular coils and are placed in the slots of the Armature. The Armature windings are insulated from the armature body by insulating materials.

d)   Commutator and brushes

The function of Commutator is to facilitate collection of current from the armature conductors and converts the alternating current induced in the armature conductors into unidirectional current in the external load circuit. The commutator is made up of insulated copper segments. Two brushes are pressed to the commutator to permit current flow. The Brushes are made of carbon or Graphite. Bearings are used for smooth running of the machine.

1.2   E.M.F. equation

Let, ϕ =flux per pole in weber

$z =$ total number of armature conductors=no. of slots× no. of conductors/slot

$P =$ no. of generator poles

$A =$ no. of parallel paths in armature

$N =$ armature rotation in revolutions per minute (rpm)

$E =$ emf induced in any parallel path in armature

Generated emf, $E_g =$ emf generated in any one of the parallel path i.e. E

Average emf generated/conductor $= \dfrac{d\phi}{dt}$ volts, $\square n = 1$

Now, flux cut per conductor in one revolution,

$d\phi = \phi P$ weber

No. of revolutions per second $= \dfrac{N}{60}$

Time for one revolution, $dt = \dfrac{60}{N}$ second

Hence, according to Faradays laws of Electromagnetic induction,

EMF generated/conductor $= \dfrac{d\phi}{dt} = \dfrac{\phi PN}{60}$ volts

For a simplex lap-wound generator:

No. of parallel paths $= P$

No. of conductors in one path $= \dfrac{z}{P}$

Hence, EMF generated/path $= \dfrac{\phi PN}{60} \times \dfrac{z}{P} = \dfrac{\phi zN}{60}$ volts

For a simplex wave-wound generator:

No. of parallel paths $= 2$

No. of conductors in one path $= \dfrac{z}{2}$

Hence, EMF generated/path $= \dfrac{\phi PN}{60} \times \dfrac{z}{2} = \dfrac{\phi zNP}{120}$ volts

In general generated EMF, $E_g = \dfrac{\phi zN}{60} \times \dfrac{P}{A}$

1.3   Types of generator

DC generators are usually classified according to the way in which their fields are excited. DC generators may be divided into, (a) separately excited dc generators, and (b) self excited dc generators.

a) separately excited dc generators

Separately excited generators are those whose field magnets are energized from an independent external source of dc current.

b) self excited dc generators

Self excited generators are those whose field magnets are energized by the current produced by the generators themselves. Due to residual magnetism, there is always present some flux in the poles. When the armature is rotated, some emf and hence some current flows which is partly or fully passed through the field coils thereby strengthening the residual pole flux.

There are three types of self excited dc generators named according to the manner in which their field coils (or windings) are connected to the armature. In shunt the two windings, field and armature are in parallel while in series type the two windings are in series. In compound type the part of the field winding is in parallel while other part in series with the armature winding.
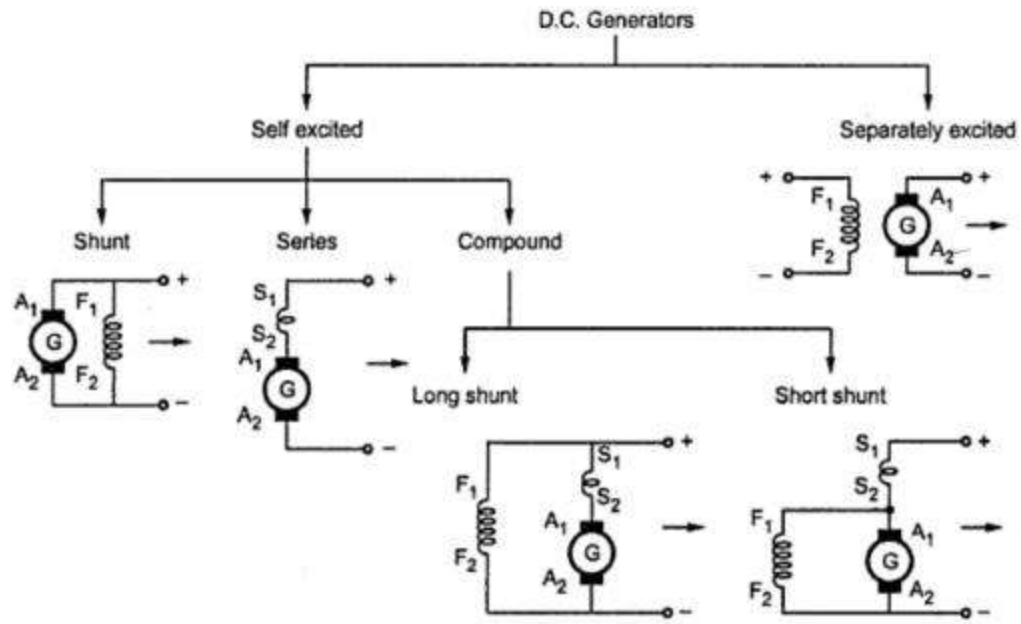
Fig.1.3 DC generators classification

D.C. Motor

An electric motor is a machine which converts electrical energy into mechanical energy.

2.1   Principle of operation

It is based on the principle that when a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force whose direction is given by Fleming's Left-hand rule and whose magnitude is given by

Force, **F = B I l** newton

Where B is the magnetic field in weber/m^2. I is the current in amperes and l is the length of the coil in meter.

Fleming's left hand rule says that if we extend the index finger, middle finger and thumb of our left hand in such a way that the current carrying conductor is placed in a magnetic field (represented by the index finger) is perpendicular to the direction of current (represented by the middle finger), then the conductor experiences a force in the direction (represented by the thumb) mutually perpendicular to both the direction of field and the current in the conductor.
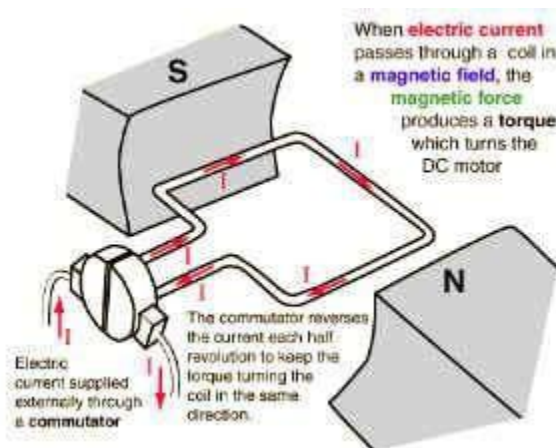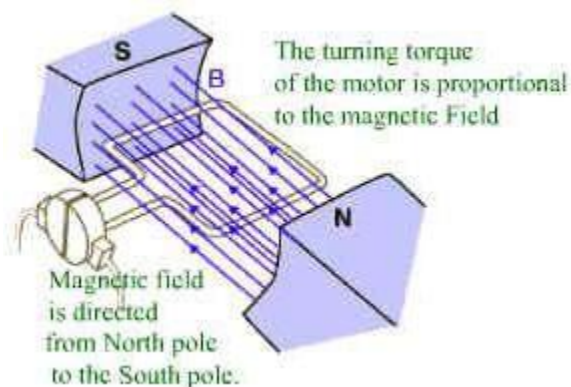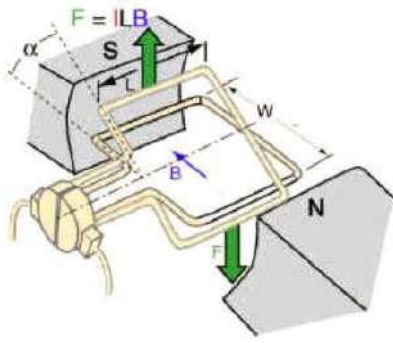

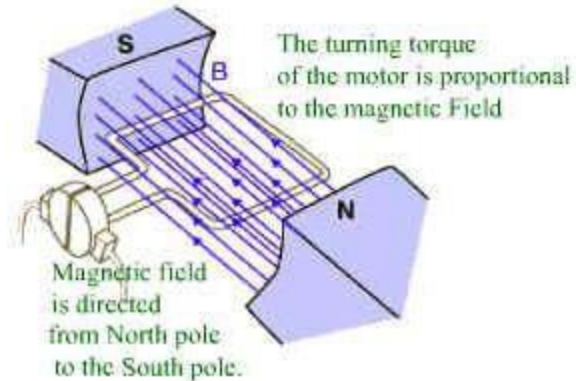**Figure 2.1: Force in DC Motor   Figure 2.2 : Magnetic Field in DC Motor**

Figure 2.3 : Torque in DC Motor   **Figure 2.4 : Current Flow in DC Motor**

Constructionally, there is no basic difference between a dc generator and motor. In fact, the same dc machine can be used interchangeably as a generator or as a motor. The basic construction of a dc motor contains a current carrying armature which is connected to the supply end through commutator segments and brushes and placed within the north south poles of a permanent or an electro-magnet.
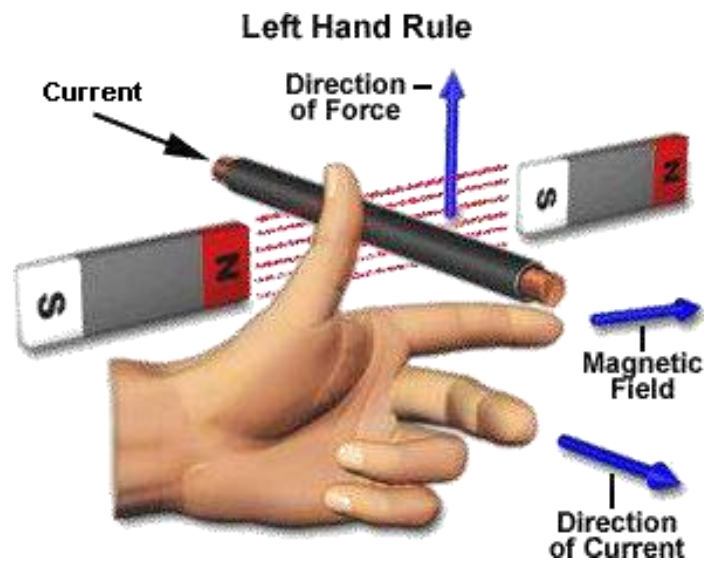
Fig. 2.5 Flemings Left hand rule

2.2   Back E.M.F

When the motor armature rotates, the conductors also rotate and hence cut the flux. In accordance with the laws of electromagnetic induction, emf is induced in them whose direction, as found by

Fleming's Right hand Rule, is in opposition to the applied voltage. Because of its opposing direction, it is referred to as counter emf of back emf E_b. V has to drive I_a against the opposition of E_b. The power required to overcome this opposition is $E_b I_a$.

2.3   Voltage Equation of a Motor

The voltage V applied across the motor armature has to,

(a) Overcome the back emf E_b, and

(b) Supply the armature ohmic drop $I_a R_a$

Hence, $V = E_b + I_a R_a$

This is known as voltage equation of a dc motor.

Now, multiplying both sides by I_a, we get

$$VI_a = E_b I_a + I_a^2 R_a$$

Where, VI_a =Electrical power input to the armature

$E_b I_a$ =Electrical equivalent of mechanical power developed in the armature

$I_a^2 R_a$ =copper loss in the armature

2.4   Condition for maximum efficiency

The gross mechanical power developed by motor is, $P_m = VI_a - I_a^2 R_a$

Differentiating both side with respect to I_a and equating the result to zero, we get

$$\frac{dP_m}{dI_a} = V - 2I_a R_a = 0$$

Hence, $I_a R_a = V/2$

As, $V = E_b + I_a R_a$ and $I_a R_a = V/2$

Hence, $E_b = V/2$

Thus gross mechanical power developed by a motor is maximum when back emf is equal to half the supply voltage. This condition is, however, not realized in practice, because in that case current would be much beyond the normal current of the motor. Moreover, half the input would be wasted in the form of heat and taking other losses (mechanical and magnetic) into consideration, the motor efficiency will be well below 50 percent.

2.5   Torque

The turning or twisting moment of a force about an axis is called torque. It is measured by the product of the force and the radius at which this force acts.

Consider a pulley of radius r meter acted upon by a circumferential force of F newton which causes it to rotate at N rpm.

Then torque $T = F \times r$ newton-metre(N-m

Work done by this force in one revolution

=Force$\times$ distance

$= F \times 2\pi r$ joule

Power developed $= F \times 2\pi r \times N$ joule/second or watt $= \left(F \times r \right) \times 2\pi N$ watt

Now, $2\pi N =$ angular velocity ω in radian per second and $F \times r =$ torque T

Hence, power developed $= T \times \omega$ watt or $P = T\omega$ watt

Moreover, if N is in rpm, then

$\omega = 2\pi N / 60$ rad/s

Hence, $P = \dfrac{2\pi N}{60} \times T$ or $P = \dfrac{2\pi}{60} . NT = \dfrac{NT}{9.55}$

2.5.1   Armature torque of a motor

Let T_a be the torque developed by the armature of a motor running at N rps. If T_a is in N-m, then

power developed $= T_a \times 2\pi N$ watt

We also know that electrical power converted into mechanical power in the armature $= E_b I_a$ watt.

Comparing above equations, we get $T_a \times 2\pi N = E_b I_a$

After simplification, if N in rps, $T_a = \dfrac{E_b I_a}{2\pi N}$

If N is in rpm, then $T_a = 9.55 \dfrac{E_b I_a}{N}$ N-m

Also, $T_a = 0.159\phi Z I_a \times (P/A)$N-m

2.5.2 Shaft torque

The whole of the armature torque, as calculated above, is not available for doing useful work, because of iron and friction losses in the motor. The torque which is available for doing useful work is known as shaft torque T_{sh}. The motor output is given by

Output $= T_{sh} \times 2\pi N$ watt provided T_{sh} is in N-m and N in rps.

Hence, $T_{sh} = \dfrac{Output\_in\_watts}{2\pi N}$, if N is in rps

And, if N is in rpm, then $T_{sh} = \dfrac{Output\_in\_watts}{2\pi N/60} = 9.55 \dfrac{Output}{N}$

2.6   Speed Control of DC Motor

Speed control means intentional change of the drive speed to a value required for performing the specific work process. Speed control is a different concept from speed regulation where there is natural change in speed due to change in load on the shaft. Speed control is either done manually by the operator or by means of some automatic control device.

One of the important features of dc motor is that its speed can be controlled with relative ease. We know that the expression of speed control dc motor is given as,

$$N = \frac{V - I_a R_a}{Z\phi} \cdot \left(\frac{A}{P}\right) = K \frac{V - I_a R_a}{\phi} \text{ rps}$$

Where, R_a armature circuit resistance.

Therefore speed (N) of 3 types of dc motor – SERIES, SHUNT AND COMPOUND can be controlled by changing the quantities on RHS of the expression. So speed can be varied by changing

(i) terminal voltage of the armature V ,

(ii) armature circuit resistance R and

(iii) flux per pole ϕ .

The first two cases involve change that affects armature circuit and the third one involves change in magnetic field. Therefore speed control of dc motor is classified as

1) armature control methods and

2) field control methods.

2.7   Motor starters

The starting of DC motor is somewhat different from the starting of all other types of electrical motors. This difference is credited to the fact that a dc motor unlike other types of motor has a very high starting current that has the potential of damaging the internal circuit of the armature winding of dc motor if not restricted to some limited value. This limitation to the starting current of dc motor is brought about by means of the starter. Thus the distinguishing fact about the starting methods of dc motor is that it is facilitated by means of a starter. Or rather a device containing a variable resistance connected in series to the armature winding so as to limit the starting current of dc motor to a desired optimum value taking into consideration the safety aspect of the motor.

Starters can be of several types and requires a great deal of explanation and some intricate level understanding. But on a brief over-view the main types of starters used in the industry today can be illustrated as:-
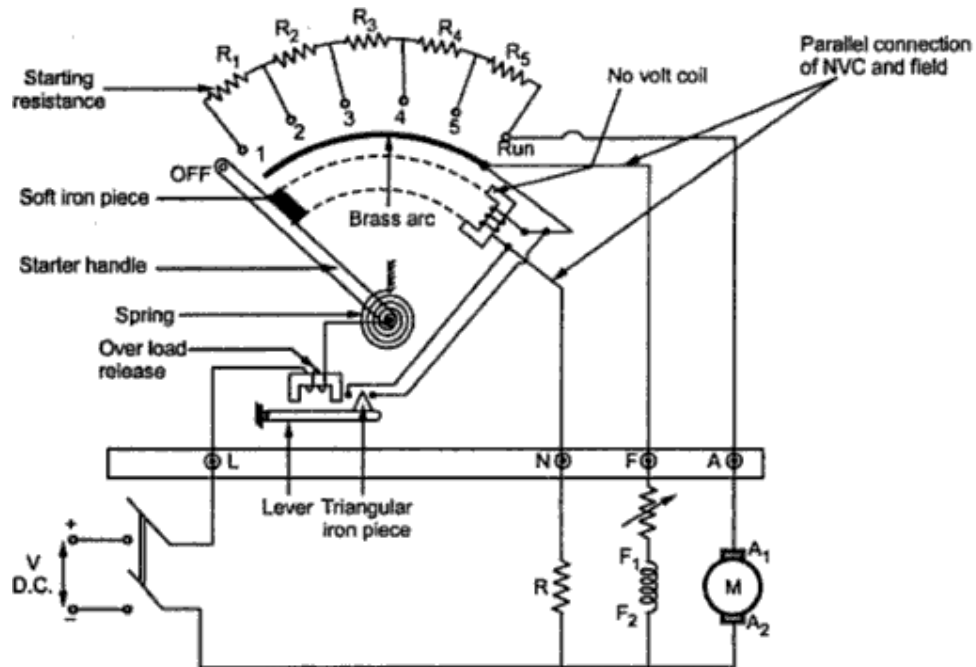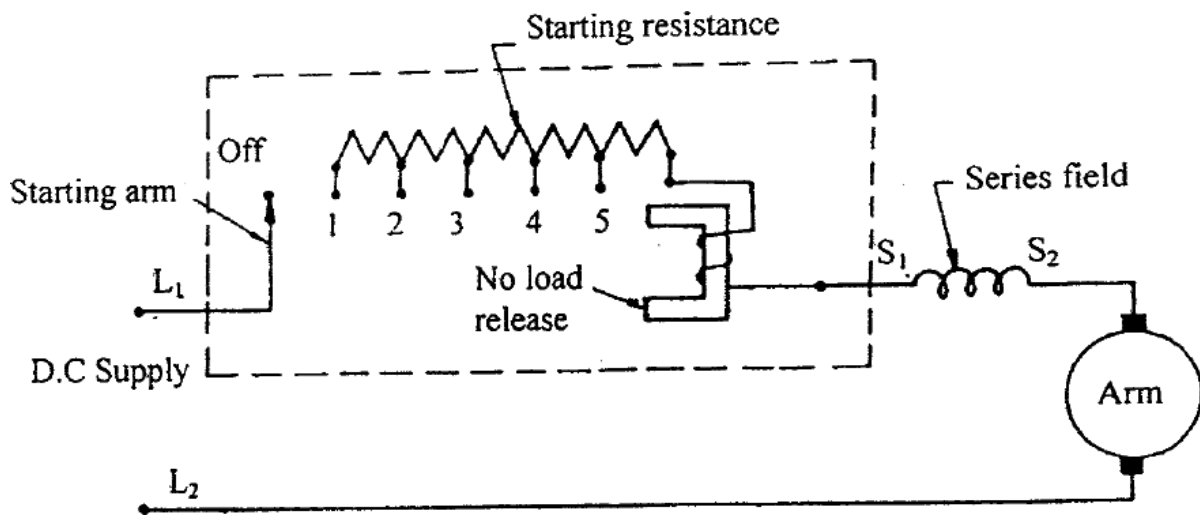
1.   3 point starter.

2.   4 point starter.
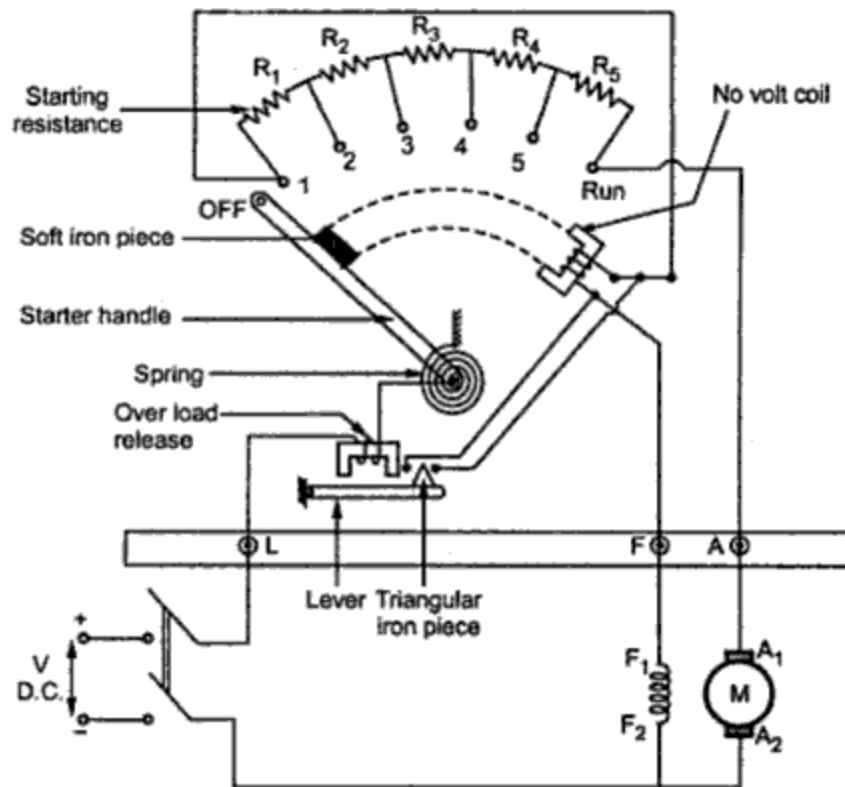
3 point Starter

Fig. 2.6

4 point Starter

Fig. 2.7

Series motor starter, no-load release.

Fig. 2.8

Single phase Transformer

3.1   Principle of operation and construction

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. Although transformers have no moving parts, they are essential to electromechanical energy conversion. They make it possible to increase or decrease the voltage so that power can be transmitted at a voltage level that results in low costs, and can be distributed and used safely. In addition, they can provide matching of impedances, and regulate the flow of power (real or reactive) in a network.

- The physical basis of a transformer is mutual induction between two circuits linked by a common magnetic field.

- In its simplest form, it consists of two inductive coils which are electrically separated but magnetically linked through a path of low reluctance. The two coils posses 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 emf.

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.

a) Core type

b) Shell type

In the so-called core type transformer, the windings surround a considerable part of the core whereas in shell-type transformer, the core surrounds considerable portions of the winding.
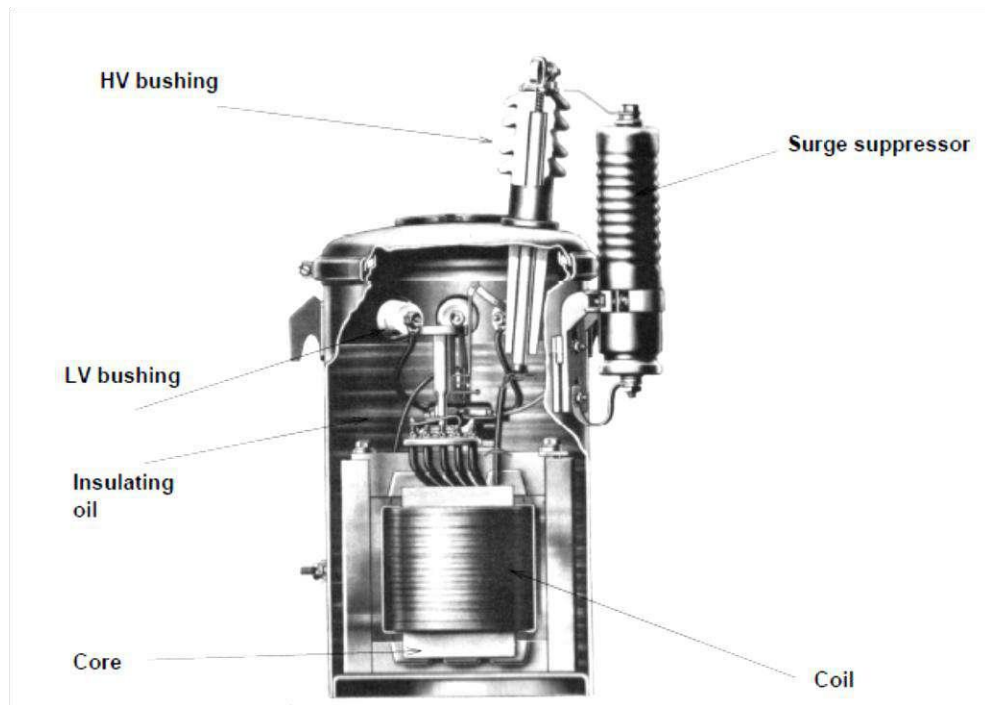
Fig.3.1 Physical diagram of a transformer

3.2   Elementary theory of an ideal transformer

An ideal transformer is one which has no losses i.e. its windings have no ohmic resistance, there is no magnetic leakage and hence which has no copper and core losses. An ideal transformer consists of two purely inductive coils wound on a loss free core.

In its simplest form it consist of, two inductive coils which are electrically separated but magnetically linked through a path of low reluctance. If one coil (primary) 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. If the second coil (secondary circuit) is closed, a current flows in it and so electric energy is transferred (entirely magnetically) from the first coil to the second coil.
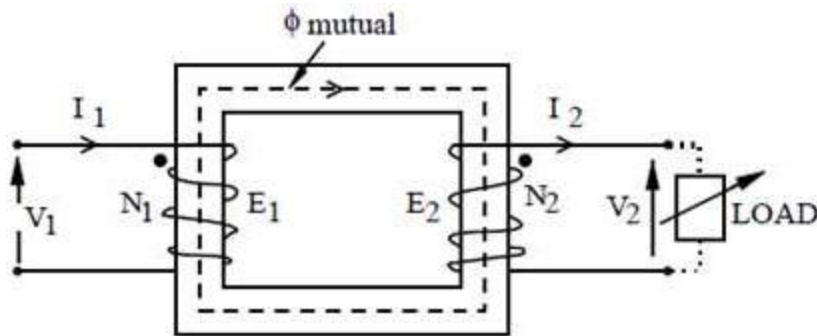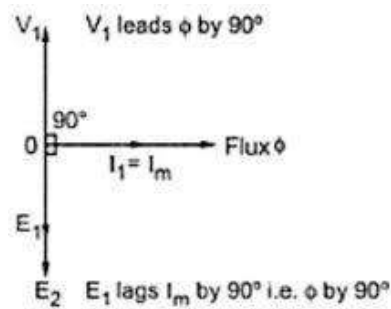
Fig.3.2 Elementary Transformer

Fig.3.3 Vector representation of applied voltage, induced emf flux and magnetizing current of a single

phase transformer

3.2   E.M.F. equation

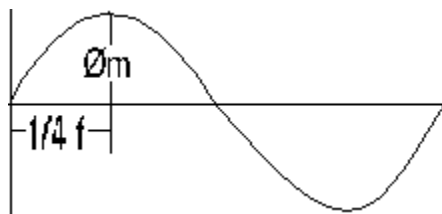Let, $N_1 =$ No. of turns in primary

$N_2 =$ No. of turns in secondary

$\phi_m =$ Maximum flux in core in webers $= B_m \times A$

$B_m =$ Maximum flux density

$A =$ Area

$f =$ Frequency of ac input in Hz

The flux increases from its zero value to maximum value ϕ_m in one quarter of the cycle i.e. in $1/4f$ second.

The average rate of change of flux $= \dfrac{\phi_m}{1/4f} = 4f\phi_m$ wb/sec or volts

Now, rate of change of flux per turn means induced emf in volts.

Hence, average EMF/turn $= 4f\phi_m$ volts

If flux varies sinusoidally, then rms value of induced emf is obtained by multiplying the average value with form factor.

$$Form\_factor = \frac{rms\_value\_of\_ac\_quantity}{average\_value\_of\_ac\_quantity} = 1.11$$

Hence, rms value of EMF/turn $= 1.11 \times 4f\phi_m = 4.44f\phi_m$ volts

Now, r.m.s value of induced e.m.f in the whole of primary winding

$\qquad$ = (induced e.m.f. / turn) x No. of primary winding

$E_1 = 4.44 f\phi_m N_1$ --------------------- (i)

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

$E_2 = 4.44 f\phi_m N_2$ ---------------------------- (ii)

Voltage transformation ratio

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

This constant K is known as voltage transformation ratio.

(i)   If K>1, then the transformer is called step-up transformer.

(ii)   If K<1, then the transformer is called step-down transformer.

3.3   Transformer with losses but no magnetic leakage

There are two cases, (i) when a transformer is on no load and (ii) when it is loaded.

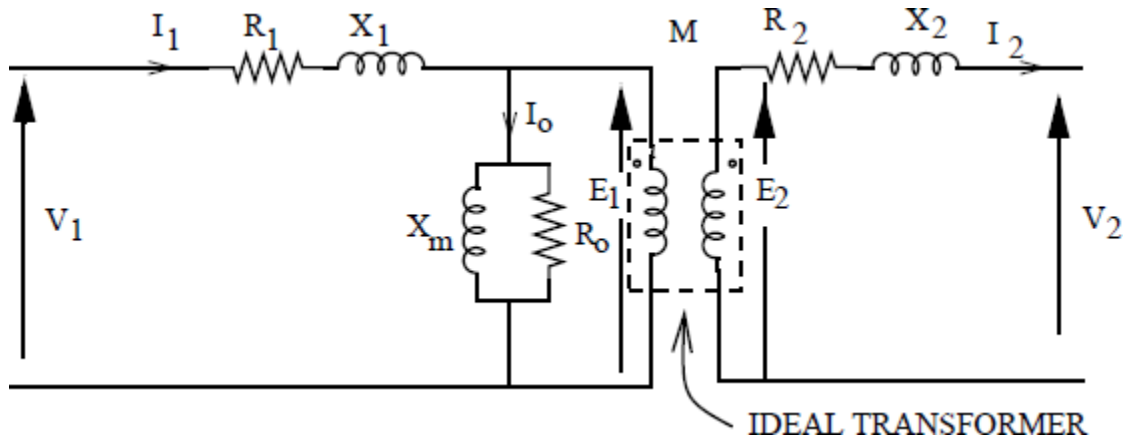3.4   Actual and approximate equivalent circuits
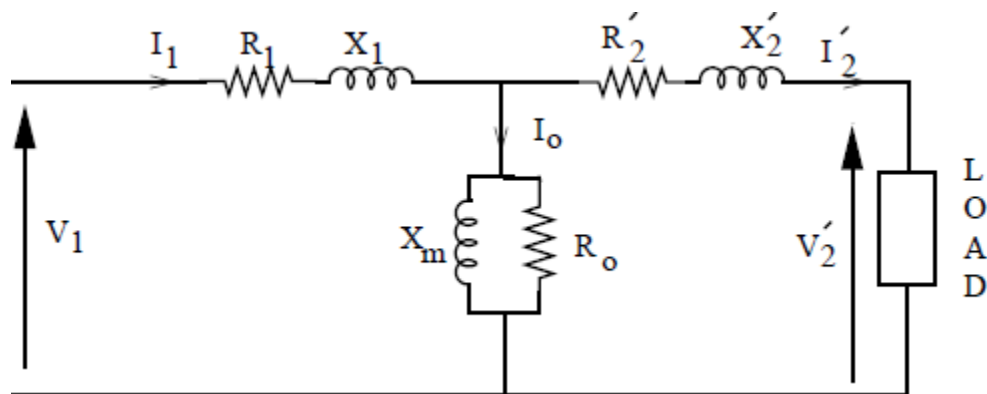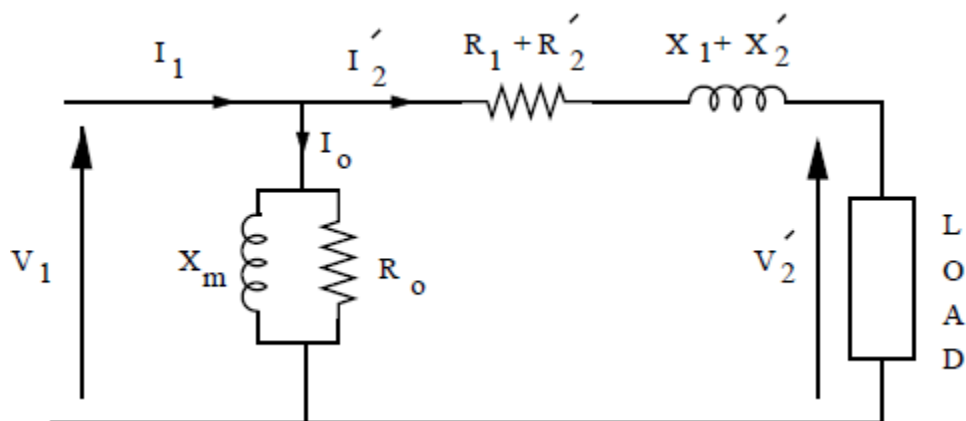

Fig. 3.3(a)

Fig. 3.3(b)

Fig.3.4 Approximate equivalent circuit of transformer

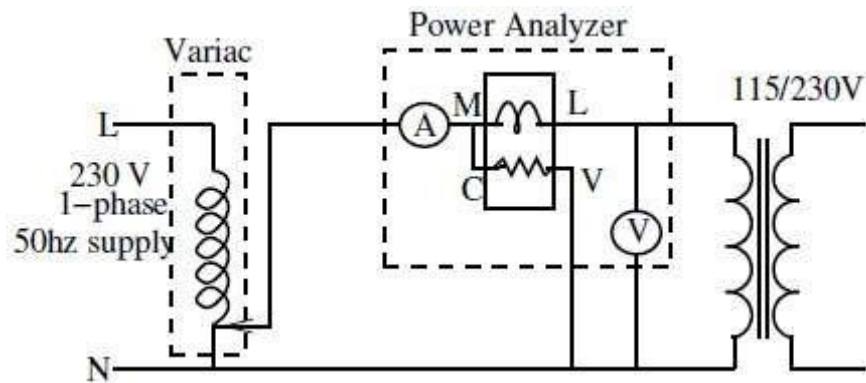## 3.5   Open and short circuit tests

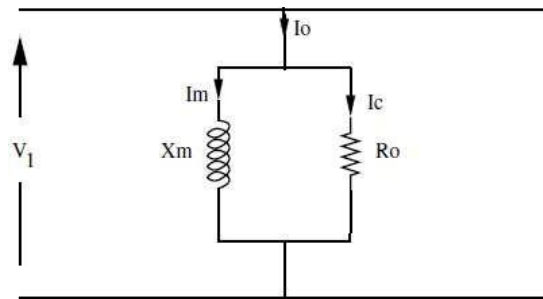Fig.3.5 Circuit Diagram for No−Load Test

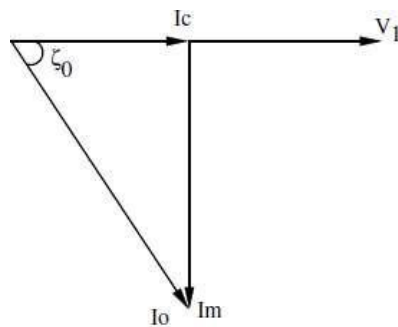Fig.3.6 (a) Equivalent Circuit on No−Load

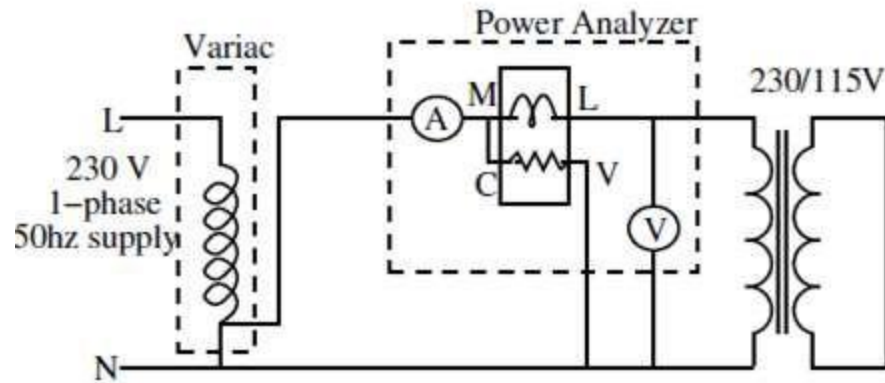Fig.3.7 (b) Phasor Diagram on No−Load
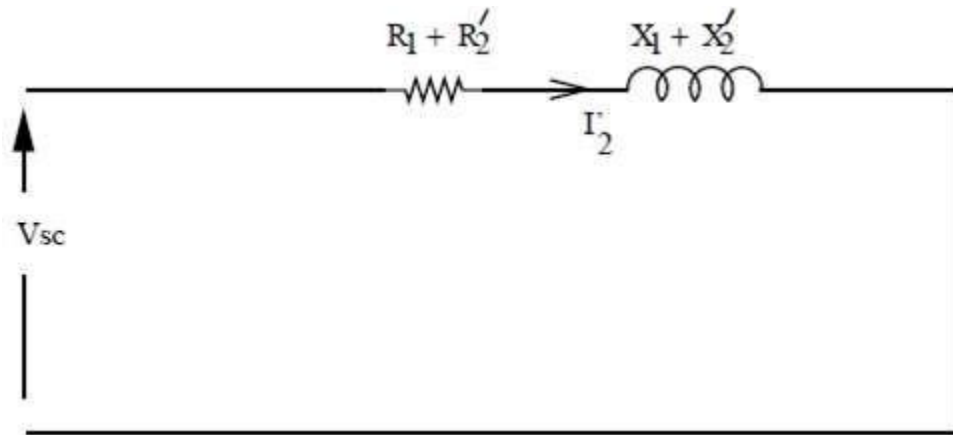
Fig.3.8 (a) Circuit Diagram for Short−Circuit Test

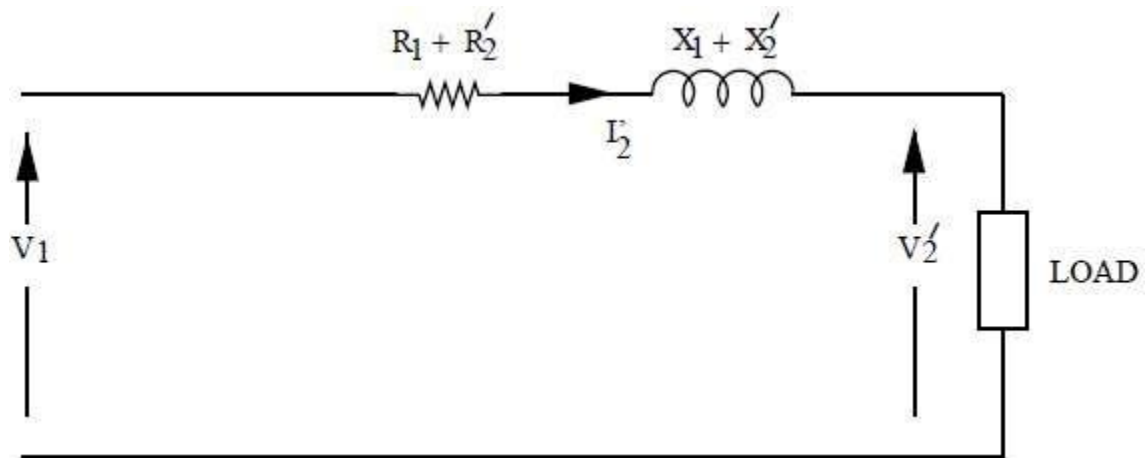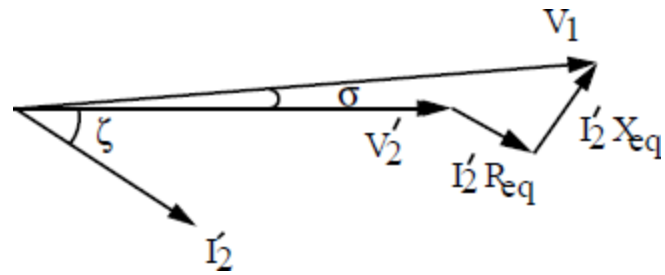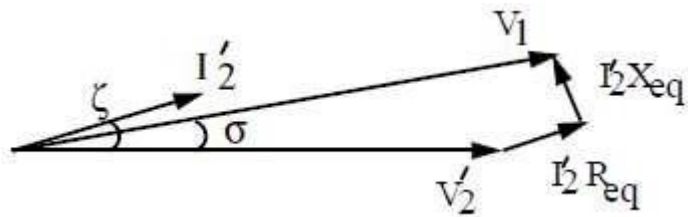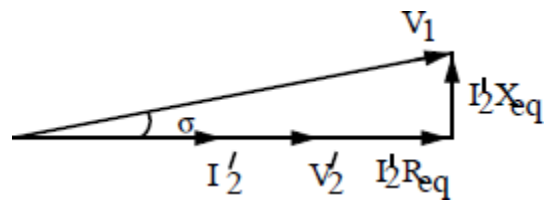Fig.3.9 (b) Equivalent Circuit on Short Circuit

Fig.3.10 Equivalent Circuit to determine Regulation

(a) Lagging Power Factor

(b) Leading Power Factor

(c) Unity Power Factor

Fig.3.11 Vector diagram for various load conditions

Three Phase Transformer

In general, for transformation, transmission and utilization of electric energy, it is economical to use the three phase system rather than the single phase. For three phase transformation, two arrangements are possible. First is to use a bank of three single phase transformer and the second, a single three phase transformer with the primary and secondary of each phase wound on three lags of a common core. The advantages of a single unit of 3-phase transformer as compared to a bank of three single phase transformer are the cost is much less, occupies less floor space for equal rating and weighs less.
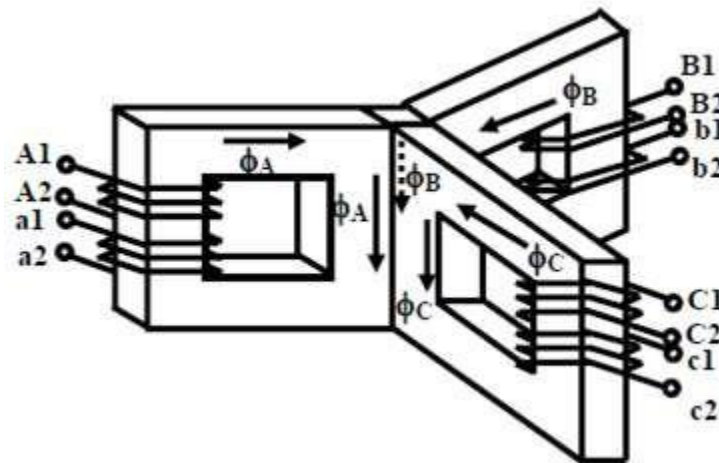
Fig.4.1 A conceptual three phase transformer
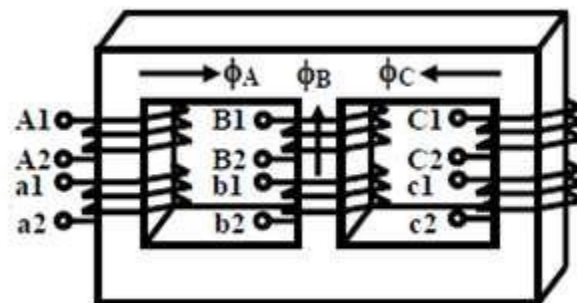
Fig.4.2 A practical three phase core type three phase transformers

4.1   Three phase transformer connections

A variety of connections are possible on each side of a 3-phase transformer. The three phases could be connected in star, delta, open delta or zig-zag star. Each of the three phases could have two windings or may have auto connection. Further, certain types of connections require a third winding known as tertiary.
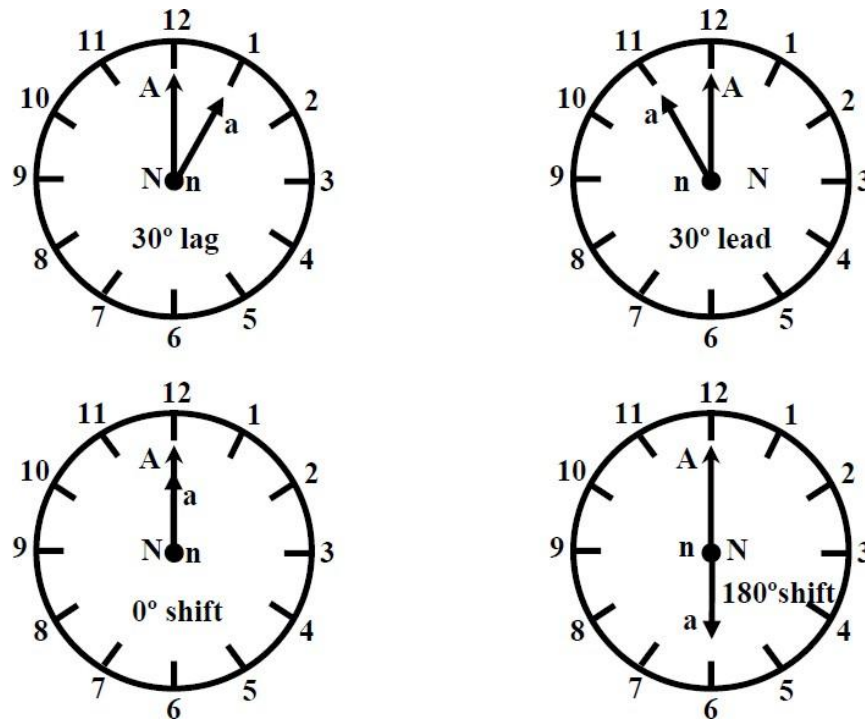
Fig.4.3 Clock convention representing vector groups

Autotransformer

It is a transformer with one winding only, part of this being common to both primary and secondary. In this transformer the primary and secondary are not electrically isolated from each other as is the case with a two winding transformer. But its theory and operation are similar to those of a two winding transformer. Because of one winding, it uses less copper and hence is cheaper. It is used where transformation ratio offers little from unity.

Weight   of   copper   in   autotransformer

$(W_a) = (1 - K) \times (Weight of copper in ordinary transormer (W_O))$

Hence, saving $= W_0 - W_a$

$= W_0 - (1 - K)W_O$

$= KW_O$

Hence, saving will increase as K approaches unity.

Power conducted inductively $= Input power \times (1 - K)$

Power conducted directly $= K \times Input power$
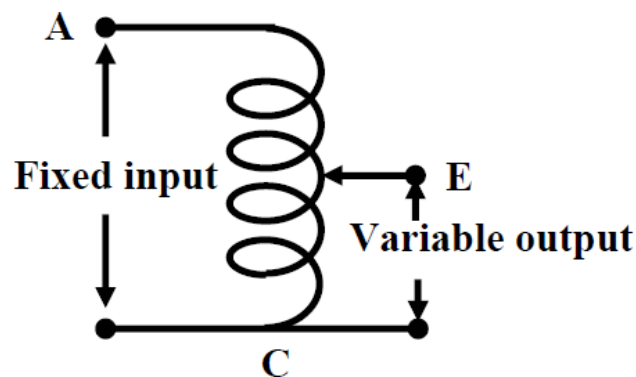
Fig.5.1 Schematic representation of autotransformer

5.1   Conventional transformer connected as Autotransformer

Any two winding transformer can be converted into an autotransformer either step-down or step-up. If we employ additive polarity between the high voltage and low voltage sides, we get a step-up transformer. If, however, we use the subtractive polarity, we get a step-down autotransformer. The connections are given in fig.2.
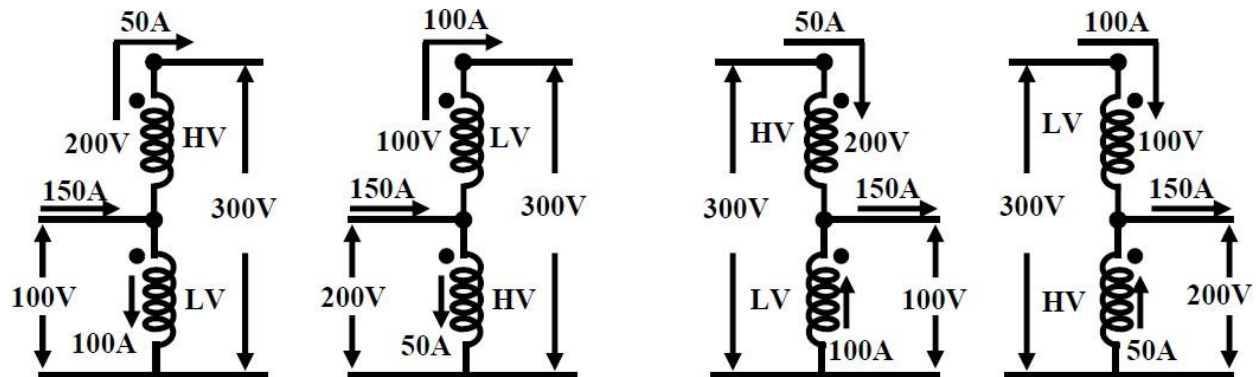
Fig.5.2 A two winding transformer connected as an autotransformer in various ways
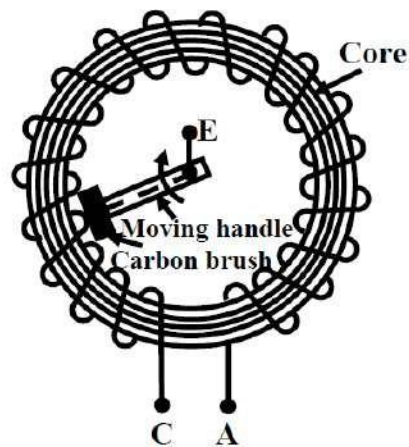
Fig.5.3 Autotransformer or Variac
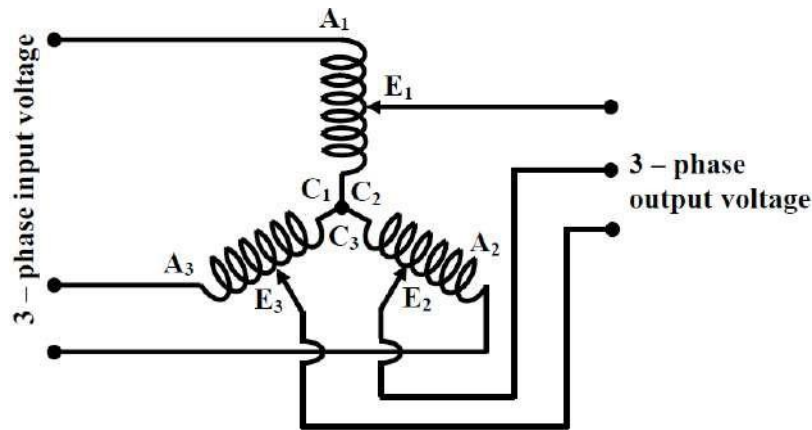
Fig.5.4 3 – Phase autotransformer connection

Synchronous Machines

A synchronous machine operates at constant speed in the steady state. Under steady state conditions, the rotating air gap field and the rotor in a synchronous machine rotate at the same speed, called the synchronous speed which depends on the frequency of the armature current and the number of field poles. Synchronous machines are used primarily as gemerators of electric power. In this case they are called alternators. Synchronous generators are the primary energy conversion devices of the worlds electric power systems today.

6.1   Construction of three phase synchronous machines

A synchronous machine consists of two main parts namely, an armature winding and a magnetic field, similar to a dc machine. The following are the main advantages of rotating field type synchronous machines.

(a) Two slip rings are required for the supply of direct current to the rotor while in stationary field type 3 to 4 slip rings would be needed.

(b) The power used in exciting the field system may be only about two percent of the ac output of the machine and that too is supplied at low voltage, thus it is easier and economical to design slip rings to carry this smaller power for the rotating field.

(c) The voltage generated in the armature is much higher and therefore greater insulation is required for the armature winding. Thus it is much easier to insulate the high voltage winding when it is mounted on a stationary structure.

(d) Note that by the use of stationary armature this high voltage insulation is not subjected to mechanical stress due to centrifugal forces. The end conductors of the armature winding can be braced securely in position thereby making it fit to withstand the large forces by sudden short circuit.

(e) The main connecting cables can be connected directly with the armature winding. With rotating armature, the current would have to be calculated by means of slip rings and with high voltage and large power, such collection, would pose serious problems.

(f) Rotating field is comparatively light and can be constructed for high speed operation.

(g) Cooling systems are comparatively easier.

6.1.1   Stator

The stator of a three phase synchronous machine consists of a stator frame, a slotted stator, which provides a low reluctance path for the magnetic flux. It has a distributed winding embedded in the slots similar to that of three phase induction machine.

6.1.2   Rotor

The rotor has a winding called the field winding, which carries direct current. The field winding on the rotating frame is normally fed from an external dc source through slip rings and bruses. Two types of rotors are used in synchronous machines, the cylindrical rotor and a salient pole rotor. Depending on the type of rotor used synchronous machines are broadly divided into two groups as follows:

- High speed machines with cylindrical (non- salient pole) rotors

- Low speed machines with salient pole rotors

The cylindrical rotor has one distributed winding and an essentially uniform air gap. These rotors are used in large generators with two or sometimes four poles and are usually driven by steam turbines. The rotors are long and have a small diameter. The features are,

- They have small diameters and very long axial length.

- Dynamic balancing is better.

- Operation is quieter and windage losses are less.

- The speed is 1000 to 3000 rpm.

- Used with steam turbines and steam engines.

The rotors of salient pole machines have concentrated winding on the poles and a non-uniform air gap. Salient pole generators have a large number of poles, sometimes as many as 50, and operate at lower speed. The alternators in hydroelectric power stations are of the salient pole type and are driven by water turbines. The rotors are shorter in length but have a large diameter. The speed is 120 to 400 rpm.

6.2   Equation of induced E.M.F.

Let, ϕ =flux per pole in weber

z = total number of armature conductors or coil sides in series/phase = $2T$

T = no. of turns or coils per phase

P = no. of generator poles

f = frequence of induced emf in Hz

N = rotor speed in revolutions per minute (rpm)

K_d = distribution factor = $\dfrac{\sin(m\beta/2)}{m\sin(\beta/2)}$

K_c or K_P = pitch or coil span factor = $\cos\dfrac{\alpha}{2}$

K_f = form factor

In one revolution of the rotor (i.e. in $60/N$ seconds) each conductor is cut by a flux of ϕP weber.

Hence, $d\phi = \phi P$ and $dt = \dfrac{60}{N}$ seconds

Hence, average emf induced/conductor $= \dfrac{d\phi}{dt} = \dfrac{\phi NP}{60}$ volts, $\square\, n = 1$

Now, we know that $f = \dfrac{PN}{120}$ or $N = \dfrac{120f}{P}$

Substituting this value of N above, we get

Average emf induced/conductor $= \dfrac{\phi P}{60} \times \dfrac{120f}{P} = 2f\phi$ volts

If there are z no. of conductors in series/phase, then average emf/phase $= 2f\phi z$ volts $= 4f\phi T$ volts

Hence, RMS value of emf/phase $= 4.44\, f\phi T$ volts

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

Hence, actually available voltage/phase $= 4.44 K_c K_d f\phi T$ volts

$$= 4K_f K_c K_d f\phi T \text{ volts}$$

If the alternator is star connected then the line voltage is $\sqrt{3}$ times the phase voltage.

6.2.1   Short-Pitch Winding

Advantages

- Copper in end connection can be saved.

- Harmonics are reduced

- Iron losses will be reduced

- Efficiency will be increased

- Generated voltage waveform will be improved is more sinusoidal.

Disadvantages:-

- The magnitude of the induced voltage will be reduced

6.2.2   Distributed Winding

Advantages

- The generated voltage waveform will be improved, is more sinusoidal.

Disadvantage

- The magnitude of induced voltage will be reduced

6.3   Synchronous motor

A synchronous motor runs under steady state condition at a fixed speed called the synchronous speed. The synchronous speed depends only upon the frequency of the applied voltage and the number of poles in the machine. The speed of the synchronous motor is independent of the load as long as the load is within the capability of the motor. If the load torque exceeds the maximum torque that can be developed by the motor, the motor simply comes to rest.

6.4   Principle of operation of synchronous motor

Synchronous motor is a doubly excited machine i.e two electrical inputs are provided to it. It's stator winding which consists of a 3 phase winding is provided with 3 phase supply and rotor is provided with DC supply. The 3 phase stator winding carrying 3 phase currents produces 3 phase rotating magnetic flux. The rotor carrying DC supply also produces a constant flux. Considering the frequency to be 50 Hz, from the above relation we can see that the 3 phase rotating flux rotates about 3000 revolution in 1 min or 50 revolutions in 1 sec. At a particular instant rotor and stator poles might be of same polarity (N-N or S-S) causing repulsive force on rotor and the very next second it will be N-S causing attractive force. But due to inertia of the rotor, it is unable to rotate in any direction due to attractive or repulsive force and remain in standstill condition. Hence it is not self starting.

To overcome this inertia, rotor is initially fed some mechanical input which rotates it in same direction as magnetic field to a speed very close to synchronous speed. After some time magnetic locking occurs and the synchronous motor rotates in synchronism with the frequency.
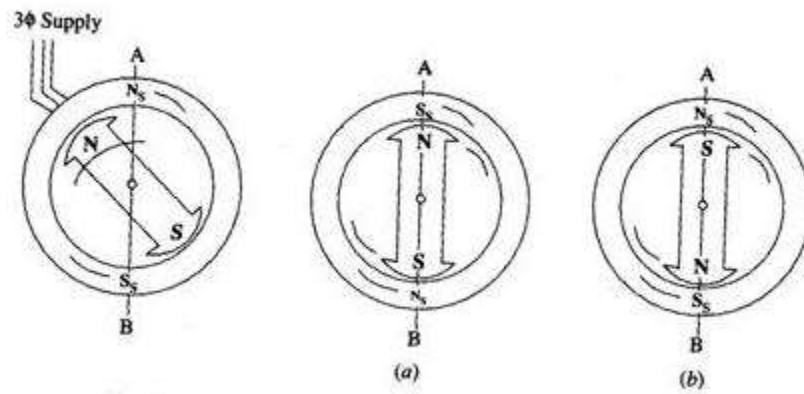

Fig.6.1

6.5   Methods of starting of Synchronous motor

1. Start with variable frequency: In this method the frequency of the source voltage is gradually increased and hence the speed also increases gradually and the motor reached its synchronous speed.

2. Pony motor start: Synchronous motors are mechanically coupled with another motor. It could be either 3 phase induction motor or DC shunt motor. DC excitation is not fed initially. It is rotated at speed very close to its synchronous speed and after that DC excitation is given. After some time when magnetic locking takes place supply to the external motor is cut off.

3. Damper winding: In case, synchronous motor is of salient pole type, additional winding is placed in rotor pole face. Initially when rotor is standstill, relative speed between damper winding and rotating air gap flux is large and an emf is induced in it which produces the required starting torque. As speed approaches synchronous speed, emf and torque is reduced and finally when magnetic locking takes place, torque also reduces to zero. Hence in this case synchronous motor is first run as three phase induction motor using additional winding and finally it is synchronized with the frequency.

6.6   Application of Synchronous Motor

1. Synchronous motor having no load connected to its shaft is used for power factor improvement.
   Owing to its characteristics to behave at any electrical power factor, it is used in power system in
   situations where static capacitors are expensive.

2. Synchronous motor finds application where operating speed is less (around 500 rpm) and high
   power is required. For power requirement from 35 kW to 2500 KW, the size, weight and cost of
   the corresponding three phase induction motor is very high. Hence these motors are preferably
   used. Ex- Reciprocating pump, compressor, rolling mills etc.

Three-phase Induction Motor

Induction Motors are the most commonly used motors in most of the applications. These are also called as Asynchronous Motors, because an induction motor always runs at a speed lower than synchronous speed. The induction motor is made up of the stator, or stationary windings, and the rotor. The stator consists of a series of wire windings of very low resistance permanently attached to the motor frame. When a voltage is applied to the stator winding terminals, a magnetic field is developed in the windings. By the way the stator windings are arranged, the magnetic field appears to synchronously rotate electrically around the inside of the motor housing.

Depending upon the input supply there are basically two types of induction motor,

(A) Single phase induction motor

- Split phase induction motor
- Capacitor start induction motor
- Capacitor start capacitor run induction motor
- Shaded pole induction motor

(B) Three phase induction motor

- Squirrel cage induction motor
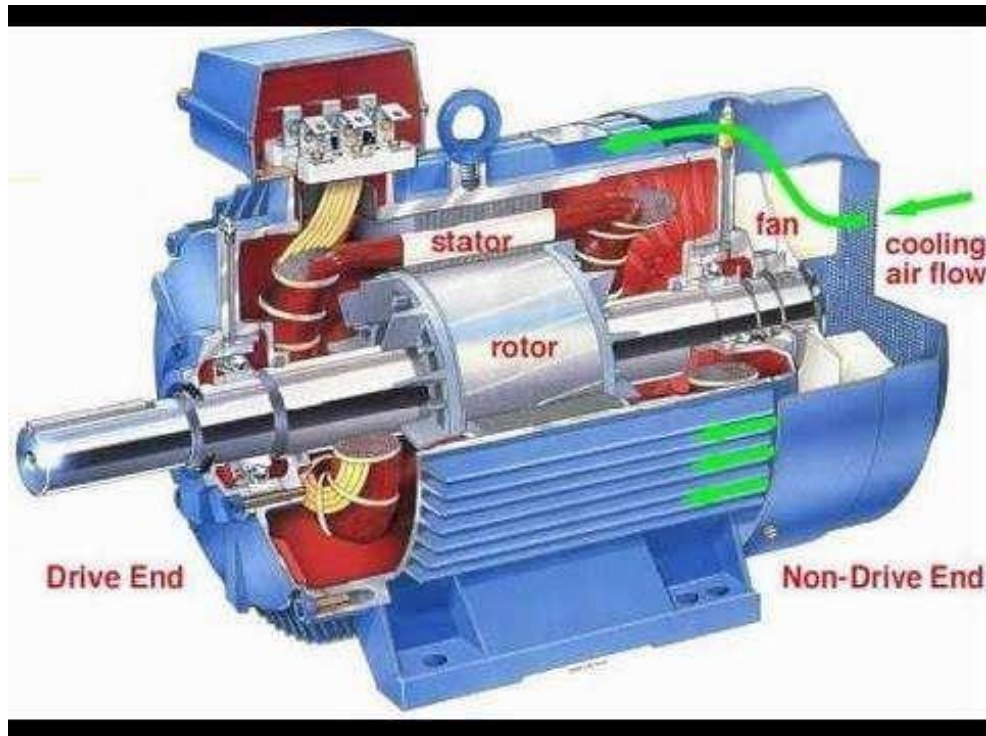- Slip ring (or phase wound) induction motor

Fig.7.1

7.1 Construction

An induction motor has two main parts:

a) a stationary stator

It consisting of a steel frame that supports a hollow, cylindrical core, constructed from stacked

laminations having a number of evenly spaced slots, providing the space for the stator winding.
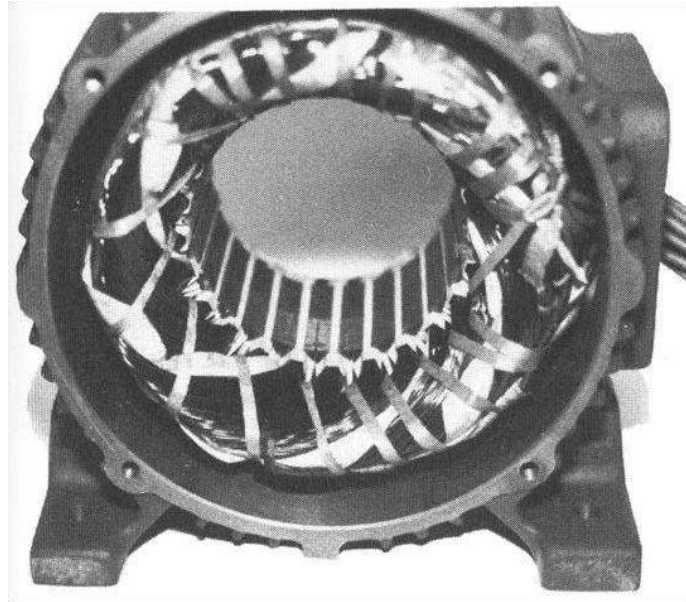
Fig.7.2 Stator

b) a revolving rotor

It composed of punched laminations, stacked to create a series of rotor slots, providing space for the rotor winding. There are two types of rotors, squirrel cage type and slip ring type.

- Squirrel-cage: conducting bars laid into slots and shorted at both ends by shorting rings.

- Slip ring: complete set of three-phase windings exactly as the stator. Usually Y-connected, the ends of the three rotor wires are connected to 3 slip rings on the rotor shaft. In this way, the rotor circuit is accessible.
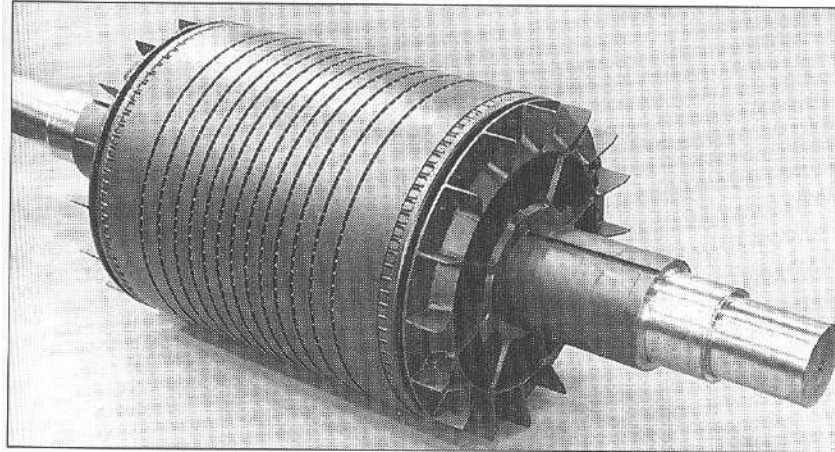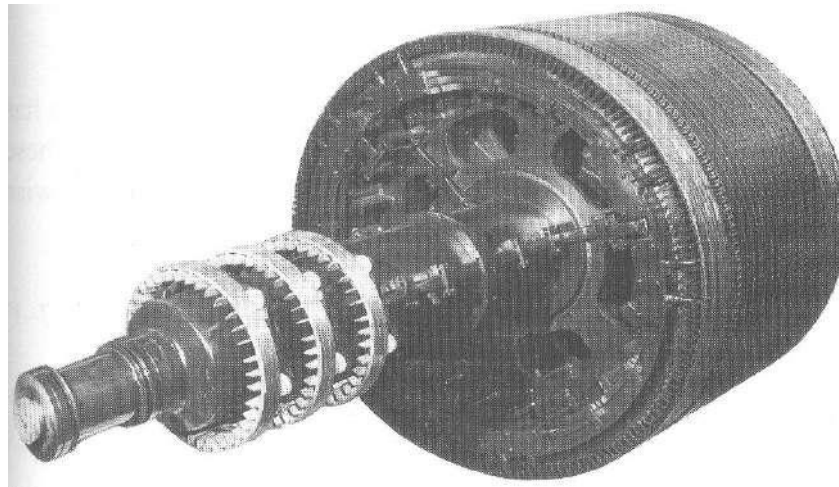
Fig.7.3 Squirrel cage rotor

Fig.7.4 Slip ring rotor

7.2   Basic Working Principle of an Induction Motor

As a general rule, conversion of electric power into mechanical power takes place in the rotating part of an electric motor. In a DC motor, the electric power is conducted directly to the armature through brushes and commutator. Hence, in this sense a dc motor can be called a conduction motor. However, in ac motors, the rotor does not receive electric power by conduction but by induction in exactly the same way as the secondary of a two winding transformer receives its power from the primary. That is why such motors are known as induction motors.

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

7.3   Slip

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

The difference between the synchronous speed and the actual speed of the rotor is known as slip. It is expressed as a percentage of the synchronous speed.

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

Sometimes, $N_s - N$ is called the slip speed.

The rotor speed is $N = N_s\left(1 - s\right)$

It may be noted here that revolving flux is rotating synchronously, relative to the stator (i.e. stationary space) but at slip speed relative to the motor.

7.4   Frequency of Rotor Current

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

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

After solving, we get, $\dfrac{f'}{f} = \dfrac{N_s - N}{N_s} = s$

Then, rotor current have a frequency of

$$f' = sf$$

7.5   Torque of an Induction motor

As we know, the torque T_a is proportional to the product of armature current and flux per pole.

$$T_a \alpha \phi I_a$$

In induction motor, $T \alpha \phi I_2 \cos\phi_2$

Hence, $T = K\phi I_2 \cos\phi_2$

Where, I_2 = rotor current at standstill

ϕ_2 = angle between rotor emf and rotor current

K = a constant

Denoting rotor emf at standstill by E_2, we have that

$$E_2 \alpha \phi$$

Hence, $T \alpha E_2 I_2 \cos\phi_2$ or $T = E_2 I_2 \cos\phi_2$

Where, K_1 is another constant.

7.5.1   Starting Torque

The torque developed by the motor at the instant of starting is called starting torque.

Let, E_2 = rotor emf per phase at standstill

R_2 = rotor resistance per phase

X_2 = rotor reactance per phase at standstill

$Z_2 = \sqrt{\left(R_2^2 + X_2^2\right)}$ = rotor impedance per phase at standstill

Then, $I_2 = \dfrac{E_2}{Z_2} = \dfrac{E_2}{\sqrt{\left(R_2^2 + X_2^2\right)}}$

$\cos\phi_2 = \dfrac{R_2}{Z_2} = \dfrac{R_2}{\sqrt{\left(R_2^2 + X_2^2\right)}}$

Starting torque, $T_{st} = K_1 E_2 I_2 \cos\phi_2 = K_1 E_2 \dfrac{E_2}{\sqrt{\left(R_2^2 + X_2^2\right)}} \dfrac{R_2}{\sqrt{\left(R_2^2 + X_2^2\right)}}$

Or, $T_{st} = K_1 \dfrac{E^2 R}{\left(R_2^2 + X_2^2\right)}$

Now, $K_1 = \dfrac{3}{2\pi N_s}$

Hence, $T_{st} = \dfrac{3}{2\pi N_s} \dfrac{E_2^2 R_2}{\left(R_2^2 + X_2^2\right)}$

Where, N_s = synchronous speed in rps

7.5.2   Condition for maximum starting torque

If supply voltage V is constant, then the flux ϕ and hence, E_2 both are constant

$T_{st} = K_2 \left(\dfrac{R_2}{R_2^2 + X_2^2}\right)$

Differentiate both side with respect to R_2, we have

$\dfrac{dT_{st}}{dR_2} = K_2 \left[\dfrac{1}{R_2^2 + X_2^2} - \dfrac{R_2 . 2R_2}{\left(R_2^2 + X_2^2\right)^2} \right] = 0$

$$\Rightarrow R_2 = X_2$$

The starting torque will be maximum if $R_2 = X_2$.

7.5.3   Torque under running condition

Let, E_2 = rotor emf per phase at standstill

R_2 = rotor resistance per phase

f_2 = frequency of rotor current at standstill

Under running condition, $E_r = sE_2$

The frequency of the induced emf will likewise become

$$f_r = sf_2$$

Due to decrease in frequency of the rotor emf, the rotor reactance will also decrease.

Hence, $X_r = sX_2$

Where, E_r and X_r are emf and reactance under running conditions.

Now, the torque under running conditions

$$T \alpha \phi I_r \cos\phi_2$$

Now, $E_r = sE_2$ and $I_r = \dfrac{E_r}{Z_r} = \dfrac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$

Also, $\cos\phi_2 = \dfrac{R_2}{Z_r} = \dfrac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$

$$T_r \alpha E_2 \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Or, $T_{st} = K\dfrac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$

Where, K is a constant. Its value can be proved to be equal to $\dfrac{3}{2\pi N_s}$. Hence, in that case,

expression for torque becomes

$$T_r = \frac{3}{2\pi N_s} \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

7.5.3   Condition for maximum torque under running conditions

The torque of a rotor under running conditions is,

$$T_r = K \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

The condition for maximum torque may be obtained by differentiating the above expression with respect to slip and then putting equal to zero, and solved we get

$$R_2 = sX_2$$

Hence, torque under running condition is maximum when at that the slip which makes rotor reactance per phase equal to rotor resistance per phase.
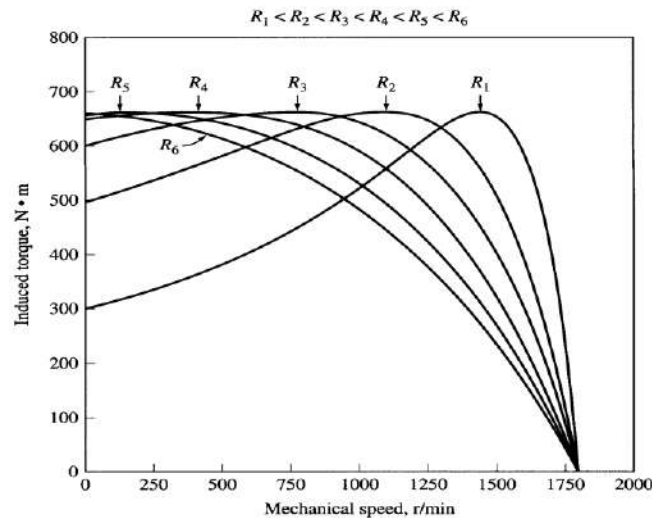

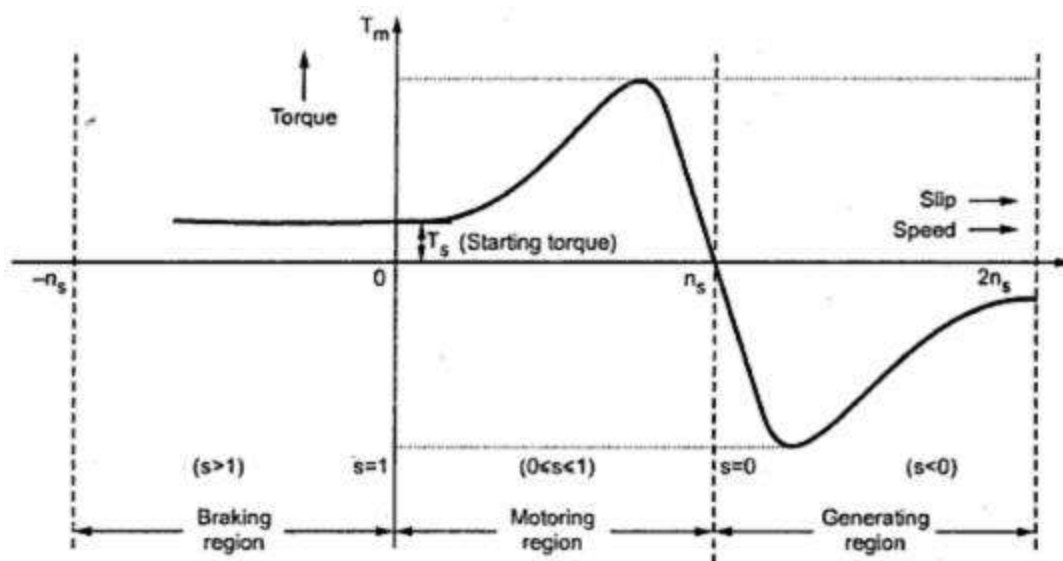Fig.7.5 Effect of rotor resistance on torque-speed characteristic

Fig.7.6 Complete torque-speed characteristic of a three phase induction machine

SINGLE PHASE MOTORS

8.1   Single Phase Motors

        Single phase motors are designed to operate from a single phase supply, are manufactured in a large number of types to perform a wide variety of useful services in home, offices, factories, workshops and in business establishments etc. Single phase motors may be classified as induction motors, repulsion motors, ac series motor and unexcited synchronous motor.
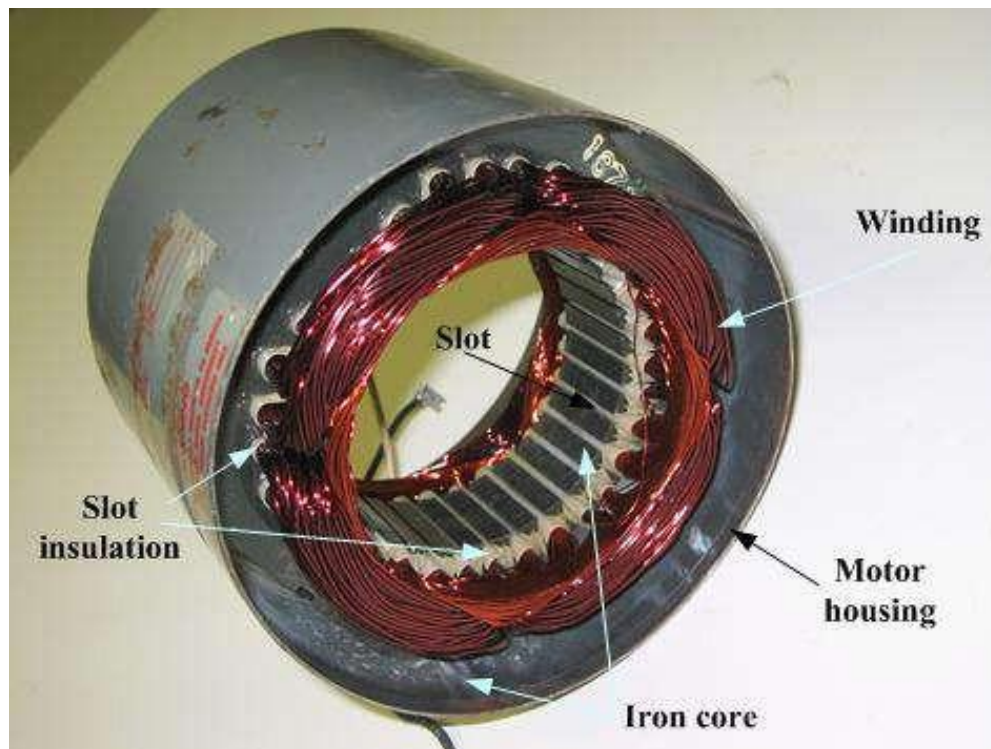
Fig.8.1 Single phase induction motor

8.2   Basics of Single-phase Induction Motor

        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.

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

The single-phase induction motor operation can be described by two methods:

– Double revolving field theory; and

– Cross-field theory

8.3   Double-field Revolving 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 $N_s = 120 f / P$ in opposite direction.

As shown in fig.8.2 (a), let the alternating flux have a maximum value of ϕ_m. Its component fluxes A and B will each be equal to $\phi_m / 2$ revolving in anticlockwise and clockwise directions respectively.

After some time, when A and B would have rotated through angle $+\theta$ and $-\theta$, as in fig.8.2 (b), the resultant flux would be

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

After a quarter cycle of rotation, fluxes A and B will be oppositely directed as shown in fig8.2(c) so that the resultant flux would be zero.

After half a cycle, fluxes A and B will have a resultant of $-2 \times \dfrac{\phi_m}{2} = -\phi_m$. After three quarters of

cycle, again the resultant is zero, as shown in fig8.2 (e) and so on. If we plot the value of resultant flux against θ between limits $\theta = 0^0$ to $\theta = 360^0$, then a curve similar to the one shown in fig8.3 is obtained. That is why an alternating flux can be looked upon as composed of two revolving fluxes, each of half the value and revolving synchronously in opposite directions.
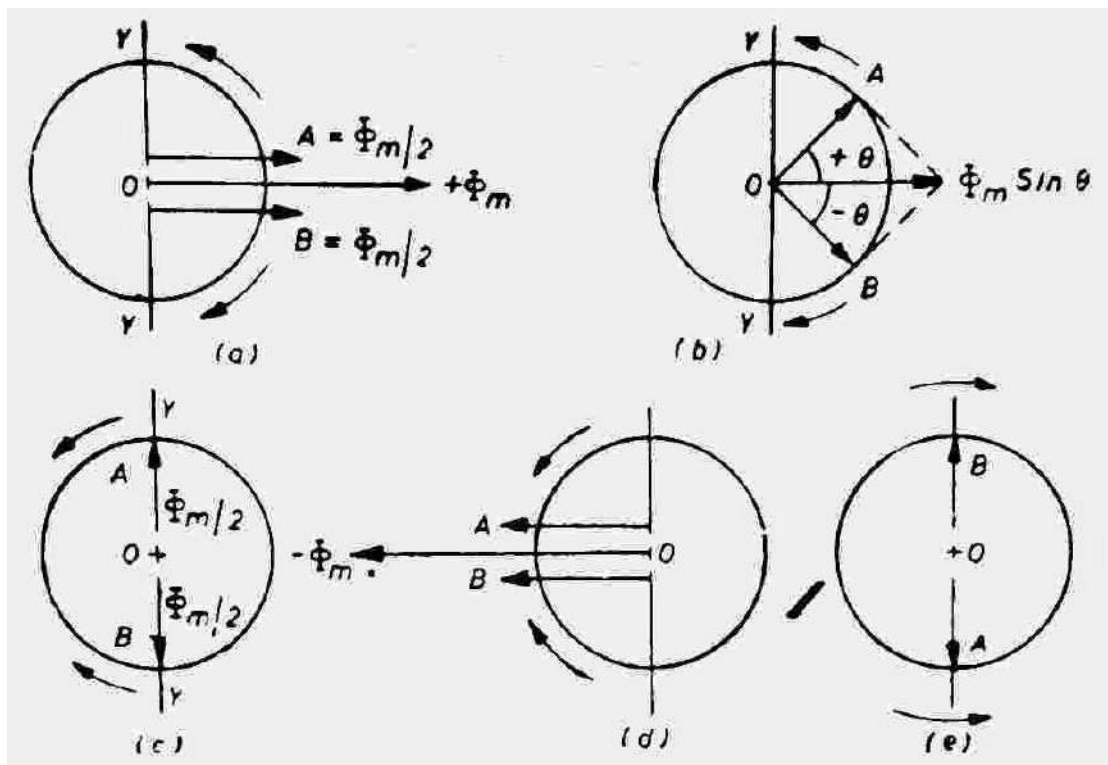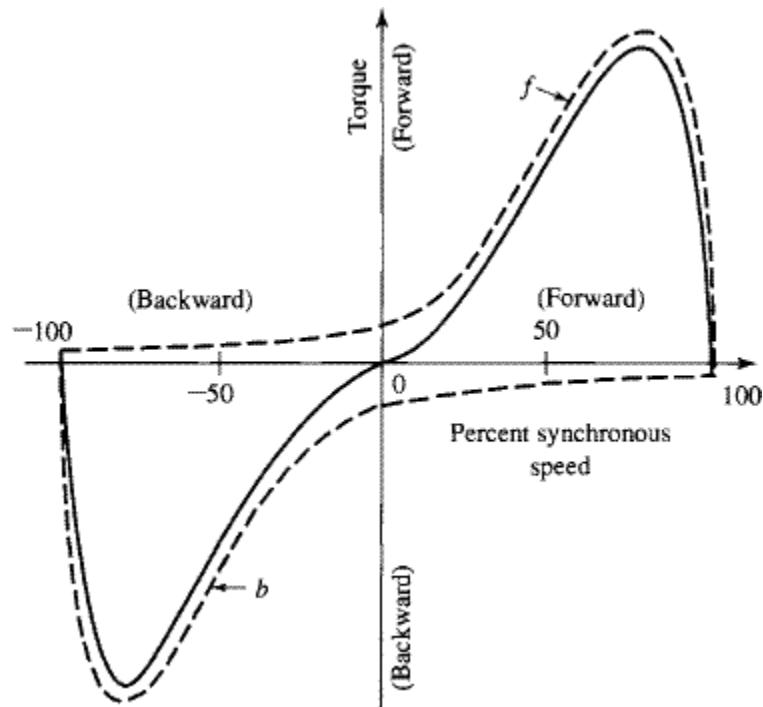

Fig.8.2 Double field revolving theory

Fig.8.3 Torque-speed characteristics of single phase induction motor

8.4   Making Single-phase Induction Motor Self-starting

A single phase induction motor is not self-starting. To overcome this drawback and make the motor self-starting, it is temporarily converted into a two-phase motor during starting period. For this purpose, the stator of a single phase motor is provided with an extra winding, known as starting winding, in addition to the main or running winding. The two windings are spaced 90^0 electrically apart and are connected in parallel across the single phase supply.

It is so arranged that the phase difference between the currents in the two stator windings is very large (ideal value being 90^0). Hence, the motor behaves like a two phase motor. The two currents produce a revolving flux and hence make the motor self-starting.
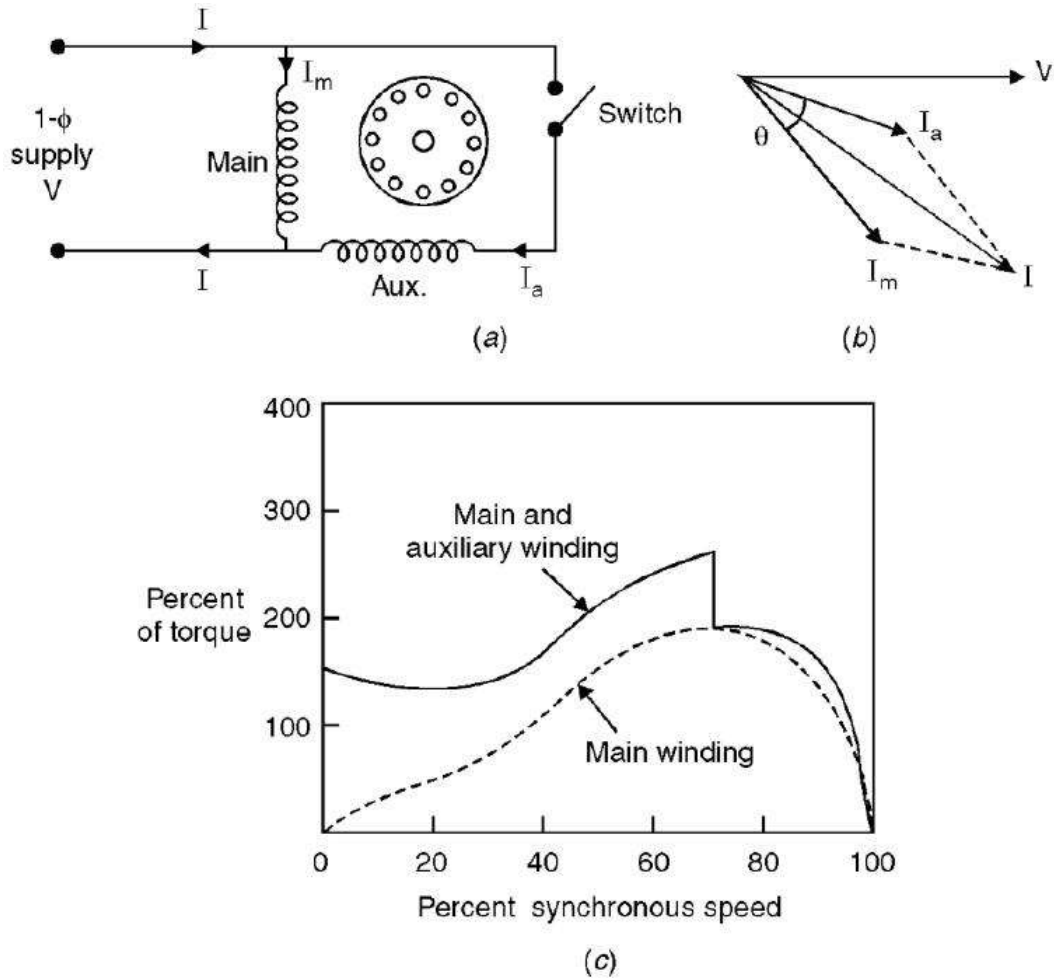
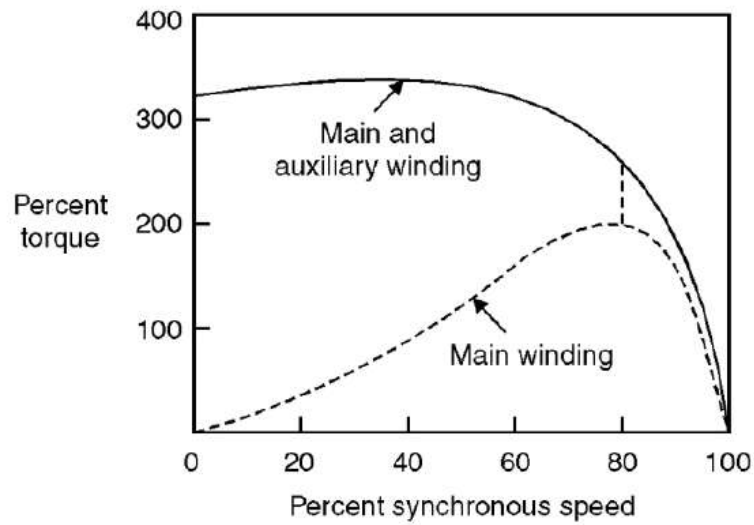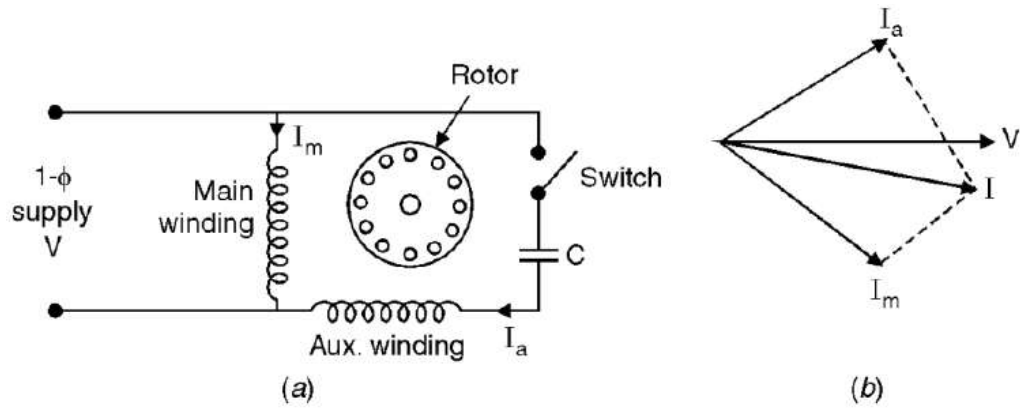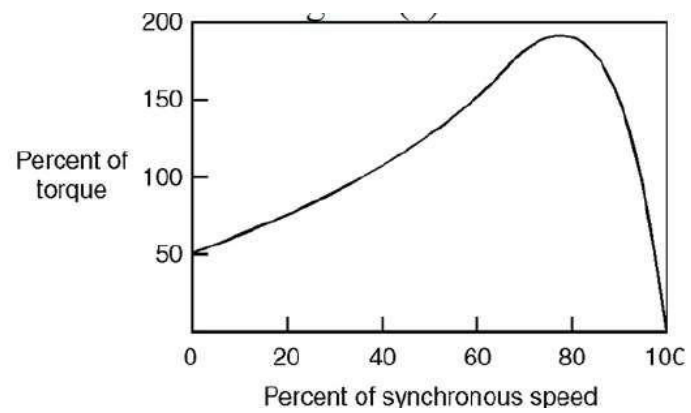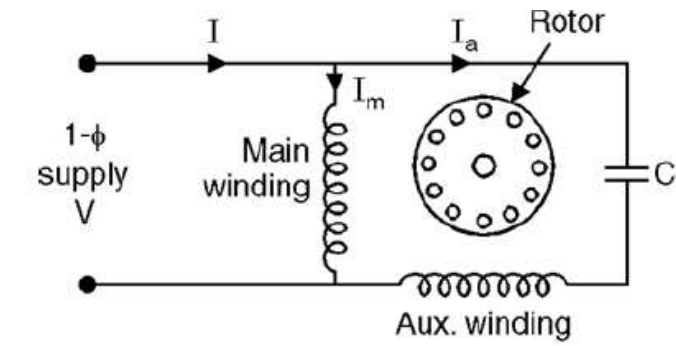Fig.8.4 Split phase single phase induction motor

Fig.8.5 Capacitor-start induction-run motor

Fig.8.6 Capacitor-start and run induction motor