

Principle of induction motor

Objectives: At the end of this lesson you shall be able to

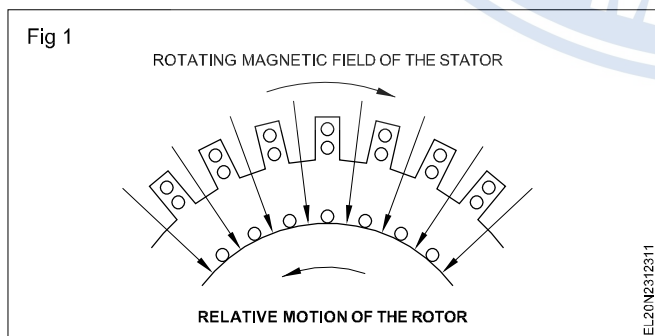
- state the principle of a 3-phase induction motor
- explain briefly the method of producing a rotating magnetic field.

The three-phase induction motor is used more extensively than any other form of electrical motor, due to its simple construction, trouble-free operation, lower cost and a fairly good torque speed characteristic.

Principle of 3-phase induction motor: It works on the same principle as a DC motor, that is, the current-carrying conductors kept in a magnetic field will tend to create a force. However, the induction motor differs from the DC motor in fact that the rotor of the induction motor is not electrically connected to the stator, but induces a voltage/current in the rotor by the transformer action, as the stator magnetic field sweeps across the rotor. The induction motor derives its name from the fact that the current in the rotor is not drawn directly from the supply, but is induced by the relative motion of the rotor conductors and the magnetic field produced by the stator currents.

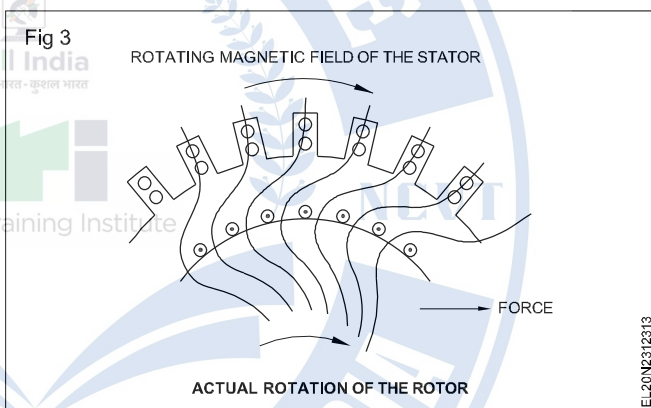
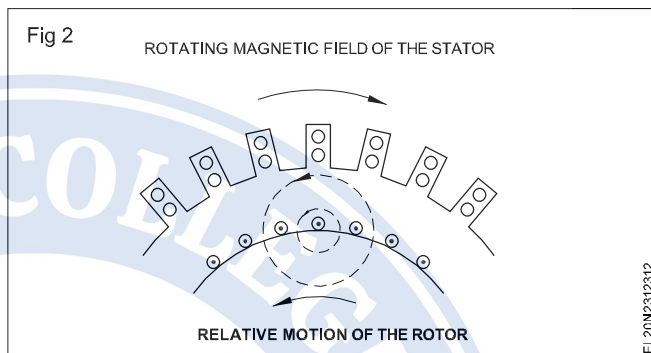
The stator of the 3-phase induction motor is similar to that of a 3-phase alternator, of revolving field type. The three-phase winding in the stator produces a rotating magnetic field in the stator core as it will be explained later. The rotor of the induction motor may have either shorted rotor conductors in the form of a squirrel cage or in the form of a 3-phase winding to facilitate the circulation of current through a closed circuit.

Let us assume that the stator field of the induction motor is rotating in a clockwise direction as shown in Fig 1. This makes for the relative motion of the rotor in an anticlockwise direction as shown in Fig 1. Applying Fleming's right hand rule, the direction of emf induced in the rotor will be towards the observer as shown in Fig 2. As the rotor conductors have a closed electric path, due to their shorting, a current will flow through them as in a short-circuited secondary of a transformer.



The magnetic field produced by the rotor currents will be in a counter-clockwise direction as shown in Fig 2 according to Maxwell's Corkscrew rule. The interaction between the stator magnetic field and the rotor magnetic field results in a force to move the rotor in the same direction as that of

the rotating magnetic field of the stator, as shown in Fig 3. As such the rotor follows the stator field in the same direction by rotating at a speed lesser than the synchronous speed of the stator rotating magnetic field.



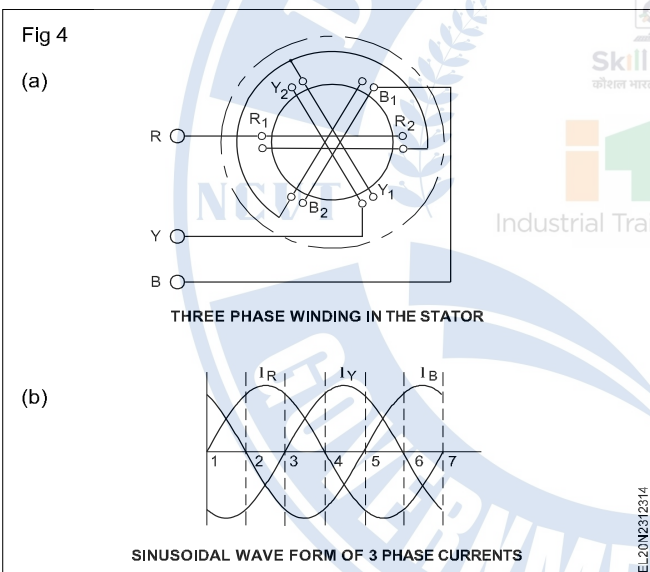
At higher speeds of the rotor nearing to synchronous speeds, the relative speed between the rotor and the rotating magnetic field of the stator reduces and results in a smaller induced emf in the rotor. Theoretically, if we assume that the rotor attains a speed equal to the synchronous speed of the rotating magnetic field of the stator, there will be no relative motion between the stator field and the rotor, and thereby no induced emf or current will be there in the rotor. Consequently there will not be any torque in the rotor. Hence the rotor of the induction motor cannot run at a synchronous speed at all. As the motor is loaded, the rotor speed has to fall to cope up with the mechanical force; thereby the relative speed increases, and the induced emf and current increase in the rotor resulting in an increased torque.

To reverse the direction of rotation of a rotor: The direction of rotation of the stator magnetic field depends upon the phase sequence of the supply. To reverse the direction of rotation of the stator as well as the rotor, the phase sequence of the supply is to be changed by changing any two leads connected to the stator.

Rotating magnetic field from a three-phase stator:

The operation of the induction motor is dependent on the presence of a rotating magnetic field in the stator. The stator of the induction motor contains three-phase windings placed at 120° electrical degrees apart from each other. These windings are placed on the stator core to form non-salient stator field poles. When the stator is energized from a three-phase voltage supply, in each phase winding will set up a pulsating field. However, by virtue of the spacing between the windings, and the phase difference, the magnetic fields combine to produce a field rotating at a constant speed around the inside surface of the stator core. This resultant movement of the flux is called the 'rotating magnetic field', and its speed is called the 'synchronous speed'.

The manner, in which the rotating field is set up, may be described by considering the direction of the phase currents at successive instants during a cycle. Fig 4a shows a simplified star-connected, three-phase stator winding. The winding shown is for a two-pole induction motor. Fig 4b shows the phase currents for the three-phase windings. The phase currents will be 120 electrical degrees apart as shown in Fig 4b. The resultant magnetic field produced by the combined effect of the three currents is shown at increments of 60° for one cycle of the current.



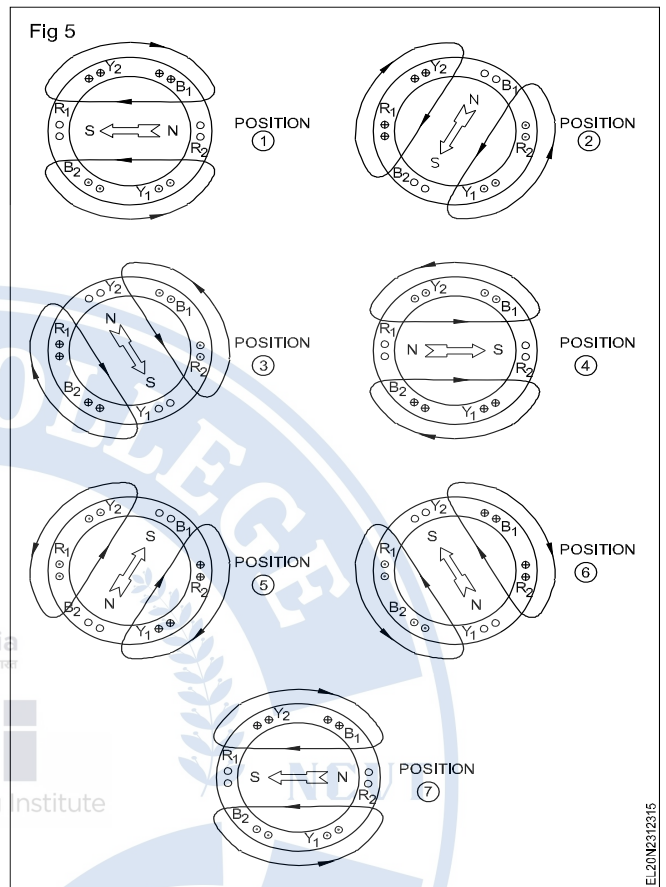
At position (1) in Fig 4b, the phase current I_R is zero, and hence coil R will be producing zero flux. However, the phase current I_B is positive and I_Y is negative.

Considering the instantaneous current directions of these three phase windings, as shown in Fig 4b at position 1, we can indicate the current direction in Fig 5(1).

For convenience the +ve current is shown as +ve sign, and the -ve current is shown as dot (•) sign. Accordingly Y_2 and B_1 are shown as positive and Y_1 and B_2 are shown as negative. Using Maxwell's corkscrew rule, the resulting flux by these currents will produce a flux as shown in Fig 5(1). The arrow shows the direction of the magnetic field and the magnetic poles in the stator core.

At position 2, as shown by Fig 5(2), 60° electrical degrees later, the phase current I_B is zero, the current I_R is positive

and the current I_Y is negative. In Fig 5 (2) the current is now observed to be flowing into the conductors at the coil ends R_1 and Y_2 , and out of the conductors at coil R_2 and Y_1 . Therefore, as shown in Fig 5(2), the resultant magnetic poles are now at a new position in the stator core. In fact the poles in position 2 have also rotated 60° from position (1).



Using the same reasoning as above for the current wave positions 3, 4, 5, 6 and 7, it will be seen that for each successive increment of 60° electrical degrees, the resultant stator field will rotate a further 60° as shown in Fig 5. Note that from the resultant flux from position (1) to position (7), it is obvious that for each cycle of applied voltage the field of the two-pole stator will also rotate one revolution around its core.

From what is stated above it will be clear that the rotating magnetic field could be produced by a set of 3-phase stationary windings, placed at 120° electrical degrees apart, and supplied with a 3-phase voltage.

The speed at which the field rotates is called synchronous speed, and, it depends upon the frequency of supply and the number of poles for which the stator is wound.

Hence

$$N_s = \text{Synchronous speed in r.p.m.} \\ = \frac{120 f}{P} \text{ rpm}$$

where 'P' is the number of poles in the stator, and 'f' is the frequency of the supply.

Construction of a 3-phase squirrel cage induction motor - relation between slip, speed, rotor frequency, copper loss and torque

Objectives: At the end of this lesson you shall be able to

- describe the construction of a 3-phase, squirrel cage induction motor
- describe the construction of double squirrel cage motor and its advantage
- explain slip, speed, rotor frequency, rotor copper loss, torque and their relationship.

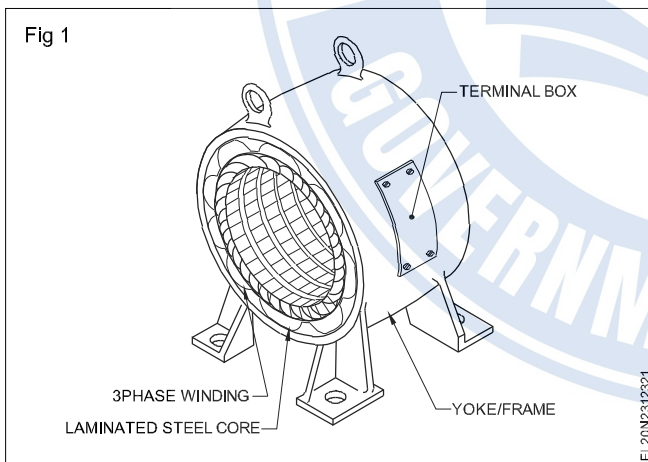
Three-phase induction motors are classified according to their rotor construction. Accordingly, we have two major types.

- Squirrel cage induction motors
- Slip ring induction motors.

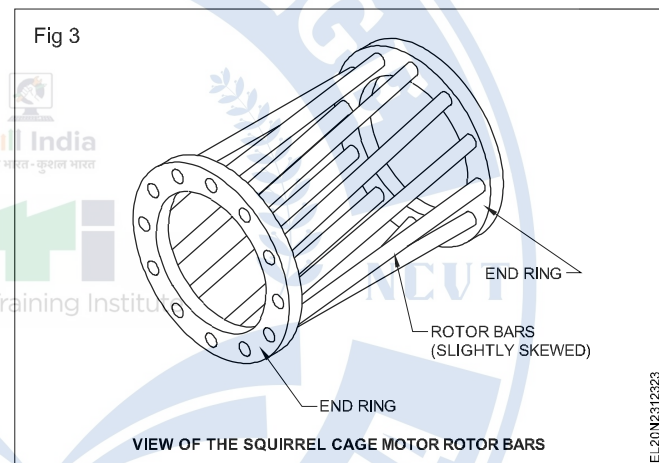
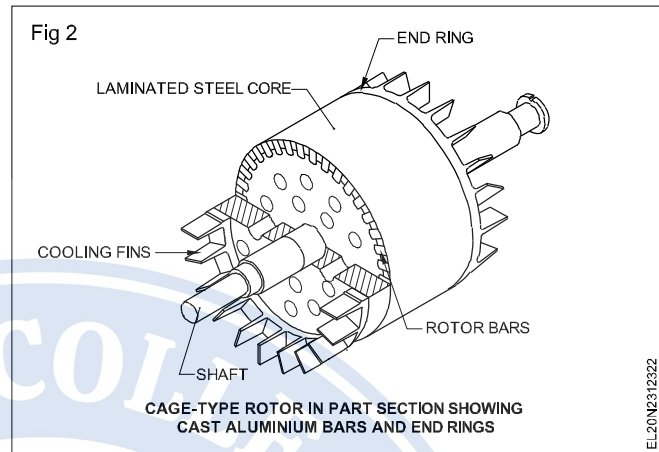
Squirrel cage motors have a rotor with short-circuited bars whereas slip ring motors have wound rotors having three windings, either connected in star or delta. The terminals of the rotor windings of the slip ring motors are brought out through slip-rings which are in contact with stationary brushes.

Stator of an induction motor: There is no difference between squirrel cage and slip-ring motor stators.

The induction motor stator resembles the stator of a revolving field, three-phase alternator. The stator or the stationary part consists of three-phase winding held in place in the slots of a laminated steel core which is enclosed and supported by a cast iron or a steel frame as shown in Fig 1. The phase windings are placed 120 electrical degrees apart, and may be connected in either star or delta externally, for which six leads are brought out to a terminal box mounted on the frame of the motor. When the stator is energised from a three-phase voltage it will produce a rotating magnetic field in the stator core.



Rotor of a squirrel cage induction motor: The rotor of the squirrel cage induction motor shown in Fig 2 contains no windings. Instead it is a cylindrical core constructed of steel laminations with conductor bars mounted parallel to the shaft and embedded near the surface of the rotor core. These conductor bars are short circuited by an end-ring at either end of the rotor core. On large machines, these conductor bars and the end-rings are made up of copper with the bars brazed or welded to the end rings as shown in Fig 3. On small machines the conductor bars and end-rings are sometimes made of aluminium with the bars and rings cast in as part of the rotor core.



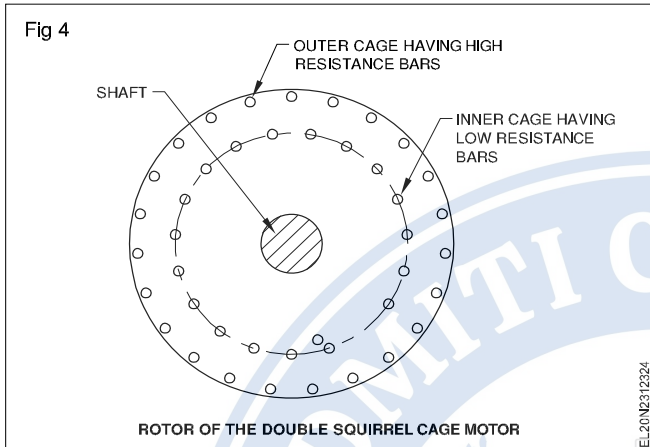
The rotor or rotating part is not connected electrically to the power supply but has voltage induced in it by transformer action from the stator. For this reason, the stator is sometimes called the primary, and the rotor is referred to as the secondary of the motor. Since the motor operates on the principle of induction; and as the construction of the rotor, with the bars and end-rings resembles a squirrel cage, the name squirrel cage induction motor is used. (Fig3)

The rotor bars are not insulated from the rotor core because they are made of metals having less resistance than the core. The induced current will flow mainly in them. Also, the bars are usually not quite parallel to the rotor shaft but are mounted in a slightly skewed position. This feature tends to produce a more uniform rotor field and torque; also it helps to reduce some of the internal magnetic noise when the motor is running.

End shields: The function of the two end shields which are to support the rotor shaft. They are fitted with bearings and attached to the stator frame with the help of studs or bolts.

Double squirrel cage induction motor

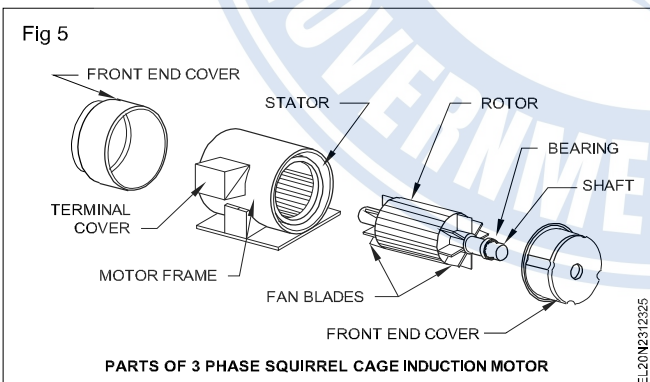
Rotor construction and its working: This consists of two sets of conductor bars called outer and inner cages as shown in Fig 4. The outer cage consists of bars of high resistance metals like brass, and is short-circuited by the end-rings. The inner cage consists of low resistance metal bars like copper, and is short-circuited by the end-rings. The outer cage has high resistance and low reactance, whereas the inner cage has low resistance but being situated deep in the rotor core, has a large ratio of reactance to resistance.



At the time of starting, the rotor frequency is the same as the stator frequency. Hence the inner cage which has higher inductive reactance offers more resistance to the current flow. As such very little current flows through the inner cage at the time of starting.

The major part of the rotor current at the time of starting could flow through the outer ring which has high resistance. This high resistance enables to produce a high starting torque.

Fig 5 shows the exploded view of 3 phase squirrel cage induction motor.



Slip and rotor speed: The speed at which the rotor rotates is called the rotor speed or speed of the motor. The difference between the synchronous speed and the actual rotor speed is called the 'slip speed'. Slip speed is the number of revolutions per minute by which the rotor continues to fall behind the revolving magnetic field.

When the slip speed is expressed as a fraction of the synchronous speed, it is called a fractional slip.

$$\therefore \text{fractional slip } S = \frac{N_s - N_r}{N_s}$$

$$\text{Then percentage slip (\% slip)} = \frac{N_s - N_r}{N_s} \times 100$$

where N_s = synchronous speed of the stator magnetic field

N_r = Actual rotating speed of the rotor in r.p.m.

Most squirrel cage induction motors will have a percentage slip of 2 to 5 percent of the rated load.

Example

Calculate the percentage slip of an induction motor having 6 poles fed with 50 cycles supply rotating with an actual speed of 960 r.p.m.

Given:

Poles (P) = 6

N_r = Rotor speed = 960 r.p.m.

F = frequency of supply = 50 Hz

N_s = Synchronous speed

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

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

$$\% \text{ slip} = \frac{N_s - N_r}{N_s} \times 100$$

$$= \frac{1000 - 960}{1000} \times 100 = 4\%$$

Torque : The torque production in an induction motor is more or less the same as in the DC motor. In the DC motor the torque is proportional to the product of the flux per pole and the armature current. Similarly in the induction motor the torque is proportional to the flux per stator pole, the rotor current and also the rotor power factor.

Thus we have,

Torque is proportionally = Stator flux x rotor current x rotor power factor.

Let E_1 be the applied voltage

Φ be the stator flux which is proportional to E_1

S be the fractional slip

R_2 be the rotor resistance

X_2 be the rotor inductive reactance at standstill

SX_2 be the rotor inductive reactance at fractional slip S

K be the transformation ratio between stator and rotor voltages

E_2 be the rotor induced emf and equal to SKE_1

I_2 be the rotor current,
 $\cos\theta$ be the rotor power factor.
 Z_2 be the rotor impedance.

We can conclude mathematically the following final results.

$$T \propto \phi I_2 \cos\theta$$

This can be deduced in to a formula

$$T \propto \frac{SKE_1^2 R_2}{R_2^2 + S^2 X_2^2}$$

$$T \propto \frac{\text{Rotor copper loss}}{\text{Fractional slip}}$$

$$\text{Starting torque} \propto \frac{R_2}{R_2^2 + X_2^2} \text{ as fractional slip } S = 1$$

$$\text{Maximum torque} \propto \frac{1}{X_2}$$

where X_2 in inductive reactance of the rotor at standstill and is constant.

Rotor copper loss: Rotor copper loss is the loss of power taking place in the rotor due to its resistance and the rotor current. Though the resistance of the rotor for a squirrel cage motor remains constant, the current in the rotor depends upon the slip, transformation ratio between the stator and rotor voltages and the inductive reactance of the rotor circuit.

Insulation test on 3 phase induction motors

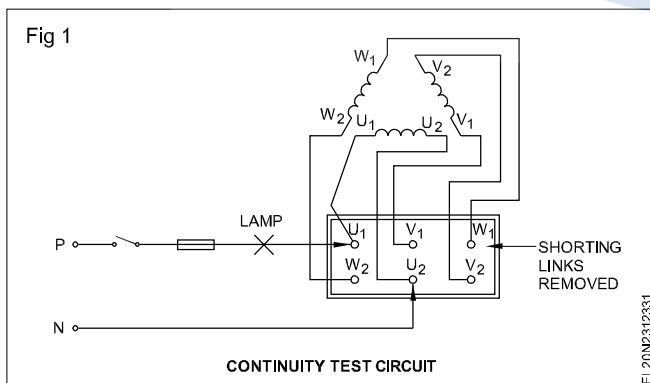
Objectives: At the end of this lesson you shall be able to

- state the necessity for and the method of testing continuity and insulation resistance in a 3-phase induction motor
- state the necessity of continuity test before insulation test.

Necessity of continuity test before insulation test:

While testing the insulation resistance between the winding and the frame, it is the usual practice to connect one prod of the Megger to the frame and the other prod to any one of the terminals of the winding. Likewise, when testing insulation resistance between windings, it is the usual practice to connect the two prods of the Megger to any two ends of a different winding. In all the cases it is assumed that the windings are in sound condition and the two ends of the same winding will be having continuity. However, it is possible the winding may have a break, and part of the winding may have a higher insulation resistance and the other part might have been grounded. Hence, to increase the reliability of the insulation resistance test, it is recommended that continuity test may be conducted in the motor before the insulation test, to be sure, that the winding is sound and the insulation resistance includes the entire winding.

Continuity test: The continuity of the winding is checked by using a test lamp in the following method as shown in Fig 1. First the links between the terminals should be removed.

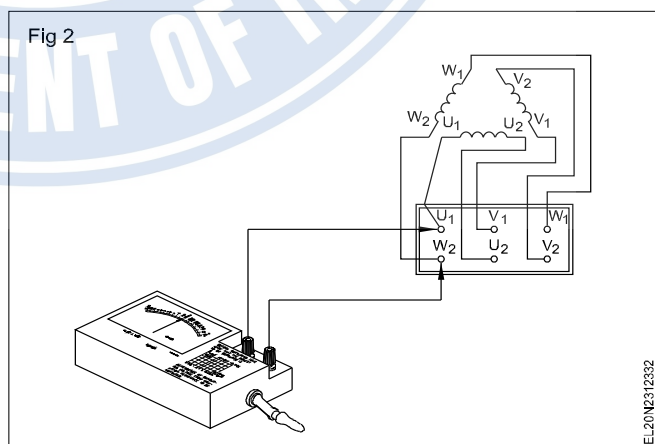


The test lamp is connected in series with a fuse and a switch to the phase wire and the other end is connected

to one of the terminals (say U_1 in Fig 1). The neutral of the supply wire is touched to the other terminals one by one. The terminal in which the lamp lights is the other end of the winding connected to the phase wire (say U_2 in Fig 1). The pairs are to be found in a similar manner. Lighting of the lamp between two terminals shows continuity of the winding. Lighting of the lamp between more than two terminals shows short between the windings.

Limitations of lamp continuity test: However, this test only shows the continuity but will not indicate any short between the turns of the same winding.

Insulation test between windings: As shown in Fig 2, one of the Megger terminals is connected to one terminal of any one winding (say U_1 in Fig 2) and the other terminal of the Megger is connected to one terminal of the other windings (say W_2 in Fig 2).

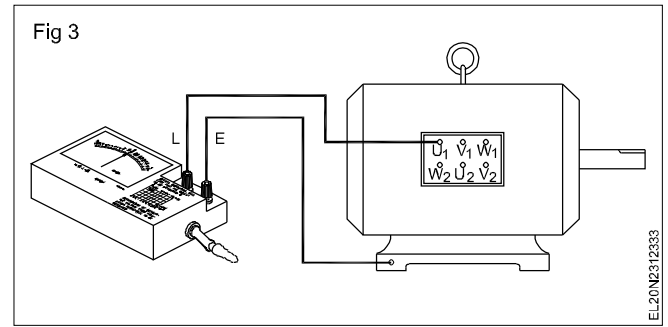


When the Megger handle is rotated at its rated speed, the reading should be more than one megohm. A lower reading than one megohm shows weak insulation between the windings, and needs to be improved. Likewise the insulation resistance between the other windings is tested.

Insulation resistance between windings and frame:

As shown in Fig 3, one terminal of the Megger is connected to one of the phase windings, and the other terminal of the Megger is connected to the earthing terminal of the frame. When the Megger handle is rotated at the rated speed, the reading obtained should be more than one megohm. A lower reading than one megohm indicates poor insulation between the winding and the frame and needs to be improved by drying and varnishing the windings.

Likewise the other windings are tested.



Starter for 3-phase induction motor - power control circuits - D.O.L starter

Objectives: At the end of this lesson you shall be able to

- state the necessity of starters for a 3-phase induction motor and name the types of starters
- explain the basic contactor circuit with a single push-button station for start and stop.

Necessity of starter: normal voltage is applied to the stationary motor, then, a very large initial current, to the tune of 5 to 6 times the normal current, will be drawn by the motor from the mains. This initial excessive current is objectionable, because it will produce large line voltage drop, which in turn will affect the operation of other electrical equipment and lights connected to the same line.

The initial rush of current is controlled by applying a reduced voltage to the stator winding during the starting period, and then the full normal voltage is applied when the motor has run up to speed. For small capacity motors, say up to 3 Hp, full normal voltage can be applied at the start. However, to start and stop the motor, and to protect the motor from overload currents and low voltages, a starter is required in the motor circuit. In addition to this, the starter may also reduce the applied voltage to the motor at the time of starting.

Types of starters: Following are the different types of starters used for starting squirrel cage induction motors.

- Direct on-line starter
- Star-delta starter
- Auto-transformer starter

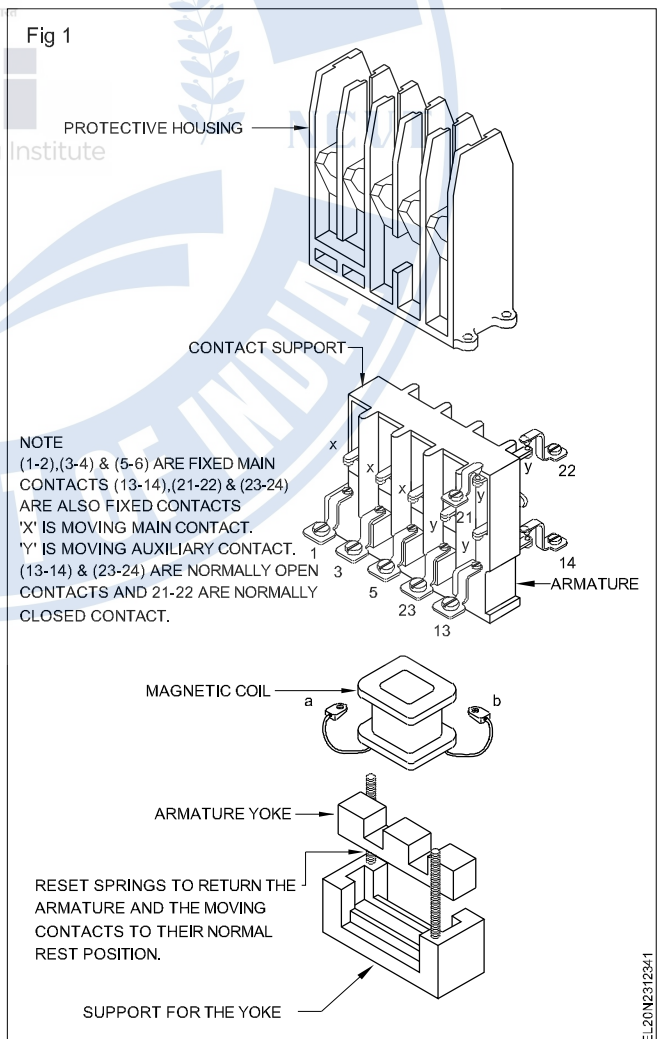
In the above starters, except for the direct on-line starter, reduced voltage is applied to the stator winding of the squirrel cage induction motor at the time of starting, and regular voltage is applied once the motor picks up the speed.

Selection of starter: Many factors must be considered when selecting starting equipment. These factors include starting current, the full load current, voltage rating of motor, voltage (line) drop, cycle of operation, type of load, motor protection and safety of the operator.

Contactors: The contactor forms the main part in all the starters. A contactor is defined as a switching device capable of making, carrying and breaking a load circuit at a frequency of 60 cycles per hour or more. It may be operated by hand (mechanical), electromagnetic, pneumatic or electro-pneumatic relays.

The contactors shown in Fig 1 consist of main contacts, auxiliary contacts and no-volt coil. As per Fig 1, there are

three sets of normally open, main contacts between terminals 1 and 2, 3 and 4, 5 and 6, two sets of normally open auxiliary contacts between terminals 23 and 24, 13 and 14, and one set of normally closed auxiliary contact between terminals 21 and 22. Auxiliary contacts carry less current than main contacts. Normally contactors will not have the push-button stations and O.L. relay as an integrated part, but will have to be used as separate accessories along with the contactor to form the starter function.



The main parts of a magnetic contactor are shown in Fig 1 shows the schematic diagram of the contactor when used along with fused switches (ICTP), push-button stations and OL relay for connecting a squirrel cage motor for

starting directly from the main supply. In the same way the direct on-line starter consists of a contactor, OL relay and push-button station in an enclosure.

D.O.L. starter

Objectives: At the end of this lesson you shall be able to

- state the specification of a D.O.L. starter, explain its construction, operation and application
- explain the necessity of a back-up fuse and its rating according to the motor rating.

A D.O.L. starter is one in which a contactor with no-volt relay, ON and OFF buttons, and overload relay are incorporated in an enclosure.

Construction and operation: A push-button type, direct on-line starter, which is in common use, is shown in Fig 1. It is a simple starter which is inexpensive and easy to install and maintain.

There is no difference between the complete contactor circuit explained in Exercise 2.3.125 and the D.O.L. starter, except that the D.O.L. starter is enclosed in a metal or PVC case, and in most cases, the no-volt coil is rated for 415V and is to be connected across two phases as shown in Fig 1. Further the overload relay can be situated between ICTP switch and contactor or between the contactor and motor as shown in Fig 1, depending upon the starter design. Trainees are advised to write the working of the D.O.L. starter on their own

Specification of D.O.L. starters: While giving specification, the following data are to be given.

D.O.L. STARTER

Phases - single or three.

Voltage 240 or 415V.

Current rating 10, 16, 32, 40, 63, 125 or 300 amps.

No-volt coil voltage rating AC or DC 12, 24, 36, 48, 110, 230/250, 360, 380 or 400/440 volts.

Number of main contacts 2, 3 or 4 which are normally open.

Number of auxiliary contacts 2 or 3. 1 NC + 1 NO or 2 NC + 1 NO respectively.

Push-button - one 'ON' and one 'OFF' buttons.

Overload from setting – amp-to-amp. Enclosure - metal sheet or PVC.

Applications: In an induction motor with a D.O.L. starter, the starting current will be about 6 to 7 times the full load current. As such, D.O.L. starters are recommended to be

used only up to 3 HP squirrel cage induction motors, and up to 1.5 kW double cage rotor motors.

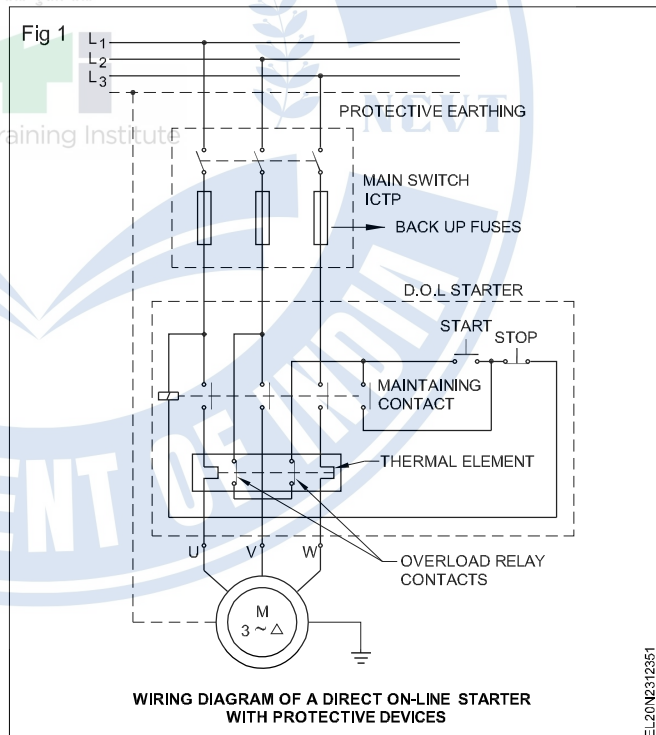
Example

A 3-phase, 400V, 50 HZ, delta-connected induction motor draws a line current of 150 amps with a P.F. of 0.85 and is delivering an output of 100 (Metric) HP. Calculate the efficiency.

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

$$= \frac{100 \times 735.5 \times 100}{\sqrt{3} \times 400 \times 150 \times 0.85}$$

$$= 83.3 \%$$



Manual star-delta starter

Objectives: At the end of this lesson you shall be able to

- state the necessity of a star-delta starter for a 3-phase squirrel cage induction motor
- explain the construction, connection and working of a star-delta switch and starter
- specify the back-up rating of the fuse in the motor circuit.

Necessity of star-delta starter for 3-phase squirrel cage motor: If a 3-phase squirrel cage motor is started

directly, it takes about 5-6 times the full load current for a few seconds, and then the current reduces to normal value

once the speed accelerates to its rated value. As the motor is of rugged construction and the starting current remains for a few seconds, the squirrel cage induction motor will not get damaged by this high starting current.

However with large capacity motors, the starting current will cause too much voltage fluctuations in the power lines and disturb the other loads. On the other hand, if all the squirrel cage motors connected to the power lines are started at the same time, they may momentarily overload the power lines, transformers and even the alternators.

Because of these reasons, the applied voltage to the squirrel cage motor needs to be reduced during the starting periods, and regular supply could be given when the motor picks up its speed.

Following are the methods of reducing the applied voltage to the squirrel cage motor at the start.

- Star-delta switch or starter
- Auto-transformer starter
- Step-down transformer starter

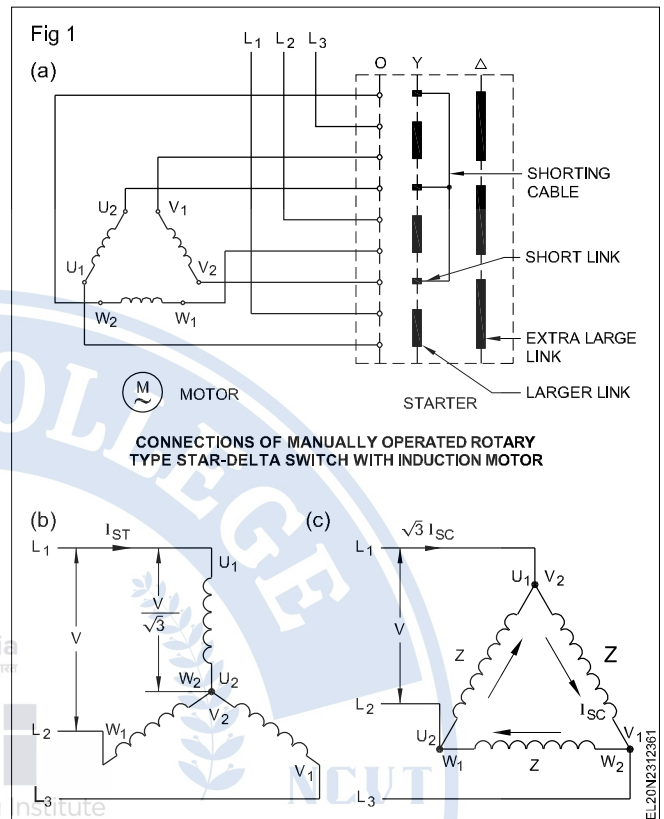
Star-delta starter: A star-delta switch is a simple arrangement of a cam switch which does not have any additional protective devices like overload or under-voltage relay except fuse protection through circuit fuses, whereas the star-delta starter may have overload relay and under voltage protection in addition to fuse protection. In a star-delta switch/starter, at the time of starting, the squirrel cage motor is connected in star so that the phase voltage is reduced to $1/\sqrt{3}$ times the line voltage, and then when the motor picks up its speed, the windings are connected in delta so that the phase voltage is the same as the line voltage. To connect a star-delta switch/starter to a 3-phase squirrel cage motor, all the six terminals of the three-phase winding must be available.

As shown in Fig 1a, the star-delta switch connection enables the 3 windings of the squirrel cage motor to be connected in star, and then in delta. In star position, the line supply L_1, L_2 and L_3 are connected to the beginning of windings U_1, W_1 and V_1 respectively by the larger links, whereas the short links, which connect V_2, U_2 and W_2 , are shorted by the shorting cable to form the star point. This connection is shown as a schematic diagram. (Fig 1b)

When the switch handle is changed over to delta position, the line supply L_1, L_2 and L_3 are connected to terminals U_1, V_2, W_1, U_2 and V_1, W_2 respectively by the extra large links to form a delta connection. (Fig 1c)

Manual star-delta starter: Fig 2a shows the conventional manual star-delta starter. As the insulated handle is spring-loaded, it will come back to OFF position from any position unless and until the no-volt (hold-on) coil is energised. When the hold-on coil circuit is closed through the supply taken from U_2 and W_2 , the coil is energised and it holds the plunger, and thereby the handle is held in delta position against the spring tension by the lever plate mechanism. When the hold-on coil is de-energised the plunger falls and operates the lever plate mechanism so as

to make the handle to be thrown to the off position due to spring tension. The handle also has a mechanism (not shown in Fig) which makes it impossible for the operator to put the handle in delta position in the first moment. It is only when the handle is brought to star position first, and then when the motor picks up speed, the handle is pushed to delta position.



The handle has a set of baffles insulated from each other and also from the handle. When the handle is thrown to star position, the baffles connect the supply lines L_1, L_2 and L_3 to beginning of the 3-phase winding W_1, V_1 and U_1 respectively. At the same time the small baffles connect V_2, W_2 and U_2 through the shorting cable to form the star point. (Fig 1b)

When the handle is thrown to delta position, the larger end of the baffles connect the main supply line L_1, L_2 and L_3 to the winding terminals W_1, U_2, V_1, W_2 and U_1, V_2 respectively to form the delta connection. (Fig 1c)

The overload relay current setting could be adjusted by the worm gear mechanism of the insulated rod. When the load current exceeds a stipulated value, the heat developed in the relay heater element pushes the rod to open the hold-on coil circuit, and thereby the coil is de-energised, and the handle returns to the off position due to the spring tension.

The motor also could be stopped by operating the stop button which in turn de-energises the hold-on coil.

Back-up fuse protection: Fuse protection is necessary in the star-delta started motor circuit against short circuits. In general, as a thumb rule for 415V, 3-phase squirrel cage motors, the full load current can be taken as 1.5 times the H.P. rating. For example, a 10 HP 3-phase 415V motor will have approximately 15 amps as its full load current.

To avoid frequent blowing of the fuse and at the same time for proper protection, the fuse wire rating should be 1.5 times the full load current rating of the motor. Hence for 10

HP, 15 amps motor, the fuse rating will be 23 amps, or say 25 amps.

Semi-automatic star-delta starter

Objectives: At the end of this lesson you shall be able to

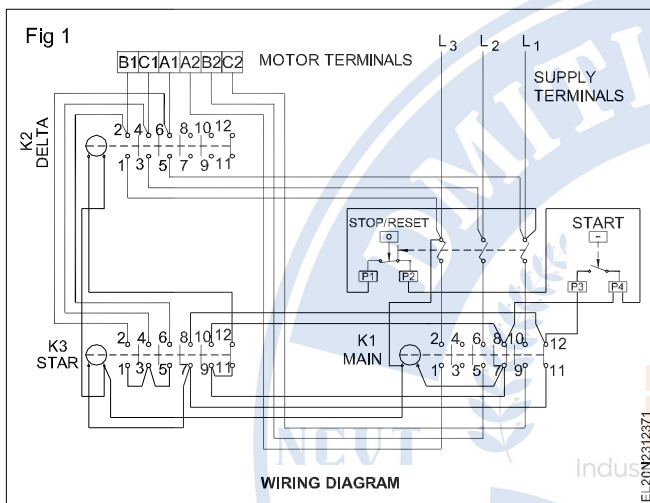
- explain the wiring diagram of semi-automatic star-delta starter
- describe the operation of semi-automatic star-delta starter.

The proper use of manual star-delta starter demands a special skill in handling the starter. The sluggish operation of the manual lever often causes damage to the moving and fixed contacts in a manual star-delta starter.

The contactors are employed for making and breaking the main line connections. Fig 1 shows the wiring diagram and Fig 2 shows the line diagram of power circuit and the control circuit.

The operator has to observe the motor starting and reaching about 70% of the synchronous speed for satisfactory starting and running of the induction motor.

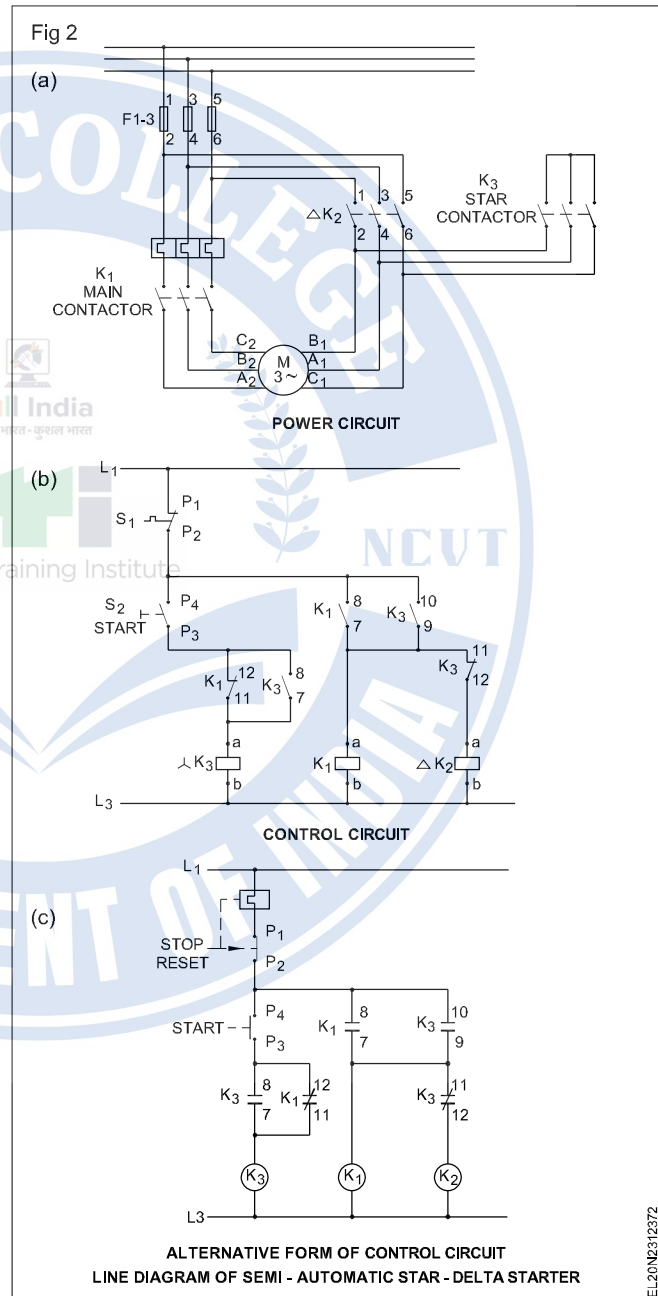
Figure 2c shows the alternative form of drawing control circuit.



Operation: Refer to the control circuit and power circuit diagrams shown in Fig 2. When the start button S_2 is pressed the contactor coil K_3 energises through P_4 , P_3 and K_1 normally closed contact 12 and 11. When K_3 closes, it opens the normally closed contact K_3 between 11 and 12 and makes contact between 10 and 9 of K_3 . The mains contactor K_1 energises through P_4 , 10 and 9 of K_3 . Once K_1 energises the NO contact of K_1 point 8 and 7 establishes a parallel path to K_3 terminals 10 and 9.

The star contactor K_3 remains energised so long as the start button is kept pressed. Once the start button is released, the K_3 coil gets de-energised. The K_3 contact cannot be operated because of the electrical interlock of K_1 and normally closed contacts between terminals 12 and 11.

When the K_3 contactor get de-energised the normally closed contact of K_3 between terminals 11 and 12 establishes contact in the contactor K_2 - coil circuit. The delta contactor K_2 closes.



Automatic star-delta starter

Objectives: At the end of this lesson you shall be able to

- state the applications of automatic star-delta and overload relay setting
- describe the operations of automatic star-delta starter.

Applications : The primary application of star-delta motor is for driving centrifugal chillers of large central air-conditioning units for loads such as fans, blowers, pumps or centrifuges, and for situations where a reduced starting torque is necessary. A star-delta motor is also used where a reduced starting current is required.

In star-delta motors all the winding is used and there are no limiting devices such as resistors or auto-transformers. Star-delta motors are widely used on loads having high inertia and a long acceleration period.

Overload relay settings : Three overload relays are provided on star-delta starters. These relays are used so that they carry the motor winding current. This means that the relay units must be selected on the basis of the winding current, and not the delta connected full load current. The motor name-plate indicates only the delta connected full load current, divide this value by 1.73 to obtain the winding current. Use this winding current as the basis for selecting and setting the motor winding protection relay.

Operation : Fig 1 shows the line diagram of the power circuit and the control circuit of the automatic star-delta starter. Pressing the start button S-energises the star contactor K_3 . (Current flows through K_4 T NC terminals 15 & 16 and K_2 NC terminals 11 & 12). Once K_3 energises the K_3 NO contact closes (terminals 23 & 24) and provide path for the current to close the contactor K_1 . The closing of contactor K_1 establishes a parallel path to start button via K_1 NO terminals 23 & 24.

Fig 2 shows the current direction and closing of contacts as explained above.

Similarly Fig 3 shows the action taking place after the timer relay operating the contact K_4 T.

Time delay contact changes opening star contact.

Fig 4 shows the connections established while the motor is running in delta with the contactors K_1 and K_2 closed. Delta contact closes.

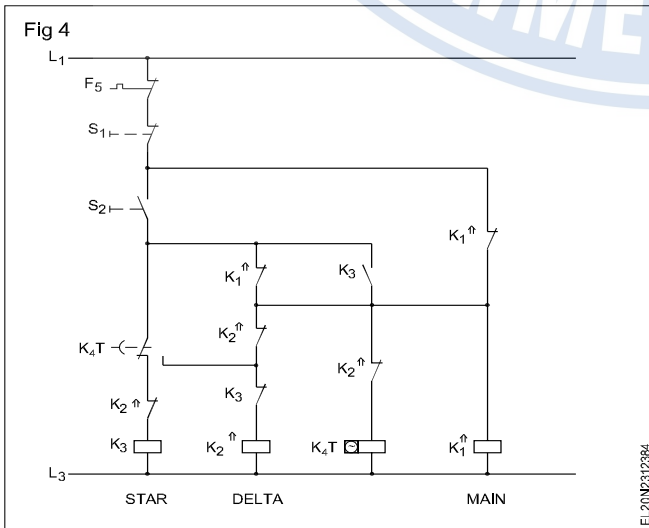
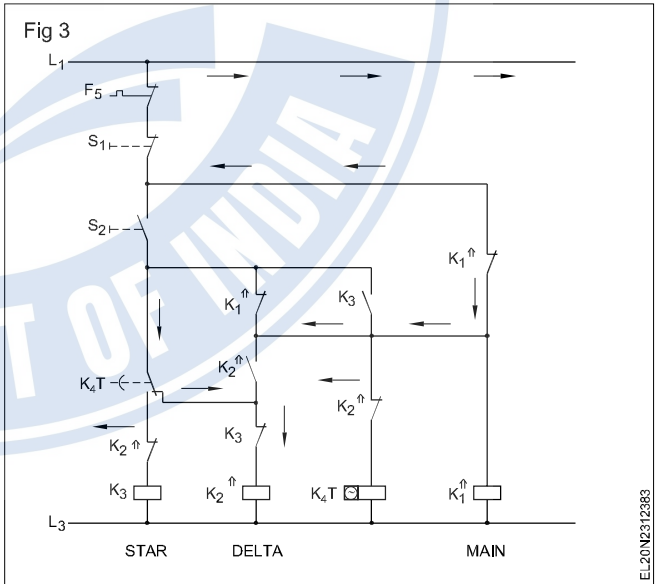
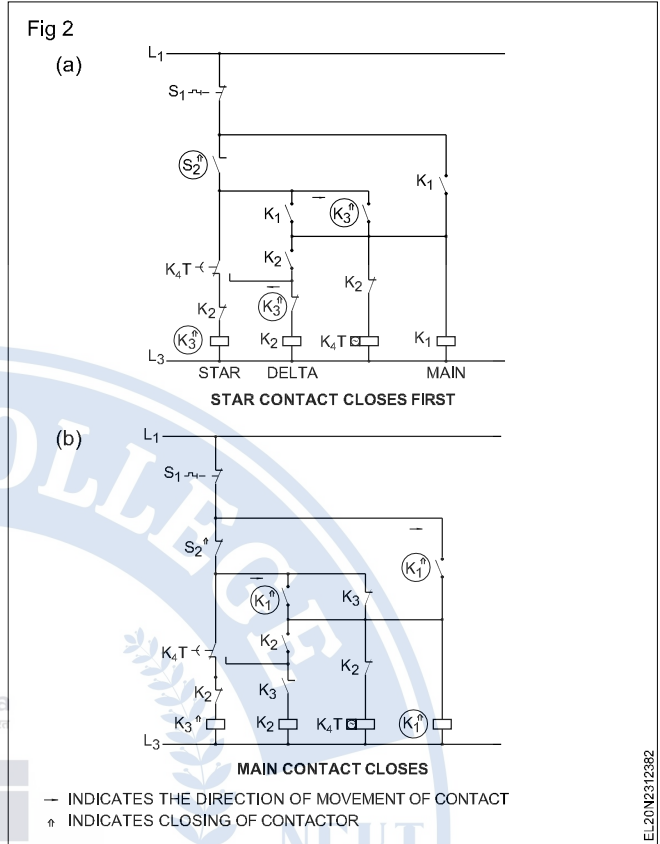
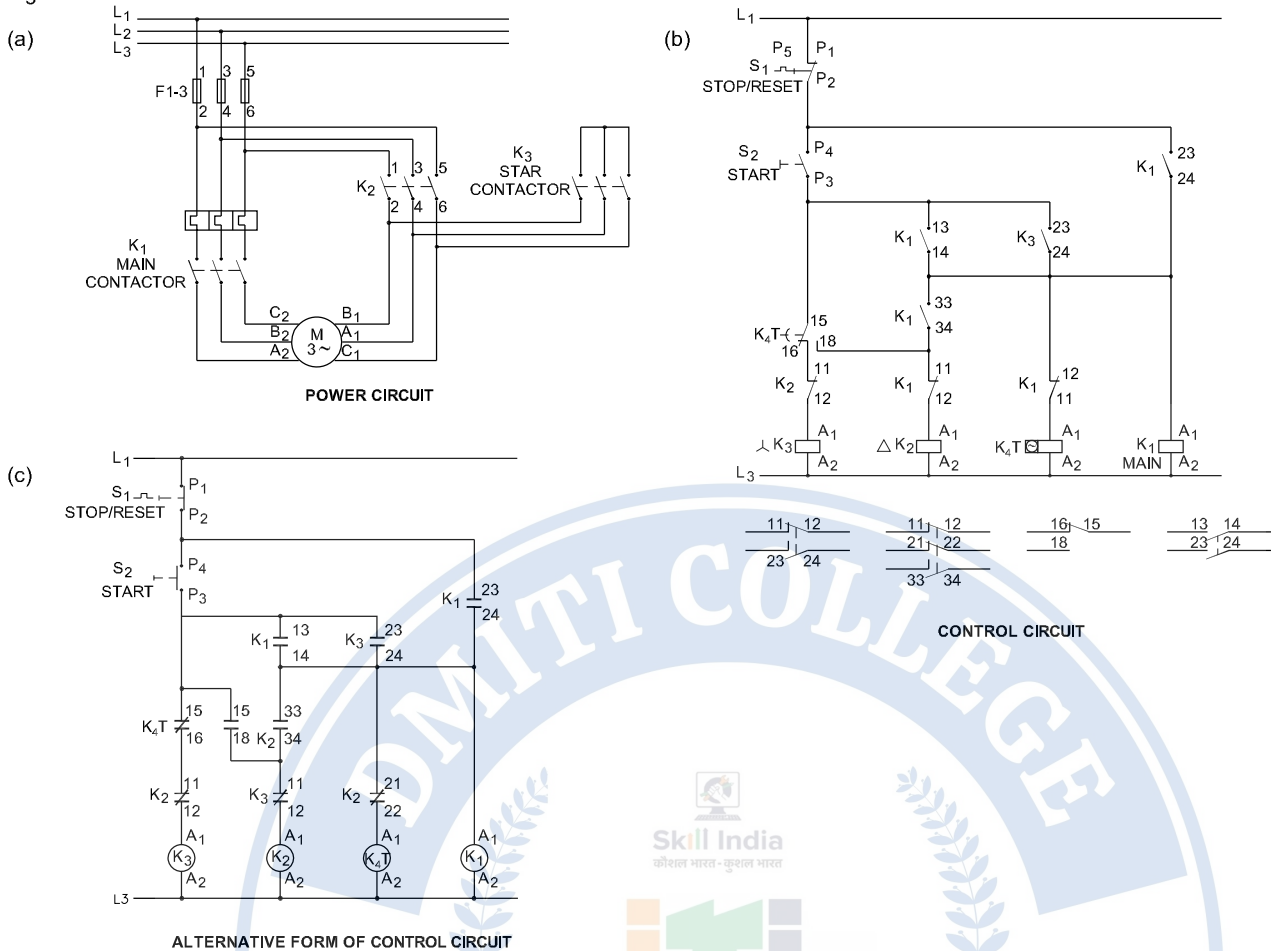


Fig 1



Three-phase, slip-ring induction motor

Objectives: At the end of this lesson you shall be able to

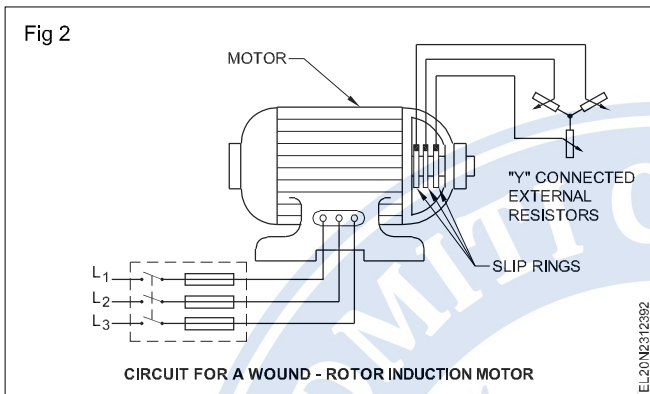
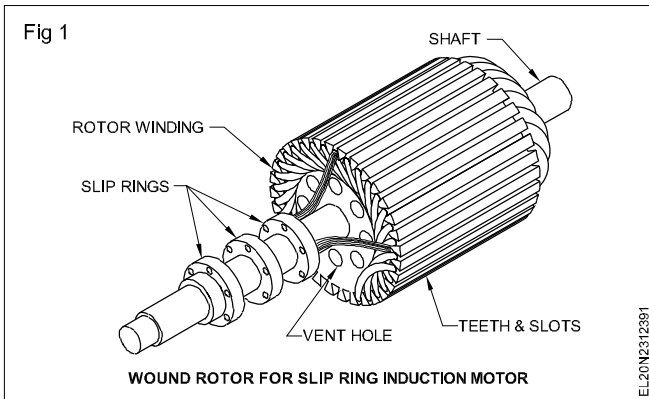
- explain briefly the construction and working of a three-phase, slip-ring induction motor
- explain how the starting torque is high due to insertion of rotor resistance
- state the characteristic of the slip-ring induction motor
- compare the slip-ring induction motor with the squirrel cage induction motor.

Construction : The slip-ring induction motor could be used for industrial drives where variable speed and high starting torque are prime requirements. The stator of the slip-ring induction motor is very much the same as that for a squirrel cage motor but the construction of its rotor is very much different. Stator windings can be either star or delta connected depending upon the design. The rotor consists of three-phase windings to form the same number of poles as in a stator. The rotor winding is connected in star and the open ends are connected to three slip-rings mounted in the rotor shaft, as shown in Fig 1. The rotor circuit is, in turn, connected to the external star-connected resistances through the brushes, as shown in Fig 2.

Working : When the stator-winding of the slip-ring motor is connected to the 3-phase supply, it produces a rotating magnetic field in the same way as a squirrel cage motor. This rotating magnetic field induces voltages in the rotor windings, and a rotor current will flow through the closed circuit, formed by the rotor winding, the slip-rings, the brushes and the star-connected external resistors.

At the time of starting, the external resistors are set for their maximum value. As such, the rotor resistance is high enabling the starting current to be low. At the same time, the high resistance rotor circuit increases the rotor power factor, and thereby, the torque developed at the start becomes much higher than the torque developed in squirrel cage motors.

As the motor speeds up, the external resistance is slowly reduced, and the rotor winding is made to be short-circuited at the slip-ring ends. Because of the reduced rotor resistance, the motor operates with low slip and high operating efficiency. The motor could be started for heavy loads with higher resistance or vice versa. However at increased rotor resistance, the motor's slip will be greater, the speed regulation poorer and it will have low efficiency. The resistance in the external circuit could be designed and varied to change the speed of the slip-ring motor between 50 to 100 percent of the rated speed. However, the I^2R losses in the rotor due to increased resistance is inevitable.



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

Let E_2 be the rotor emf per phase at standstill

X_2 be the rotor reactance per phase at standstill and R_2 be the rotor resistance per phase.

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

$$\text{Then } I_2 = \frac{E_2}{Z_2}, \cos \theta_2 = \frac{R_2}{Z_2}$$

Standstill or starting torque $T_{st} = K_1 E_2 I_2 \cos \theta_2$ or

$$T_{st} = K_1 E_2 \times \frac{E_2}{\sqrt{(R_2)^2 + (X_2)^2}} \times \frac{R_2}{\sqrt{(R_2)^2 + (X_2)^2}}$$

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

Therefore $T_{st} = K_2 \frac{R_2}{Z_2}$ where K_2 is another constant.

The starting torque of such a motor is increased by adding external resistance in the rotor circuit. The resistance is progressively cut out as the motor gain speed.

Rotor emf and reactance under running condition : When the starter is stationary i.e. $S = 1$, the frequency of the rotor emf is the same as that of the stator supply frequency. The value of emf induced in the rotor at standstill is maximum

because the relative speed between the rotor and the rotating stator flux is maximum.

When the rotor starts running, the relative speed between the rotor and the rotating stator flux is decreased. Hence the rotor induced emf is also decreased. The rotor emf become zero if the rotor speed become equal to the speed of stator rotating flux.

Hence, for a slip (s), the rotor induced emf will be s times the induced emf at standstill.

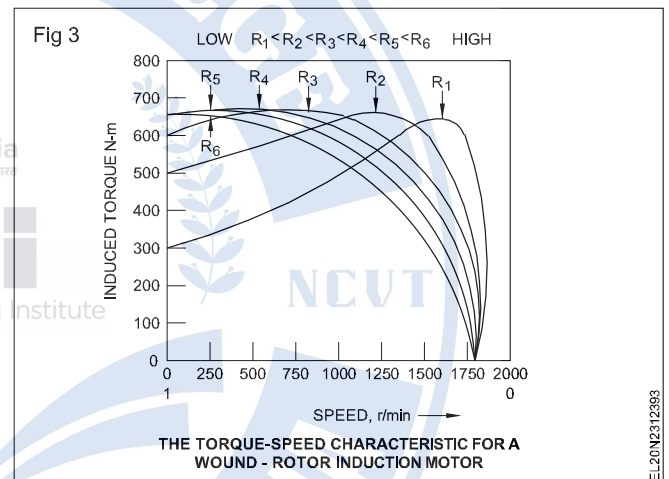
Therefore, under running condition $E_r = sE_2$.

The frequency of induced emf will likewise become $f_r = sf_2$ where f_2 is the rotor current frequency at standstill.

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

Therefore $X_r = sX_2$.

Characteristic and application of slip-ring induction motor: Insertion of higher, external resistance alters the starting torque to a higher value, as shown in Fig 3, by the torque speed characteristic.



By inserting the suitable value rotor resistance, the speed of the slip ring motor could be controlled in spite of power loss in resistance.

As shown in the curve, higher, external resistance improves the starting torque to a higher value. However the maximum torque remains constant for the variation of the rotor resistance.

By these curves, it is clear that the slip-ring motor could be used to start heavy loads by insertion of high resistance in the rotor to facilitate higher starting torque. At the same time the running efficiency of the motor could be achieved by cutting out the external resistance when the motor picks up its speed.

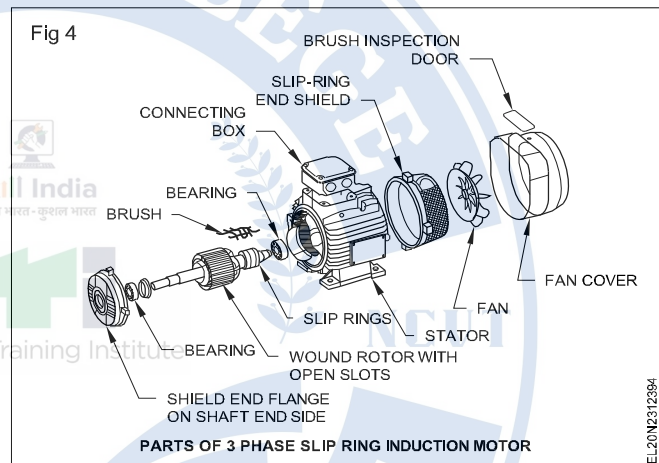
This motor could be used for drive which demands a higher starting torque and also a variable speed control - like compressors, conveyors, cranes, hoists, steel mills and printing presses.

Comparison between squirrel cage and slip-ring induction motors is given below:

Sl. No.	Property	Squirrel cage	Slip-ring motor
1	Rotor construction	Bars are used in rotor. Squirrel cage rotor is very simple, rugged and long lasting. No slip-rings.	Winding wire is used. Wound rotor requires attention. Slip-ring and brush gear need frequent maintenance.
2	Starting	Can be started by DOL star-delta, auto-transformer starters.	Rotor resistance starter is required
3	Starting torque	Low	Very high
4	Starting current	High	Low
5	Speed variation	Not easy, but could be varied in larger steps by pole-changing or smaller incremental steps through thyristors or by frequency variation.	Easy to vary speed, but speed change through pole-changing is not possible.

			Speed change possible by - insertion of rotor resistance - using thyristors - using frequency variation - injecting emf in the rotor circuit - cascading
6	Acceleration on load	Just satisfactory	Very good
7	Maintenance	Almost nil	Requires frequent maintenance
8	Cost	Low	Comparatively high

Fig 4 shows the exploded view of the slip ring induction motor.

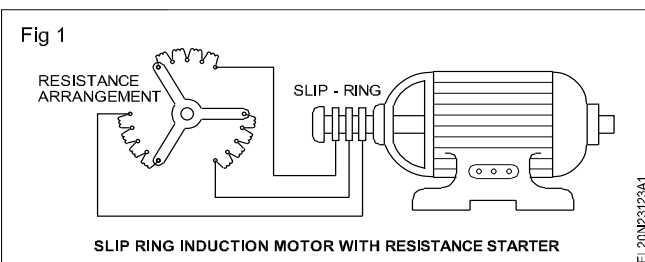


Resistance starter for 3-phase, slip-ring induction motor

Objective: At the end of this lesson you shall be able to

- explain the rotor resistance starters used for a 3-phase, slip-ring induction motor.

Slip-ring induction motors are started with full-line voltage across the stator winding. However, to reduce the heavy rush of the starting current, a star-connected external resistance is added in the rotor circuit as shown in Fig 1. The external resistances are cut out, and the rotor winding ends are shorted once the motor picks up its speed.



If such a manual starter is used, there is a possibility that someone may apply full voltage to the stator when the rotor resistance is in a completely cut-out position, resulting in heavy rush of the starting current and poor starting torque.

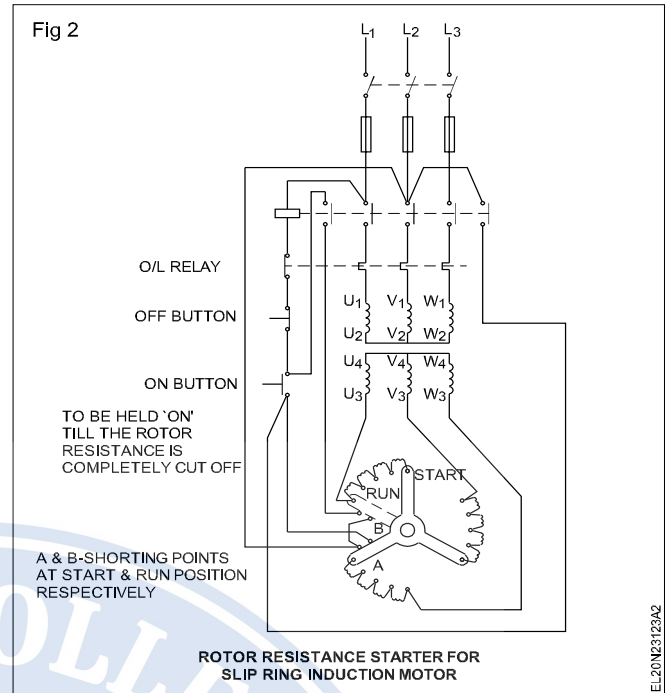
This could be eliminated by the use of a protective circuit in the resistance starter; thereby motor cannot be started until and unless all the rotor resistances are included in the rotor winding. Such a semi-automatic starter is shown in Fig 2.

By pressing the 'ON' button, the contactor will close, only when the shorting point 'A' at the rotor resistance is in a closed position. This is possible only when the handle is in the start position. Once the motor starts running, the handle of the rotor resistance should be brought to 'run' position to cutout the rotor resistance.

The position of the handle clearly indicates that at the start position, the contact 'A' is in the closed position, and at the run position, contact 'B' is in the closed position, but both cannot close at the same time. The 'ON' push-button needs to be held in the pushed-position till the handle is brought to the run-position. During the run-position, the

handle contact 'B' closes the no-volt coil circuit, and the pressure on the 'ON' button can be released.

In general, for small machines, the rotor resistance is air-cooled to dissipate the heat developed during starting. For larger machines, the rotor resistance is kept in an insulating oil tank for cooling. The starter shown is intended to start the motor only. As speed regulation through the rotor resistance needs intermediate positions, they are specially designed and always oil-cooled.

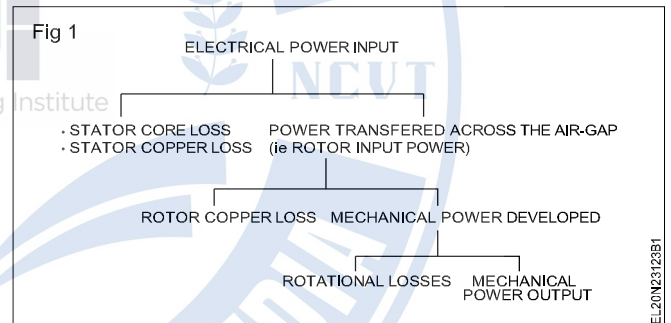


Efficiency - characteristics of induction motor- no load test - blocked rotor test

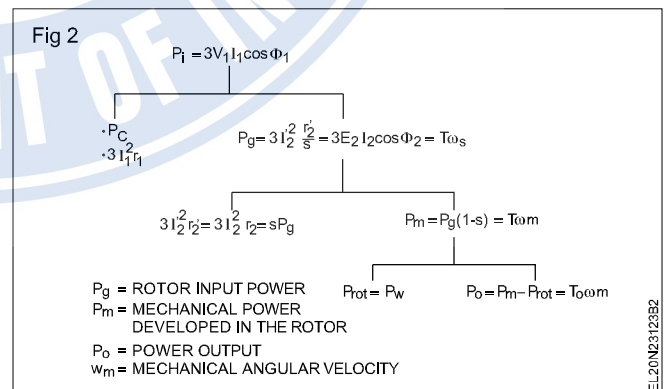
Objectives: At the end of this lesson you shall be able to

- state the power flow diagram of an induction motor indicating the losses
- calculate the efficiency from the given data.

When the three-phase induction motor is running at no-load, the slip has a value very close to zero. The torque developed in the rotor is to overcome the rotational losses consisting of friction and windage. The input power to the motor is to overcome stator iron loss and stator copper loss. The stator iron loss (consisting of eddy current and hysteresis) depends on the supply frequency and the flux density in the iron core. It is practically constant. The iron loss of the rotor is, however, negligible because the frequency of the rotor currents under normal condition is always small.



If a mechanical load is then applied to the motor shaft, the initial reaction is for the shaft load to drop the motor speed slightly, thereby increasing the slip. The increased slip subsequently causes I_2 to increase to that value which, when inserted into the equation for torque calculation (i.e $T = K\phi_s I_2 \cos \phi_s$), yields sufficient torque to provide a balance of power to the load. Thus an equilibrium is established and the operation proceeds at a particular value of slip. In fact, for each value of load horsepower requirement, there is a unique value of slip. Once slip is specified then the power input, the rotor current, the developed torque, the power output and the efficiency are all determined. The power flow diagram in a statement form is shown in Fig 1. Note that the loss quantities are placed on the left side of the flow point. Fig 2 is the same power flow diagram but now expressed in terms of all the appropriate relationships needed to compute the performance.



The stator output is transferred fully inductively to the rotor circuit.

Obviously, rotor input $P_g =$ stator output.

Rotor gross output, $P_m =$ rotor input $P_g -$ rotor cu. losses.

Torque, Mechanical power and Rotor output : Stator input $P_i =$ stator output + stator losses.

This rotor output is converted into mechanical energy and gives rise to the gross torque T . Out of this gross torque developed, some is lost due to windage and friction losses in the rotor, and the rest appear as useful torque T_o .

Let n r.p.s be the actual speed of the rotor and if it is in Nm, then

$T \times 2\pi n$ = rotor gross output in watts, P_m .

$$\text{Therefore, } T = \frac{\text{rotor gross output in watts, } P_m}{2\pi n} \text{ N.m}$$

The value of gross torque in kg.m is given by

$$T = \frac{\text{rotor gross output in watts}}{9.81 \times 2\pi n} \text{ Kg m}$$

$$= \frac{P_m}{9.81 \times 2\pi n} \text{ Kg m}$$

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

$$\text{Therefore, } T = \frac{\text{rotor input } P_g}{2\pi n_s}$$

From the above two equations we get,

$$\text{Rotor gross output} = P_m = Tw = T \times 2\pi n$$

$$\text{Rotor input} = P_g = Tw_s = T \times 2\pi n_s$$

The difference between the two equals the rotor copper loss.

$$\begin{aligned} \text{Therefore, rotor copper loss} &= s \times \text{rotor input} \\ &= s \times \text{power across air gap} \\ &= sP_g \end{aligned}$$

$$\text{Also rotor input, } P_g = \frac{\text{rotor copper loss}}{s}$$

$$\begin{aligned} \text{Rotor gross output } P_m &= \text{Input } P_g - \text{rotor cu.loss} \\ &= (1 - s) P_g \end{aligned}$$

$$\text{or } \frac{\text{rotor gross output, } p_m}{\text{rotor input, } p_g} = 1 - s$$

$$\text{rotor gross output. } P_m = (1 - s)P_g$$

$$\text{Therefore rotor efficiency} = \frac{n}{n_s}$$

Example

The power input to a 4-pole, 3-phase, 50 Hz. induction motor is 50kW, the slip is 5%. The stator losses are 1.2 kW and the windage and friction losses are 0.2 kW. Find (i) the rotor speed, (ii) the rotor copper loss, (iii) the efficiency.

Data given

No. of poles	$P = 4$
Frequency	$f = 50 \text{ Hz}$
Phases	$= 3$
Input power	$= 50 \text{ kW}$
% Slip	$s = 5\%$
Stator losses	$= 1.2 \text{ kW}$
Friction & Windage losses	$= 0.2 \text{ kW}$

Find:

Rotor speed	$= N$
Rotor copper loss	$= s \times \text{input power to rotor}$
efficiency	$= \eta$

SOLUTION

$$\text{Synchronous speed} = N_s = \frac{120f}{p} = \frac{6000}{4} = 1500 \text{ rpm}$$

$$\text{Fractional slip} = s = \frac{N_s - N_r}{N_s}$$

$$\frac{5}{100} = \frac{1500 - N_r}{1500}$$

$$75 = 1500 - N_r$$

$$\text{Therefore, rotor speed, } N_r = 1500 - 75 = 1425 \text{ rpm.}$$

$$\text{Input power to rotor} = (50 - 1.2) \text{ kW}$$

$$\begin{aligned} \text{Rotor copper loss} &= s \times \text{input power to rotor} \\ &= 0.05 \times 48.8 \\ &= 2.44 \text{ kW.} \end{aligned}$$

$$\begin{aligned} \text{Rotor output} &= \text{Rotor input} - (\text{Friction and windage loss} + \text{rotor cu.loss}) \\ &= 48.8 - (0.2 + 2.44) \\ &= 46.16 \text{ kW} \end{aligned}$$

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{46.16 \times 100}{50} = 92.32\%$$

Characteristics of squirrel cage induction motor

Objective: At the end of this lesson you shall be able to

- describe the characteristics and application of a 3-phase squirrel cage induction motor.

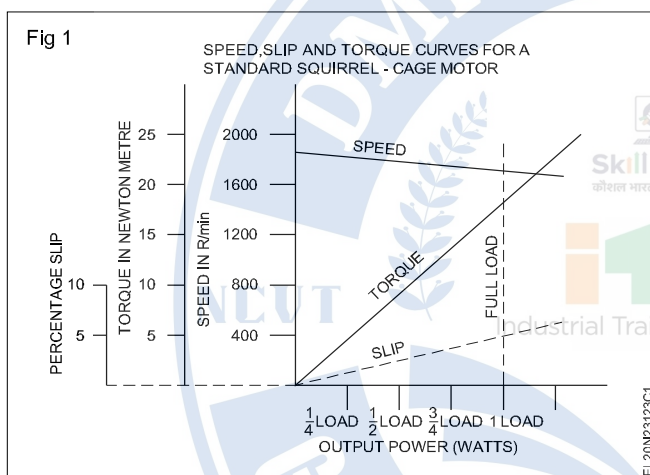
The most important characteristic of the induction motor is the speed torque characteristic which is also called the

mechanical characteristic. A study of this characteristic will give an idea about the behaviour of the motor in load

conditions. As the torque of the motor is also dependent on the slip, it will be interesting to study the characteristic of the squirrel cage induction motor to find the relationship between load, speed, torque and slip.

Speed, torque and slip characteristics : It has already been made clear that the rotor speed of a squirrel cage motor will always lag behind the synchronous speed of the stator field. The rotor slip is necessary in order to induce the rotor currents required for the motor torque. At no load, only a small torque is required to overcome the motor's mechanical losses, and the rotor slip will be very small, say about two percent. As the mechanical load is increased, however, the rotor speed will decrease, and hence, the slip will increase. This increase in slip in turn increases the induced rotor currents, and the increased rotor current in turn, will produce a higher torque to meet the increased load.

Fig 1 shows the typical speed torque and slip characteristic curves for a standard squirrel cage motor. The speed curve shows that a standard squirrel cage motor will operate at a relatively constant speed from no load to full load.



Since the squirrel cage rotor is constructed basically of heavy copper/aluminium bars, shorted by two end rings, the rotor impedance will be relatively, low and hence, a small increase in the rotor induced voltage will produce a relatively large increase in the rotor current. Therefore, as the squirrel cage motor is loaded, from no-load to full load, a small decrease in speed is required to cause a relative increase in the rotor current. For this reason, regulation of a squirrel cage motor is very good. But the motor is often classified as a constant speed device.

The slip curve shows that the percentage slip is less than 5% load, and is a straight line.

Since the torque will increase in almost direct proportion to the rotor slip, the torque graph is similar to the slip graph which also has a straight line characteristic as shown in Fig 1.

Relationship between torque, slip rotor resistance and rotor inductive reactance : It was stated earlier that torque is produced in an induction motor by the interaction of the stator and the rotor fluxes. The amount of torque produced is dependent on the strength of these two fields and the phase relation between them. This may be

expressed mathematically as

$$T = K \phi_s I_R \cos \phi$$

where T = torque in Newton metre

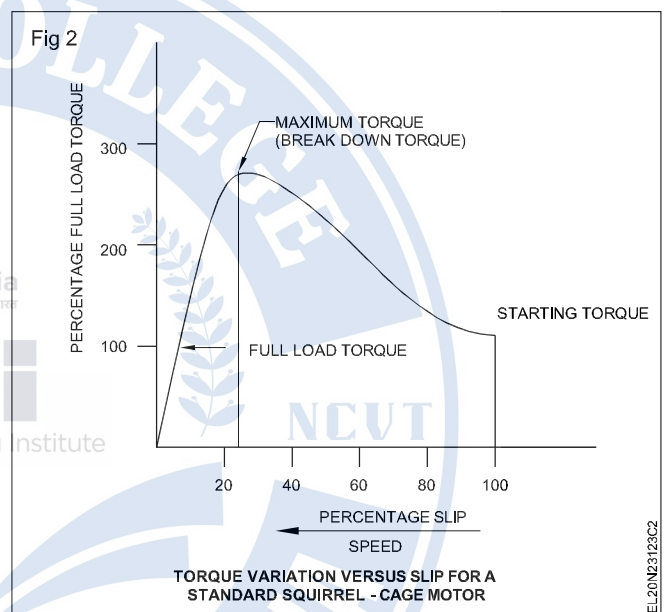
K = a constant

ϕ_s = stator flux in weber

I_R = rotor current in ampere

$\cos \phi$ = rotor power factor

From no load to full load, the torque constant (K), the stator flux (ϕ_s) and the rotor power factor ($\cos \phi$) for a squirrel cage motor will be practically constant. Hence the motor's torque will vary almost directly with the induced rotor current (I_R) since the rotor current in turn will vary almost directly with its slip. Variation of the torque of a squirrel cage motor is often plotted against its rotor slip as shown in Fig 2.



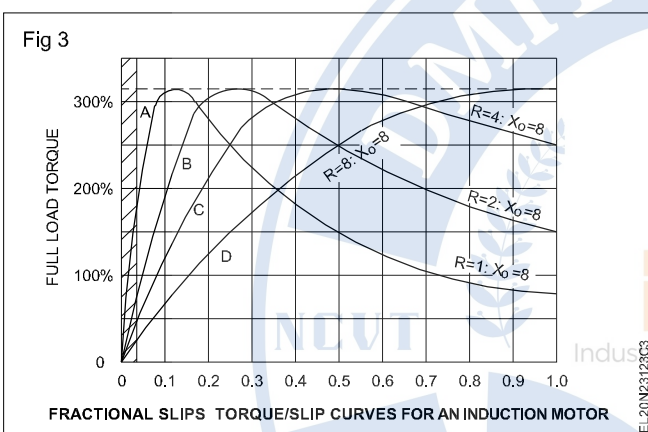
The increase in the rotor current, and hence, the increase in the rotor torque for a given increase in the rotor slip is dependent on the rotor power factor. The rotor resistance for a squirrel cage motor will be constant. However, an increase in slip will increase the rotor frequency, and the resulting inductive reactance of the rotor from no load to full load and even upto 125 percent of rated load, the amount of rotor slip for a standard squirrel cage motor is relatively small and the rotor frequency will seldom exceed 2 to 5 Hz. Therefore, for the above range of load the effect of frequency change on impedance will be negligible, and as shown in Fig 2, the rotor torque will increase in almost a straight relationship with the slip.

In between 10 to 25 percent slip the squirrel cage motor will attain its maximum possible torque. This torque is referred to as the maximum breakdown torque, and it may reach between 200 and 300 percent of the rated torque as shown in Fig 2. At the maximum torque, the rotor's inductive reactance will be equal to its resistance.

However, when the load and the resulting slip are increased much beyond the rated full load values, the increase in rotor frequency, and hence, the increase in rotor reactance

and impedance become appreciable. This increase in rotor inductive reactance and the resulting decrease in rotor power factor will have two effects; first, the increase in impedance will cause a decrease in the rate at which the rotor current increases with an increase in slip, and second, the lagging rotor power factor will increase; that means, the rotor flux will reach its maximum sometime after the stator peak flux has been swept by it. The out-of-phase relationship between these two fields will reduce their interaction and their resulting torque. Hence, if the motor load is increased beyond the breakdown torque value, the torque falls rapidly due to the above two effects and the motor operation becomes unstable, and the motor will stall.

Effect of rotor resistance upon the torque/slip relationship: Fig 3 shows the relationship between torque and slip when the rotor resistance is changed. The shaded portion of the curve shows the actual operating area. Curve A for an induction motor with low rotor resistance, say 1 ohm, Curve B is for 2 ohm, Curve C is for 4 ohm and Curve D for 8 ohm.



Breakdown torque : In all these cases the standstill inductive reactance of the rotor is the same, say 8 ohm. From the curves it is clear that the maximum (breakdown) torque is the same for the four values of R. Further it is also clear that the maximum torque occurs at greater slip for higher resistance.

Starting torque : At the time of starting, the fractional slip is 1, and the starting torque is about 300% of the full load torque for the rotor having maximum resistance as shown by curve D of Fig 3, and at the same time the rotor having low resistance will produce a starting torque of 75% of the full load torque only, as shown by curve A of Fig 3. Hence, we can say that an induction motor having high rotor resistance will develop a high torque at the time of starting.

Running torque : While looking at the normal operating region in the shaded portion of the graph, it will be found the torque at running is appreciably high for low resistance rotor motors and will be conspicuously less for high resistance rotor motors.

As squirrel cage induction motors will have less rotor resistance, their starting torque is low but running torque is quite satisfactory. This is partly compensated by the double squirrel cage motors which produce high starting and normal running torque. On the other hand, the slip ring induction motor, due to its wound rotor, has the possibility of inclusion of resistance at the time of starting and reducing the same while running.

Application of squirrel cage induction motor : Single squirrel cage motors are used widely in industries and in irrigation pump sets where fairly constant speed is required. This motor has fairly high efficiency, costs less and is found to be robust in construction.

Double squirrel cage induction motors are used in textile mills and metal cutting tool operations where high starting torque is essential.

No-load test of induction motor

Objectives: At the end of this lesson you shall be able to

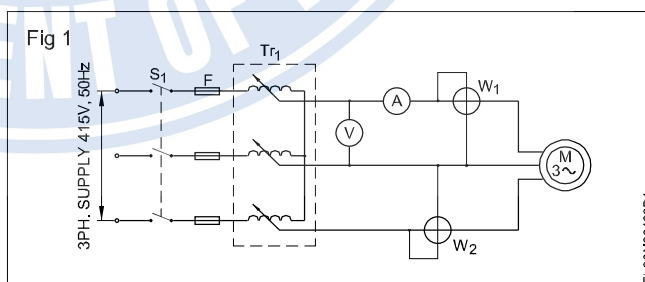
- determine the constant (mechanical and iron losses of induction motor) by no-load test
- calculate the total equivalent resistance per phase.

No-load test

The induction motor is connected to the supply through a 3-phase auto-transformer (Fig 1). The 3-phase auto-transformer is used to regulate the starting current by applying low voltage at the start, and then gradually increased to rated voltage. The ammeter and voltmeters are selected based upon the motor specification. The no-load current of the motor will be very low, up to 30% of full load.

As the power factor of the motor on no-load is very low, in the range of 0.1 to 0.2, the wattmeters selected are such as to give a current reading at low power factor. The wattmeter full scale reading will be approximate equal to the product of the ammeter and voltmeter full scale deflection values.

The calculation is done as follows to determine the constant losses of the induction motor.



At no-load, the output delivered by the motor is zero. All the mechanical power developed in the rotor is used to maintain the rotor running at its rated speed. Hence the input power is equal to the no-load copper loss plus iron losses and mechanical losses.

Calculation

V_{NL} is ϕ line stator voltage

I_{NL} is @ line current

P_{NL} is @ Three-phase power input.

The input power consists of the core loss P_c , friction and windage loss $P_{(rot)}$ and the stator copper loss.

$$P_{NL} = P_c + P_{rot} + 3 I_{NL}^2 R_s$$

This permits the sum of rotational loss to be evaluated.

$$P_{rot+C} = P_{NL} - 3 I_{NL}^2 R_s$$

where the stator resistance R_s per phase obtained from a resistance measurement at the stator terminal.

In star connection $R_s = R/2$.

Delta connection $R_s = 2/3 R$.

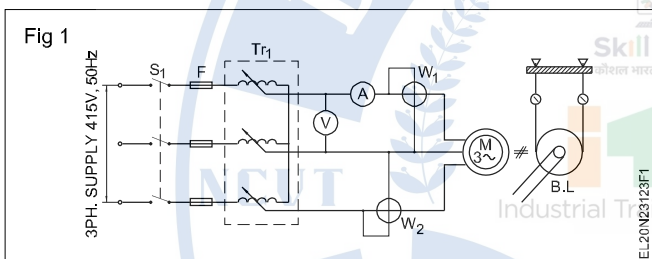
Blocked rotor test

Objectives: At the end of this lesson you shall be able to

- determine the full load copper loss of a 3-phase induction motor by blocked rotor test
- calculate the total equivalent resistance per phase and efficiency.

The connections are made similar to that of the no-load test. In this case the ammeter is selected to carry the full load current of the motor. Wattmeters will be of a suitable range and its power factor is 0.5 to unity.

An auto-transformer is used to give a much lower percentage of the rated voltage. The rotor is locked by a suitable arrangement such that it cannot rotate even if the supply is given to the motor. One such arrangement is shown in Fig 1. The belt is over-tightened on the pulley to prevent rotation.



As the rotor is in a locked condition it is equivalent to the short circuit secondary of a transformer. Therefore, a small induced voltage in the rotor cage winding will be sufficient to cause a large current to flow in the cage.

It is very essential to limit the supply voltage to a value less than 5% at start and then gradually increase until the starter current is equal to the full load current. The frequency of the starter supply voltage is maintained at normal rated supply frequency.

The method of calculating the copper losses from the result is illustrated through the example given below.

Example

A 5 HP 400V, 50 Hz, four-pole, three-phase induction motor was tested and the following data were obtained.

Blocked rotor test: $V_s = 54$, $P_s = 430$, $I_s = 7.5$ A.

The resistance of the stator winding gives a 4 V drop between the terminals' rated DC current flowing.

Find the power factor at short circuit and R_e and X_e and full load copper loss.

Given:

Output = 5 HP

Voltage = 400 V

Frequency = 50 Hz.

Blocked rotor voltage, $V_s = 54$ V

Power $P_s = 430$ W

Current, $I_s = 7.5$ A

Find:

Power factor at short circuit = $\cos \theta_s$

Equivalent resistance, R_e /phase

Equivalent reactance X_e /phase

Full load copper loss = $3I^2 R_e$

Known:

$$W_s = \sqrt{3} V_s I_s \cos \phi_s$$

$$\text{Equivalent impedance } Z_e = \frac{V_s}{\sqrt{3} I_s} = \sqrt{R_e^2 + X_e^2}$$

$$R_e = \text{equivalent resistance} = \frac{P_s}{3 I_s^2}$$

$$X_e = \text{equivalent reactance} = \sqrt{Z_e^2 - R_e^2}$$

Solution:

$$W_s = \sqrt{3} V_s I_s \cos \phi_s$$

$$\cos \phi_s = \frac{W_s}{\sqrt{3} V_s I_s}$$

$$\cos \phi_s = \frac{430}{1.73 \times 54 \times 7.5}$$

$$= \frac{430}{696.6}$$

$$= 0.61$$

$$\begin{aligned} \text{Equivalent resistance } R_e/\text{phase} &= \frac{P_s}{3 \times I_s^2} \\ &= \frac{430}{3 \times (7.5)^2} \\ &= \frac{430}{168.75} = 2.5 \Omega \end{aligned}$$

$$X_e = \text{equivalent reactance/phase} = \sqrt{Z_e^2 - R_e^2}$$

$$Z_e = \frac{54}{\sqrt{3} \times 7.5} = \frac{54}{12.90} = 4.1 \Omega$$

$$\begin{aligned} X_e &= \sqrt{4.1^2 - 2.5^2} = \sqrt{16.81 - 6.25} \\ &= \sqrt{10.56} = 3.24 \Omega \end{aligned}$$

$$\begin{aligned} \text{Full load copper loss} &= 3 I^2 R_e \\ &= 3 \times 7.5^2 \times 2.5 = 421.875 \text{ watts} \end{aligned}$$

Answer

- i $\cos \phi_s = 0.61$
- ii Equivalent resistance $R_e/\text{phase} = 2.5 \Omega$
- iii Equivalent reactance $X_e/\text{phase} = 3.24 \Omega$
- iv Full load copper loss = 421.875 watts

Auto-transformer starter

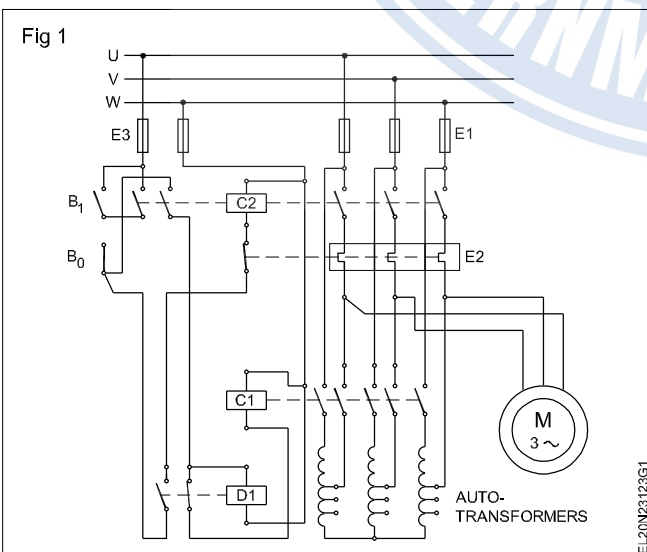
Objectives: At the end of this lesson you shall be able to

- explain the construction and operation of auto-transformer starter
- explain power circuit and control circuit of auto-transformer starter.

Auto-transformer starter

By connecting series resistances reduced voltage is obtained at the motor leads. It is simple and cheap, but more power is wasted in the external series resistances.

In auto transformer starting method the reduced voltage is obtained by taking tapplings at suitable points from a three phase auto-transformer as shown in Fig 1. The auto transformers are generally tapped at 55, 65, 75 percent points. So that the adjustment at these voltages may be made for proper starting torque requirements. Since the contacts frequently break, large value of current acting some time quenched effectively by having the auto-transformer coils immersed in the oil bath.



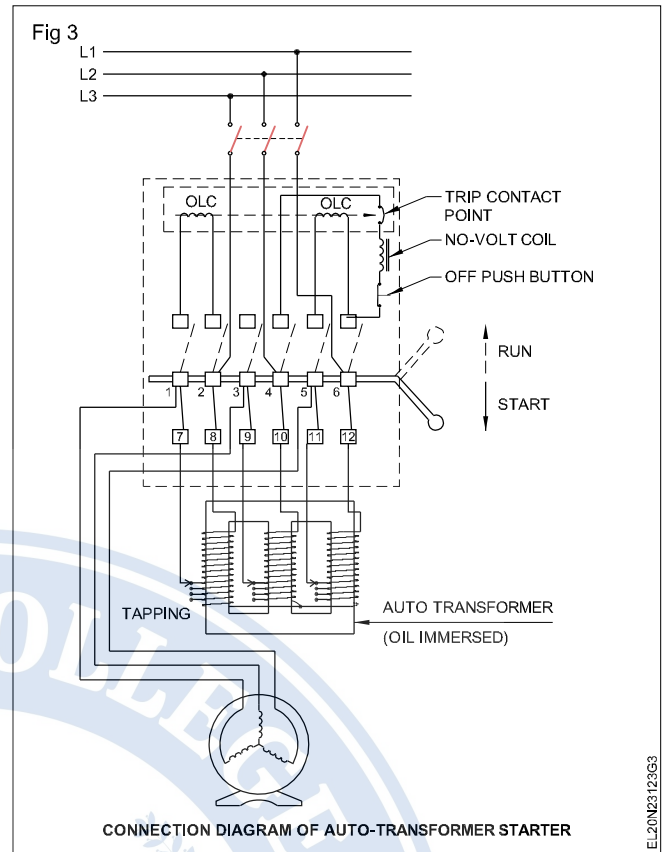
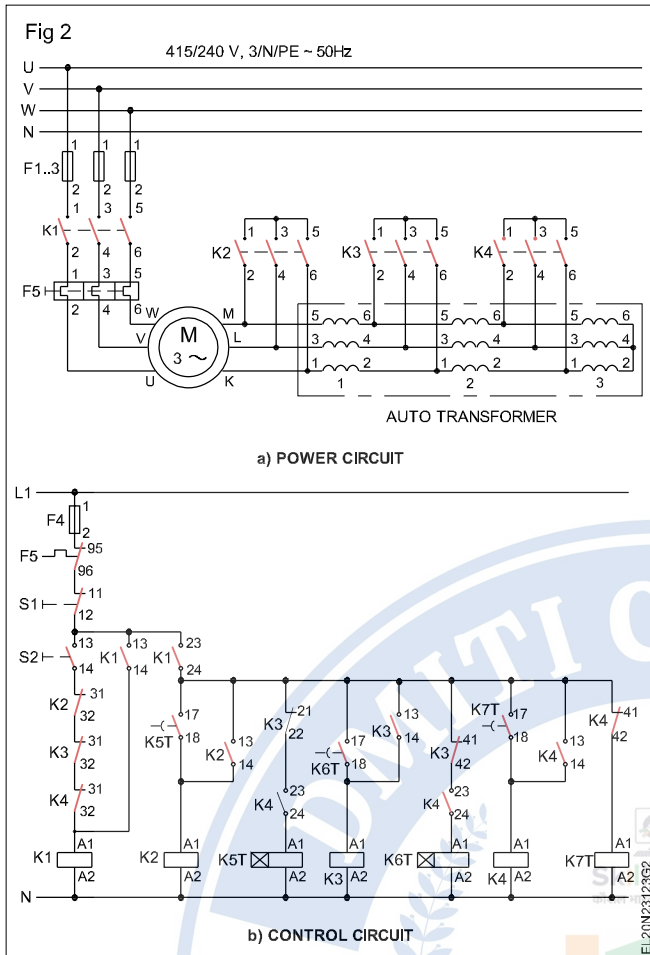
The power circuit of the auto-transformer is shown in Fig 2a and control circuit of auto-transformer is shown in Fig 2b.

Auto-transformer starter - operation

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

Fig 3 shows the connection of an auto-transformer starter. To start the motor the handle of the starter is turned downward and the motor gets a reduced voltage from the auto-transformer tapplings. When the motor attains about 75% of its rated speed the starter handle is moved upward and the motor gets full voltage. The auto-transformer gets disconnected from the motor circuit.

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



Single phasing preventer/phase failure relay

Objectives: At the end of this lesson you shall be able to

- define single phasing
- state the effects of single phasing
- explain the necessity of a single phasing preventer
- classify the single phasing preventers
- explain the installation procedure
- explain the procedure for troubleshooting and servicing of single phasing preventer.

Single phasing preventer/phase failure relay : When one of the three lines of a three-phase supply system fails or opens, the load current flows between the other two lines only and the fault is known as single phasing.

Effect of single phasing: The effect of single phasing is different with different types of loads as follows

- In 3-phase heating loads, the heat produced decreases to around 50% at the same time it does not harm the equipment.
- In three-phase motors, the effect of single phasing is different on different occasions. i) During starting, if single phasing occurs, the motor fails to start or stalls as proper rotating magnetic field is not created. But the motor draws a very large current and motor windings gets heated up. ii) During running, if single phasing occurs, the motor may or may not run depending upon the load condition and the phase in which supply is

available will draw a large current and the winding is likely to burn out due to overheating.

Necessity of single phasing preventer/phase failure relay: If two phases of the supply to a three-phase induction motor are interchanged, the motor will reverse its direction of rotation. This action is called phase reversal. In the operation of elevators and in many industrial applications, phase reversal may result in serious damage to the equipment and injury to people using the equipment. In other situations, if a fuse blows or a wire connected to the motor breaks while the motor is running, the motor will continue to operate on two phase but will experience serious overheating. To protect motors against these conditions of phase failure, a single phase preventer is used.

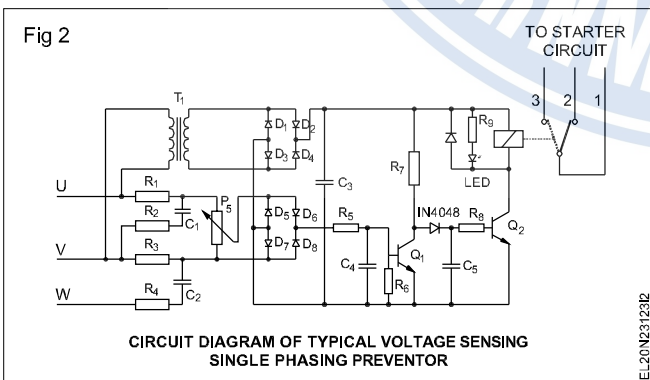
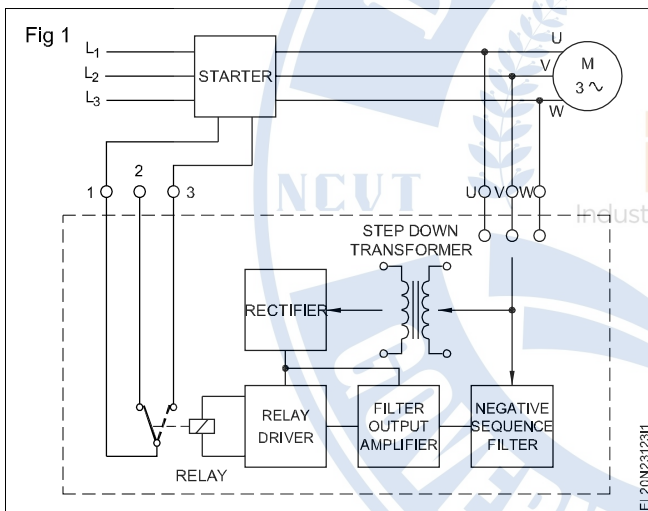
Types of preventers: Single phasing preventers are available in three types.

- Mechanical

- Current sensing
- Voltage sensing

Single phasing preventer - voltage sensing : In an AC three-phase supply the order in which three-phase voltages reach the maximum value is known as phase sequence. The phase voltage reaches their maximum positive value one after another at 120° in clockwise known as positive phase sequence and in anti-clockwise known as negative phase sequence. In the case of phase reversal or unbalanced voltages or no voltage in a line it results in a super-imposition of negative phase sequence over the normal positive phase sequence of supply voltages. This negative sequence is filtered by a resistance capacitance or resistance, capacitance and inductor network and de-energise the relay in the voltage the sensing single phasing preventer.

Fig 1 and Fig 2 shows the block diagram and circuit diagram of a typical voltage sensing single phasing preventer. In this a resistance, capacitance network is utilized to sense the negative phase sequence. When phase sequences and voltages are correct, no voltage will be generated across the filtered output i.e. across capacitor. C_4 in the circuit which drives the transistor Q_1 to cut off transistor Q_2 to drive the relay.

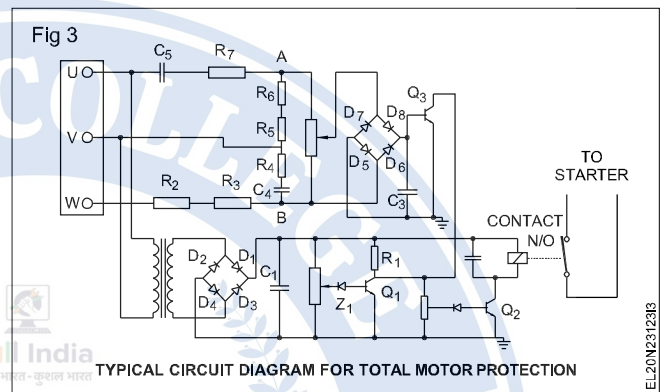


When the negative sequence occurs due to unbalanced supply voltage or phase reversal, a voltage is developed across the capacitor C_4 which drives the transistor Q_1 to saturation and transistor Q_2 to cut off. This results in switching off the relay circuit.

Some of the single phasing preventors are provided with the facility to adjust unbalanced settings. For example when the relay is found to operate very frequently for the set value, the unbalanced pre-set can be changed by operating the pre-set P_5 in Fig 2.

Single phasing preventor with over-voltage and under voltage cut off (Total motor protection) : When a motor is fed with reduced voltage, the motor draws excess current to drive the load and with an over-voltage, also it draws excess current. To protect the motor from under-voltage or over-voltage and also from single phasing a preventer with over and under voltage protection is used for total motor protection.

Fig 3 shows an arrangement of over-voltage and under-voltage cut off circuit along with single phasing preventer.



In the circuit transistor Q_1 serves as over-voltage cut off and transistor Q_2 serves as under-voltage cut off where-as transistor Q_3 serves as single phasing preventer.

Installation of single phasing preventer : Installation and connection of single phasing preventer shall be done as recommended by the manufacturer. Preferably single phasing preventers shall be located nearer to the equipment and not subjected to abnormal vibration. Care should be taken to locate the unit away from a heat generating source such as oven, furnace etc.

A single phase preventer shall be connected with the supply line and starter to the appropriate terminals and circuits.

Some of the commonly used single phasing preventors and their connection with starter are shown in Figs 4 & 5 for your reference.

Troubleshooting and maintenance of single phasing preventer : The arrangement of components and their circuits of single phasing preventers vary from one make to another make as well as from one type to another type.

It is preferred to follow the manufacturer's recommendations for troubleshooting and maintenance of single phase preventers. A few general guide lines for troubleshooting of single phase preventers are given in the Table-1.

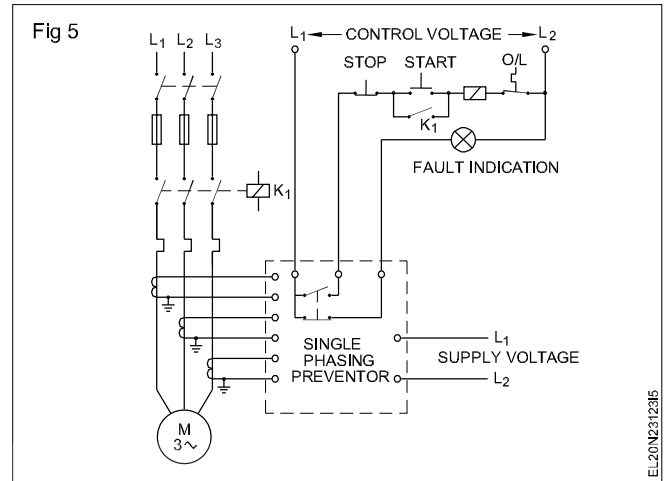
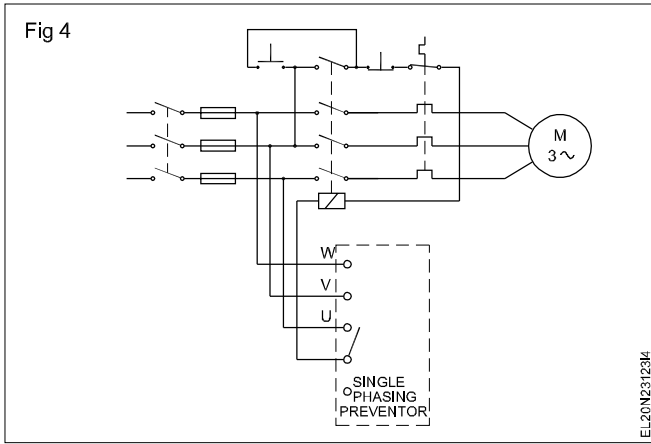


Table 1

S.No.	Symptoms	Possible causes	Remedy
1	Starter with single phase preventer does not start.	No supply. Low supply voltage.	Check and resume supply. Verify and correct the voltage.
		Unbalanced line voltages.	Verify and correct.
		Improper phase sequence.	Reverse the phase sequence by interchanging any two incoming lines.
		Single phasing	Check and rectify.
		No control circuit voltage.	Check and rectify.
2	Starter with single phase preventer does not hold on.	Low supply voltage. Unbalanced line voltages.	Verify and correct. Verify and correct.
		Single phasing.	Verify and correct.
		Improper phase sequence.	Reverse the phase sequence.
		Defect in single phase preventer electronic circuit.	Check, repair or replace.
		Relay of single phase preventer is not energised.	Check, rectify or replace.
		Improper function of relay contacts.	Check, rectify or replace.
		Open in holding circuit.	Check and correct.
3	Starter with single phase preventer trips frequently.	Abnormal fluctuations in line voltages.	Check and rectify.
		Improper settings or unbalanced settings.	Adjust the unbalanced settings.
		Loose contact in supply lines/ control circuit.	Check and rectify.

Braking system of motors

Objectives: At the end of this lesson you shall be able to

- state the necessity of braking system for motors
- list and explain each type of braking system.

Necessity of braking system

The term braking comes from the term brake. The brake is an equipment to reduce the speed of any moving or

rotating equipment, like vehicles, locomotives etc. The process of applying brakes can be termed as **braking**.

The term braking in two parts **i) Mechanical braking** and the **ii) Power braking**. In mechanical braking the

speed of the machine is reduced solely by mechanical process but in Powerbraking the whole process is depended on the flux and torque directions. Each type of Power braking is the reversal of the direction of the flux. **Braking** is the process of reducing speed of any rotating machine. The application of braking is in factories, industrial areas or be it in locomotives or vehicles. Everywhere the use of mechanical and Power brakes is inevitable.

Types of braking

Brakes are used to reduce or cease the speed of motors. There are various types of motors available (DC motors, induction motors, synchronous motors, single phase motors etc.) and the specialty and properties of these motors are different from each other, hence this braking methods also differs from each other. Braking can be divided in to three methods mainly, which are applicable for almost every type of motors.

- 1 Plugging type braking
- 2 Regenerative Braking
- 3 Dynamic braking.

1 Plugging type braking: In this method the terminals of supply are reversed, as a result the generator torque also reverses which resists the normal rotation of the motor and as a result the speed decreases. During plugging external resistance is also introduced into the circuit to limit the flowing current. The main

disadvantage of this method is that here power is wasted.

2 Regenerative braking: Regenerative braking takes place whenever the speed of the motor exceeds the synchronous speed. This braking method is called regenerative braking because here the motor works as generator and supply itself is given power from the load, i.e. motors. The main criteria for regenerative braking is that the rotor has to rotate at a speed higher than synchronous speed, only then the motor will act as a generator and the direction of current flow through the circuit and direction of the torque reverses and braking takes place. The only disadvantage of this type of braking is that the motor has to run at super synchronous speed which may damage the motor mechanically and electrically, but regenerative braking can be done at sub synchronous speed if the variable frequency source is available.

3 Dynamic braking: Another method of reversing the direction of torque and braking the motor is dynamic braking. In this method of braking the motor which is at a running condition is disconnected from the source and connected across a resistance. When the motor is disconnected from the source, the rotor keeps rotating due to inertia and it works as a self-excited generator. When the motor works as a generator the flow of the current and torque reverses.

Method of speed control of 3 phase induction motor

Objectives: At the end of this exercise you shall be able to

- list the speed control methods from stator and rotor side
- explain the speed control methods of 3 phase induction motor.

In 3 phase induction motor, speed can be controlled from both stator and rotor side

- 1 Speed control methods from stator side
 - By changing the applied voltage
 - By changing the applied frequency
 - By changing the number of stator poles
- 2 Speed control from rotor side
 - Rotor rheostat control
 - Cascade operation
 - By injecting EMF in rotor circuit

1 Speed control from stator side

a By changing the applied voltage: Torque equation of induction motor is

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

$$= \frac{3}{2\pi N_s} \frac{s E_2^2 R_2}{\sqrt{R_2^2 + (s X_2)^2}}$$

Rotor resistance R_2 is constant and if slip s is small then sX_2 is so small that it can be neglected. Therefore, $T \propto$

$$s E_2^2 \text{ where } E_2 \text{ is rotor induced emf and } E_2 \propto V$$

And hence $T \propto V^2$, thus if supplied voltage is decreased, torque decreases and hence the speed decreases.

This method is the easiest and cheapest, still rarely used because-

- 1 A large change in supply voltage is required for relatively small change in speed.
- 2 Large change in supply voltage will result in large change in flux density, hence disturbing the magnetic conditions of the motor.

b By changing the applied frequency: Synchronous speed (N_s) of the rotating magnetic field of induction motor is given by,

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

where, f = frequency of the supply and P = number of stator poles.

Thus, synchronous speed changes with change in supply frequency, and thus running speed also changes. However, this method is not widely used. This method is used where, only the induction motor is supplied by a generator (so that frequency can be easily changed by changing the speed of prime mover).

c Changing the number of stator poles: From the above equation, it can be also seen that synchronous speed (and hence, running speed) can be changed by changing the number of stator poles. This method is generally used for squirrel cage induction motors, as squirrel cage rotor adapts itself for any number of stator poles. Change in stator poles is achieved by two or more independent stator windings wound for different number of poles in same slots.

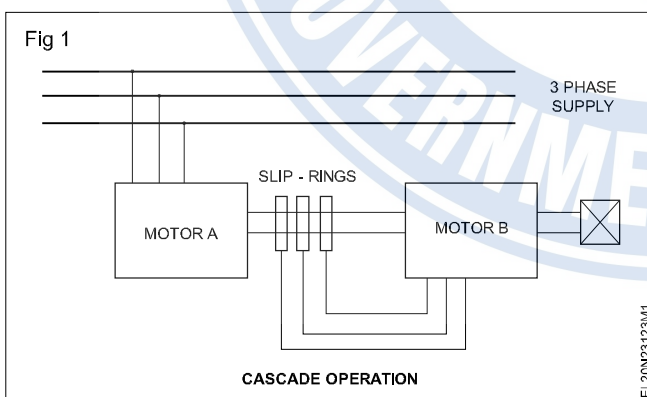
For example, a stator is wound with two 3phase windings, one for 4 poles and other for 6 poles.

For supply frequency of 50 Hz

- i Synchronous speed when 4 pole winding is connected, $N_s = 120 \times (50/4) = 1500$ RPM
- ii Synchronous speed when 6 pole winding is connected, $N_s = 120 \times (50/6) = 1000$ RPM

2 Speed control from rotor side

- a Rotor rheostat control:** This method is similar to that of armature rheostat control of DC shunt motor. But this method is only applicable to slip ring motors, as addition of external resistance in the rotor of squirrel cage motors is not possible.
- b Cascade operation:** In this method of speed control, two motors are used. Both are mounted on a same shaft so that both run at same speed. One motor is fed from a 3phase supply and other motor is fed from the induced emf in first motor via slip-rings. The arrangement is as shown in Fig 1.



Motor A is called main motor and motor B is called auxiliary motor.

- Let, N_{s1} = frequency of motor A
 N_{s2} = frequency of motor B

P_1 = number of poles stator of motor A

P_2 = number of stator poles of motor B

N = speed of the set and same for both motors

f = frequency of the supply

Now, slip of motor A, $S_1 = (N_{s1} - N) / N_{s1}$.

Frequency of the rotor induced emf in motor A, $f_1 = S_1 f$. Now, auxiliary motor B is supplied with the rotor induced emf therefore, $N_{s2} = (120f_1) / P_2 = (120S_1 f) / P_2$. Now putting the value of $S_1 = (N_{s1} - N) / N_{s1}$

$$N_{s2} = \frac{120f (N_{s1} - N)}{P_2 N_{s1}}$$

At no load, speed of the auxiliary rotor is almost same as its synchronous speed. i.e. $N = N_{s2}$. From the above equations, it can be obtained that

$$N = \frac{120f}{P_1 + P_2}$$

With this method, four different speeds can be obtained

- 1 When only motor A works, corresponding speed = $N_{s1} = 120f / P_1$
- 2 When only motor B works, corresponding speed = $N_{s2} = 120f / P_2$
- 3 If cumulative cascading is done, speed of the set = $N = 120f / (P_1 + P_2)$
- 4 If differential cascading is done, speed of the set = $N = 120f (P_1 - P_2)$

c By injecting EMF in rotor circuit: In this method, speed of induction motor is controlled by injecting a voltage in rotor circuit. It is necessary that voltage (emf) being injected must have same frequency as of slip frequency. However, there is no restriction to the phase of injected emf. If we inject emf which is in opposite phase with the rotor induced emf, rotor resistance will be increased. If we inject emf which is in phase with rotor induced emf, rotor resistance will decrease. Thus, by changing the phase of injected emf, speed can be controlled. The main advantage of this method is a wide range of speed control (above normal as well as below normal) can be achieved. The emf can be injected by various methods such as Kramer system, Scherbius system etc.

Fundamental terms used in AC winding

Objectives: At the end of this lesson you shall be able to

- state the terms used in AC winding
- explain the different types of AC winding.

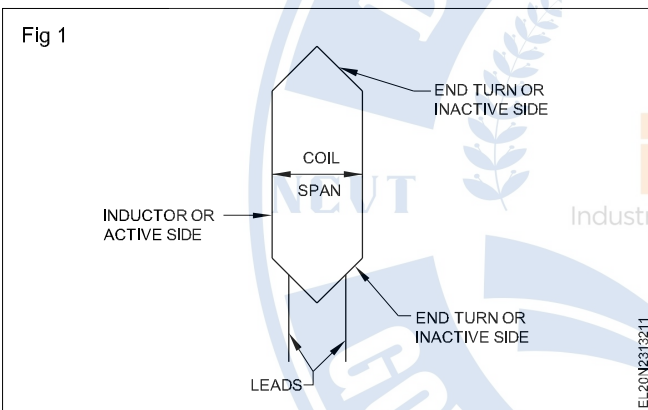
Fundamental terms used in AC Winding: Before taking up AC winding, the trainee should be familiar with the terms used in AC winding as explained in the following paragraphs.

Coil : A number of turns connected in series is called a coil. A coil has two active sides and two inactive sides.

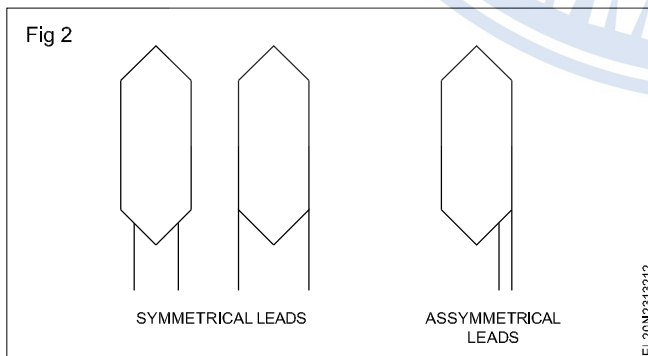
Turn: It is the closed path of the conductor which is formed by connecting the two inductors under two dissimilar poles N and S. (Fig 1)

Active side of a coil : It is that part of the coil which lies in the slots of the core. It is also known as an inductor. (Fig 1)

Inactive side of a coil : It is the portion of the coil which joins the two active sides of a coil. (Fig 1)



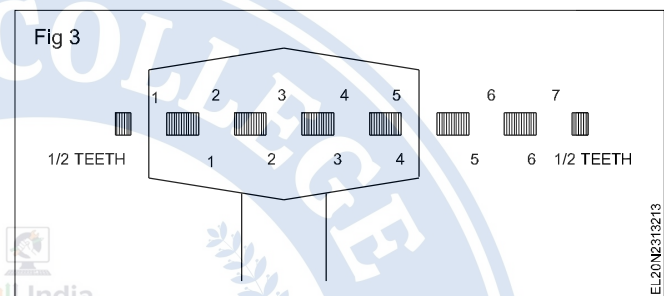
Leads of a coil : These are the two ends of a coil which are used for the connection. Leads are also known as jumpers which may be symmetrical or unsymmetrical as shown in Fig 2.



Pole pitch : The distance between the centre of two adjacent opposite poles is called the pole pitch. Pole pitch is measured in terms of slots or coil sides.

$$\text{Pole pitch} = \frac{\text{No. of slots in the stator}}{\text{No. of poles}}$$

Coil pitch/span and coil throw : The distance between the two active sides of a coil under adjacent dissimilar poles is called coil pitch/span. Fig 3 shows the coil pitch/span and coil throw (i.e. coil pitch/span = 4 and coil throw is 1-5).



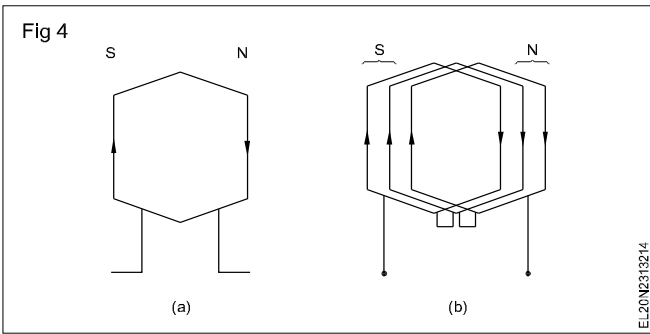
Pitch factor : Winding pitch need not be equal to the pole pitch. If the pole pitch and winding pitch are equal, the winding is called full pitched winding. If the winding pitch is less than the pole pitch, the winding is called fractional pitch winding or short pitch winding. While rewinding, the original winding pitch should not be changed. The machine designer would have chosen the winding pitch after considering the different factors required for the better performance of the machine. Any change in the original winding pitch of a machine will affect the performance of that machine. If the winding pitch is 4, then the coil throw is 1 to 5, and one side of the coil is placed in slot No.1 and the other side of the coil is inserted in slot No.5 as shown in Fig 3. Then the winding pitch is 5-1 = 4. The ratio between the winding pitch and pole pitch is called the pitch factor.

$$\text{Pitch factor} = \frac{\text{Winding pitch}}{\text{Pole pitch}}$$

Short pitch winding is usually used in almost all machines except variable speed motors. The reasons for adopting short pitch winding are given below.

- 1 Winding requires less copper.
- 2 Copper loss is less.
- 3 Efficiency of the machine is increased.
- 4 Winding occupies less space.
- 5 In alternators, the winding produces uniform sine wave.

Coil group : When you observe the direction of the current flow in a coil, you will see current in the two coil sides have opposite directions as shown in Fig 4(a).



Accordingly the current in a single coil produces two dissimilar poles. In an ordinary winding, according to the design, one or more coils may be connected in series to form a group as shown in Fig 4(b). (Three coils form one group) The total number of coil groups in a winding is equal to the number of phases multiplied by the number of poles.

Total No. of coil groups = No. of phases x No. of poles

$$\text{Coil group per phase} = \frac{\text{Total No. of coil groups}}{\text{No. of phases}}$$

Coil group per phase per pole =

$$\frac{\text{Total No. of coil groups}}{\text{No. of phases} \times \text{No. of poles}}$$

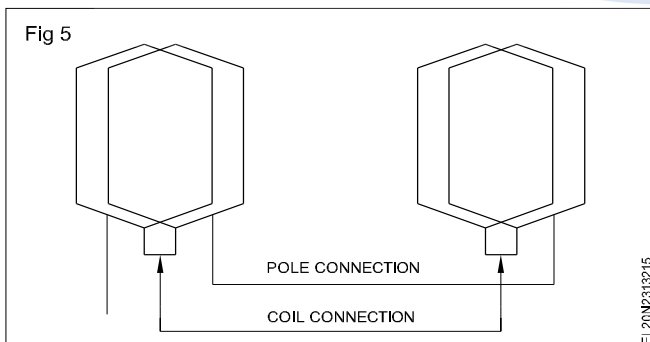
Further the number of coils in a group per phase per pole

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

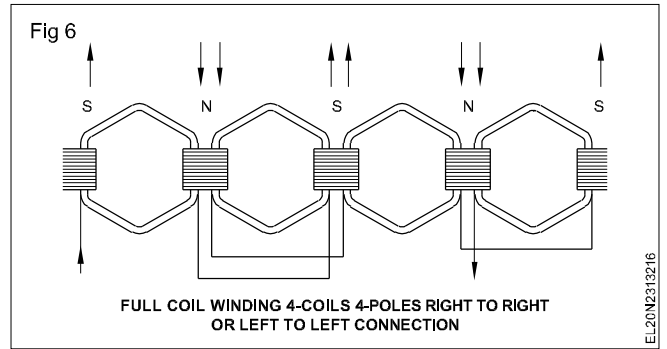
$$= \frac{\text{Total number of coils}}{\text{Total number of groups}}$$

Coil connections : The connection which joins a coil lead of one coil to the other coil lead of the same coil group is called 'coil connection' and is shown in Fig 5.

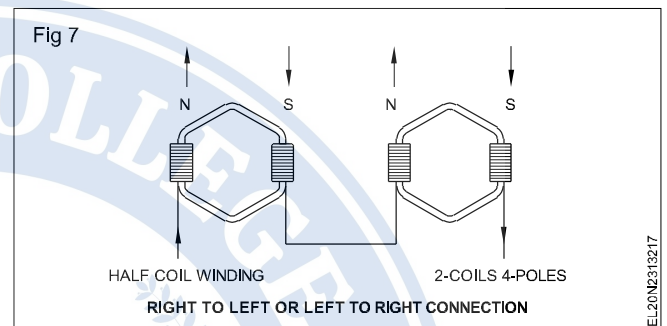
Pole connection : The connection which joins a coil group of one phase to another coil group of the same phase of the winding is called pole connection or group connection, and is shown in Fig 5.



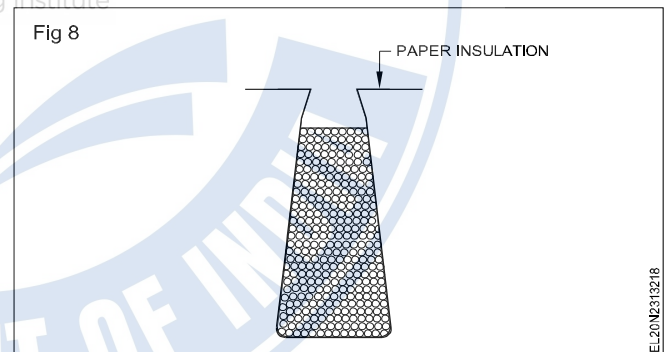
Whole-coil winding : A whole coil winding is one in which the number of coils per phase is equal to the number of poles in the machine. Refer to Fig 6.



Half coil winding : A half coil winding is one in which the number of coils per phase is equal to half the number of poles in the machines. Half coil winding is generally done in the winding of ceiling fans, double speed motors etc. Refer to Fig 7.



Single layer winding : In single layer winding each slot contains only one coil side as shown in Fig 8 and the number of coils in the machine is equal to half the number of slots in the stator or armature. In single layer winding the coil pitch is usually taken in odd numbers.

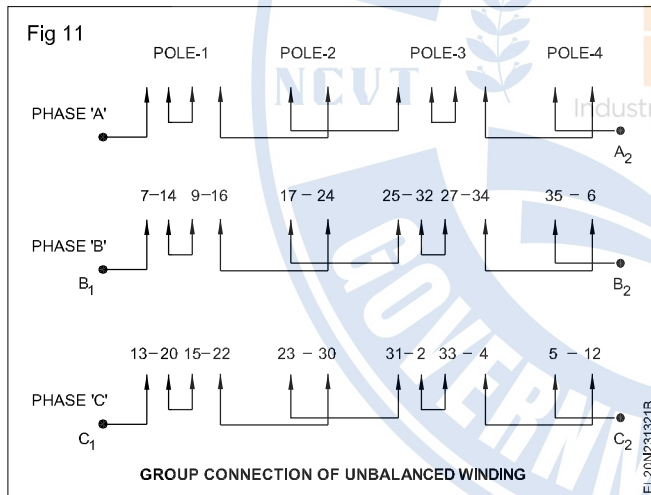
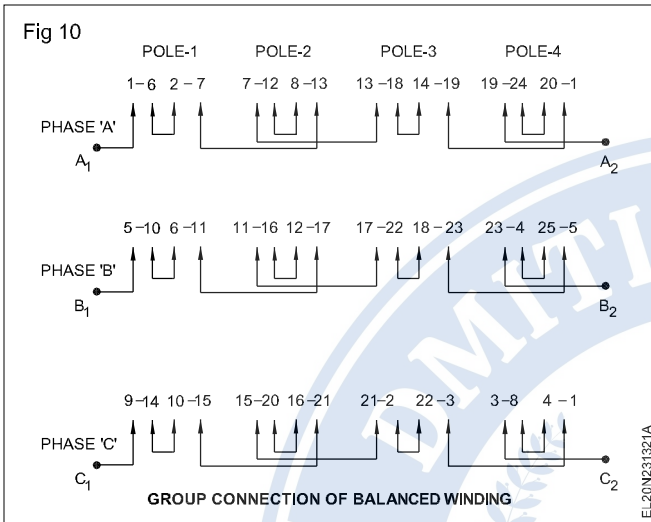
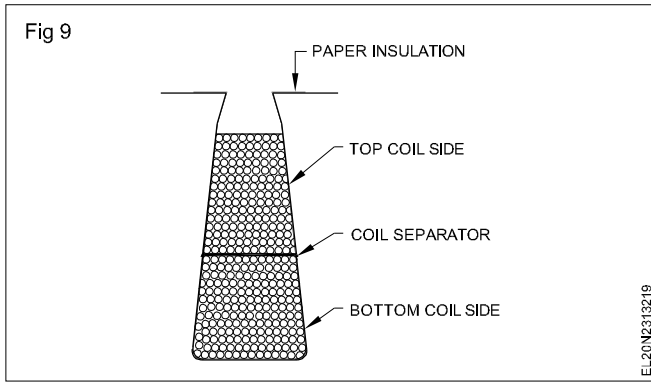


Double layer winding : In double layer winding each slot contains two coil sides (i.e. one upper and one lower) as shown in Fig 9 and the number of coils is equal to the number of slots in the stator.

Balanced winding : When the coil groups contain the same number of coils per phase per pole the winding is termed as 'balanced winding'. It is also known as 'Even Group' winding and is shown in Fig 10.

Unbalanced winding : If the coil group contains an unequal number of coils per phase per pole then the winding is called 'unbalanced winding'. It is also sometimes called 'odd group' winding and is shown in Fig 11.

It is important that there must be an equal number of coils in each phase whether the winding is balanced or unbalanced as shown in Figs 10 and 11.

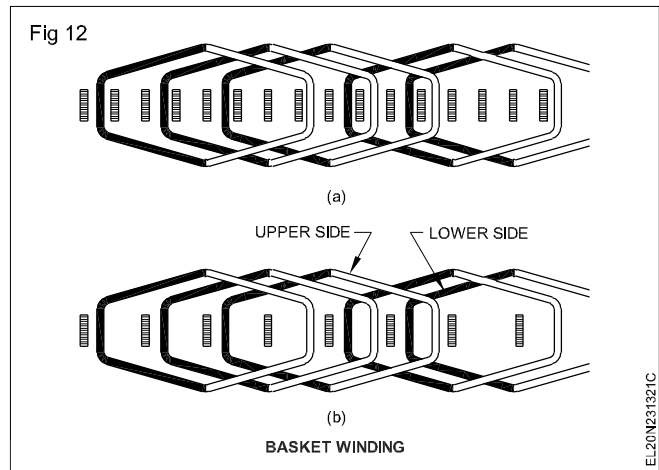


Concentrated winding : If in any winding the number of coils/pole/phase is one, then the winding is known as 'concentrated winding'. In this winding each coil side occupies one slot.

Distributed winding : In this winding the number of coil/pole/phase is more than one - arranged in different slots. In this case each coil has the same pole pitch.

Partially distributed winding : In this winding the coil sides do not occupy all the slots, but some slots remain empty and they are called dummy slots.

Fully distributed winding : It is a winding in which not a single slot remain empty.



Different types of AC Windings

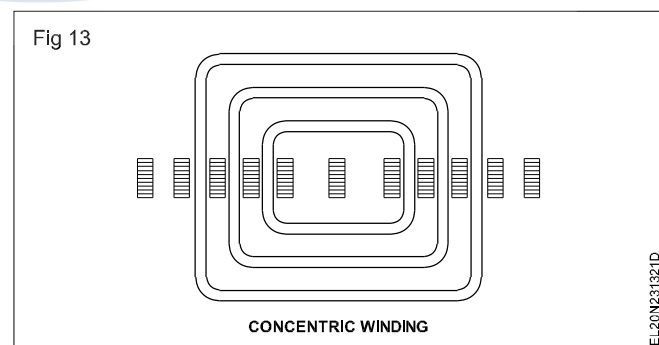
The types of AC windings according to shape are as follows.

- Basket winding
- Concentric winding
- Skein winding
- Flat loop Non-overlapped winding
- Flat loop overlapped or chain winding
- Skew winding
- Diamond coil winding
- Involute coil winding

Basket winding : After the completion of the winding, the ends of the winding resemble the weaving of a basket and hence it is known as basket winding. Basket winding is of two types. a) Single layer basket winding as shown in Fig 12a, double layer basket winding as shown in Fig 12b.

Concentric (or box type) winding : This winding has two or more than two coils in a group, and the coils in each group have the same centre. In each group, the coil pitch is not equal, and, therefore, do not overlap each other.

In this winding the coil pitches are not equal and each coil of the group has a difference of 2 slots in its pitch. Though it requires more labour to insert coils due to different coil spans, the design allows more cooling space. This winding is usually provided in single phase motor winding. This is shown in Fig 13.



3 phase squirrel cage induction motor winding (single layer distributed winding)

Objectives: At the end of this lesson you shall be able to

- explain the winding terms and calculations pertaining to single layer distributed type winding
- explain how to draw the end and coil connection diagrams
- state how to draw the ring and developed diagrams.

Distributed type winding: The most common type of winding found in 3-phase motors is the distributed type winding. A distributed type winding is one in which the size of all the coils, coil pitch and shape will be the same as these coils are normally former wound. By virtue of the arrangement of these coils in slots, the coils overlap each other. Distributed winding may be of single or double layer type.

Single layer winding : Single layer winding is one in which there will be as many coils as half the number of slots. For example 6 coils in the case of 12 slots, 12 coils in case of 24 slots, 18 coils in the case of 36 slots and so on. In short, there will be only one coil side per slot.

Calculation for single layer distributed winding : The winding data of the distributed single layer winding will be within the following limitation. (As an example 3-phase, 24 slots, 12 coils, 4 poles is illustrated below).

I Grouping

As in the example

No. of coils per phase = $12/3 = 4$ coils/phase.

ii For whole coil connection

As in the example

iii For half coil connection

As in the example

For the example taken, half coil connection is possible for distributed winding by taking full pitch and placing coil in alternate two slots., but it is not in practice. Hence whole coil connection is taken as an example.

II Pitch

As in the example, pole pitch = $24/4 = 6$ slots.

ii Coil pitch

In AC winding the relation between the coil pitch and the pole pitch is given below.

a Coil pitch = Pole pitch Then the winding is called full pitch winding.

b Coil pitch < Pole pitch Then the winding is called fractional pitch - short chorded winding.

c Coil pitch > Pole pitch Then the winding is called as fractional pitch - long chorded winding.

Further, if the winding is double layer, all the above 'a', 'b' and 'c' are possible. But for single layer distributed winding as the coils should be placed in alternate slots only, the coil pitch ought to be in odd number.

As in the example, coil pitch = pole pitch = $24/4 = 6$ slots.

Here 6 is an even number and winding cannot be of full pitch, so the next alternative is to select a fractional pitch. Therefore the coil pitch can be taken either as 5 or 7. Normally AC windings should either have full pitch or short chorded fractional pitch. Hence a suitable pitch is taken of 5 slots.

iii Coil throw

The coil throw for coil pitch '5' as in the example is 1 - 6.

III Electrical degrees

i Total electrical degrees = $180^\circ \times$ No. of poles
(180° is the distance between poles)

ii

As in the example: Slot distance = $(180 \times 4)/24 = 30^\circ$

IV Phase displacement

i For three-phase winding, displacement between the phases should be 120° .

ii Phase displacement in terms of slots = $120^\circ/\text{slot distance}$

As in the example, $120^\circ/30^\circ = 4$ slots

V Winding sequence

In three-phase winding the distance between the starting end of one phase to the starting end of another phase should have 120 electrical degrees. Hence we should arrange the winding such that

'A' phase starts from say 1st slot

'B' phase starts from 1st slot + 120° and

'C' phase starts from 1st slot + 120° + 120°.

As in the above example, 'A' phase starts from say 1st slot

'B' phase should start from 1+4 = 5th slot

'C' phase should start from 1+4+4 = 9th slot.

VI Arrangement of coils

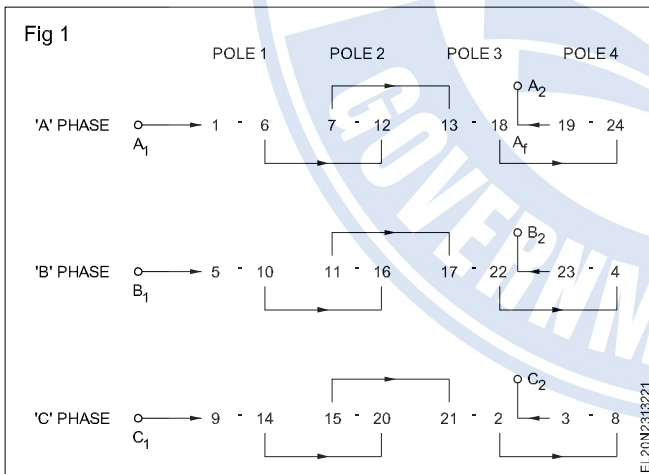
As the winding is in a single layer, the coil shall be placed in alternate slots i.e. if one coil side of coil number one is placed in slot number one which is an odd number, the other coil side of the first coil should be laid in an even number slot. Hence placement of coils should start in slot numbers 1,3,5,7,9 and so on leaving the slot numbers 2,4,6,8 and so on to receive the other coil sides of the coils.

As in the example the 12 coils are to be laid in slots (pitch = 5 slots)

1-6, 3-8, 5-10, 7-12, 9-14, 11-16, 13-18, 15-20,
17-22, 19-24, 21-26(2), 23-28(4).

VII End connections

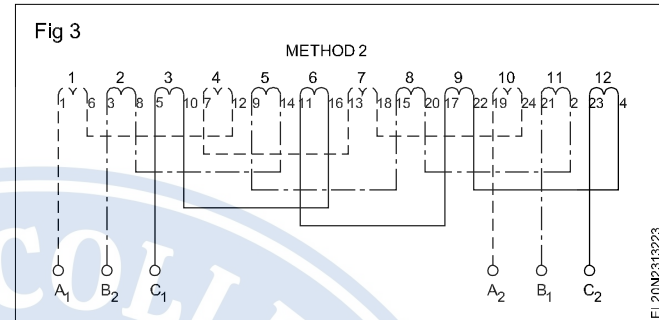
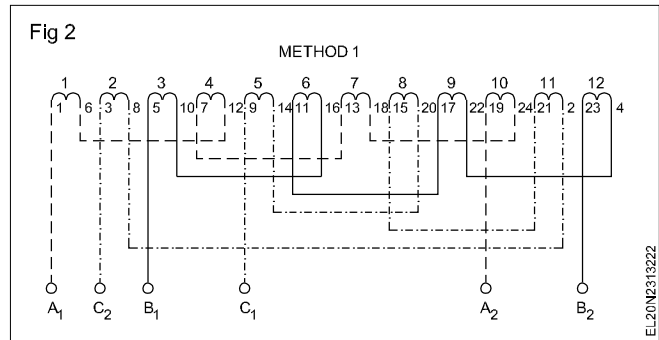
As discussed, for grouping of coils in normal practice, the end connections shall be whole coil connection. As in the example in Fig 1.



VIII Coil connections

In whole coil connection, the connection of the coil group shall be from finish to finish and start to start for the group of coils.

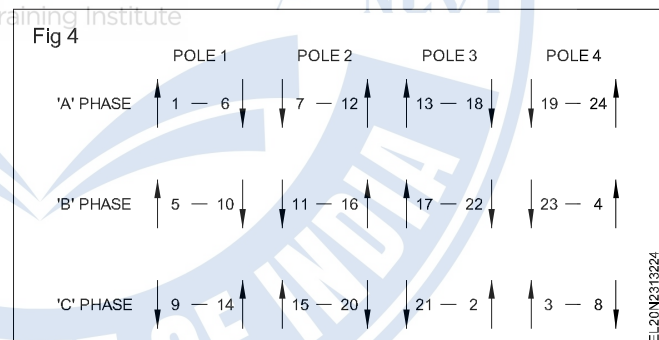
There are several ways of connecting the coils in groups. Fig 2 shows one method and Fig 3 shows another method. However, you are advised to check the formation of the poles with the help of a ring diagram and clock rule. The procedure is explained in the subsequent paras.



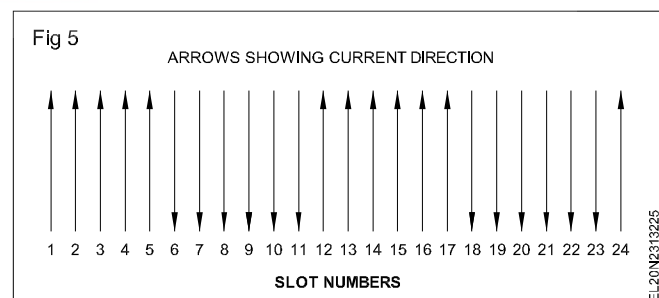
XI Ring diagram

Cross check the end connections as follows. Write the end connection table and mark the direction of current using the clock rule. Note that when three-phase supply is given to the windings, and if two phases carry current inward, the third phase will carry current outward.

Referring to method 1 shown in Fig 2, the current direction in the coil sides can be marked as shown in Fig 4.

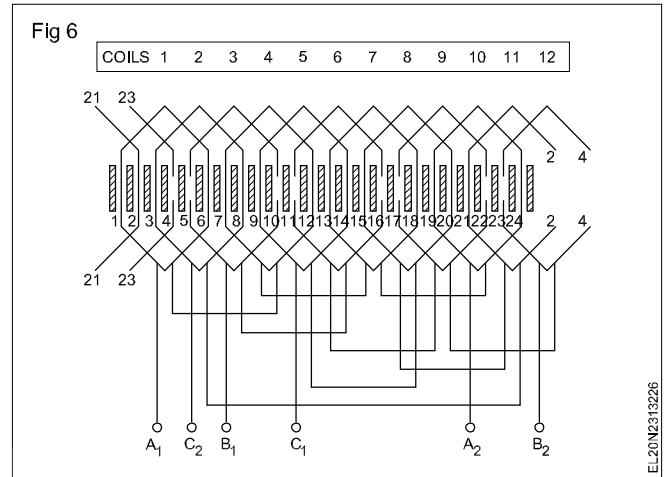


Now arrange the slots in the sequential order and mark the direction of current in the slots accordingly by arrows which ultimately shall represent production of the required number of poles as shown in Fig 5.



Developed winding diagram: The development winding diagram will give a clear picture of the coil sides in relevant slots grouping, coil end connections and lead termination. A 24 slots, 12 coil, 4 pole, 3 phase single layer distributed

winding development diagram is shown in Fig 6 for your guidance.



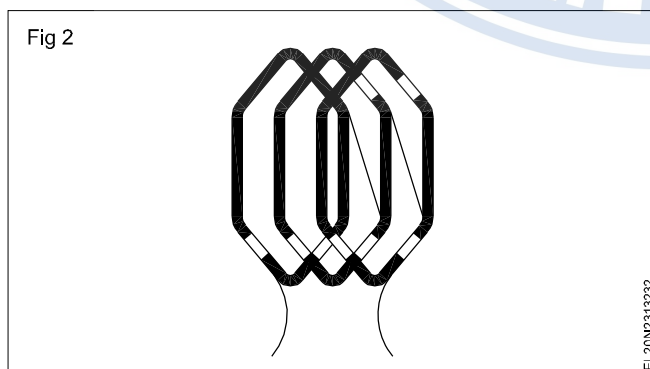
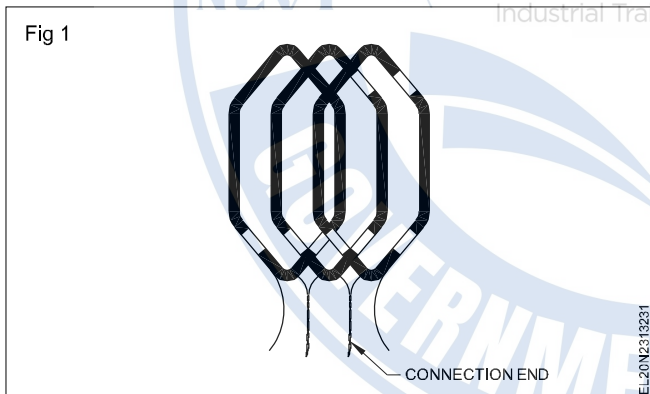
Method of placing coils in a basket or distributed winding

Objectives: At the end of this lesson you shall be able to

- state the various methods employed to prepare gang or group of coils
- explain the method of placing coils in the single layer basket winding
- explain the method of placing coils in a double layer basket winding.

The procedure outlined below is common for single or three-phase distributed winding. However this type of basket (distributed) winding is very popular in three phase motors.

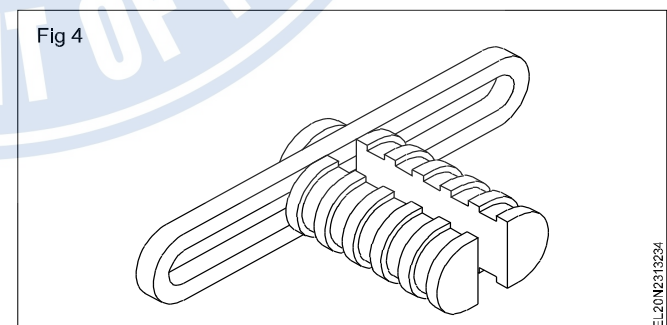
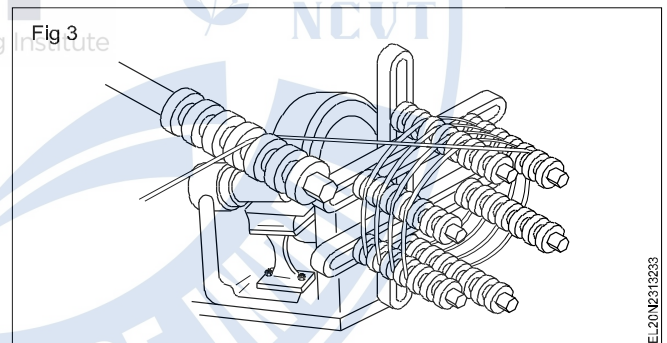
The coils can be wound using a single former and then they can be interconnected by coil connections as shown in Fig 1. Most of the three-phase motors with the exception of very large ones with formed windings, use coils wound in groups as shown in Fig 2.



The number of coils in each group will depend on the number of phases and number of poles. This practice of winding coils in groups is called group or gang winding.

In group winding several coils are wound before the wire is cut. This saves time and space by eliminating the necessity of connecting coils to one another then soldering them and then insulating them.

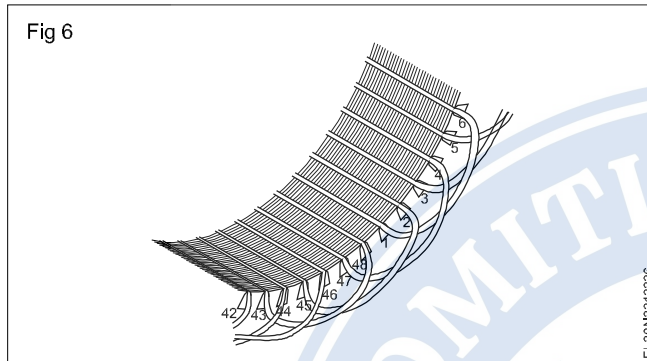
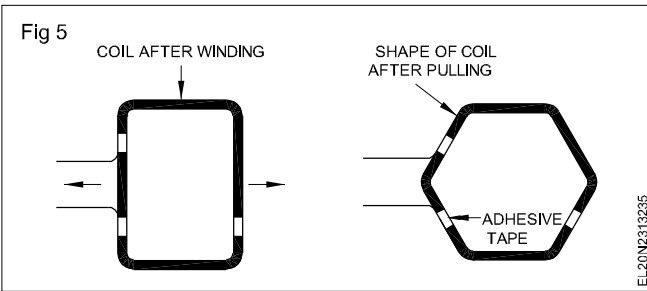
Fig 3 shows a winding head mounted on a bench type coil winding drive. The wire is wound around six wheels mounted on a shaft. Other types of forms are also used. Fig 4 shows a coil winder for producing oval or round coils.



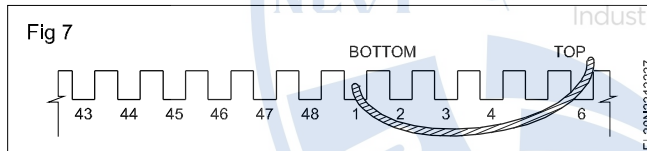
Coils for small motors may be wound in rectangular form and then two sides shaped into a diamond shape by pulling at the centre of the opposite ends as shown in Fig 5. Insertion of coils in single layer basket winding (formed individual coils).

In single layer winding there are half the number of coils as there are slots. For example a machine with 12 coils and

24 slots will have single layer winding. The appearance of a single layer winding is shown in Fig 6 in which the coil pitch is 1-6. While placing coils in a single layer we have to place the coil sides in alternate slots only.



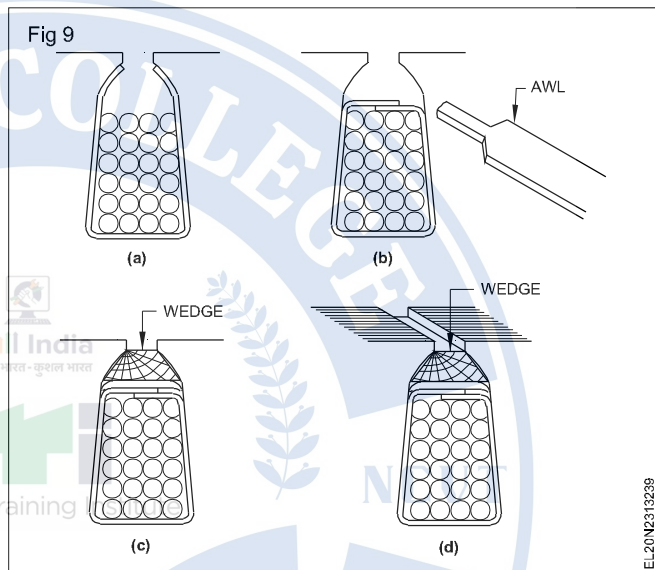
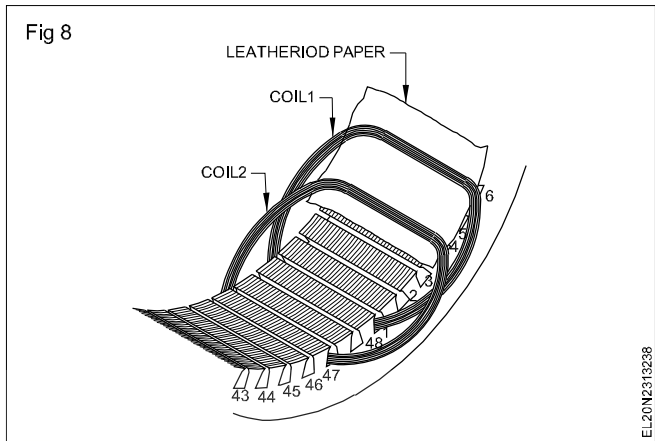
Let us take for example a 48 slot 24 coil 8 pole motor with the coil pitch of 1 to 6. Fig 7 illustrates the way in which the single layer winding is to be placed in the slot. This will be noticed from the diagrams there is only one coil side per slot. Fig 7 shows one coil side of the first coil placed in slot number 1.



Generally any slot can be identified as slot 1 with the help of chalk markings or a spot of paint. The other coil side of the same coil is left out on the core. This coil is called a throw coil. The left out coil side may lie in the right hand side as shown in Fig 7 or left hand side of the stator, when viewed from the connection end. However this depends upon the original winding pattern. The coil overhanging ends can be wrapped up to 2/3 of the length with a cotton tape of 0.175 mm thickness. To avoid the inserted coil turns from coming out of the slot while handling other coils, it is preferred to wedge temporarily the slot using a foot (Skill Information 1203) soon after the insertion of coil is over. In single layer winding the coil sides should be placed in alternate slots as shown in Fig 8.

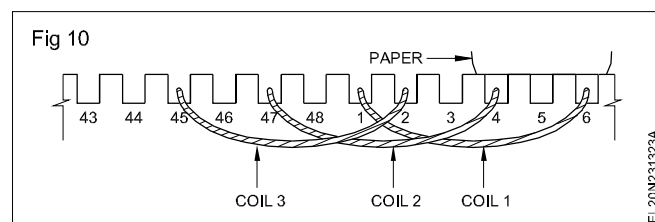
In Fig 8 coil 1 is placed in slot No.1 and the other coil side of the same coil is left over the stampings. To avoid damage to the left out coil side, a leatheroid paper of width larger than the width of the core is placed between the core and the coil as shown in Fig 8. After placing the coil side in the slot use the awl to fold the insulation paper (slot liner) one side over the other, slip the separator paper over the folding and then slip the formed fibre or bamboo wedge over the top of the coil. The wedge should extend about 3 to 6

mm beyond the slot liner. The procedure is shown in Fig 9.



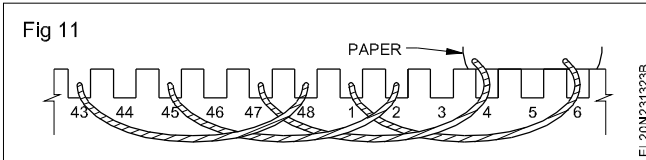
Some prefer to wedge the slots temporarily till all the coils are inserted and the winding is tested for grounding. Once the test results are o.k., then permanently wedge the slots.

In the next step left coil side of coil 2 is placed in slot number 47 (leaving slot No.48 which is adjacent to slot No.1) and the right coil side of coil 2 is left in the core. (Fig 8) Next place left side of the coil 3 in slot number 45 and leave the right side of the coil over the core. Remember to extend the leatheroid paper insulation between the core and the coil. By examination it will be found that the left out (right) coil side of coil No.3 which has left coil side inserted in slot No.45 should be inserted in slot 2 according to the assigned coil pitch. Now insert the left out right coil side of coil 3 in slot No.2 as shown in Fig 10.



In general, unless the left out coil side of any coil falls, according to the assigned pitch, next to the occupied slot, proceed further to insert one coil side only. Again proceed

to insert the left coil side of coil 4 in slot No.43 and the right coil side of coil 4 in slot No.48 as shown in Fig 11.



Proceed likewise to fill up the slots and complete the insertion of coils in the slots.

Insertion of coils in double layer (lap) winding

Let us consider a 3-phase machine with 24 slots, 24 coils, 4 poles and having a slot pitch of 1-6 and a coil pitch 1-12 in terms of coil sides.

ASSUMPTION: Individual coils numbering 24 are former wound and kept ready . Procedure given below is for the developed winding diagram shown in Fig 12.

Accordingly Fig 13 shows the numbered slots. Table 1 shows the position of the coil sides in the slots. The coil sides in the bottom are given odd numbers and the coil sides of top are given even numbers.

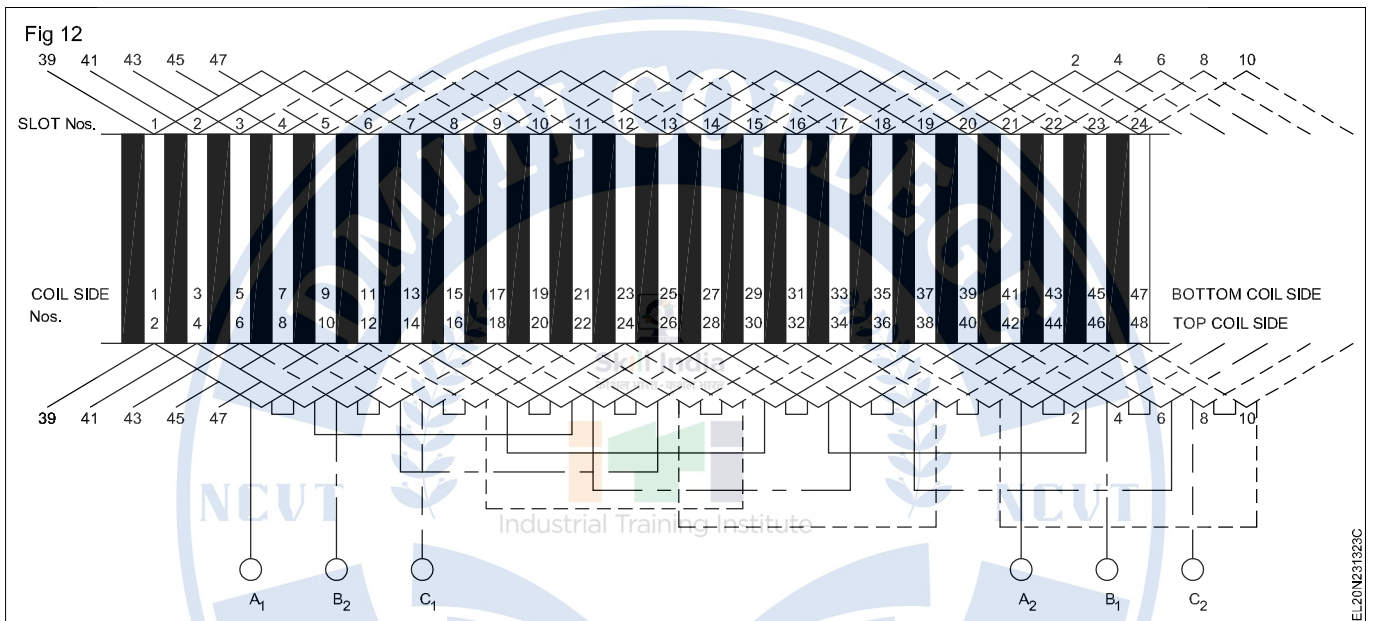
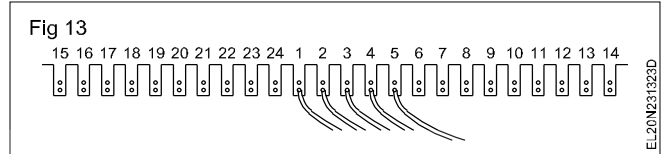
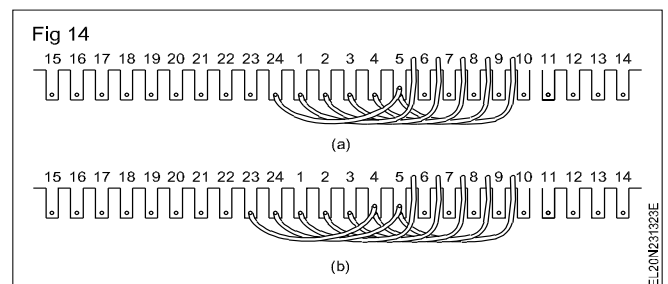


Table 1

Slot	Bottom	Top
1	1	2
2	3	4
3	5	6
4	7	8
5	9	10
6	11	12
7	13	14
8	15	16
9	17	18
10	19	20
11	21	22
12	23	24
13	25	26
14	27	28
15	29	30
16	31	32
17	33	34

18	35	36
19	37	38
20	39	40
21	41	42
22	43	44
23	45	46
24	47	48

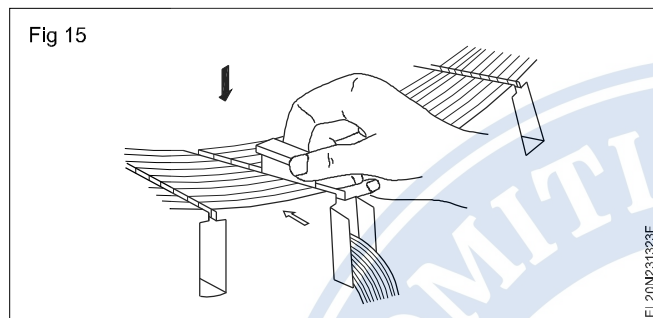
Winding is arranged such that looking from the connection end, the bottom coil is on the left side and the top coil sides is in the right side as shown in Figs 13 and 14.



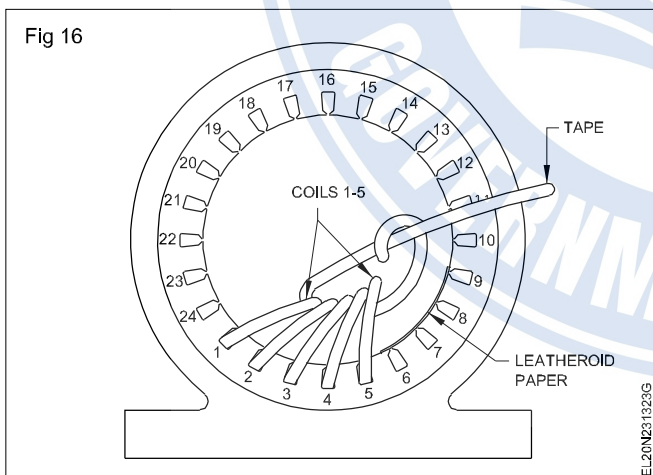
Further the connection end of the winding in the stator is to be identified from the data with respect to the terminal box.

Referring to the developed diagram (Fig 12) and Table 1, if the bottom coil side 1 is inserted in slot 1, then the other coil side of the same coil which is 12, should be inserted in the slot number 6 as a top coil side. As such there should be a certain approved procedure to start the winding.

Proceed as, first insert one coil in slot number 5 and leave the other coil side on the core. Use a suitable fibre foot or wedge for slot 5 to secure the winding. (Fig 15). To avoid damage to the insulation in the process of winding, insert a thick leatheroid paper of a width larger than the core between the left out coil side and the core, as shown in Fig 8. Let the length of the leatheroid paper be sufficient enough to cover 5 coil sides at a stretch.



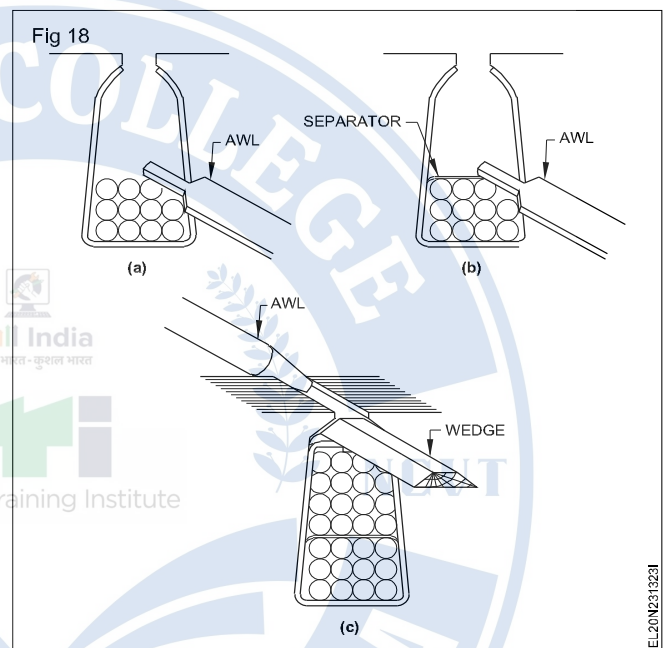
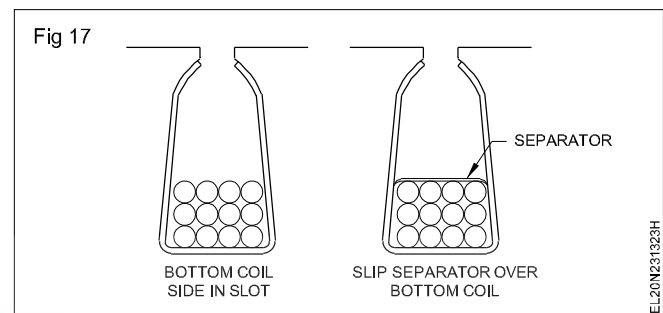
Insert the coils in slot numbers 4,3,2 and 1 in sequence as shown in Fig 13 and wedge them temporarily as shown in Fig 15. Let the other coil side lie on the core with the protected leatheroid paper between the coils and the core. These coils are called throw coils. For the protection of insulation of the throw coil you can tie the bunch of coil sides together with a cotton tape and tie the whole lot to the stator as shown in Fig 16. Remember to ensure the leatheroid paper is well kept between the bunched coils and the core.



Use of coil separation : Before inserting the top coil side over the bottom coil side of the same slot it is necessary to insulate the coil sides inside the slot by the use of coil separators. This is because each coil side within one slot may belong to different phases and the voltage between them may be high.

To insulate the coil sides from each other within the slot follow the procedure shown in Fig 17 for both open and semi-closed slots. A creased separator or insulation paper of proper width, length and thickness (usually 0.25

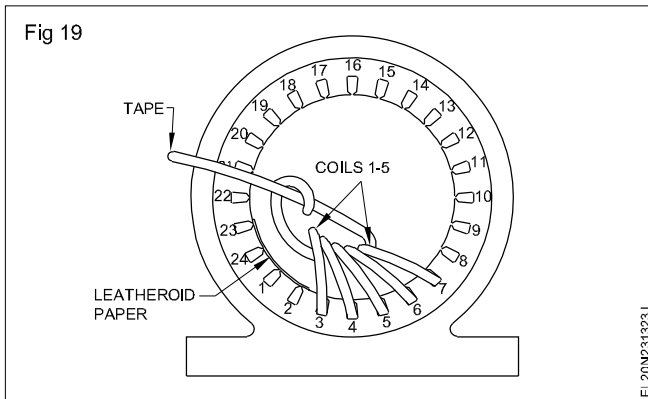
to 0.375 mm) is used as insulation between the top and bottom coil sides in the slot. Slide an awl over the bottom coil side as shown in Fig 18a and press it over the bottom coil and slide the separator underneath the awl as shown in Fig 18b. Let the separator project about 10mm beyond the core on either side.



Method of overlapping : Now insert one coil side in slot number 24 (coil side 47) and the other coil side of the same coil (coil side 10) in slot number 5 as the top coil over the bottom coil side 9. Likewise insert another coil side 45 of a next coil in slot number 23 and the other coil side 7 of the same coil in slot number 4. Proceed likewise till you reach slot number 6. During this process as you reach near about the 10th slot or much earlier you will feel the hindrance of the throw coils which are tied to the stator. At that time untie the cotton tape from the stator and tie the bunch in the opposite side of the stator as shown in Fig 19 with a leatheroid paper in between the coils and the core.

While tying the cotton tape see that the slot number 6 is easily approachable without any difficulty. After inserting the bottom coil side 11 in slot 6 insert the corresponding other coil side 22 in slot 11 as the top coil side. After inserting the top coil side fold the slot liners one side over the other, insert the separator and the wedge.

Now untie the throw coil bunch and release the free end of the coil in slot 5 and insert the same as top coil side in slot 10. Proceed likewise to insert the coils from slots 4,3,2 and 1 in the corresponding slots.

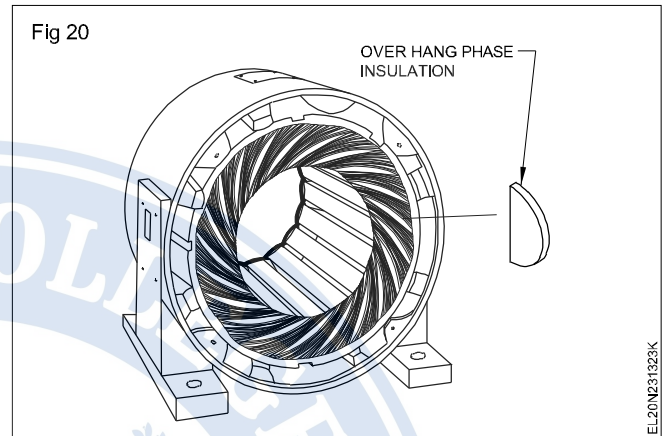


Overhang Insulation : Now cut and prepare the leatheroid paper to the shape of half moon as in the original which is to be used as phase insulation between the overhanging coils. According to the developed diagram coil sides 1 and 3 form the first phase, 5 and 7 the second phase and 9 and 11 form the 3rd phase. Identify these coils and start inserting the leatheroid paper between 3 and 5 as well as between 7 and 9.

Thus proceed to insert this phase insulation for the entire winding as shown in Fig 20. If you find the space between these coils is less, you may use a fibre wedge to prime the coils to facilitate insertion of the leatheroid paper. Do not use too much force which may crack the slot liner

insulation and result in grounding the coils with the stator core.

End connections : There are three types of connections to be made - first the coil connection for coil grouping, second for connecting the coil groups in one phase, and thirdly connecting the lead wires. Better to proceed one by one in the above sequence. Any connection to be made in winding the wires should start with proper identification of the coil ends. For a beginner, it may be necessary to refer to the developed diagram, connection diagram, as well as the actual winding often to eradicate the confusion.



Three-phase induction motor winding (single layer - concentric type - half coil connection)

Objectives: At the end of this lesson you shall be able to

- state the general requirements pertaining to the concentric type of winding in 3-phase motors
- state the merits and demerits of concentric type winding
- explain the preparation of a winding table for concentric type winding
- explain how to draw the end and coil connection diagrams
- explain how to draw the developed and ring diagrams.

3-phase concentric winding : In general, concentric winding is found in single phase motors, and occasionally, this type of winding is also used for 3-phase motors.

This concentric winding has to have two or more coils in a group consisting of different pitches. Further in 3-phase concentric winding, all the three phases consist of the same number of coils, and produce similar concentric poles. Stepped formers are used to prepare coils for concentric winding.

Merits and Demerits of concentric winding: This type of winding has some merits and demerits also.

Merits

- 1 This type of winding has more space for cooling.
- 2 No need of raising (lifting) the coil sides to interleave them during the winding.
- 3 It is easy to shape the coils uniformly.
- 4 Possible to save copper, because in distributed winding all the coils are of the same size; on the other hand in concentric winding, coil groups only will be uniform, but coils of different pitches in concentric form are used.

5 As there is no interleaving of the coil sides, the winding could be done by machine resulting in faster production.

6 It is easy to make the end connection.

7 Easy to wind, as there is no overlapping of coils.

Demerits

- 1 Skilled labour is required to insert the coils in the slots.
- 2 A stepped former is required.
- 3 Not as efficient as basket winding.

1 Grouping

The example given below will clarify the following:

- a whether concentric type of winding is possible for a given stator
- b If yes, whether it should be half coil or whole coil connected winding.

Example

3-phase induction motor having 36 slots 12 coils 4 pole stator

We have

For whole coil connection

$$\begin{aligned} \text{No. of coils/phase/pole} &= \frac{\text{No. of coils/phase}}{\text{No. of poles}} \\ &= \frac{4}{4} = 1 \text{ coils/phase/pole} \end{aligned}$$

As such there will be only one coil in a group. But concentric winding should have two or more coils in a group. In this case concentric winding is not possible. Alternatively grouping can be done for half-coil connection, i.e.

$$\begin{aligned} \text{No. of coils/phase/pair of poles} &= \frac{\text{Total No. of coils}}{\text{No. of phase} \times \text{No. of pair of poles}} \\ \text{As per the example} &= \frac{12}{3 \times 2} = 2 \text{ coils} \end{aligned}$$

i.e. 2 coils/phase/pair of poles.

As per the above example, only half-coil connected concentric winding is possible whereas for the following example having data 48 slots, 24 coils, 4-pole, 3-phase stator winding both whole coil and half coil connections are possible. Hence it is necessary to trace the group connection very carefully before stripping the stator to determine whether the winding connection is whole coil or half coil.

2 Pitch

$$1 \text{ Pole pitch} = \frac{\text{No. of slots}}{\text{No. of poles}}$$

$$\text{As per the example} = \frac{24}{4} = 6 \text{ slots}$$

As the winding is concentric, there should be 2 or more pitches normally. According to the above example 2 pitches for half-coil connections are required.

Further it is necessary to have the average pitch equal i.e. to the pole pitch.

$$\text{(i.e.) coil pitch} = \text{pole pitch} \pm 1$$

As per the example coil pitch is 6 ± 1 .

Therefore outer coil pitch = $6 + 1 = 7$

and inner coil pitch will be = $6 - 1 = 5$

(i.e.) Coil throw = 1 - 8 and 1 - 6 In practice it is written as 1 - 8 and 2 - 7.

3 Electrical degrees

i Total electrical degrees = $180^\circ \times \text{No. of poles}$.

As per the example = $180^\circ \times 4 = 720^\circ$.

ii Slot distance in degrees = $\frac{180^\circ \times 4}{\text{No. of slots}}$

$$= \frac{180^\circ \times 4}{24} = 30^\circ$$

4 Phase displacement

i For three-phase winding phase displacement should be equal to 120°

ii Phase displacement in terms of slots

$$= \frac{120^\circ}{\text{slot distance in degrees}}$$

$$\text{As per the example} = \frac{120^\circ}{30^\circ} = 4 \text{ slots}$$

5 Winding sequence

As per the example

A phase starts from 1st slot.

B phase starts from $1+4 = 5$ th slot and

C phase starts from $1+4+4 = 9$ th slot.

6 Arrangement of coils

As in the example 12 coils with pitches as 7 & 5 slots.

1-8, 2-7; 5-12, 6-11; 9-16, 10-15; 13-20, 14-19; 17-24, 18-23; 21-4, 22-3.

Grouping of coils

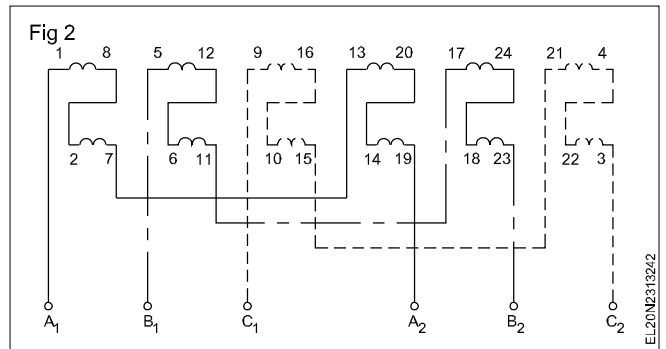
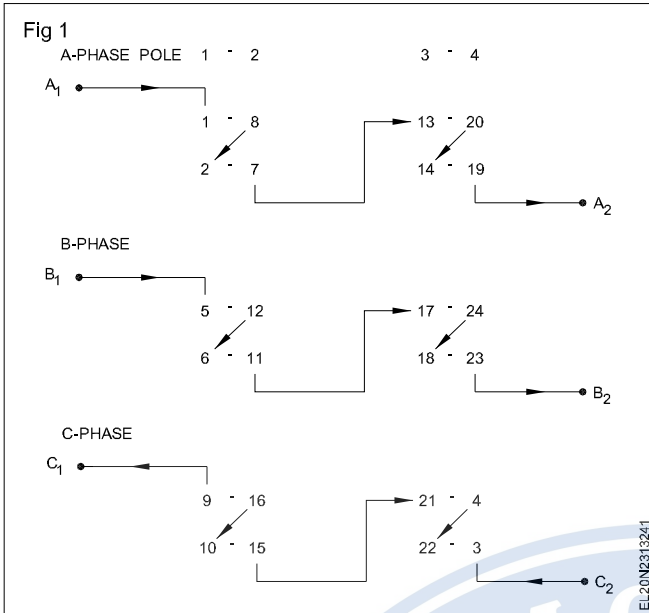
The coil should start from every alternate 2 slots (i.e.) 2 slots for top sides and two slots for bottom sides. As per the example, coils start from 1 & 2, 5 & 6, 9 & 10, 13 & 14, 17 & 18, 21 & 22.

As the connection is half-coil type, with the help of one group of coils, 2 poles need to be created. Hence grouping is as follows:

A	B	C
1-8, 2-7	5-12, 6-11	9-16, 10-15
13-20, 14-19	17-24, 18-23	21-4, 22-3

In whole coil connection, the starting end connection is from the alternative groups (i.e.) if 'A' starts from the first group, 'B' starts from third group and 'C' starts from fifth group. Whereas in half-coil connection, the starting ends will be from continuous group, if 'A' starts from the first group, 'B' starts from second group and 'C' starts from the third group. Refer to the developed diagram.

7 End connections (Fig 1): Half coil connection. (End to start and start to end)



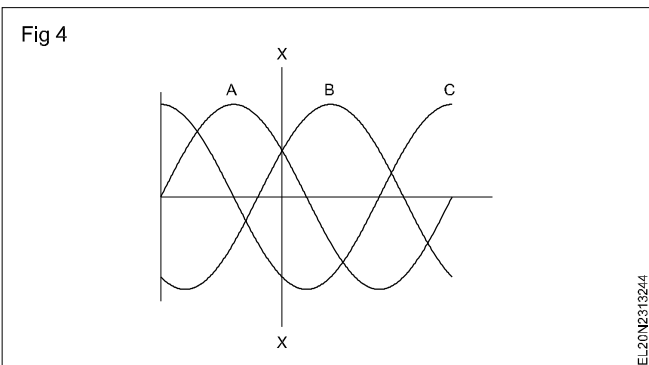
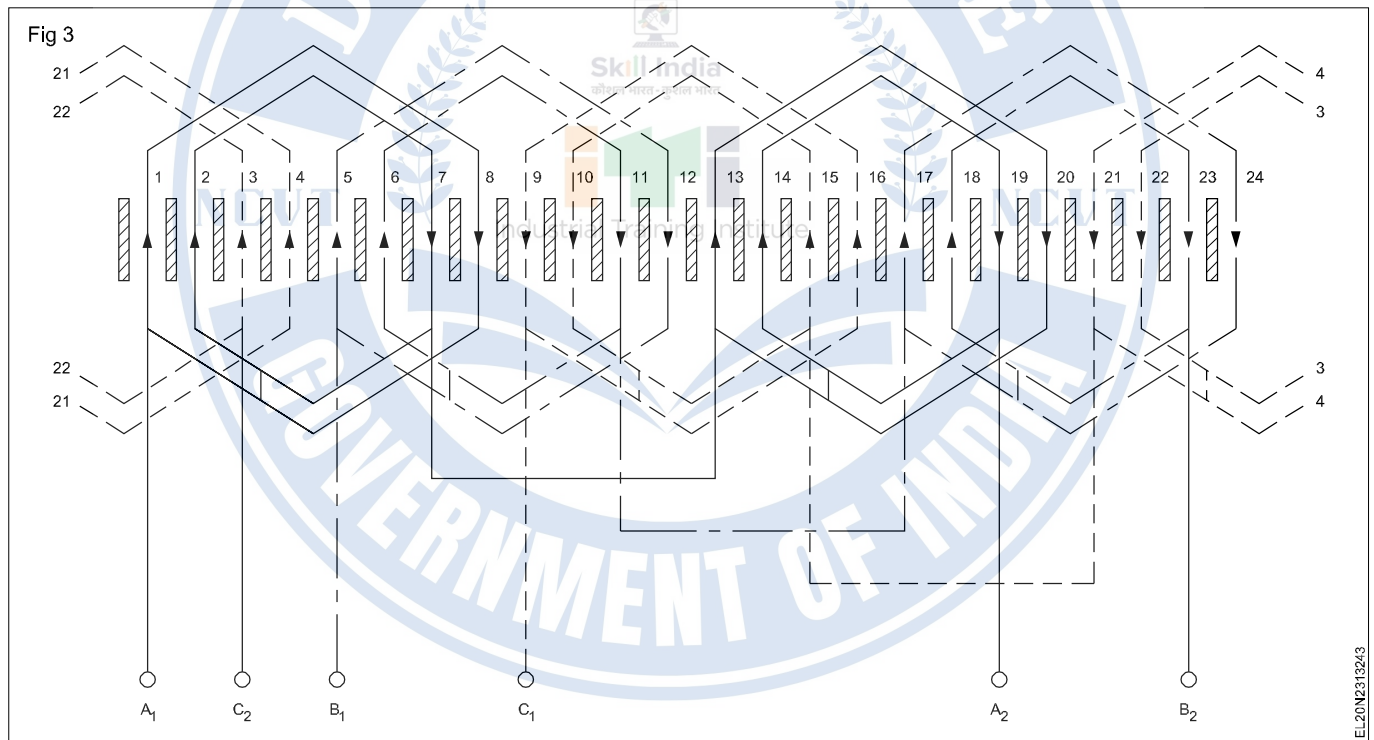
Development diagram : Draw the development diagram showing the coil group and end connection. As an example a development diagram is shown in Fig 3.

10 Ring diagram

Cross check the end connection with the help of the ring diagram as explained below. Write the end connection table and mark the direction of current using the clock rule. Note that when a three-phase supply is given to the windings at an instant, and if two phases carry current in one direction, the third phase carries current in the opposite direction as shown in Fig 4.

Coil connections : Half coil connection. (Fig 2)

In half coil connection, the connection of the coil group shall be from the finish end to the start end and then from the start end to the finish end of the group coils as shown in Fig 2.



PHASE	P ₁ & P ₂	P ₃ & P ₄
A phase	↑1 - 8↓ ↑2 - 7↓	↑13 - 20↓ ↑14 - 19↓
B phase	↑5 - 12↓ ↑6 - 11↓	↑17 - 24↓ ↑18 - 23↓
C phase	↓9 - 16↑ ↓10 - 15↑	↓21 - 4↑ ↓22 - 3↑

Refer to Fig 4 in which at the instant shown in x-x we have phases A and B as positive polarity and C has negative polarity.

Mark the direction of current in the slot and it shall represent production of the required number of poles as per the example given below.

↑ ↑ ↑ ↑ ↑ ↑	↓ ↓ ↓ ↓ ↓ ↓	↑ ↑ ↑ ↑ ↑ ↑	↓ ↓ ↓ ↓ ↓ ↓
1 2 3 4 5 6	7 8 9 10 11 12	13 14 15 16 17 18	19 20 21 22 23 24
N		S	

Whenever you come across a 3-phase induction motor having a single layer concentric type half coil winding follow the above mentioned procedure and prepare the winding table. Subsequently draw the end connection, development and ring diagrams.

3 phase squirrel cage induction motor - double layer distributed type winding

Objectives: At the end of this lesson you shall be able to

- explain the meaning of double layer winding
- explain the winding terms and calculations pertaining to double layer distributed type winding
- draw the end and coil connection diagrams
- draw the ring and developed diagrams.

There are different types of winding used in 3-phase AC motors. Some of the 3-phase windings are double layer, that is, there will be as many coils as the number of slots. For example 12 coils in the case of 12 slots, 24 coils in the case of 24 slots. 36 coils in the case of 36 slots, 48 coils in the case 48 slots. Further in the case of distributed winding the size of all the coils, pitch and shape will be the same as these coils are normally former wound. By virtue of the arrangement of these coils in slots, they overlap each other just like in a woven basket. This is also a type of distributed winding.

In double layer winding each slot contains two coil sides i.e. the bottom half contains the left hand coil side while the top half contains the right coil side of some other coil.

Calculations for double layer distributed winding :
The winding data of the distributed double layer winding will be within the following limitations. As an example 3-phase double layer distributed winding for an induction motor having 36 slots 36 coils 4 poles is discussed below.

I Grouping

$$\text{No. of coils/phase} = \frac{\text{Total No. of coils}}{\text{No. of phase}}$$

As per the example,

$$\text{No. of coils/phase} = \frac{36}{3} = 12 \text{ coils per phase.}$$

II Pitch

$$1 \quad \text{Pole pitch} = \frac{\text{No. of slots}}{\text{No. of poles}}$$

As per the example, pole pitch = $\frac{36}{4} = 9$ slots

2 Coil pitch : Similar to the single layer winding the coil pitch can be short-chorded, long-chorded or equal to the pole pitch. The pitch of the double layer distributed winding may be odd or even number. As per the example, the pole pitch is equal to $36/4 = 9$ slots and the no. of coils per group is 3. Hence the coil pitch may vary from 9 ± 3 that is 6, 7 or 8 in the case of short corded winding, 9 in the case of full pitch winding and 10, 11 or 12 in the case of long chorded winding. Hence the possible coil throws can be taken as

1 to 7 and 1 to 8 for short chorded winding

1 to 9 and 1 to 10 for full pitched winding

1 to 11, 1 to 12 and 1 to 13 for long chorded winding.

Normally the winding is designed for either short chorded or full pitch. Occasionally a long chord is used by the designer in double speed winding. The reason for not using long chorded winding is, it requires more chord length resulting in the requirement of more copper, and hence, increased heat losses.

3 Coil throw : According to the above example the coil throw for the coil pitch of 8 will be 1-9.

III Electrical degrees :

Total electrical degrees = $180^\circ \times \text{No. of poles}$

[180° distance between poles]

Slot distance in degrees =

$$= \frac{180^\circ \times \text{No. of poles}}{\text{No. of slots}}$$

As per the example $\frac{180 \times 4}{36} = 20^\circ$

IV Phase displacement

- For three-phase winding each phase winding should be displaced by 120 electrical degrees.
- Phase displacement in terms of slots =

$$\frac{120^\circ (\text{Electrical})}{\text{Slot distance in degrees}}$$

As per the example $\frac{120^\circ}{20^\circ} = 6 \text{ slots}$

V Winding sequence : In three-phase winding, the starting end of one phase winding to the starting end of

the second phase winding should have a distance of 120 electrical degrees.

Hence if the 'A' phase starts say in the 1st slot then the 'B' phase should start from the 1st slot + 120°.

Further 'C' phase should start from the 1st slot + 120° + 120°.

As in the example 'A' phase starts from, say, 1st slot

'B' phase should start from 1 + 6 = 7th slot and

'C' phase should start from 1 + 6 + 6 = 13th slot.

VI Placing of the coils in double layer winding: As the winding is double layer, the laying of coils should start in adjacent slots.

That is the coils should be placed in slot 1, slot 2, slot 3 and so on.

As in the above example the arrangement of coils for the selected pitch 8 will be as given below:

Fractional pitch Short chorded winding

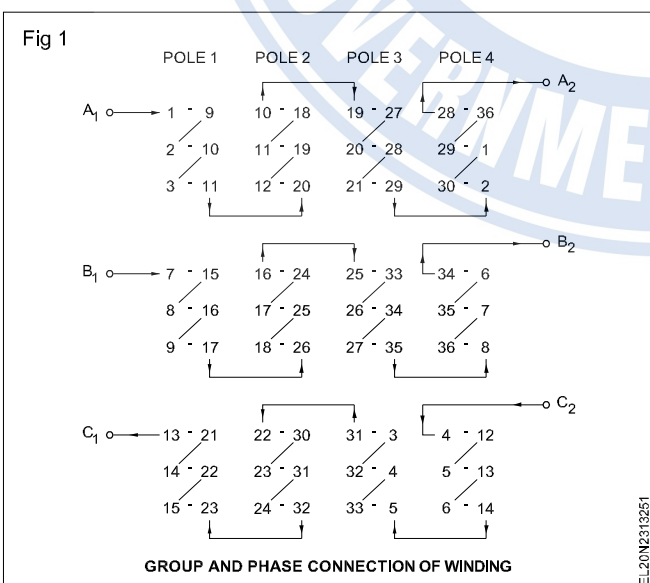
	Pitch 8	Coil throw 1-9	
Pole	A-Group	C-Group	B-Group
P1	1-9, 2-10, 3-11	4-12, 5-13, 6-14	7-15, 8-16, 9-17
P2	10-18, 11-9, 12-20	13-21, 14-22, 15-23	16-24, 17-25, 18-26
P3	19-27, 20-28, 21-29	22-30, 23-31, 24-32	25-33, 26-34, 27-35
P4	28-36, 29-1, 30-2	31-3, 32-4, 33-5	34-6, 35-7, 36-8

Though the possible pitches are 6,7,8,9,10,11 and 12 the above example is given for the pitch equal to 8 only. Trainees are advised to write the table for other pitches to have a better understanding of the winding.

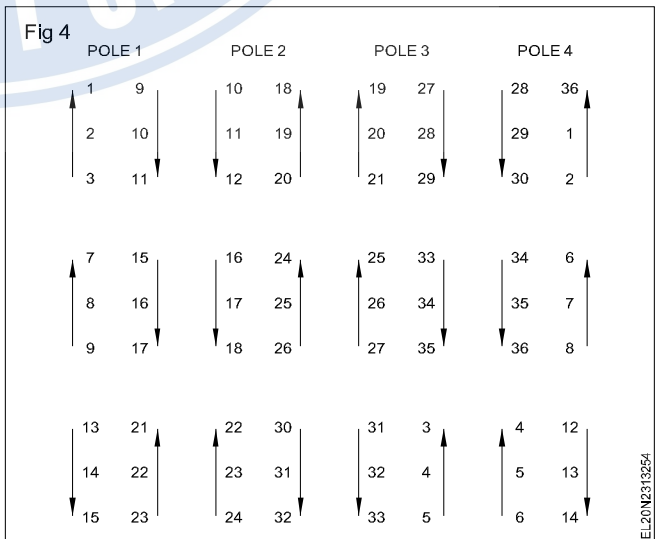
the group of coils of the same phase. Either of the following two methods shown in Figs 2 and 3 could be followed.

VII End connections : Draw the end connections as shown in Fig 1.

IX Cross check the end connections: Write the end connections table as illustrated below in Fig 4 and mark the direction of currents using the clock rule.

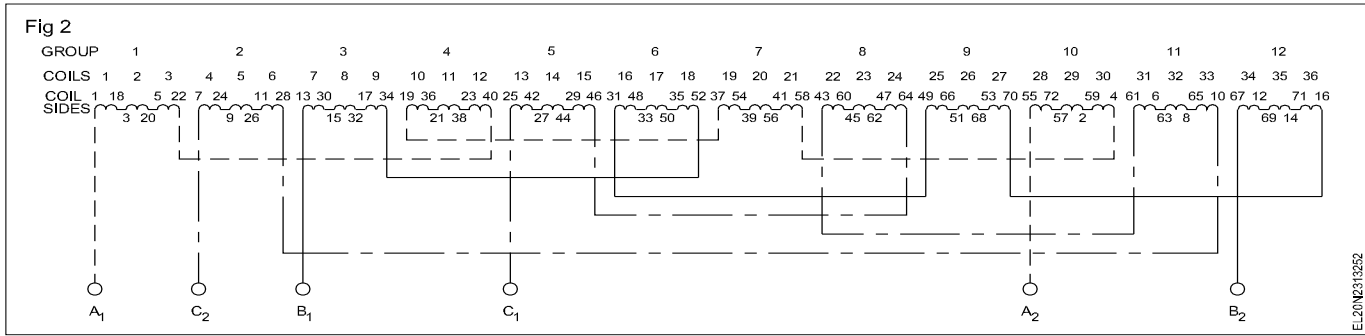


When three phase supply is given to the 3-phase winding, if two phases carry current inwards, the third phase will carry current outwards.

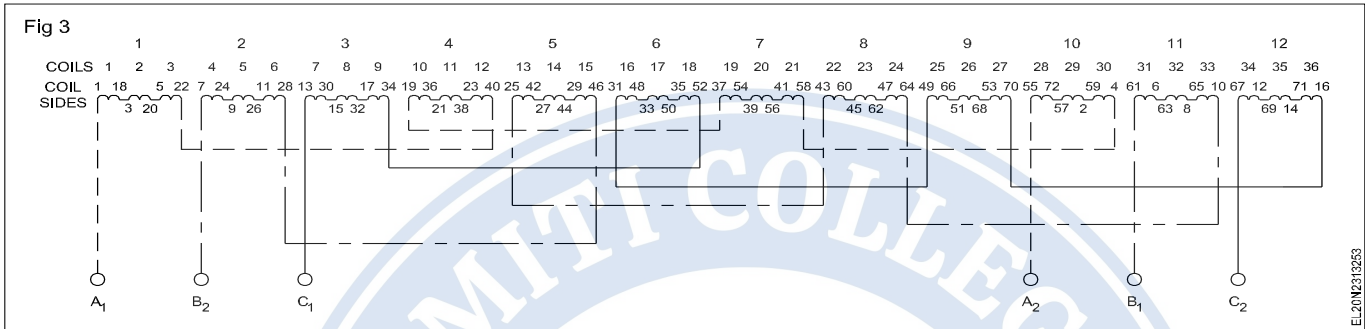


VIII Coil connections : In whole coil connection, the connection of coil groups shall be from the finish end to the finish end and the start end to the start end of

METHOD 1

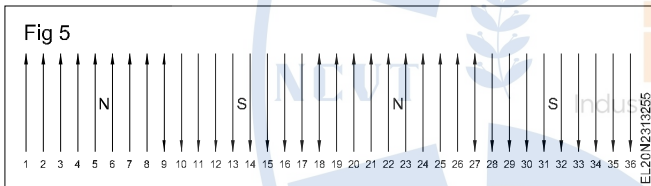


METHOD 2



X Ring diagram

Mark the direction of current in the respective slots and then check the production of the required number of poles as shown with ring diagram. (Fig 5)



As per the above ring diagram, in all 4 poles are produced. One pole is produced at each of the area contained by the eight slots. In slots 9, 18, 27 and 36 coil sides carry current in the opposite directions and hence, the flux in those slots gets neutralized. This happens in the short chorde

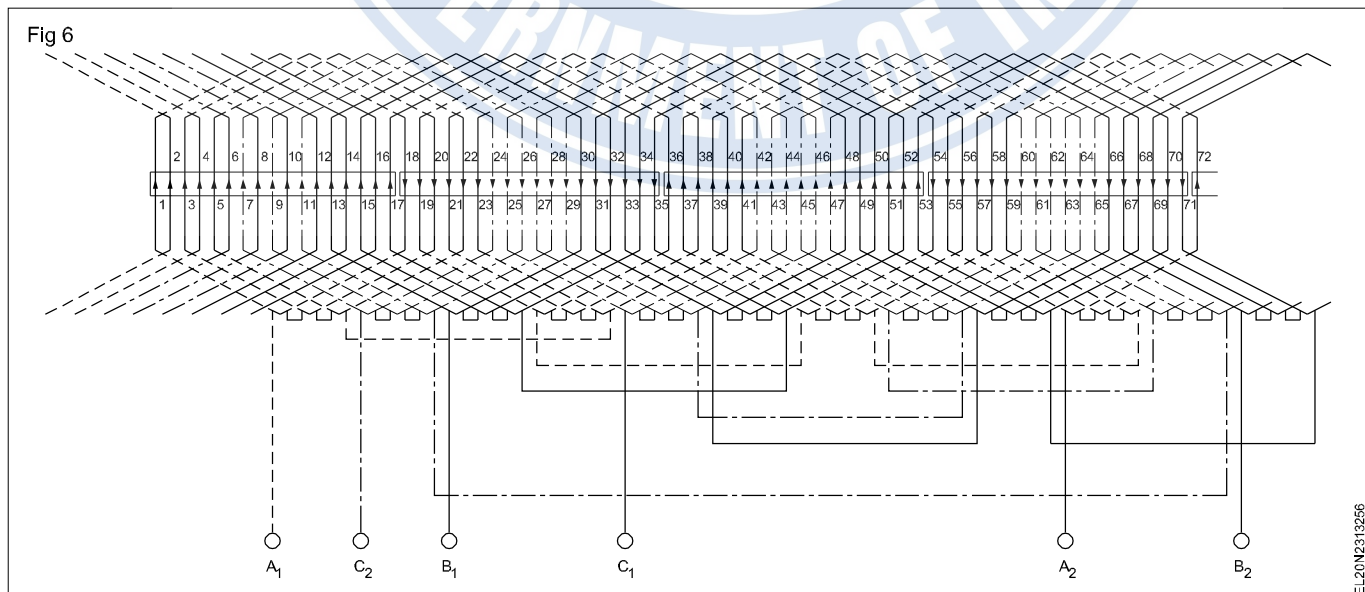
winding. Based on the above information draw the developed diagram.

XI Developed diagram : A developed diagram is shown in Fig 6 in which the connections are shown for the method 1 referring to Fig 2.

XII Fractional pitches : After the group and lead connections are over, the sleeved joints are to be tied with the overhang with the help of hemp threads.

Winding is then to be tested and varnished.

The motor is then to be assembled and test run for at least eight hours to check its performance on no load. Wherever loading facilities are available the newly wound motor can be checked for its load performance.



Testing of windings

Objectives: At the end of this lesson you shall be able to

- test the rewound motor for continuity and measure the coil resistance
- test the coils of the winding for short circuit using internal growler or voltmeter or ohmmeter
- test the winding for ground and insulation resistance
- test the winding for correct magnetic polarity using a magnetic compass or screwdriver or a search coil
- test the 3-phase winding for equal value of phase currents
- test the newly wound motor under no-load.

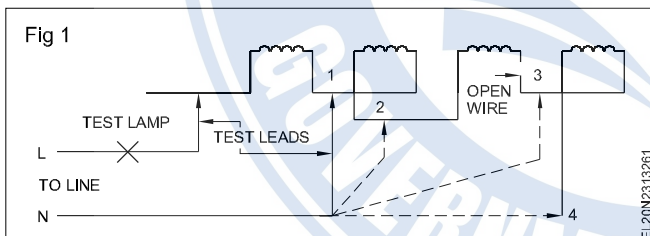
After the motor is rewound the following tests are carried out in the windings.

- 1 Continuity test/resistance test.
- 2 Short circuit test/growler test.
- 3 Insulation resistance test.
- 4 Polarity test.
- 5 Unbalanced current test - for 3-phase winding.
- 6 No-load test.

Continuity test/resistance test : This test is done to check up the continuity of each winding. If there is any open in the winding, it is to be rectified.

The usual cause of an open circuit in a winding is loose connection or break in the winding wire. The open circuit may be located by connecting one lead of the test lamp to one end of the winding and touching the other lead to the end of each coil end in sequence in the same phase.

Referring to Fig 1, if the lamp does not glow at point 3 but glows at point 2 then the third coil is faulty. If the lamp glows at 2 and 3 but not at 4 then the fourth coil is faulty. By repeating this process the coil which has the open circuit, can be identified.



Similarly, the other winding can also be tested for open circuit.

The resistance of each coil may be measured by a low range ohmmeter. The resistance of each coil must be the same. The high value of resistance or infinity value indicates open in the windings.

If there is any open in one coil, that coil can be bypassed and left out in the chain of windings. Then the motor can run, but if the open is in more than one coil, bypassing of the coil is not possible. This type of repairing is possible for small capacity motors where the winding has a large number of coils. Ex: Ceiling fans. But this procedure should be avoided as far as possible.

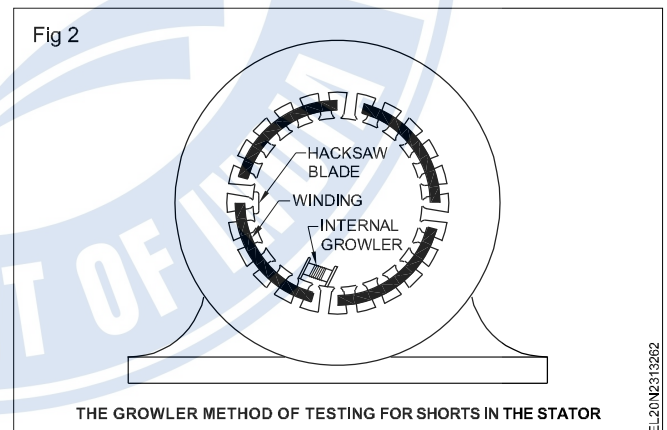
If the polarity of one or two coils in a multiple pole fan motor is changed the fan will run slowly and produces more heat.

Short circuit test/growler test : Two or more turns that contact each other electrically will cause a short circuit in the winding. This short circuit will cause excessive heat to be developed during the operation of the machine.

Short circuit can be detected by any one of the following methods.

- a Internal growler method
- b Voltage drop test
- c Ohmmeter method.

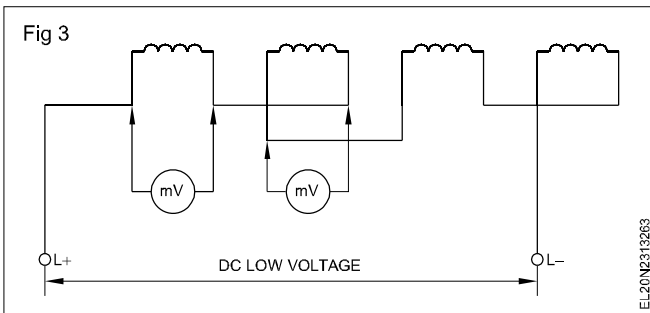
Internal growler method : The internal growler consists of a coil of wire wound on a laminated iron core and connected to 240V AC supply. After the stator is removed the growler is placed on the core of the stator and moved from slot to slot as shown in Fig 2. A shorted coil will be indicated by rapid vibration of a metal blade provided with the growler and in some types of internal growlers, glow of the neon lamp provided with the growler indicates short in winding.



Voltage drop method : In this method the winding is connected to a low voltage DC supply as shown in Fig 3 and the voltage drop is measured across each coil by a milli voltmeter. The voltage drop across good coils will be the same whereas voltage drop across shorted coils will be low.

Ohmmeter method : For this method, measure the resistance of the each coil by a low range ohmmeter or Kelvin bridge or Post Office Box. All the coils should read the same value of resistance. The coil which reads lower resistance than the other coils or that which reads zero resistance is assumed to be shorted and needs

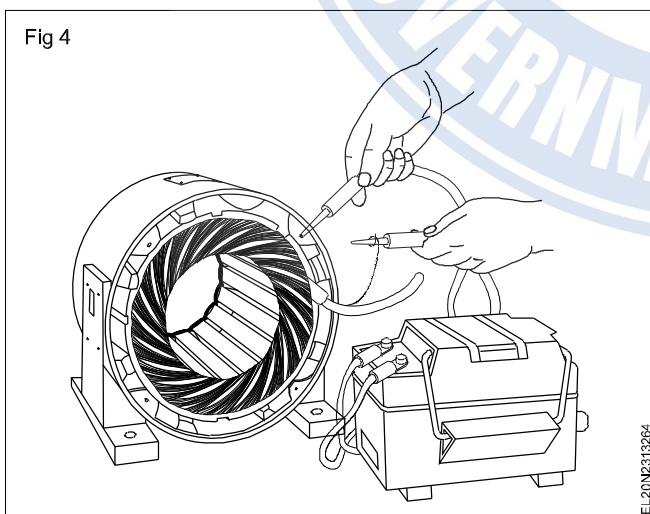
replacement. On the other hand the coil which reads high resistance when compared to similar coils or which reads infinite value of resistance indicates open in that particular coil.



Ground test and insulation/resistance test : Grounded winding may cause a fuse to blow up or it may cause the winding to smoke, depending on the extent of the ground. It may give shock to persons when they come in contact with the frame which is not properly earthed.

The aim of this test is to check any direct connection between windings and earth (ground). For this, the neutral of the supply is connected to the body of the machine and the phase wire is connected through a series test lamp. The open end of the test lamp is touched to each end of the winding in sequence. If the lamp remains dark it means winding is not grounded and if it glows, the winding is earthed. This is a fast, rough practical method.

If a Megger is used for testing the grounded winding, one terminal of the Megger is connected to the body and other to the windings as shown in Fig 4. If the pointer of the Megger shows infinity, the winding is correct and there is no connection between the windings and the body. Insulation resistance between windings and the body of the machine is measured by a 500 volts Megger and the readings so obtained shall not be less than 1 Megohm in the case of 3-phase and single phase motors. For additional safety 2 megohms are necessary in the case of ceiling and table fans.

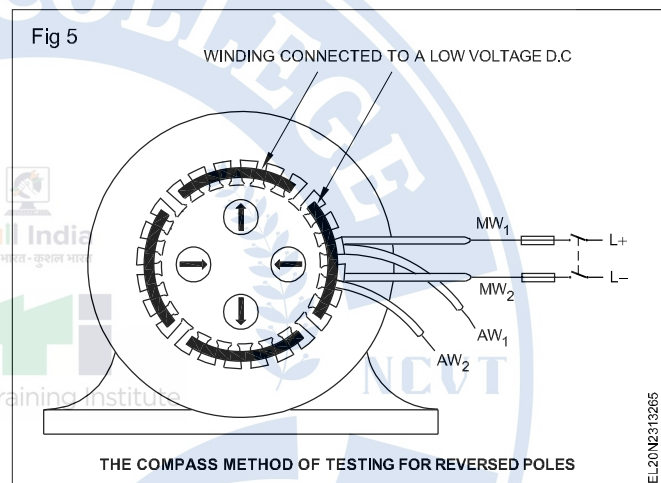


Polarity Test: Correct coil group connection in the winding ensures correct polarity. If there is any confusion in the coil group connections then the polarity test is necessary to be carried out to check proper polarity.

There are three methods recommended as explained below.

- a Magnetic compass method
- b Two screwdrivers method
- c Search coil method

Magnetic compass method : In this method, the stator is placed in a horizontal position and a low DC voltage is applied to the winding. The compass needle is then held inside the stator and moved slowly from one pole area to another pole area as shown in Fig 5. The compass needle will reverse itself on each pole if the winding is correctly connected. If there is same direction of indication between two adjacent poles, a reverse pole is indicated.



No-load test : After impregnation and assembly of motor, check the rotor for free rotation. Connect the motor to the rated supply voltage. Run the motor at no load and record the no-load voltage, current and speed of the motor. In no case these readings increase beyond name-plate values. Inspect the bearing sound and vibration. Normal sound without vibration is an indication of a good job. However, the perfection of the winding job could be ascertained only through a load test.

Maintenance, service and troubleshooting in AC 3 phase squirrel cage induction motor and starters

Objectives: At the end of this lesson you shall be able to

- list and state about the maintenance schedule of AC 3 phase motor
- list out the possible faults, causes and remedies in 3 phase motors
- explain the mechanical problems in motor, bearings and their remedies
- state the lubrication techniques on learning
- explain the troubleshooting of AC motor starters and maintenance of starters.

Generally due to the rugged construction of the AC squirrel cage induction motor, it requires less maintenance. However to get trouble-free service and maximum efficiency, this motor needs a scheduled routine maintenance. As found in most of the industries the AC squirrel cage motor is subjected to full load for 24 hours a day and 365 days a year. Therefore the maintenance should be scheduled to have periodic maintenance for a selected area on daily, weekly, monthly, half yearly and yearly periods for increasing the working life of the motor and to reduce the break down time.

Maintenance schedule: Suggested maintenance schedule for the AC squirrel cage induction motor is given below as a guide.

Daily maintenance

- Examine earth connections and motor leads.
- Check motor windings for overheating. (Note that the permissible maximum temperature is above that which can be comfortably felt by hand.)
- Examine the control equipment.

In the case of oil ring lubricated machines

- i examine bearings to see that oil rings are working
- ii note the temperature of the bearings
- iii add oil if necessary
- iv check end play.

Weekly maintenance

- Check belt tension. In a case where this is excessive it should immediately be reduced and in the case of sleeve bearing machines, the air gap between the rotor and stator should be checked.
- Blow out the dust from the windings of protected type motors, situated in dusty locations.
- Examine the starting equipment for burnt contacts where motor is started and stopped frequently.
- Examine oil in the case of oil-ring lubricated bearings for contamination by dust, dirt etc. (This can be roughly ascertained on inspection by the colour of the oil).

Monthly maintenance

- Overhaul the controllers.

- Inspect and clean the oil circuit breakers.
- Renew oil in high speed bearings in damp and dusty locations.
- Wipe brush holders and check the bedding of brushes of slip-ring motors.
- Check the condition of the grease.

Half-yearly maintenance

- Clean the winding of the motors which are subjected to corrosive or other such elements. Also bake and varnish if necessary.
- In the case of slip ring motors check slip rings for grooving or unusual wear.
- Renew grease in ball and roller bearings.
- Drain all oil bearings, wash with kerosene, flush with lubricating oil and refill with clean oil.

Annual maintenance

- Check all high speed bearings and renew if necessary.
- Blow out clean dry air over the windings of the motor thoroughly. Make sure that the pressure is not so high as to damage the insulation.
- Clean and varnish dirty and oily windings.
- Overhaul motors that are subject to severe operating conditions.
- In the case of slip ring motors, check the slip ring for pittings and the brush for wear. Badly pitted slip rings and worn out brushes should be replaced.
- Renew switch and fuse contacts if badly pitted.
- Renew oil in starters that are subjected to damp or corrosive elements.
- Check insulation resistance to earth and between phases of motor windings, control gear and wiring.
- Check resistance of earth connections.
- Check air gaps.

Records: Maintain independent cards or a register (as per specimen shown in trade practical) giving a few pages for each machine and record therein all important inspections and maintenance works carried out from time to time. These records shall show past performance, normal

insulation level, gap measurements, nature of repairs and time between previous repairs, and other important information which would be of help for good performance and maintenance.

Faults which occur in AC 3-phase squirrel cage motor can be broadly divided into two groups

They are

- 1 Electrical faults
- 2 Mechanical faults.

In most of the cases both the faults may be individually present or both may be present, as one type of fault creates the other fault. The following charts give the cause, the test to be carried out and possible remedy.

Chart 1

Motor fails to start

S.No	Cause	Test	Remedy
1	Overload relay tripped.	Wait for overload coils to cool. Push the reset button if separately provided. In some starters the stop button has to be pushed to reset the overload relay.	If motor could not be started check the motor circuit for other causes as outlined in this chart.
2	Failure of power supply.	Test the power supply at the starter incoming terminals.	If the supply is present in the incoming terminals of the starter, check the starter for fault. If not, check the main switch and fuses. Replace the fuses if necessary or restore power supply.
3	Low voltage.	Measure the voltage at the mains and compare with the name-plate rating.	Restore normal supply or check the cables for underrating.
4	Wrong connection.	Compare the connection with the original diagram of the motor.	Still if motor does not start, reconnect, after disconnecting the connection of the motor.
5	Overload.	Measure the starting torque required by load.	Reduce load, raise tapping on auto-transformer, install a motor of a higher output.
6	Damaged bearings.	Open the motor and check the play of bearings.	Replace if required.
7	Faulty stator winding.	Measure current per phase and they should be equal, if required measure resistance per phase; check insulation resistance between winding and earth.	Repair the fault if possible or rewind stator.
8	Wrong control connections.	Check the control circuit and compare it with the circuit diagram.	Reconnect the control circuit according to the manufacturer's circuit diagram.
9	Loose terminal connections at mains or at starter or at motor.	Check the terminal connection of the main switch, starter and motor for discolouring and loose nuts.	Tighten the terminals.
10	Driven machine is locked.	Disconnect the motor from the load.	If the motor starts satisfactorily check the driven machine and rectify the defect.
11	Open circuit in stator or rotor.	Check visually and then with multimeter/megger.	Rectify the defect or wind.
12	Short circuit in stator winding.	Check the phases and coil groups with the help of an ohmmeter or use internal growler.	Repair the winding or rewind.

S.No	Cause	Test	Remedy
13	Winding is grounded.	Test with a Megger or test lamp.	If the fault is found, repair or rewind.
14	Bearing stiff.	Rotate the rotor by hand.	If the rotor is stalled, dismantle the motor and rectify the defect.
15	Overload.	Check the load and belt tension.	Reduce the load or loosen the tight belts.

Chart 2

Motor starts but does not share load (Runs at low speed when loaded.)

S.No	Cause	Test	Remedy
1	Too low a voltage.	Measure voltage at the motor terminals and verify it with the name-plate.	Renew bad fuses; repair circuit and remove the cause of low voltage, like loose or bad contacts in starter, switches, distribution box, etc.
2	Bad connection.	Check the connection and contact of starter for loose contact.	Remove the fault as required.
3	Too low or high tension on driving belt.	Measure the tension and verify it with the instruction of the manufacturer.	Adjust the belt tension.
4	Open circuit in rotor winding.	Examine the rotor bars and joints.	Re-solder the rotor bars.
5	Faulty stator winding.	Check for continuity, short circuit and leakage.	Repair the circuit if possible or rewind the stator.
6	Defective bearings.	Examine bearings for play.	Replace the bearings.
7	Excessively loaded.	Measure the line current of the motor and compare it with its rated current.	Reduce the mechanical load on the motor.
8	Low frequency.	Measure the line frequency with a frequency meter.	If the line frequency is low inform the supply authorities and get it corrected.

Chart 3

Motor blows off fuses

S.No	Cause	Test	Remedy
1	Incorrect size of fuses	Check the size of the fuse wire (it should be rated for 1½ times its normal current); connect the ammeter in the circuit and test for excess load current.	Replace the fuse wire if necessary; repair the motor if it is due to electrical fault of stator or rotor.
2	Low voltage	Measure the line voltage.	Remove the cause of low voltage.
3	Excessively loaded	Measure the line current and compare it with its rated current.	Rectify the cause of overload or install a motor of higher output rating.
4	Faulty stator winding	Check for open circuit, short circuit or leakage of the stator as explained earlier.	Repair the fault; if not possible then rewind the stator.
5	Loose connection in starter	Check for loose or bad connection in the starter because it may cause unbalancing of current.	Rectify the loose connection; loose all the contact points of the starter with sandpaper and align the contacts.
6	Wrong connection	Check the connection with the original diagram.	Reconnect the motor if it still does not start.

Chart 4

Over Heating of the motor

S.No.	Cause	Test	Remedy
1	Too high or low voltage or frequency.	Check the voltage and frequency at the terminal of the motor.	Rectify the cause of low or high voltage or frequency as the case may be.
2	Wrong connection.	Compare the connection with the given circuit diagram.	Reconnect the connection if required.
3	Open circuit in rotor.	Loose joints of rotor bars cause heat.	Resolder the joints of rotor bars and end rings.
4	Faulty stator winding.	Check for continuity, short circuit and leakage as stated before.	Remove the fault if possible; otherwise rewind the stator winding. Remove dirt and dust from them if any.
5	Dirt in ventilation ducts.	Inspect ventilation ducts for any dust or dirt in them.	Reduce the load or loosen the belt. Rectify the single phasing defect.
6	Overload.	Check the load and the belt.	If the defect is with the driven machine repair it. If the problem is with the bearing, investigate and repair or replace with new one.
7	Unbalanced electrical supply.	Check the voltage for single phasing. Check the connections and fuses. Remove the load and check the rotor for free rotation.	If required replace the motor designed for this purpose.
8	Motor stalled by driven machine or tight bearing.	Check the motor - starter contactor	Loose the machine bearing or grease the bearing or replace the bearing.
9	Motor when used for reversing heats up.	Check the connection	Check the manufacturer's instructions.

Chart 5

Vibration and noise in motors

S.No.	Cause	Test	Remedy
1	Loose foundation bolts or nuts.	Inspect nuts and bolts of foundation for loose fittings.	Tighten the foundation nuts.
2	Wrong alignment of coupling.	Check alignment with a spirit level through dial test indicator.	Realign the coupling.
3	Faulty magnetic circuit of stator or rotor.	Measure the current in each phase and they should be equal. Check also per-phase resistance and they should be equal. Check the insulation resistance between the windings and the frame. In a newly wound motor there may be reversed coils in a pole-phase group which can be detected by the compass test.	Repair fault if possible or rewind the motor.
4	Motor running on single phase.	Stop the motor, then try to start. (It will not start on single phase). Check for open in one of the lines or circuits.	Rectify the supply.
5	Noisy ball bearing.	Check the lubrication for correct grade and low noise in the bearing.	If found, replace the lubricant or replace the bearing.
6	Loose punching or loose rotor on shaft.	Check the parts visually.	Tighten all the holding bolts.

7	Rotor rubbing on the stator.	Check for rubbing marks on the stator and rotor.	If found, realign the shaft to centre it or replace the bearings.
8	Improper fitting of end-covers.	Measure the air gap at four different points for uneven position of rotor covers.	Open the screws of the side covers, and then tighten one by one. If trouble still persists, remove the end cover, shift for next position and tighten the screws again.
9	Foreign material in air-gap.	Examine the air-gap.	File or clean out air-gap.
10	Loose fan or bearings.	Check looseness of the fan screw or bearings.	Tighten the fan screws or refit new bearings, if necessary.
11	Slackness in bearing on shaft or in housing.	Remove the bearings and inspect the inner looseness of the race on the shaft and outer race in the housing.	Send the motor to the repair shop for removing the looseness of the shaft and housing, if any.
12	Improper fitting of bearings.	Remove the end-covers and examine the assembly of bearings on the shaft or in the housing.	Refit the bearings on the shaft or in the housing.
13	Minor bend in shaft.	Check for alignment on the lathe.	Remove the bend or replace the shaft, if required.

Troubleshooting of motor starters

Objectives : At the end of this lesson you shall be able to

- state the troubles in the D.O.L. starter, their cause and their remedy
- check out the troubles in the mini manual starter, their cause and their remedy.

Introduction : The D.O.L. starter consists of the fixed contacts, movable contacts, no-volt coil, overload relay and start button which is in green colour and a stop button in red colour with a locking arrangement. The main purpose of the contactor is to make and break the motor circuit. These contacts in the contactor suffer maximum wear, due to frequent use and hence these contacts are made of silver alloy material.

A no-volt coil acts as under-voltage release mechanism disconnecting supply to the motor when the supply voltage fails or is lower than the stipulated value. Thus the motor will be disconnected from supply under these conditions.

A thermal overload relay unit is provided for the protection of the motor. This unit consists of a triple pole, bimetallic relay housed in a sealed bimetallic enclosure. This is provided with a current setting arrangement. After tripping on overload, the relay has to be reset by pressing the stop button. The relay can be reset only after bimetallic strips get cooled sufficiently.

In case the motor does not start even though the start button is pressed, observe whether the stop button is locked with a metallic locking piece provided near the stop button. Release it and press the start button, then observe the functioning of the motor.

Suppose the three phase supply is available and starter NVC is energising but the motor does not start, check for any foreign material in between the contact points. Remove it and test the starter again. Visually observe whether the contacts are closing properly.

If any contact is not closing properly or any burns and pittings are noticed on the contact surface, then remove the contact strips. Dress up properly with zero number sandpaper or with a smooth file or replace it if necessary.

When the no-volt coil is activated by the start button, the auxiliary contact of the starter should close to complete the NVC circuit and should remain in the closed position even after the start button is released.

If the overload relay is not functioning properly i.e. not tripping the motor as per setting of the current rating, then replace it with a new one as per with the original specification of the manufacturer.

If a humming and chattering noise is observed in the starter then check for the rated voltage. If the voltage is okay, then check for any gummy material adhered to the pole faces. If found, clean it properly. See whether the shading ring over the pole faces of the NVC is loose. Tighten it properly and also check the spring tension of NVC housing.

Suppose the starter trips often then, check up the load on the motor. (Might be due to overload or over tension of the belt) Reduce the load or tension of the belt. Further check up the motor current in each phase. If the motor takes higher current than specified even though the load is normal, then the fault is with the motor and not with the starter. After attending to the faults and rectifying them, reassemble the starter, connect it to the motor for proper functioning.

Starter check - chart given below could be used to locate trouble in a D.O.L. starter.

Maintenance of DOL starters

Trouble	Cause	Remedy
I Starter check chart		
1 Contacts chatter	Low voltage, coil is not picking up properly. Broken pole shading ring. Poor contact between the pole faces of the magnet. Poor contact between fixed and movable contacts.	Correct the voltage condition. In case there is persistent low voltage, check the supply of the transformer tapping. Replace. Clean the pole faces. Clean contacts and adjust, if necessary.
2 Welding or overheating.	Low voltage preventing magnet from sealing. Abnormal in rush current. Short circuit in the motor. Foreign matter preventing contacts from closing. Rapid inching.	Correct the voltage condition. In case of persistent low voltage, which is accepted normal change the NVC to lower voltage coil. Check excessive load current or use larger contactor. Remove the fault and check to ensure that the fuse rating is correct. Clean contacts with suitable solvent. Install larger device or caution the operator not to operate the inch button too quickly.
3 Short life of contact points	Weak contact pressure.	Adjust or replace contact springs.
4 Noisy magnets	Broken shading coil. Magnet faces not mating. Dirt or rust on magnet faces.	Replace magnet. Align or replace magnet assembly. Clean with suitable solvents.
5 Failure to pick up and seal the contacts.	Low voltage. Coil open or short-circuited. Mechanical obstruction for the moving parts.	Check system voltage. In case persistent low voltage, change to a lower voltage coil. Replace the coil. Clean and check for free movement of contact assembly.
6 Failure of moving mechanism to drop out.	Voltage not removed. Worn or rusted parts causing binding. Residual magnetism due to lack of air gap in magnet path. Gummy substance on pole faces causing binding.	Check wiring in the NVC coil circuit. Replace parts. Replace worn out magnet parts or demagnetise the parts. Clean with suitable solvent.
7 Overheating of coil	Over-voltage. Short circuited turns in coils caused by mechanical damage or corrosion. High ambient temperature. Dirt or rust on pole faces increasing the air gap.	Check and correct terminal voltage. Replace coil. Relocate starter in a more suitable area or use a fan. Clean pole faces.
II Overload relays/ release		
1 Starter is tripping often. Sustained overload.	Incorrect setting of over load relay.	Reset properly. Check for faults/excessive motor currents.
2 Failure to trip (causing motor burn out).	Wrong setting of O.L relay. Mechanical binding due to dirt, corrosion etc.	Check O.L relay ratings and set a proper relay. Clean or replace. Incorrect control wiring. Check the circuit and correct it.

III Fuses		
1 Constant blowing of fuses	Short circuit or poor insulation in winding/wiring.	Check the motor and the circuit for insulation resistance.
2 Fuse not blowing under short circuit condition.	Fuse rating too high.	Replace with suitable fuse.
3 Fuse blowing off frequently.	Fuse rating too low. Overloading of feeder.	Replace with suitable fuse. Check for over-current, leakage and short circuit.

