

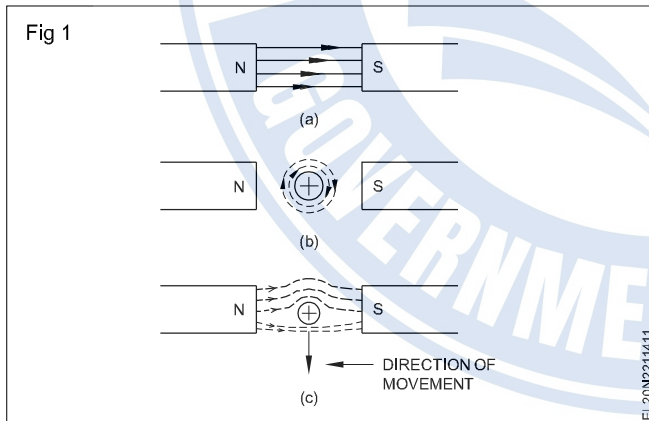
DC motor - principle and types

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

- explain the working principle of a DC motor
- state the different types of DC motors.

Introduction: A DC motor is a machine which converts DC electrical energy into mechanical energy. It is similar to a DC generator in construction. Therefore, a DC machine can be used as a generator or as a motor. Even today, because of the excellent torque, speed and load characteristics of DC motors, 90% of the motors used in precision machines, wire drawing industry and traction are of this type.

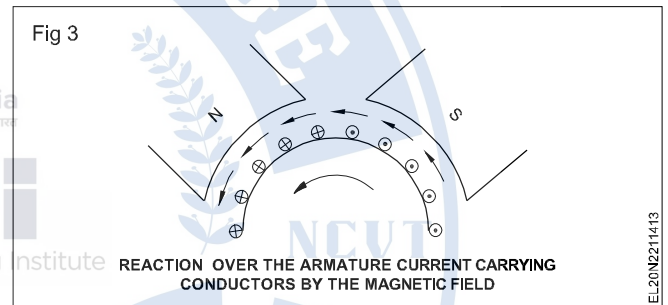
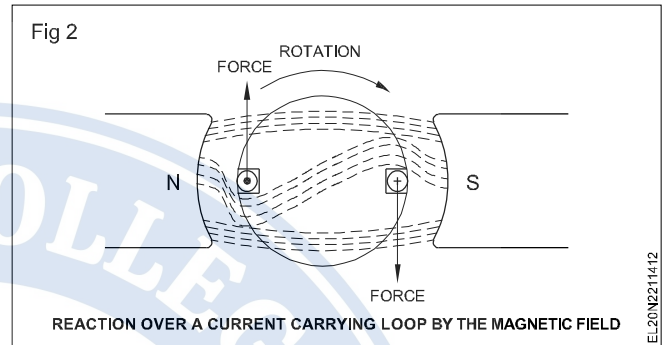
Principles of a DC motor: It works on the principle that whenever a current-carrying conductor is kept in a uniform magnetic field, a force will be set up on the conductor so as to move it at right angles to the magnetic field. It can be explained as follows. Fig 1a shows the uniform magnetic field produced by a magnet, whereas Fig 1b shows the magnetic field produced around the current-carrying conductor. Combining the effects of Fig 1a and Fig 1b in one figure, Fig 1c shows the resultant field produced by the flux of the magnet and the flux of the current-carrying conductor. Due to the interactions of these two fields, the flux above the conductor will be increased and the flux below the conductor is decreased as represented in Fig 1c. The increased flux above the conductor takes a curved path thus producing a force on the conductor to move it downwards.



If the conductor in Fig 1 is replaced by a loop of wire as shown in Fig 2, the resultant field makes one side of the conductor move upwards and the other side move downwards. It forms a twisting torque over the conductors, and they tend to rotate, if they are free to rotate. But in a practical motor, there are a number of such conductors/coils. Fig 3 shows the part of a motor. When its armature and field are supplied with current, the armature experiences a force tending to rotate in an anticlockwise direction as shown in Fig 3.

The direction of rotation or movement can be determined by Fleming's left hand rule. Accordingly, the direction of

rotation of the armature could be changed either by changing the direction of armature current or the polarity of the field.



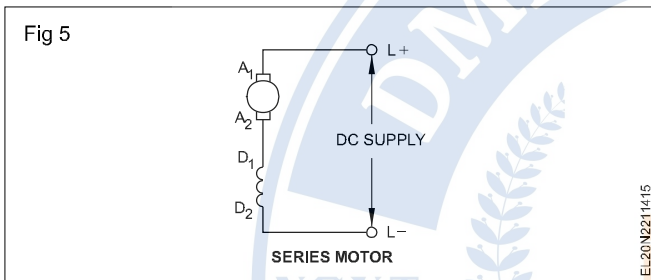
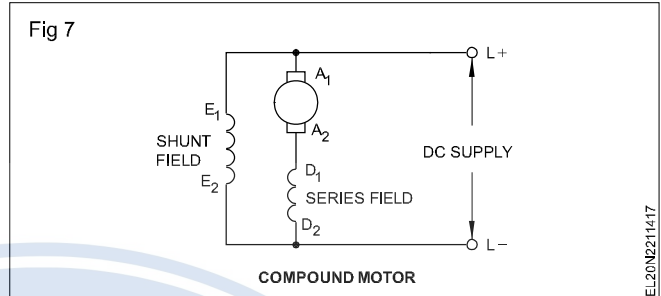
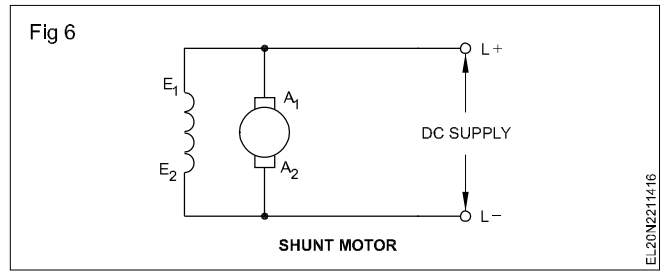
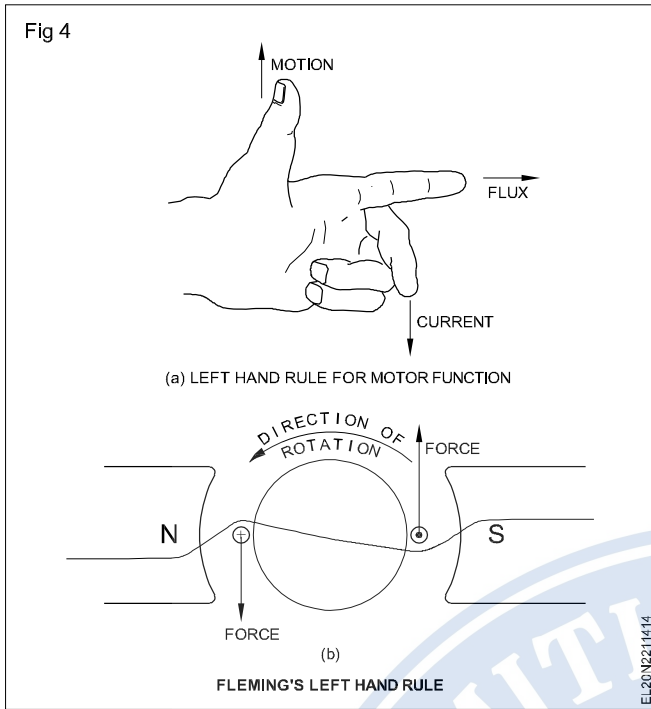
Fleming's Left Hand Rule: The direction of force produced on a current-carrying conductor placed in a magnetic field can be determined by this rule. As shown in Fig 4a, hold the thumb, forefinger and middle finger of the left hand mutually at right angles to each other, such that the forefinger is in the direction of flux, and the middle finger is in the direction of current flow in the conductor; then the thumb indicates the direction of motion of the conductor. For example, a loop of coil carrying current, when placed under north and south poles as shown in Fig 4b, rotates in an anticlockwise direction.

Types of DC motors: As the DC motors are identical in construction to that of DC generators, they are also classified as series, shunt and compound motors, depending upon their connection of field winding with the armature and supply.

When the armature and field are connected in series, as shown in Fig 5, it is called a series motor.

When the armature and field are connected in parallel across supply, as shown in Fig 6, it is called a shunt motor.

When the motor has two field coils, one in series with the armature and the other in parallel with the armature, as shown in Fig 7, it is called a compound motor.



The relation between applied voltage, back emf, armature voltage drop, speed and flux of DC motor - method of changing direction of rotation

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

- explain the relation between applied voltage, back emf, armature voltage drop - speed - flux
- describe the method of changing the direction of rotation of a DC motor.

Back emf: As the armature of a DC motor starts rotating, the armature conductors cut the magnetic flux produced by the field poles. Due to this action, an emf will be produced in these conductors. The induced emf is in such a direction as to oppose the flow of current in the armature conductor as shown in Fig 1. As it opposes the supply voltage it is called 'BACK EMF' and is denoted by E_b . Its value is the same as that found in the generator. It could be written as

$$E_b = \frac{\phi ZNP}{60A} \text{ volts}$$

The direction of the induced (back) emf could be determined by Fleming's right hand rule.

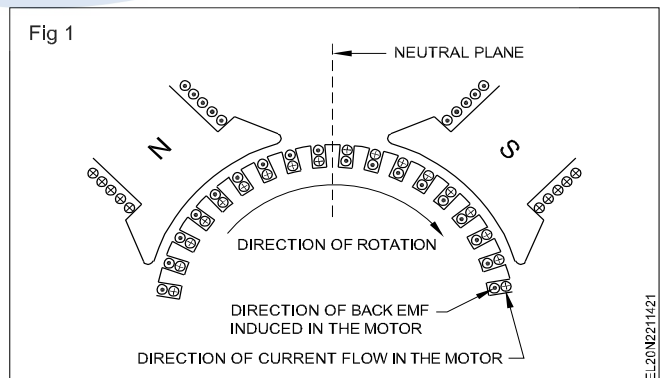
Applied voltage: The voltage applied across the motor terminals is denoted by 'V'.

Armature voltage drop: Since armature conductors have some resistance, whenever they carry current a voltage drop occurs. It is called $I_a R_a$ drop because it is

proportional to the product of the armature current I_a and armature resistance R_a . It has a definite relation with the applied voltage and back emf as shown by the formula

$$V = E_b + I_a R_a$$

$$\text{Alternatively, } I_a R_a = V - E_b$$



Further the back or counter emf E_b depends upon flux per pole ' Φ ' and speed ' N '. Therefore, the applied voltage, back emf, armature drop, flux and speed are related to one another as follows.

$$E_b = V - I_a R_a$$

$$\frac{\Phi ZNP}{60A} = V - I_a R_a$$

$$\therefore N = \frac{(V - I_a R_a) \times 60A}{\Phi ZP} \text{ rpm}$$

For a given motor ZPA and 60 are constants and can be denoted by a single letter K

$$\text{where } K = \frac{60A}{ZP}$$

$$\text{Therefore } N = K E_b / \Phi.$$

It shows that the speed of a DC motor is directly proportional to E_b and inversely proportional to the flux Φ .

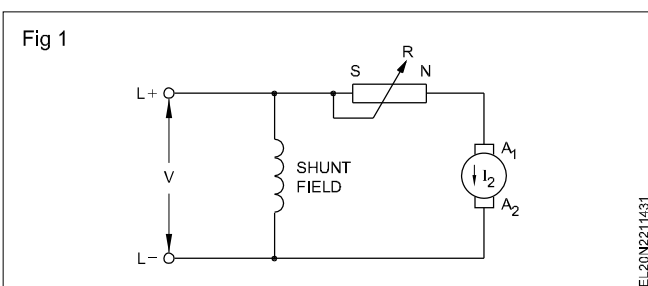
Reversing the direction of rotation of DC motors: The direction of rotation of a DC motor can be changed either by changing the direction of the armature current or by changing the direction of the field current. The direction of rotation of a DC motor cannot be changed by interchanging the supply connections because this changes the direction of the field as well as the armature current.

DC motor starters

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

- state the necessity of starter for a DC motor
- state the different types of starters - construction and working principle of 2-point, 3-point and 4-point starters.

Necessity of starters: Since the armature is stationary before starting, the back emf which is proportional to speed is zero. As the armature resistance is very small, if the rated voltage is applied to the armature, it will draw many times the full load current, and thereby, there is every possibility of damaging the armature due to heavy starting current. Therefore, the starting current should be limited to a safe value. This is done by inserting a resistance in series with the armature at the time of starting for a period of 5 to 10 seconds. As the motor gains in speed, back emf is built up, and then the starting resistance could be gradually cut off. Fig 1 shows such an arrangement. Resistance R is fully included in the armature circuit by keeping the moving arm in position 'S' at the time of starting, and then it is moved towards position 'N' to exclude the resistance 'R' when the motor has picked up its speed. But such an arrangement will be purely manual and needs constant monitoring. For example, if the motor is running, the resistance 'R' will be excluded, and the moving arm position will be at position 'N'. In case the supply fails, the motor will stop but the moving arm will still be in position 'N'. When the supply returns, as there is no resistance included in the armature circuit through 'R', the armature may draw heavy current and may get damaged. To prevent such a happening a device called starter is used in motor circuits.



Types of starters: Starters used to start the DC motors are generally of three types.

- Two-point starter
- Three-point starter
- Four-point starter

Two-point starter: This contains the following components.

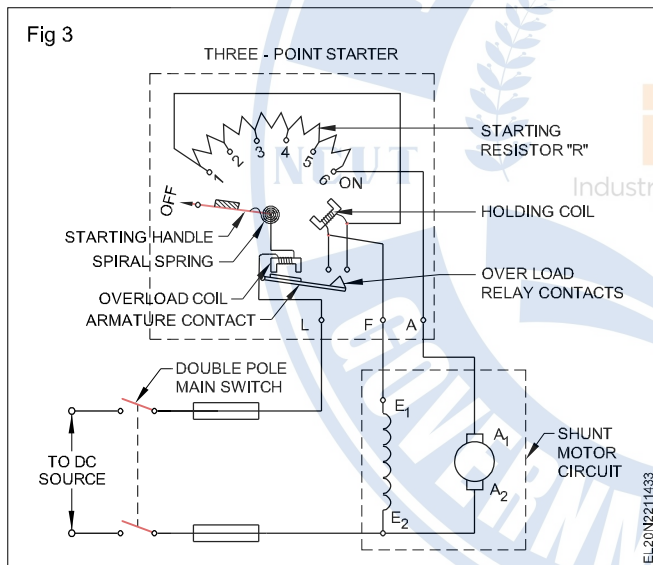
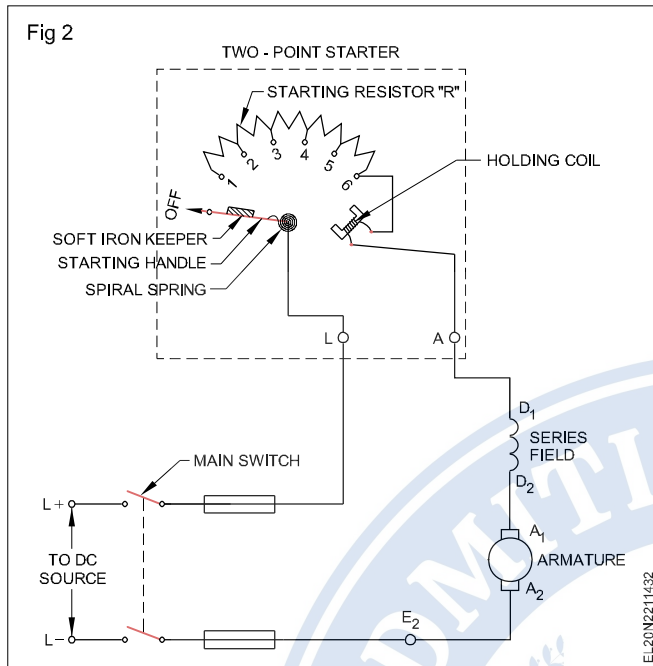
- The series resistor required for starting a motor.
- The contacts (brass studs) and switching arm required to include or exclude the resistor in the armature circuit.
- A spring on the handle to bring the handle to the 'OFF' position when supply fails.
- An electromagnet to hold the handle in the 'ON' position.

The two-point starter is frequently used with a DC series motor. The starting resistance, electromagnet armature and the series field are all connected in series as shown in Fig 2.

When the arm is moved to the first contact point, the circuit is completed, and the armature begins to rotate. As the armature speed increases, the arm is slowly moved towards the right side electromagnet, thereby the starter resistance is reduced. When the arm is against the electromagnet, complete starter resistance is cut off from the circuit.

Three-point starter: Fig 3 shows the internal diagram of a three (terminal) point starter connected to a DC shunt motor. The direct current supply is connected to the starter, the motor circuit through a double pole switch and suitable fuses. The starter has an insulated handle or knob for the operator's use. By moving the starter handle from the 'off' position to the first brass contact (1) of the starter, the armature is connected across the line through the starting resistance. Note that the armature is in series with the total starting resistance. The shunt field, in series with

the holding coil, is also connected across the line. In this mode of operation, the rush of the initial current to the armature is limited by the resistance. At the same time, the field current is at the maximum value to provide a good starting torque.

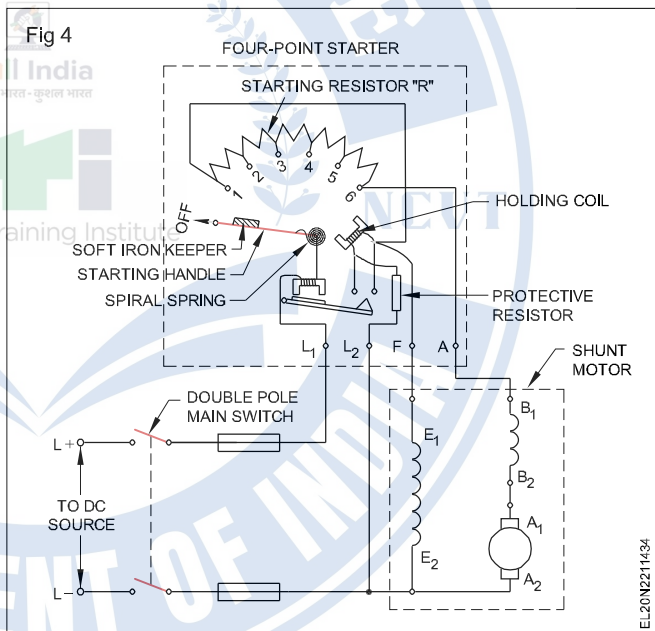


As the handle arm is moved to the right, the starting resistance is reduced and the motor gradually accelerates. When the last contact is reached, the armature is connected directly across the supply; thus, the motor is at full speed.

An overload coil is provided to prevent damage to the motor from overload. Under normal load condition, the flux produced by the over load coil will not be in a position to attract the armature contact. When the load current increases beyond a certain specified value, the flux of the over load coil will attract the armature. The contact points of the armature then short-circuit the holding coil and demagnetize it. This enables the handle to come to the 'OFF' position due to the tension of the spiral spring.

This type of starter can be used to start both shunt and compound motors.

Four-point starter: In applications where many motor speeds are to be increased beyond their rated value, a four-terminal, face plate starter is used with the motor. The four-terminal point starter, shown in Fig 4, differs from the three-point starter in that the holding coil is not connected in series with the shunt field. Instead, it is connected across the supply in series with a resistor. This resistor limits the current in the holding coil to the desired value. The holding coil serves as a no-voltage release rather than as a no-field release. If the line voltage drops below the desired value, the magnetic attraction of the holding coil is decreased, and then the spring pulls the starter handle back to the 'off' position.



Relation between torque, flux and armature current in a DC motor

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

- explain the relation between torque, flux and armature current
- solve problems pertaining to metric HP; load current, rated voltage, torque and speed of DC motors.

Relation between armature current, flux and torque

Torque: The turning or twisting moment of a force about an axis is called torque. It is equal to the product of force and the radius of the pulley.

Consider a pulley of radius 'r' metres acts upon by a circumferential force 'F' Newton, and rotates at a speed of 'n' r.p.s. as shown in Fig 1.

Then torque $T = F \times r$ Newton-metres(N-m)

Work done by this force

in one revolution = Force x distance

$$= F \times 2\pi r \text{ joules.}$$

Power developed in one second = $F \times 2\pi r \times n$ joule/second or watts

$$= (F \times r) 2\pi n \text{ watts}$$

As $2\pi n$ is angular velocity ω in radian/second and

$$(F \times r) = \text{Torque } T$$

Power developed = $T \times \omega$ watts

$$P = T\omega \text{ watts.}$$

or

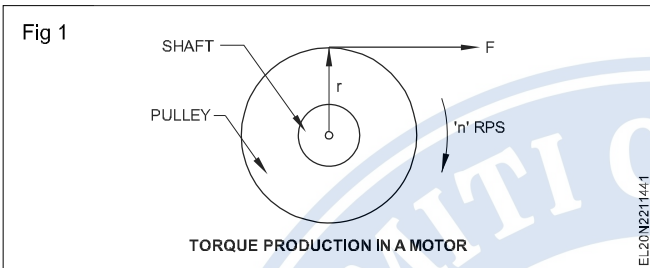
For a given motor, ZP and A are constants as they depend upon the design.

$$\frac{0.159 ZP}{A} \text{ can be regarded as constant 'K'}$$

$$\text{Then } T_a = K\phi I_a$$

where ϕ is the flux pole in weber

I_a is the armature current



T_a is the armature torque in newton metres.

Therefore, we can say the torque of a DC motor is directly proportional to the field flux and the armature current.

The other formula which gives torque

Torque of a motor: Let T_a be the torque developed by the armature of a motor in newton-metre and 'n' the speed of armature in r.p.s.

Then the power developed in the armature = $T_a 2\pi n$ watts.

As we know the Electrical power is converted into mechanical power

Electrical power supplied to the armature = $E_b I_a$ where

E_b is the back emf

I_a is the armature current.

Electrical power supplied to the armature = Mechanical power developed in the armature

$$\text{We get } E_b I_a = T_a 2\pi n$$

Since (By taking 'n' in r.p.s.)

$$T_a \times 2\pi n =$$

By cross multiplication we get

where 'N' is speed in r.p.m.

Shaft torque: The complete armature torque calculated above is not available for doing useful work because of the losses in the motor.

The torque which is available for doing work is known as shaft or output torque, and it is denoted as T_{sh} .

The difference ($T_a - T_{sh}$) is known as loss of torque due to iron, friction and windage losses of motor.

where 'n' is the speed in r.p.s., N is the speed in r.p.m. and T_{sh} is the shaft torque in newton metre.

If the torque is given in kg. metre, it can be converted into newton metre as given below.

$$\text{Newton metre} = \text{Kg. metre} \times 9.81$$

Service and maintenance of DC motor starters

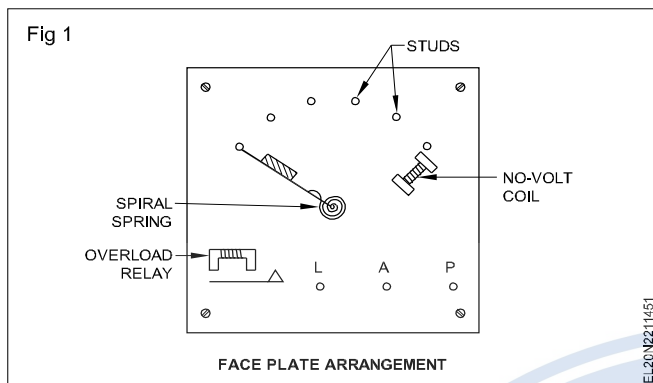
Objectives: At the end of this lesson you shall be able to

- explain the procedure of service and troubleshoot the DC motor starter
- state how to check the handle for its spring tension and contact pressure against the studs
- state how to check the no-volt coil assembly
- explain the overload relay for the desired current rating.

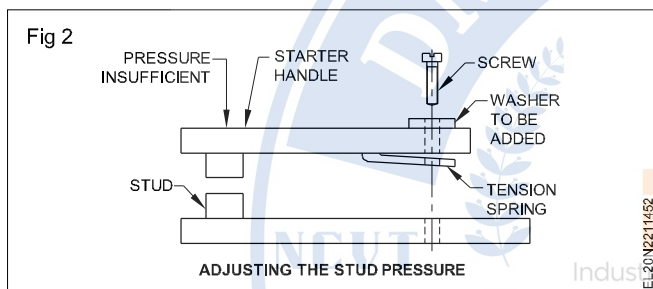
Servicing the starter: The starting resistance of the 3-point and 4-point starters is made up of coiled Eureka wire and it is fixed between the studs of the starter. The brass

studs are arranged on the face plate of the starter in a circular form as shown in Fig 1. The studs are firmly fixed on the insulated face plate. During maintenance the studs

should be dressed with zero number sandpaper if the burrs are small and a smooth file should be used for pittings and big burrs, and then cleaned properly with a contact cleaner. In case the starter resistance is found open, replace it with a new resistance coil as per the original specification of the manufacturer.

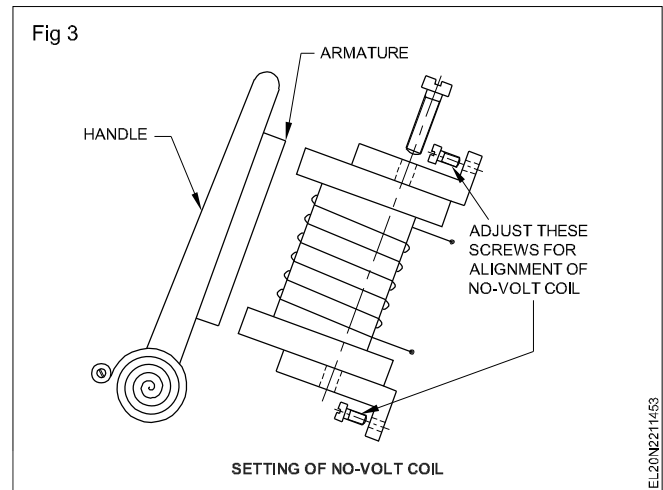


Proper pressure of the movable contact of the arm is available against the brass studs of the face plate. If proper tension is not found then the starter handle is to be tightened with the help of fixing screw by adding one or two flat washers on the top of the handle as shown in Fig 2



When the handle of the starter is moved to the running position, the armature of the handle should be touching the core assembly of the no-volt coil. In case the core assembly is not touching properly, loosen the mounting screws of the core/coil assembly, align the core and tighten the screws. (Fig 3).

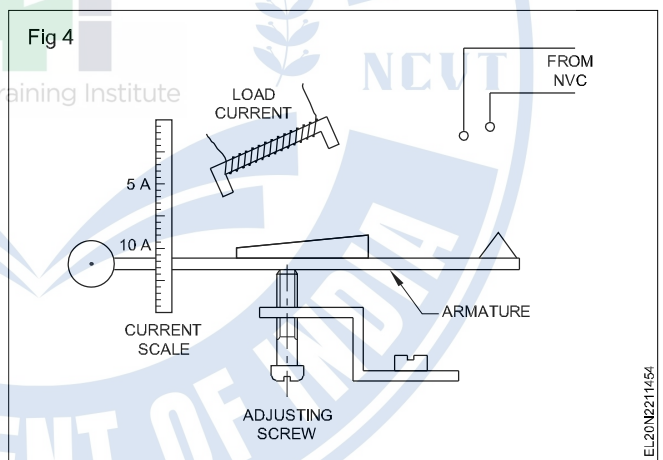
If the NVC is not energised check visually the condition of the NVC. Measure the value and resistance of the coil as well as the insulation value and make a note of these readings.



Maintenance of overload relay (Fig 4): A magnetic overload relay is provided near the handle on the left side of the starter face plate; underneath the overload relay an armature is provided and it is adjusted as per the load current of the motor.

To test the overload relay the motor has to be loaded and the tripping of the overload relay to be observed. In case the overload relay trips at a lower current or higher current value when compared to set current value the current scale has to be recalibrated.

In the case of chattering noise observed at the no-volt coil the surfaces of the core assembly and armature need to be cleaned.



Characteristics and applications of a DC series motor

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

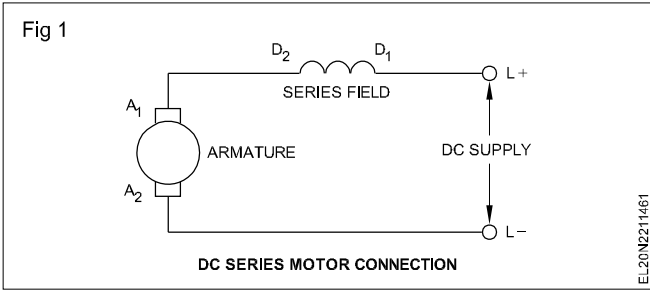
- explain the characteristics of a series motor
 - torque versus load
 - speed versus load
 - speed versus torque
- state the uses of a DC series motor
- state the method of loading the motor and explain the brake test.

DC series motors : A DC series motor has a very high starting torque. In some motors, it may be as high as five times the full load torque. Further, the speed of the DC series motor also varies with the load. (Fig 1)

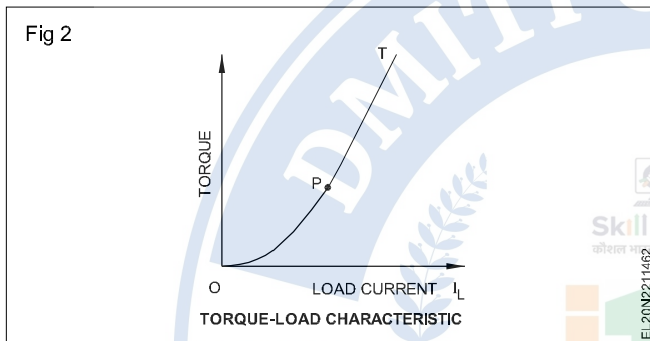
Characteristics of DC series motors: The torque ' T ' in a DC motor is proportional to the flux ' ϕ ' and the armature

current ' I_a '. The speed is inversely proportional to the flux. The relation between these factors i.e. torque vs load, speed vs load and torque vs speed are plotted on a graph, and are known as characteristic curves of motors. The study of these characteristics enables us to understand the behaviour of the motors under different conditions.

Torque load characteristics of the DC series motor: Fig 2 shows the torque load characteristic curve of a DC



series motor. At low or light load, the torque is low due to the low armature current and low field flux. But as the load increases, the torque also increases proportionate to the square of the armature current up to the point 'P' of the curve. This could be illustrated by the formula $T \propto I_a \Phi_{se}$ as Φ_{se} is proportional to I_{se} and, further, I_{se} is proportional to the armature current. We have



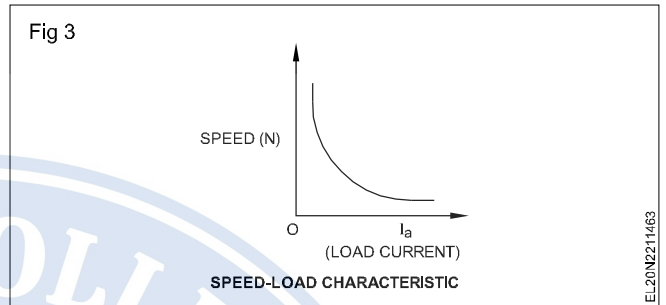
$$T \propto I_a I_{se}$$

$$T \propto I_a^2$$

$$T \propto I_a^2$$

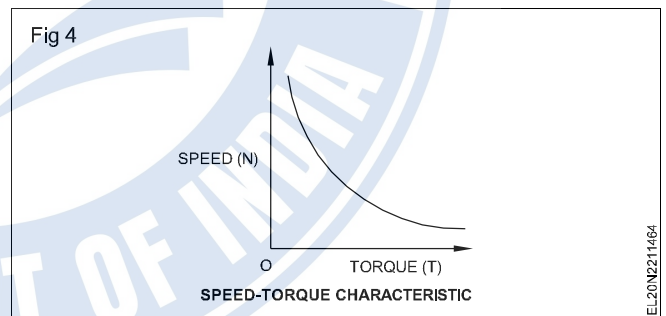
Beyond this point 'P' the curve becomes a straight line, and indicates the torque is proportional to the armature current only as the field cores are saturated. This curve shows that the torque is low at light loads and increases at heavy loads. Further the starting current of a DC series motor is about 1.5 times the full load current and the torque is about 2.25 times (1.5²) the full load torque assuming the poles are not saturated.

Speed Vs load characteristics: Fig 3 shows the speed load characteristic curve of a DC series motor. From the curve it is clear that when the load is small the speed is high, and as the load increases the speed decreases. As the curve shown is parallel to the 'Y' axis at low load currents, it can be inferred that the speed attains a dangerous value. Therefore, the DC series motors are seldom used without load. Care should be taken while using belt drives where the load can be 'OFF' if the belt breaks or slips out. To avoid this, usually the load is connected directly or through gears to a DC series motor.



Speed-torque characteristics: Fig 4 shows the speed-torque characteristic of a DC motor. It shows that when the torque is low, the speed is high. This is due to the low field flux (N ∝ 1/Φ). As the torque increases the motor draws more current and causes the speed to reduce. This is due to the increased field flux by increased load current in the DC series field.

Uses of a DC series motor: The DC series motor is used in applications where torque and speed requirements vary substantially, and in jobs that require a heavy starting torque and a high rate of acceleration as in traction, hoists, cranes, and heavy construction trucks.



Characteristics and applications of a DC shunt motor

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

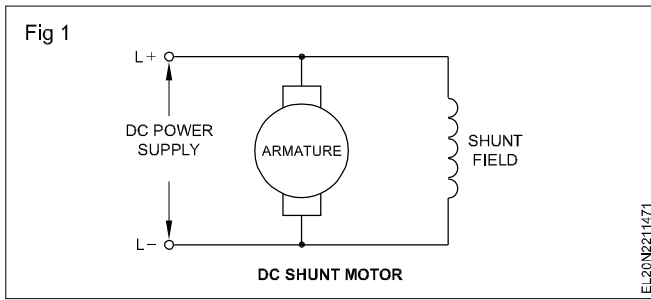
- describe the characteristics of a DC shunt motor
 - speed vs load characteristics
 - torque vs load characteristics
 - torque vs speed characteristics
- state the applications of a DC shunt motor.

Shunt motor (Fig 1) : In a shunt motor, the field is connected directly across the armature and the supply. The field current, and hence, the field flux are constant. When operating without a load, the torque requirement is small, since it is only needed to overcome windage and friction losses. Because of the constant field flux, the

armature will develop a back emf that will limit the current to the value needed to develop only the required torque.

Speed load characteristic of the DC shunt motor: Shunt motors are classified as constant speed motors. In other words, there is very little variation in the speed of the shunt motor from no load to full load. Equation 1 may be

used to determine the speed of the DC motor at various loads.



where

N - speed of the armature in r.p.m.

V - applied voltage

I_a - armature current at a specific load

R_a - armature resistance

Φ - flux per pole

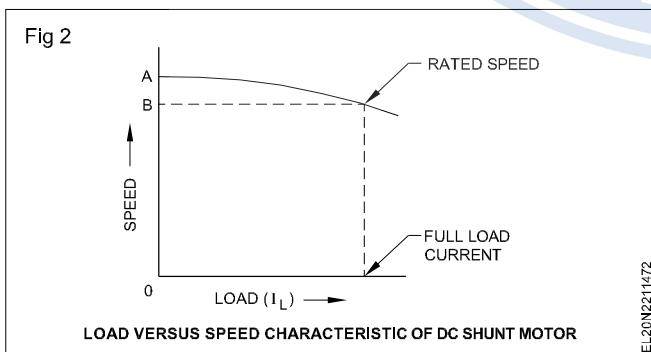
K_1 - a constant value for the specific motor

E_b - the back emf

In a shunt motor, V, R_a, K_1 and Φ are practically constant values, and the armature current is the only variable. At no load the value of I_a is small, leading to the maximum speed. At full load, $I_a R_a$ is generally about 5 percent of V . The actual value depends upon the size and design of the motor. Consequently, at full load, the speed is about 95 percent of the no-load value.

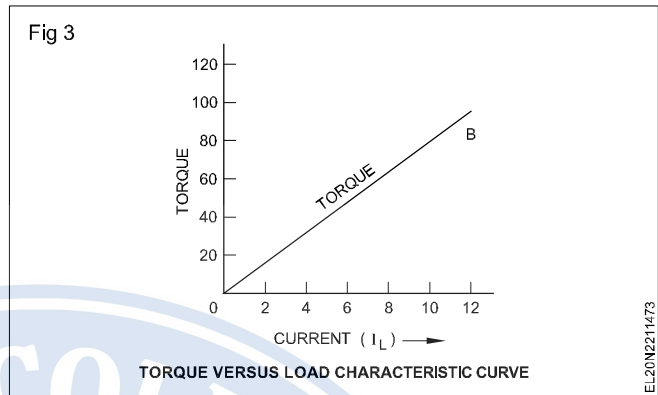
However the speed will drop slightly to reduce the back emf such that the armature can draw more current to develop an increased torque from no load to full load.

Fig 2 shows the speed-load characteristic of a DC shunt motor. From the curve it is observed that the speed slightly drops from its no-load speed OA to OB when the motor delivers full load. This is due to the increased $I_a R_a$ drop in armature. As the drop is small, the DC shunt motor is regarded as a practically constant speed motor.



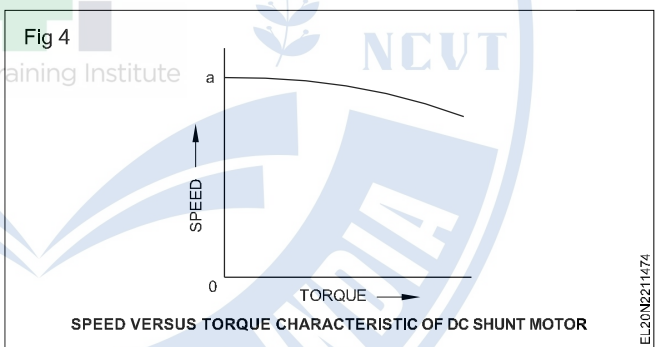
Torque vs load characteristics of the DC shunt motor:

Motor torque is proportional to the product of the field flux and the armature current. As the field flux is constant, the torque varies as the load current varies. Fig 3 shows the torque vs load curve of a DC shunt motor. From this it is clear that the torque is directly proportional to load or armature current I_a .



The starting torque of a shunt motor is about 1.5 times the full load torque indicating that the shunt motor does not have as high a starting torque as the series motor, but it has much better speed regulation.

Torque Vs speed characteristics: Fig 4 shows the torque speed characteristic of a DC shunt motor. From the curve it is observed that the increase in torque has negligible effect on the speed. The speed slightly drops as the torque increases.



Application of DC shunt motor: A DC shunt motor is best suited for constant speed drives. Some specific applications are machine tools, wood planers, circular saws, grinders, polishers, printing processes, blowers and motor generator sets.

When working with a shunt motor, never open the field circuit when it is in operation. If this happens, as the flux is only due to the residual field, the motor speed increases to a dangerous magnitude. At light loads this speed could become dangerously high, and the armature may fly off.

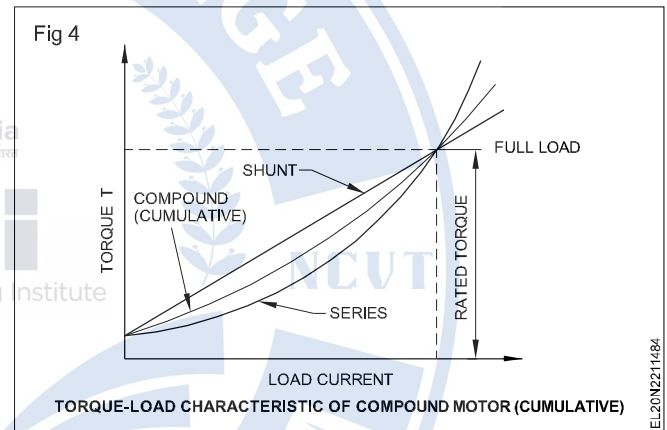
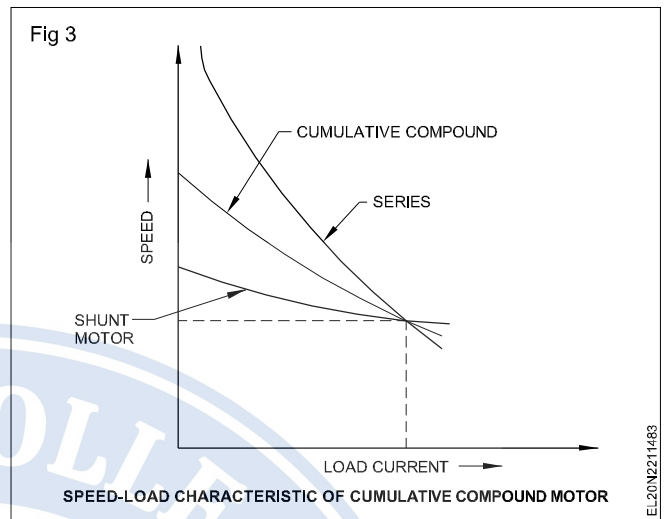
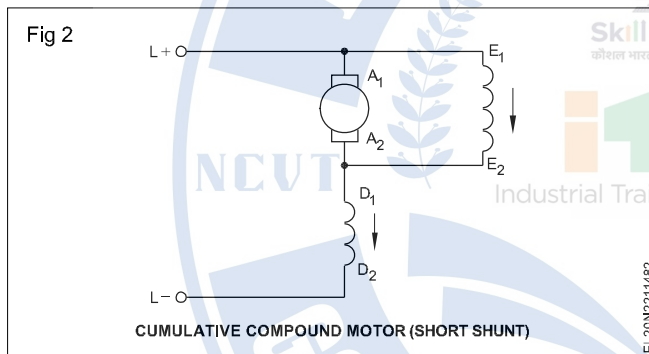
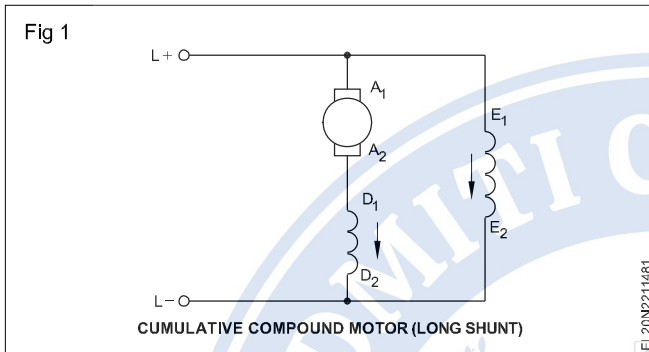
DC compound motor - load characteristics

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

- state the types, applications of DC motors
- state the characteristic of a DC compound motor
- state the precautions to be observed while starting a differential compound motor.

Cumulative compound motor: When the series field of the DC compound motor is connected in such a way that its flux aids the flux produced by the shunt field, as shown in Fig 1, then it is called a cumulative compound motor.

Depending on the shunt field connection, it is further subdivided as the long shunt, (Fig 1) the short shunt (Fig 2) cumulative compound motor.



Speed-load characteristic: Fig 3 shows the speed-load characteristic of the cumulative compound motor, and also of the series and shunt motors for comparison. The speed of this motor falls more than the shunt motor but falls less than the series motor. As the speed load curve starts from Y-axis, unlike in a DC series motor, the cumulative compound motor can also run on no-load at a specified speed.

The increased drop in speed at load is due to the combined drop of the voltage due to armature and series field resistances.

Torque-load characteristic: Fig 4 shows the torque-load characteristic of the cumulative compound motor, and also that of the series and shunt motors for comparison. Up to full load, the torque developed in a cumulative compound motor is less than that in the shunt motor but more than in the series motor.

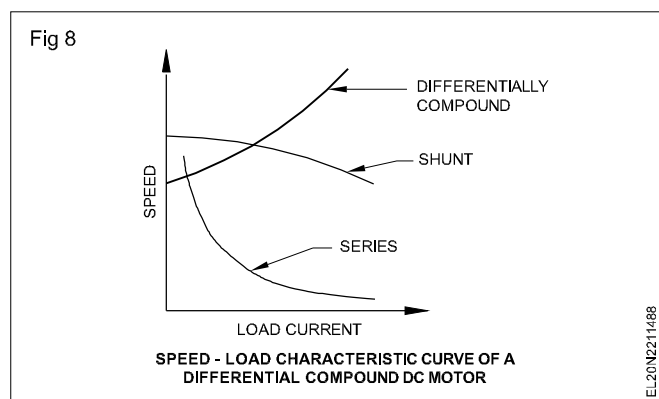
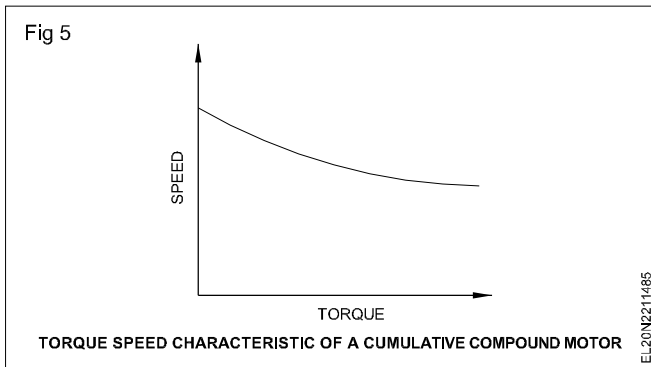
However, at the time of starting, the starting current is about 1.5 times the full load current, and hence, the cumulative compound motor produces a high torque, which is better than that of the shunt motor during starting.

Torque-speed characteristic: Fig 5 shows the torque-speed characteristic of the cumulatively compound motor. As the total flux of the motor increases with load, the speed decreases but the torque increases. As the output power is proportional to the product of speed and torque, the cumulative compound motor will not be overloaded in case of sudden appearance of load as in rolling mills.

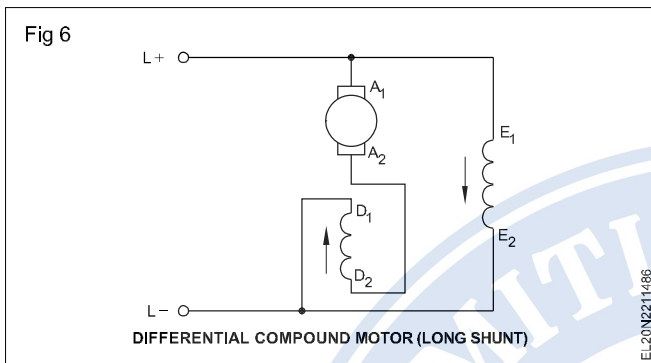
Application of cumulative compound motors: Compound motors are used to drive machines that require a relatively constant speed under varying loads. They are frequently used on machines that require sudden application of heavy loads, such as presses, shears, compressors, reciprocating tools, steel rolling machinery and elevators.

Never open the shunt field of a compound motor when the motor is operating at high load.

Differential compound motor: When the series field of the DC compound motor is connected in such a way that its flux opposes (bucks) the flux produced by the shunt field as shown in Fig 6, it is called a differential compound motor.



The torque-load characteristic of the DC differential compound motor shown in Fig 9, indicates that the torque increases with the increased load.



Depending upon the shunt field connection, the compound motor is further subdivided as long shunt (Fig 6) and short shunt (Fig 7) differential compound motor.

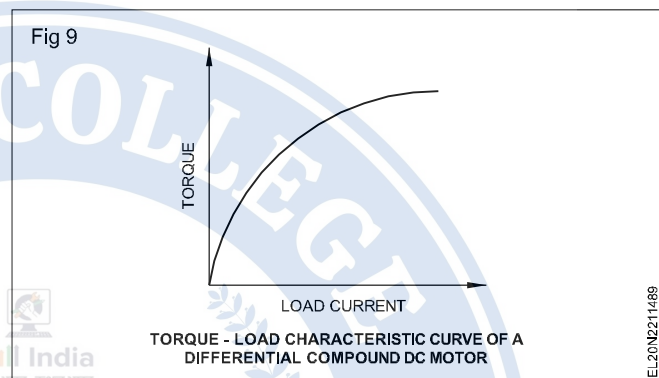
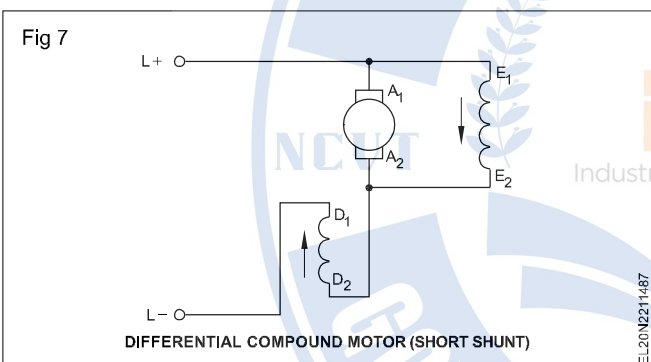
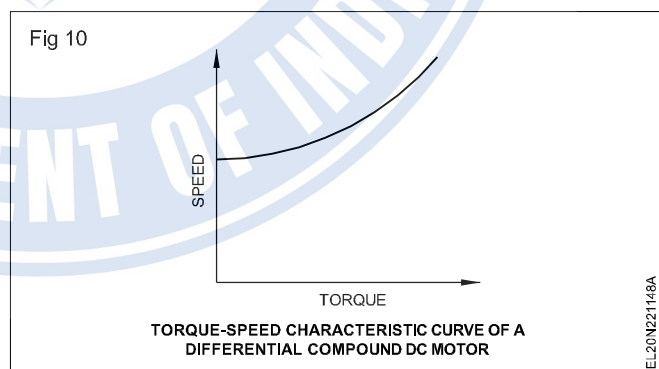


Fig 10 shows the torque-speed characteristic indicating that both speed and torque increase in the machine, resulting in the overloading of the machine initially, and thereby, reaching an unstable state.



Application of DC differential compound motor: This motor is not in common use due to its unstable behaviour at overloads. This motor is dangerous to use unless there is no possibility of the load exceeding the normal full load value as it is designed to work within full load limits.

As the series field flux is in the opposite direction to the shunt field flux, there is some inherent problem at the time of starting. At the time of starting, the shunt field takes some time to build up, whereas a heavy rush of current will be through the series field and armature. The motor will, therefore, tend to start up the wrong way. When the shunt field is fully established, the total flux, which is the difference of series and shunt field fluxes, may be so small that the motor may not produce sufficient torque to run the motor. Hence it is advisable to short-circuit the series field of the differential compound motor at the time of starting, and then put the series field in the circuit when the motor is running.



Characteristics of a differential compound motor: The speed-load characteristic of the differential compound motor, shown in Fig 8, indicates that the motor speed increases with the increase in load due to the fact that the total flux decreases at the increased load.

Speed control methods of a DC motor and their applications

Objective: At the end of this lesson you shall be able to
 • explain the principle and the methods of controlling the speed of a DC motor.

Principle of speed control in DC motors: In certain industrial applications, the variation of speed is a necessity. In DC motors the speed can be changed to any specified value easily. This is the main reason for certain industries to prefer DC motors for drives rather than AC motors. The speed of a DC motor can be varied, based on the following simple relationship.

It is known that the applied voltage = back emf + armature resistance voltage drop

$$V = E_b + I_a R_a.$$

Hence $E_b = V - I_a R_a$ and also

$$\text{the back emf } E_b = \frac{P\phi N}{60} \times \frac{Z}{A} = K\phi N$$

where K is a constant.

$$\text{Therefore } N = \frac{E_b}{K\phi} = \frac{V - I_a R_a}{K\phi} \dots\dots\dots \text{Eqn.1}$$

From the above expression, it is clear that the speed of a DC motor is directly proportional to the back emf E_b , and inversely proportional to flux (ϕ). Thus the speed of the DC motor can be varied by changing either the back emf E_b or the flux ϕ or both. In fact, if the back emf is decreased across the armature, the speed decreases, and if the flux is decreased the speed increases. The following are the most common methods of controlling the speed of DC motors based on the above principle.

Methods of speed control in DC shunt motors and compound motors

Armature control method: This method works on the principle that the speed of the DC motor could be varied by varying the back emf. As the back emf = $V - I_a R_a$, by varying the armature resistance we can obtain various speeds. A variable resistance called controller is connected in series with the armature as shown in Fig 1. The controller should be selected to carry the armature current for a longer period.

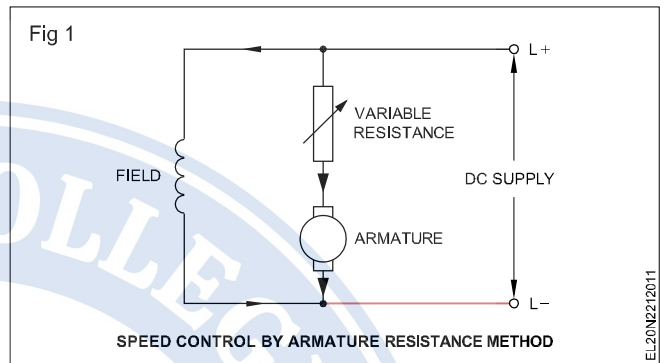
Let the initial and final speeds of the motor be N_1 and N_2 , and the back emf be E_{b1} and E_{b2} respectively,

$$\text{Then } N_1 = \frac{E_{b1}}{k} \dots\dots \text{Eqn.2.}$$

$$N_2 = \frac{E_{b2}}{k} \dots\dots \text{Eqn.3.}$$

By dividing Eqn.3 by Eqn.2 we have

$$N_2 = \frac{E_{b2} N_1}{E_{b1}}$$



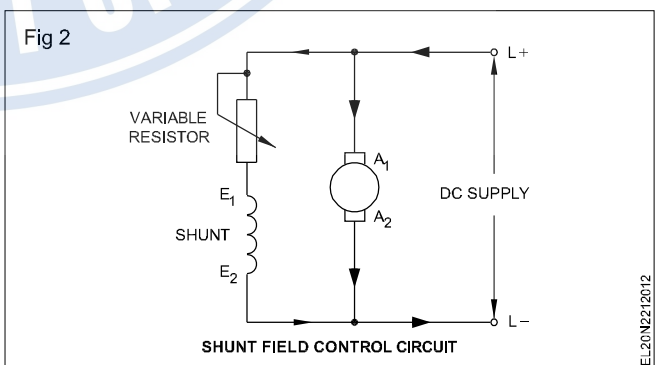
By varying the controller resistance value in the armature circuit, the back emf can be varied from E_{b1} to E_{b2} , thereby, the speed can be varied from N_1 to N_2 .

Advantages

This method is suitable for constant load drives where speed variations from low speed up to normal speed are only required.

Application of the armature control method: Suitable for DC shunt and compound motors used in printing machines, cranes and hoists where the duration of low speed operation is minimum.

The shunt field control method: This method works on the principle that the speed of the DC motor could be varied by varying the field flux. For this, a variable resistance (rheostat) is connected in series with the shunt winding as shown in Fig 2.



When the resistance is increased in the field circuit, the field current and the flux are reduced. Due to the reduction of flux, the speed is increased.

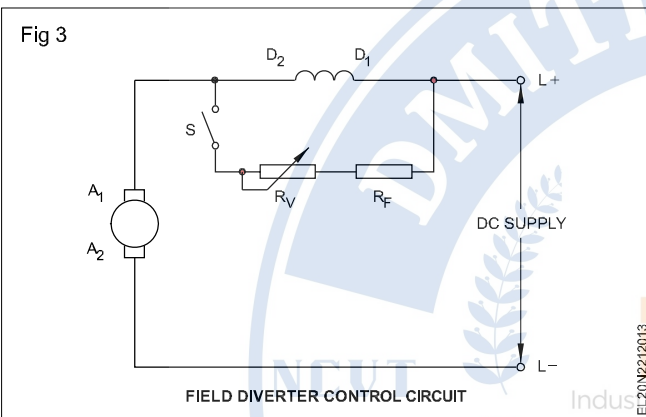
Advantages

- Higher speeds i.e. above normal speed only can be obtained which will be stable from no load to full load.
- As the magnitude of the field current is low, the power loss in the field rheostat is minimum.
- Control is easy, economical and efficient.

Application of shunt field control: This method is the most widely used speed control method where speeds above normal are required, and at the same time, the load applied to the motor changes often.

Method of speed control in DC series motors

Field diverter method: A variable resistance, called a diverter, is connected in parallel with the field winding as in Fig 3. R_V represents the variable portion of the diverter and R_F the fixed portion. The function of R_F is to prevent the series winding being short-circuited, when the diverter is operated.



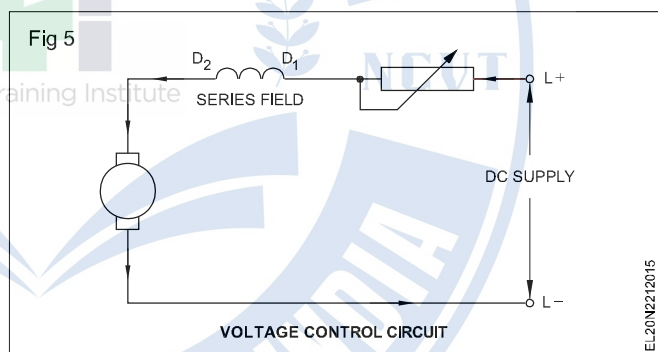
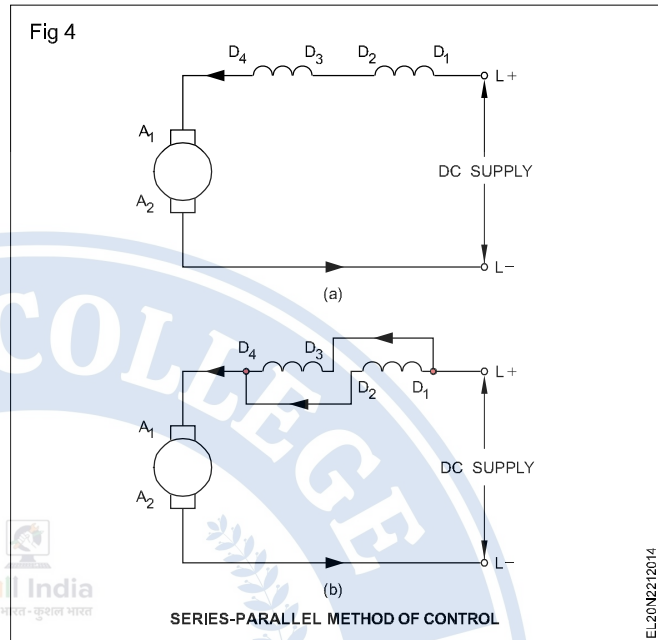
The smaller the value of $R_V + R_F$, the greater is the current diverted from the series winding, and, higher the speed of the motor. The minimum speed for a given input current is obtained by opening the switch 'S', thereby breaking the circuit through the diverter.

Application of the series field diverter method: This method is mainly used in the speed control of electric trains. By this method, speeds above normal only could be obtained, and the power loss in the diverter is quite considerable.

Series parallel method: Fig 4 (a) shows a series motor with two halves of the field winding connected in series. If the two halves of the field winding are connected in parallel as in Fig 4 (b), then for a given current 'I' taken from the supply, the current in each field coil is reduced to half and the flux is, therefore, reduced and the speed increased.

Application of series parallel method: This is the simplest method though only two speeds are possible. This method is often used for controlling the speed of fan motors.

Supply voltage control method: A controller (variable resistance) is connected in series with the motor as shown in Fig 5. This method can be used to control the speed from zero up to full normal speed.



The disadvantage in this method is that there is loss of energy in the control resistance in the form of heat. But with the introduction of SCR based control circuit, obtaining a variable supply voltage to motor is achieved with the least power loss. This method is widely used in larger modern machines where power loss is a major concern.

Troubleshooting in DC machines

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

- use the trouble shooting chart to rectify defects in i) DC machines in general ii) DC motors iii) DC generators.

DC machines have Power problems which are not normally found in AC machines. DC motors and generators have commutators and brushes, which cause special problems. If the commutator is properly maintained, it will give many years of useful service.

Chart 1 deals with DC motors and Chart 2 is for DC generator.

Chart 1

Troubleshooting chart for DC motors

Symptoms	Cause	Remedies
Motor will not start	a) Open circuit in starter. b) Low or no terminal voltage. c) Bearing frozen. d) Overload. e) Excessive friction.	a) Check for open starting resistor, b) Check the incoming voltage with name-plate rating and correct the supply voltage. c) Recondition the shaft and replace the bearing. d) Reduce the load. e) Check the bearing lubrication to make sure that the oil is sufficient quantity and of good quality. Disconnect motor from driven machine and turn motor by hand to see if trouble is in motor. Strip and reassemble motor; then check part by part for proper location and fit. Straighten or replace bent shaft.
Motor stops after running short time	a) Motor is not getting power. b) Motor is started with weak or no field. c) Motor torque insufficient to drive load.	a) Check voltage in the motor terminals: also fuses and overload relay. Rectify the defect. b) If adjustable-speed motor, check the rheostat for correct setting. If correct, check the condition of rheostat. Check the field coils for open winding. Check the wiring for loose or broken condition c) Check the line voltage with name plate rating. Use larger motor or one with suitable characteristic to match the load.
Motor runs too slow under load.	a) Line voltage too low. b) Brushes ahead of neutral plane. c) Overload.	a) Rectify the supply voltage or under load check and remove any excess resistance in supply line, connections or controller. b) Set brushes on neutral plane. c) Check to see that load does not exceed allowable load on motor.

Motor runs too fast under load.	<ul style="list-style-type: none"> a) Weak field. b) Line voltage too high. c) Brushes are out of neutral plane. 	<ul style="list-style-type: none"> a) Check for resistance in shunt-under load field circuits. Check for grounds. b) Correct high voltage condition. c) Set brushes on neutral plane.
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Chart 2

Troubleshooting chart for DC Generators

Symptoms	Cause	Remedies
Generator fails to build up voltage	<ul style="list-style-type: none"> a) The direction of rotation must have been reversed. b) Brushes not resting on the commutator. c) Residual magnetism is completely lost. d) Generator speed is too low. e) Short circuit in the armature. f) Open circuit in the armature. g) Short circuit in the field circuit. h) Open circuit in field winding. 	<ul style="list-style-type: none"> a) Change the direction of rotation b) Brushes to be set over the commutator in correct position. c) Run the generator as a DC motor or sometime (few seconds) or connect the field circuit to a battery or DC voltage to reestablish the residual magnetism. d) Generator speed should be restored to normal speed by increasing the prime mover speed. e) Rectify the short circuit in the armature. f) Test and rectify the open circuit. g) Test and rectify the short circuit which may be in the coil. Faulty coil will show much less resistance than a good coil. h) Check the continuity of the circuit and rectify the defect.

Maintenance procedure for DC machines

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

- state what is meant by preventive maintenance and its importance
- describe the recommended maintenance schedule for DC motors
- explain how to maintain the maintenance record.

Preventive maintenance: Preventive maintenance of Power machines consists of routinely scheduled periodical inspections, tests, planned minor maintenance repairs and a system of maintaining inspection records for future reference. Preventive maintenance is a combination of routine and planned operations.

Routine operations: Routine operations are those which follow fixed schedules to maintain Power motors at daily, weekly or at other fixed intervals.

Planned operation: By contrast, planned operation consists of additional work which is performed at irregular frequencies, and is determined by inspection and previous operating experience or the details of defects found in the maintenance records.

Necessity of preventive maintenance: By carrying out an effective preventive maintenance programme on Power machines, we can eliminate major failures of the machines, accidents, heavy repair costs and loss of production time. Proper preventive maintenance will lead to economy of operation, less down-time, dependable machine operation, longer machine life and lower overall cost of maintenance and repair.

Scheduling of preventive maintenance: Routine periodical inspection and tests may be scheduled to be carried out daily, weekly, monthly, half-yearly and annually depending upon the following factors.

- The importance of the motor/generator in the production
- The duty cycle of the machine

- The age of the machine
- The earlier history of the machine
- The environment in which the machine operates
- The recommendations of the manufacturer.

Recommended maintenance schedule for machines:

While carrying out routine periodical maintenance, an electrician will make full use of his senses to diagnose and locate problems in Power machines. The sense of smell directs attention to burning insulation: the sense of feel detects excessive heating in winding or bearing; the sense of hearing detects excessive noise, speed or vibration and the sense of sight detects excessive sparking and many other mechanical faults.

Sensory impressions must also be supplemented by various testing procedures to localize the trouble. A thorough understanding of Power principles and the efficient use of test equipment are important to an electrician during this phase of operation.

The following maintenance schedule is recommended for DC machines.

1 Daily maintenance

- Examine visually earth connections and machine leads.
- Check the sparking at the commutator.
- Check the motor windings for overheating. (The permissible maximum temperature is near about that which can be comfortably felt by hand.)
- Examine the control equipment.
- In the case of oil-ring lubricated machines
 - a) examine the bearings to see that the oil rings are working
 - b) note the temperature of the bearings
 - c) add oil, if necessary
 - d) check end play.
- Check for unusual noise at the machine while running.

2 Weekly maintenance

- Examine the commutator and brushes.
- Check belt tension. In cases where this is excessive it should immediately be reduced. In the case of sleeve-bearing machines, the air gap between the rotor and stator should be checked.
- Blow out air through the windings of protected type machines situated in dusty locations.
- Examine the starting equipment for burnt contacts where machine is started and stopped frequently.
- Examine oil in the case of oil-ring lubricated bearings for contamination by dust, grit, etc. (This can be roughly judged from the colour of the oil.)
- Check foundation bolts and other fasteners.

3 Monthly maintenance

- Overhaul controllers.
- Inspect and clean the oil circuit breakers.
- Renew the oil in high- speed bearings which are in damp and dusty locations.
- Wipe the brush-holders and check the bedding of brushes of DC machines.
- Test the insulation of windings.

4 Half-yearly maintenance

- Check the brushes and replace, if necessary.
- Check the windings of machines subjected to corrosive and other elements. If necessary, bake the windings and varnish.
- Check the brush tension and adjust, if necessary.
- Check the grease in the ball and roller bearings, and make it up, where necessary, taking care to avoid overfilling.
- Check the current input to the motor or the output of the generator and compare it with normal values.
- Drain all the oil bearings, wash with petrol to which a few drops of oil have been added; flush with lubricating oil and refill with clean oil.

5 Annual maintenance

- Check all the high speed bearings, and renew, if necessary.
- Blow out all the machine winding thoroughly with clean dry air. Make sure that the pressure is not that high as to damage the insulation.
- Clean and varnish the oily windings.
- Overhaul the motors which have been subjected to severe operating conditions.
- Renew the switch and fuse contacts, if damaged.
- Check the oil in the starter and the grease/oil in the bearings.
- Renew the oil in the starters subjected to damp or corrosive elements.
- Check the switch conditions, resistance to earth between motor/generator windings, control gear and wiring.
- Check the resistance of earth connections.
- Check the air gaps in between the armature and field.
- Test the insulation of windings before and after overhauling the motors/generators.

6 Records

- Maintain a register giving one or more pages for each machine, and record therein all important inspections and maintenance works carried out from time to time. These records should show past

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

periods, the planned maintenance requires to be done during holidays or by taking shut-downs of small duration.

Planned maintenance schedule needs to be decided, based on the routine maintenance reports entered in the maintenance card.

While routine maintenance could be done either during the working of the machine or during short interval 'down'

Initial test results	Page 1
Resistance value of shunt winding _____	
Resistance value of series winding _____	
Resistance value of armature _____	
Insulation resistance value between	
armature and shunt field _____	
armature and series field _____	
series field and shunt field _____	
armature and frame _____	
shunt field and frame _____	
series field and frame _____	
The 2 nd page gives the record of maintenance carried out, and, in particular the defects noted therein.	

Maintenance record

Maintaining a system of inspection records is a must in preventive maintenance schedule. This system uses a register as stated above or cards as shown below which are kept in the master file. By referring to these maintenance cards, the foreman can schedule the planned maintenance.

Maintenance card: The 1st page gives initial test results etc pertaining to the machine.

A careful study of the maintenance card helps the foreman to plan the shut-down date to facilitate early overhauling or planned maintenance schedule to prevent a major breakdown.

Method of maintenance: During the routine maintenance inspection, the investigations and adjustment to be carried out for the parts and accessories of the motors/generators are given below to improve the efficiency of preventive maintenance.

- Clean daily the motor/generator, switch gear and associated cables free from dirt, dust and grease. Use dry compressed air to drive away the dust from the machines.
- Check the bearing daily for excessive noise and temperature. If required, re-grease or re-oil the bearing with the same grade of grease/oil as in original. Do not mix different grades of grease together as it may result in forming sludge or acids, and spoil the bearings.
- Check the machine daily against strains of water or oil or grease which may leak from the surroundings. Take the necessary protective steps to prevent the leakage.

- Check daily the belts, gears and coupling for looseness, vibration and noise. Adjust/replace the parts, if found defective.
- Check weekly the brushes and the commutator for sparking and wear.
- Check weekly the bearing for proper lubrication.
- Check weekly the terminals and switch contacts.
- Inspect the brushes and the commutator once in a month for excessive wear, chatter and sparking. Worn-out brushes need to be replaced with the same grade brushes. Check spring tension on the brushes, and adjust, if necessary. Badly worn-out commutators need to be turned in a lathe or be replaced.
- Check monthly the brushes for proper seating. If necessary, reshape the brushes to proper curvature to suit the commutator surface.
- Check monthly the end plates and the shaft for excessive end play.
- Check monthly the main and auxiliary contact points of the switch gear for wear, pitting and burns. Badly worn out contact point needs replacement. Check the connection terminals for loose connection and scales or burning. Rectify the defects.
- Test monthly once the field windings and armature for insulation and ground faults. Low reading of insulation below 1 megohm indicates weak insulation. Dry out the winding, and re-varnish, if necessary.
- Check monthly once the foundation bolt and other fasteners for tightness.
- Once a year undercut the mica in between the commutator bars. Test the commutator and armature for shorts, open and ground faults.

Maintenance card

Report on routine maintenance

Page 2

Date of maintenance	Scheduled maintenance carried out	Defects noted	Attended by (Signature)	Reported to (Signature)	Remarks

The 3rd page gives the details of the test carried out in the motor at intervals with corresponding readings

Maintenance card

Report on test details

Page 3

Date of Test	Schedule	Test particulars	Test results	Tested by (Signature)	Reported to (Signature)	Remarks

From the above it is clear that atleast once in a year, the motor/generator needs a thorough overhauling in addition to frequent routine maintenance.

The 4th page gives the details of the defects, causes and repair carried out

Motor service card

Page 4

Date of repair	Repair and parts replaced	Cause	Repaired by (Signature)	Supervised by (Signature)	Remarks

Materials used for winding - field coil winding

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

- list out the insulating materials used for winding and their applications.

Insulating materials : In winding work, proper selection of insulating materials is an important criterion. The ageing factor of the insulation of Power equipment and apparatus depends upon many factors, such as temperature, Power and mechanical stress, vibration, moisture, dirt and chemical reaction.

Materials: The following are the common insulating materials used for winding purposes.

- Leatheroid paper
- Pressphan paper
- Triplex paper
- Millinex paper
- Micanite paper (mica folium)

- Empire cloth
- Cotton tape
- Fibre glass tape
- Empire sleeves
- PVC sleeves
- Hemp thread
- Varnish
- Glass fibre cloth
- Empire tape
- Cotton sleeves
- Fibre glass sleeves
- Bamboo
- Terylene thread

Winding wires

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

- list out the winding wires used for winding.

Winding wires : The annealed copper conductors, normally in round shape, are used for winding small and medium capacity Power machines and equipments. These copper wires are provided with a variety of insulation as stated below.

- Super-enamelled copper wire (S.E.)
- Single cotton-covered copper wire (S.C.C.)
- Double cotton-covered copper wire (D.C.C.)
- Single silk-covered copper wire (S.S.C.)
- Double silk-covered copper wire (D.S.C.)
- PVC-covered copper winding wire

Generally super-enamelled copper winding wire with medium covering is used for most of the winding applications, whereas for some special applications super-enamelled copper wire with thick covering may be used.

Field coils and armature of certain DC machines might be wound with super-enamelled, DCC or DSC copper winding wires.

PVC covered copper winding wire is mainly used for submersible pumps.

The winding wires are available in different sizes and grades of insulation.

Armature winding - terms - types - rewinding of mixer/liquidizer

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

- define the general terms used in DC armature winding
- explain the different types of DC armature winding.

DC armature winding : It is a closed coil winding, wherein the coil ends are connected through the commutator segments to form the closed circuit.

Terms used in DC armature winding

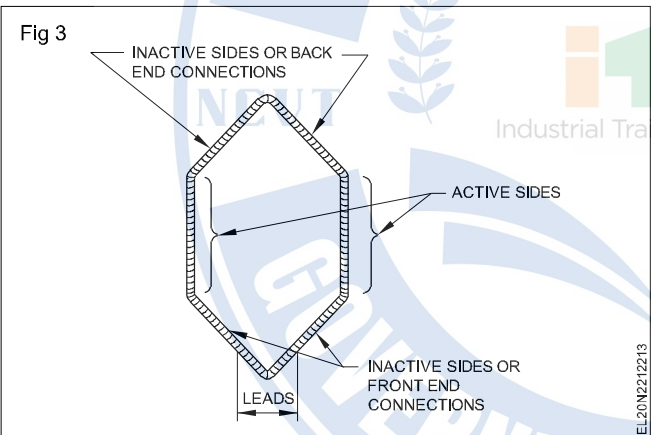
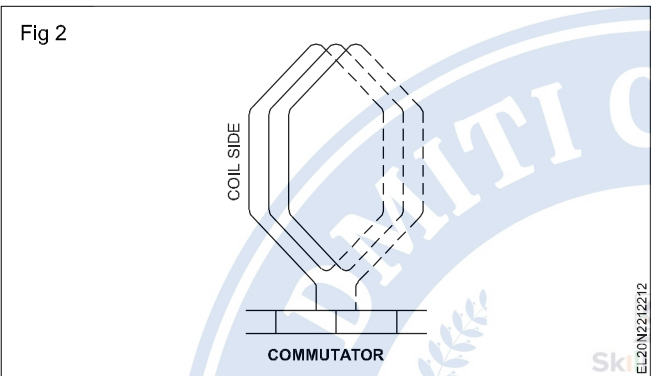
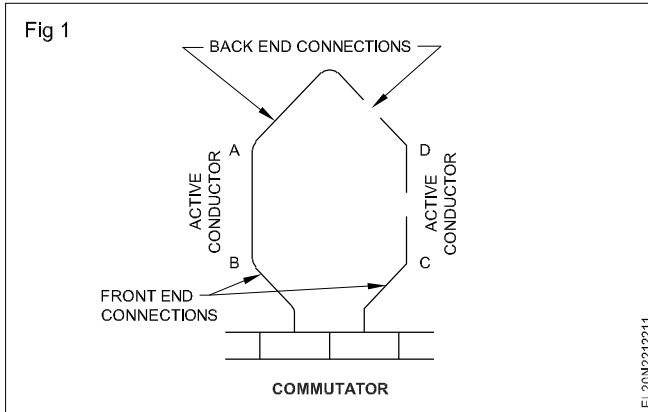
Coil or winding element : Length of a wire lying in the magnetic field and in which an emf is induced is called an active conductor.

Referring to Fig 1, we find the two active conductors AB and CD along with their end connections constitute one coil or winding element of the armature winding. The coil may consist of a single turn only as shown in Fig 2 or multi-turns as shown in Fig 3. A single-turn coil or winding

element will have two conductors only. But a multi-turn coil may have many conductors per coil side. In Fig 2 for example, each coil side has 3 conductors. The group of conductors constituting a coil side of a multi-turn coil is tied together with a tape as a unit (Fig 3) and is placed in the armature slot. It may be noted that each winding element has two connecting leads and each commutator bar has two connecting leads brought from the winding. As such there are as many commutator bars as the number of winding elements.

Active sides : These are the sides which lie within the slots. They are also known as coil sides. The induction

takes place only in the active sides of the coil while they move in the magnetic field. (Fig 3)



In winding calculation these active sides are considered as conductors. The coil has got two conductors irrespective of the number of turns.

Inactive sides : That part of a coil which does not lie in the slot is known as the inactive side of a coil. No induction takes place in the inactive sides.

Example: Back and front end connections. (Fig 3)

Leads of coil : The ends coming out from a coil are known as leads of a coil. Every coil has got two leads.

Pole-pitch(Y_p) : It may be variously defined as:

- the periphery of the armature divided by the number of poles of the machine i.e. the distance between two adjacent poles. It is denoted by Y_p .
- it is equal to the number of armature conductors (or armature slots) per pole. For example, if there are 48

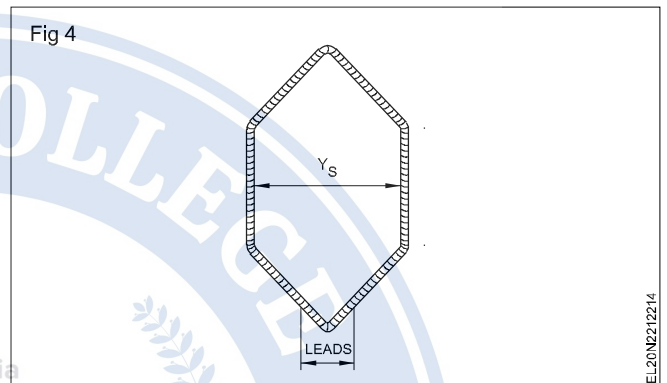
conductors, 24 coils, 24 slots and 4 poles, then the pole pitch is

$$Y_p = \frac{\text{Number of slots}}{\text{Number of poles}} = \frac{24}{4} = 6 \text{ in terms of slots}$$

or

$$Y_p = \frac{\text{No. of conductors}}{\text{No. of poles}} = \frac{48}{4} = 12 \text{ in terms of conductors}$$

Coil-span or coil-pitch(Y_s) : The coil-span or coil-pitch is the distance, measured in terms of armature slots or armature conductors between two sides of a coil. It is in fact the periphery of the armature measured in terms of slots or conductors spanned by the two sides of the coil. It is denoted by Y_s as shown in Fig 4.



Coil-pitch Y_s is calculated in the same way as is done for Pole pitch.

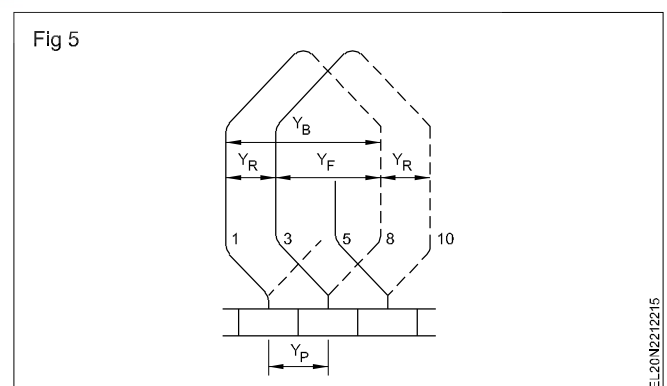
Hence the modified calculation will be

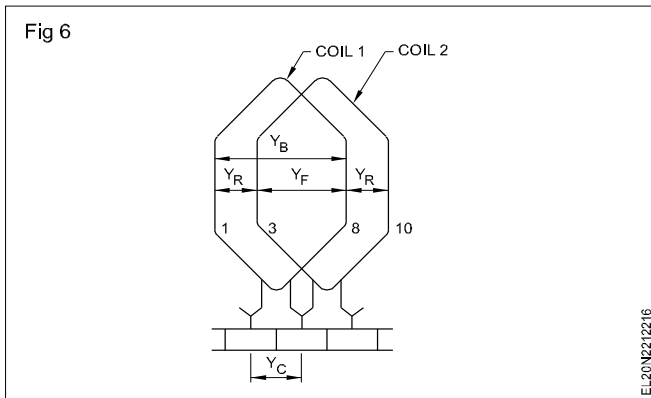
$$Y_s = \frac{\text{No. of slots}}{\text{No. of poles}} - K = \frac{S}{P} - K \text{ (in terms of slots)}$$

$$= \frac{\text{No. of conductors}}{\text{No. of poles}} - K = \frac{C}{P} - K \text{ (in terms of conductors)}$$

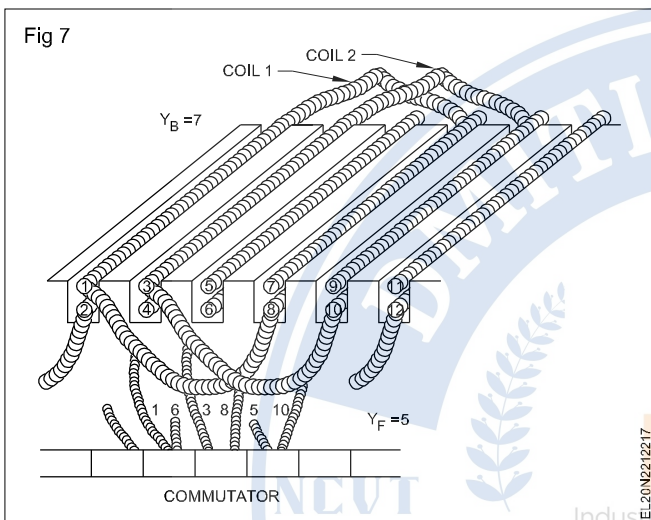
where K = any part of S/P or C/P that is subtracted to make Y_s an integer.

Back pitch (Y_b) : The distance measured in terms of the armature conductors which a coil advances on the back of the armature is called back pitch and is denoted by Y_b . This is illustrated in Figs 5 and 6. The back pitch is also equal to the coil-pitch.





As shown in Fig 7, coil side 1 is connected on the back of armature to coil side 8 (same coil). Hence $Y_B = 8 - 1 = 7$ conductors.



Front pitch (Y_F): The number of armature conductors or elements spanned by a coil on the front (commutator end of an armature) is called the front pitch and is designated by Y_F . This is shown in Figs 5,6 and 7. Coil side 8 is connected to coil side 3 (second coil) through the commutator segment. Hence $Y_F = 8 - 3 = 5$ conductors.

Average pitch (Y_A): The average of the front pitch Y_F and the back pitch Y_B is called average pitch. Y_A

$$\text{i.e., } Y_A = \frac{Y_B + Y_F}{2}$$

It is expressed in number of conductors.

Resultant pitch (Y_R): In general, it may be defined as the distance between the beginning of one coil and the beginning of the next coil to which it is connected or it is the distance between the beginnings of two consecutive coil sides as shown in Figs 7 and 8 and denoted by letter Y_R . As in Fig 9, $Y_R = Y_B - Y_F$, i.e. $Y_R = 7 - 5 = 2$ conductors. The resultant pitch Y_R depends upon the type of winding like lap or wave, as well as simplex or multiplex.

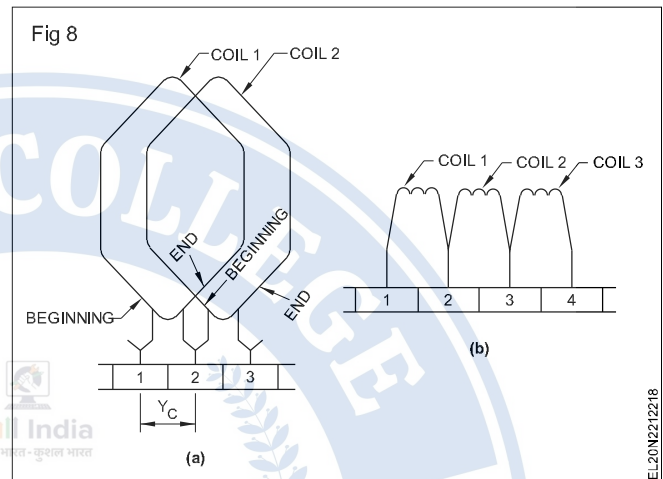
Commutator pitch (Y_C): It is the distance (measured in commutator bars or segments) between the segments to which the two ends of a coil are connected. It is denoted by Y_C . From the Figs 5,6 and 7, it is clear the commutator pitch $Y_C = 1$ segment.

The commutator pitch Y_C varies with the type of winding, like lap or wave as well as simplex or multiplex.

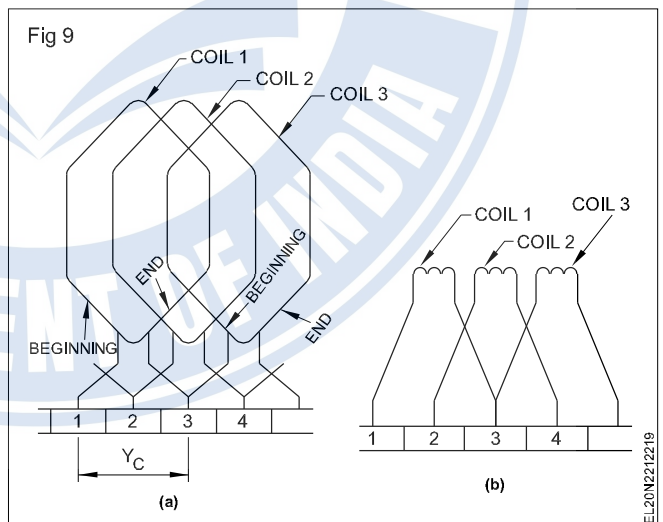
Types of DC armature windings

Lap and wave winding : The DC armature windings are classified into two main groups, lap and wave windings. The difference between them is the manner in which, the leads are connected to the commutator segments.

Simplex lap winding : In a simplex lap winding, the end lead of coil 1 is connected to the beginning lead of the adjacent coil (coil 2) through the commutator segments. The commutator pitch of one segment is maintained. Fig 8 shows the lead connection of a simplex lap winding.



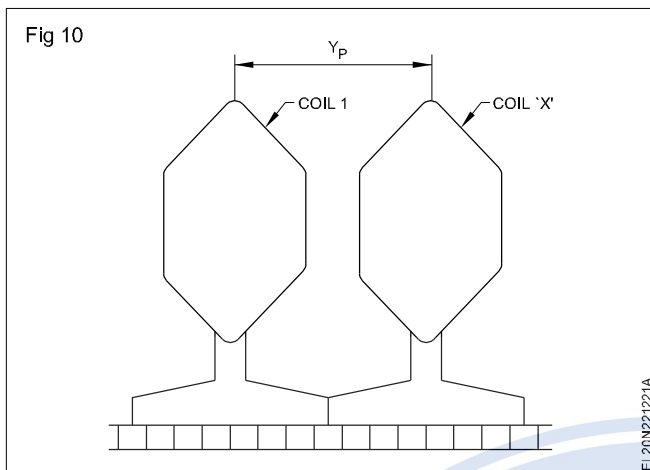
Duplex lap winding : In duplex lap winding, the end lead of coil 1 is connected to the beginning lead of coil 3, through commutator segments. The commutator pitch of two segments is maintained as shown in Figs 9a and b.



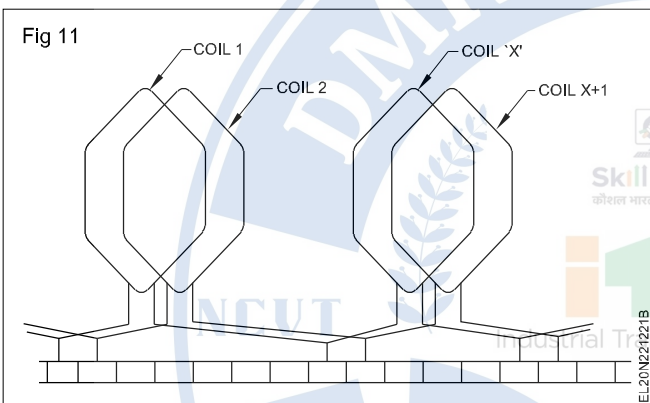
In triplex lap and quadruplex lap windings, the end leads of coil 1 are connected to the beginning leads of coil 4 and coil 5 respectively through commutator segments. In general commutator pitches

- $Y_C = 1$ segment for simplex lap winding
- $Y_C = 2$ segments for duplex lap winding
- $Y_C = 3$ segments for triplex lap winding
- $Y_C = 4$ segments for quadruplex lap winding.

Simplex wave winding : In simplex wave winding, the end lead of the coil 1 is connected to the beginning of a coil placed at a distance equal to one pole pitch. (Fig 10)



Duplex wave winding : In duplex wave winding there is parallel combination of two simplex wave windings as shown in Fig 11.

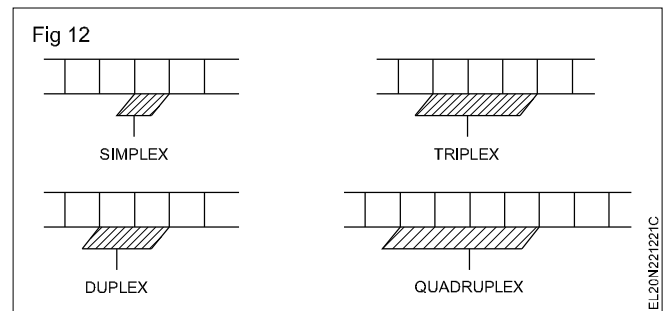


Triplex wave winding : Triplex wave winding will have a parallel combination of three simplex wave windings, and so on.

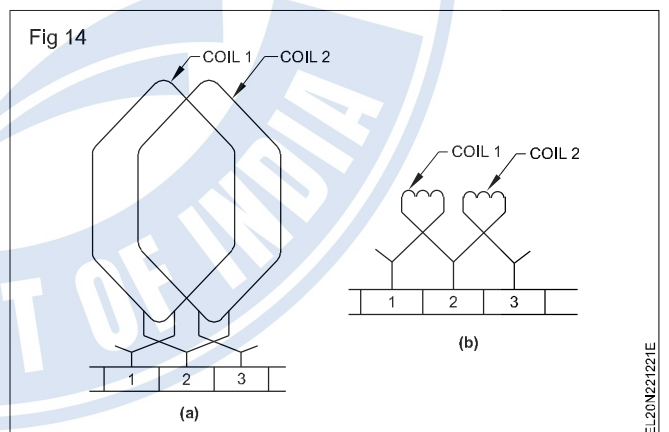
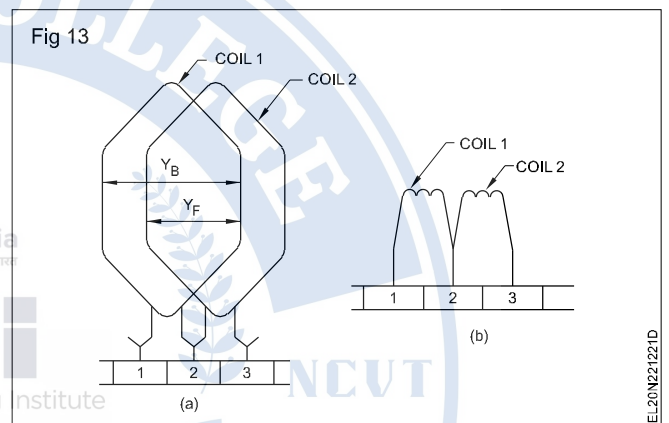
The width of the brush will be such that in simplex lap or wave winding, the brush will make contact with only one segment. The brush will contact two segments in duplex, three in triplex and four in quadruplex. (Refer to Fig 12)

Progressive lap or wave winding : In progressive lap or wave winding, the front pitch Y_F will be less than the back pitch Y_B , i.e. as you lay the coils clock-wise, the

connections to the commutator segments will also proceed clockwise as in Figs 13a and b. In progressive winding, Y_c is referred to as +1.



Retrogressive lap or wave winding: In retrogressive lap or wave winding, the front pitch Y_F will be greater than the back pitch Y_B , i.e. as you lay the coils clockwise, the connection to the commutator segments will proceed anticlockwise as shown in Figs 14 a & b. In retrogressive winding Y_c is represented as -1.



Simplex lap and wave winding - developed diagram

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

- state the conditions for Lap winding and wave winding
- calculate and draw the developed ring diagram for simplex lap and wave winding.

Development winding diagram : To draw the development winding diagram, the winding particulars like number of conductors, number of poles, pitches, types of windings etc. are required. For any DC armature winding, there shall be as many coils as the number of commutator segments. Further, the number of coils will be the multiple

of the number of slots, i.e. for a single layer, there will be double the number of slots as that of the commutator segments and for a double layer there will as many slots as the commutator segments.

Lap winding

Conditions for lap winding : For lap winding the following terms and conditions are to be fulfilled.

- The front pitch Y_F and the back pitch Y_B should be approximately equal to the pole-pitch Y_P .
- Both the front pitch Y_F and the back pitch Y_B should be an odd number.
- The back pitch Y_B and the front pitch Y_F should differ by 2 conductors, for simplex lap winding. In the case of multiplex winding, it is equal to $2 \times$ No. of 'plex'.

Ex. For duplex $2 \times 2 = 4$ conductors.

For triplex $2 \times 3 = 6$ conductors and so on.

The average pitch should be as given by the formula

Commutator pitch should be

$$Y_C = \pm 1 \text{ for simplex}$$

$$= \pm 2 \text{ for duplex}$$

$$= \pm 3 \text{ for triplex and so on.}$$

- The number of parallel paths 'A' in the armature will be the multiple of the number of poles. $A = P$, in the case of simplex lap winding, i.e 2-pole armature winding will have 2 parallel paths, 4-pole armature winding will have 4 parallel paths and so on. However, the number of parallel paths for multiplex winding will be equal to $A = P \times$ No. of 'plex'.
- There must be as many brushes as there are poles.
- The brushes must be wide enough to cover at least m segments, where 'm' is the 'plex' (multiplicity) of the winding.

Progressive winding

$$\text{Back pitch } Y_B = \frac{Z}{P} + 1$$

$$\text{Front pitch } Y_F = Y_B - 2 \times \text{plex}$$

Retrgressive winding

$$\text{Front pitch } Y_F = \frac{Z}{P} + 1 \quad \text{Back pitch } Y_B = Y_F - 2 \times \text{plex}$$

To make the winding possible as lap-winding, Z/P must be an even number.

Considering the above points, only the armature having the designated slots can be wound for lap winding.

Calculations : The following calculations are made for finding out winding pitches and coil connections with commutator segments for simplex lap winding.

Example

No. of commutator segments	6
No. of slots	6
No. of poles	2

Type of winding simple lap.

As pointed out earlier the winding should be in double layer only.

Solution

No. of coils = No. of commutator segments = 6 coils

No. of conductors or coil sides = No. of coils \times 2
 $= 6 \times 2 = 12$ conductors.

$$\text{Pole pitch } Y_P = \frac{\text{No. of slots}}{\text{No. of poles}} = 6/2 = 3 \text{ slots}$$

$$\text{Also } Y_P \text{ in terms of conductors} = \frac{\text{No. of conductors}}{\text{No. of poles}} = 12/2 = 6 \text{ conductors}$$

No. of conductors/slot = $12/6 = 2$ conductors/slots.

Hence the winding is double layer winding.

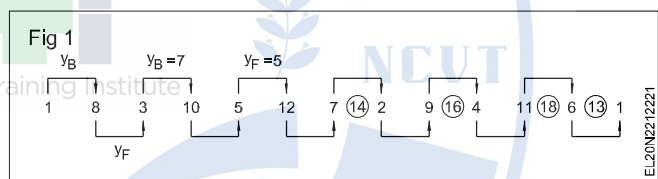
$$\text{Back pitch } Y_B = \frac{Z}{P} + 1 = 12/2 + 1 = 6 + 1 = 7$$

$$\text{Front pitch } Y_F = Y_B - 2 \times \text{Plex} = 7 - 2 = 5$$

$Y_B = 7$ and $Y_F = 5$ for progressive winding

$Y_B = 5$ and $Y_F = 7$ for retractive winding

The winding sequence of conductors for progressive lap winding is shown in Fig 1.



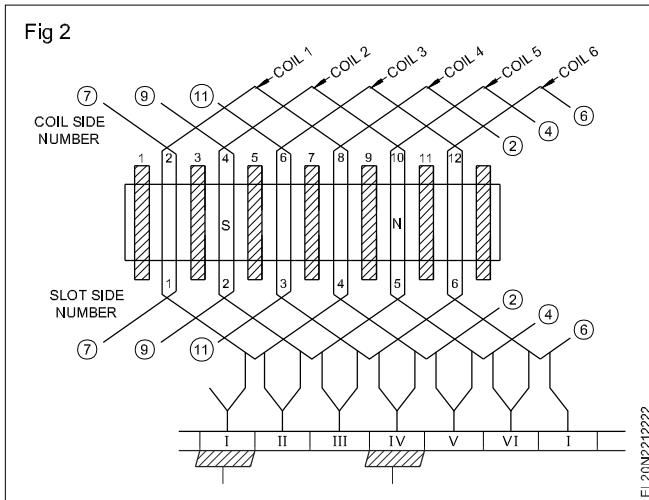
Winding Table

Coil	Conductor		Slot		Commutator segments	
	From	To	From	To	From	To
1	1	8	1	4	I	II
2	3	10	2	5	II	III
3	5	12	3	6	III	IV
4	7	2	4	1	IV	V
5	9	4	5	2	V	VI
6	11	6	6	3	VI	I

Development winding diagram for 12 conductors, 2 poles, 6 slots, 6 segments, simplex double layer lap winding

Fig 2 shows the arrangement of coils in the respective slots and the connection of the coils with the segments.

Development diagram with conductors : Fig 3 shows the arrangement of armature conductors in the slots and connections to commutator segments.

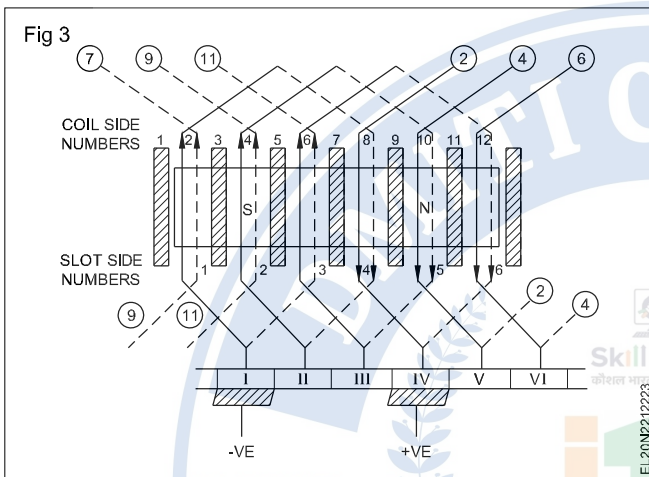


- The front pitch Y_F and back pitch Y_B should be approximately equal to the pole pitch Y_P .
- Both the front pitch Y_F and the back pitch Y_B should be an odd number.
- The back pitch Y_B and the front pitch Y_F may be of the same value or may differ by 2 conductors, in the case of simplex, and the same or 2 or 4 conductors for multiplex wave winding, depending upon the condition

$$Y_A = \frac{Y_B + Y_F}{2} \text{ approximately}$$

- The average pitch should be as given by the formula

$$Y_A = \frac{Y_B + Y_F}{2} \text{ (or)}$$



$$Y_A = \frac{\text{No. of conductors} \pm 2 \times \text{plex}}{\text{No. of poles}}$$

$$Y_A = \frac{Z \pm 2}{P} \text{ for simplex wave winding}$$

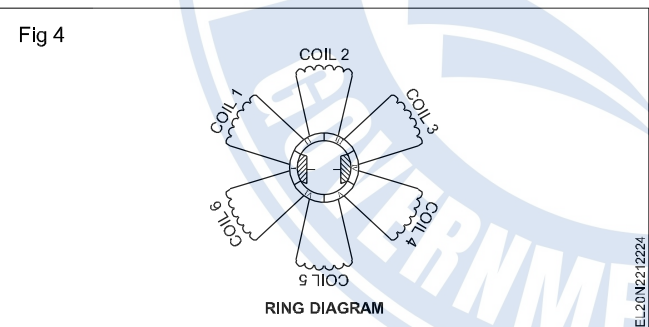
$$= \frac{Z + 2}{P} \text{ for progressive simplex wave winding}$$

$$= \frac{Z - 2}{P} \text{ for retrogressive simplex wave winding}$$

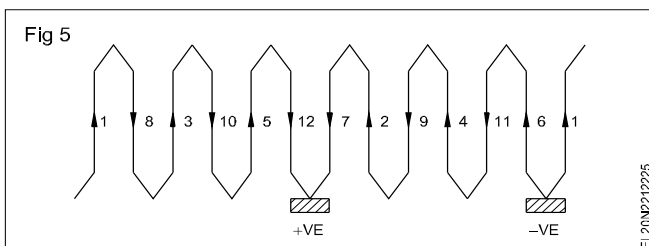
$$Y_A = \frac{Z \pm 4}{P} \text{ for duplex wave winding}$$

$$Y_A = \frac{Z \pm 6}{P} \text{ for triplex wave winding and so on}$$

Ring diagram : Fig 4 shows the connection of 6 coils with the commutator segments in the form of a ring diagram.



Sequence diagram : This diagram is mainly used to trace the direction of current in the coil sides (conductors). With the help of this diagram the brush position can be located. (Fig 5)



Wave winding

Conditions for wave winding : For wave winding, the following terms and conditions should be fulfilled.

$$Y_C = \frac{\text{No. of commutator segments} \pm m}{\text{Pairs of poles}} = \frac{C \pm m}{p/2}$$

where Y_c is the commutator pitch

C = total number of commutator segments

p = number of poles

m = the plex of the winding.

The commutator pitch Y_c shall be equal to the average pitch

$$Y_A \cdot Y_c = Y_A$$

The resultant pitch is the sum of the front and back pitches. $Y_R = Y_B + Y_F$

- The number of coil sides must satisfy the following relations.

$$Z = P \times Y_A \pm 2 \text{ where } P \text{ is the number of poles.}$$

- In the case of simplex wave winding the number of parallel paths 'A' is equal to 2 only, irrespective of the number of poles. However the number of parallel paths increases in multiples of the plex of the windings.

Eg. $A = 2 \times \text{plex.}$

Considering the above points, only an armature having designated slots can be wound for wave winding.

- Two brushes are necessary, but as many brushes as there are poles may be used, and they must be set so that they short-circuit only the coils cutting no flux.
- The brushes must be wide enough to cover atleast 'm' segments where 'm' is the 'plex' of the winding.

Calculations : The following calculations are made for finding out winding pitches and coil connections with commutator segments for simplex wave winding.

Example

Number of commutator segments	7 Nos.
Number of slots	7 Nos.
Number of poles	2 Nos.
Type of winding	Wave.

Winding table

- The number of coils = Number of commutator segments = 7 coils.
- The number of conductors or No. of coil sides = No. of coils x 2 = 7 x 2 = 14 conductors.

3 Pole pitch $Y_p = \frac{\text{No. of slots}}{\text{No. of poles}} = 7/2 = 3.5$ slots, say 3 slots

Also, $Y_p = \frac{\text{No. of conductors}}{\text{No. of poles}} = 14/2 = 7$ conductors

- No. of conductors/slot = $14/7 = 2$ conductors/slot. Hence, the winding is double layer.

5 Average pitch $Y_A = \frac{Z \pm 2}{P}$
 $= \frac{14 + 2}{2} = 16/2 = 8$ (for progressive winding).
 $= \frac{14 - 2}{2} = 12/2 = 6$ (for retrogressive winding).

Hence $Y_A = Y_C = 8$ or 6 .

- Taking $Y_A = 8$ for progressive winding we have

$$2Y_A = 2 \times 8 = 16 = Y_B + Y_F$$

$$Y_B - Y_F = 2$$

$$Y_B + Y_F = 16.$$

Hence back pitch $Y_B = 9$ and front pitch $Y_F = 7$.

- Taking $Y_A = 6$ for retrogressive winding we have

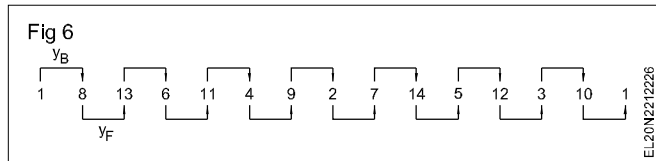
$$2Y_A = 2 \times 6 = 12 = Y_B + Y_F$$

$$Y_B - Y_F = 12.$$

Hence, back pitch $Y_B = 7$ and front pitch $Y_F = 5$ for retrogressive wave winding.

The winding sequence of conductors for retrogressive wave winding is shown in Fig 6.

$$Y_B = 7, Y_F = 5.$$

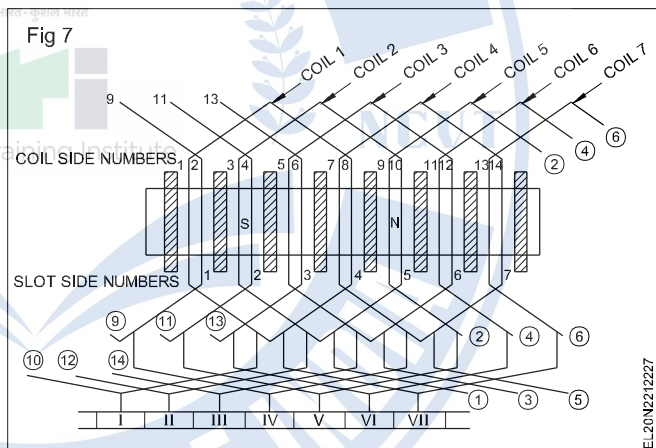


Winding Table

Coil	Conductor		Slot		Commutator segments	
	From	To	From	To	From	To
1	1	8	1	4	I	VII
2	13	6	7	3	VII	VI
3	11	4	6	2	VI	V
4	9	2	5	1	V	IV
5	7	14	4	7	IV	III
6	5	12	3	6	III	II
7	3	10	2	5	II	I

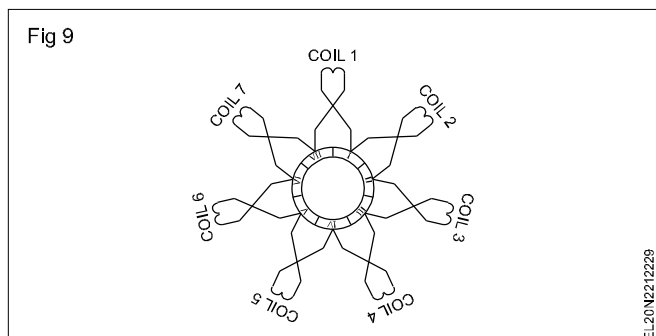
Development winding diagram for 14 conductors, 2 poles, 7 slots, 7 segments, simplex, double layer wave winding

Development diagram with coil connection : Fig 7 shows the arrangement of coils in their respective slots and their connection to the segments.

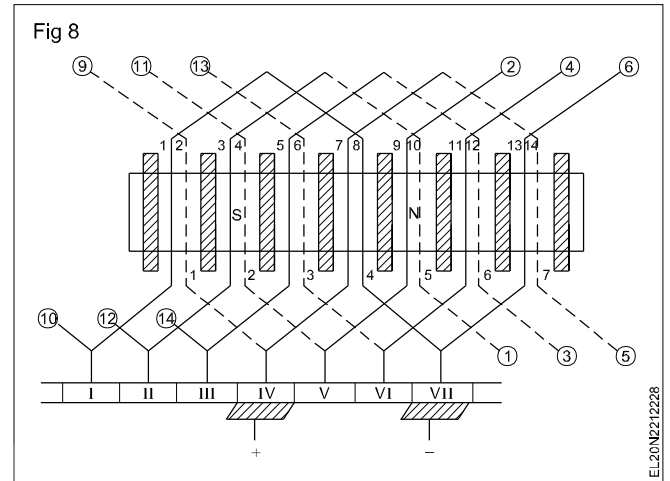
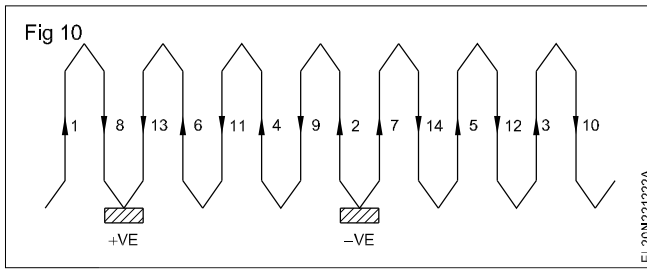


Development diagram with conductors : Fig 8 shows the arrangement of armature conductors in the slots and the connection to commutator segments.

Ring diagram : The ring diagram of wave winding in the case of a 2-pole armature will appear similar to that of lap winding, but the coil ends will be connected as shown in Fig 9.



Sequence diagram : This diagram (Fig 10) is mainly used to trace the current direction of the coil sides (conductors) and, thereby, locate the brush position. Please note the brush is placed at a distance of 3 commutator segments i.e. less than 180° geometrical (app.155°).



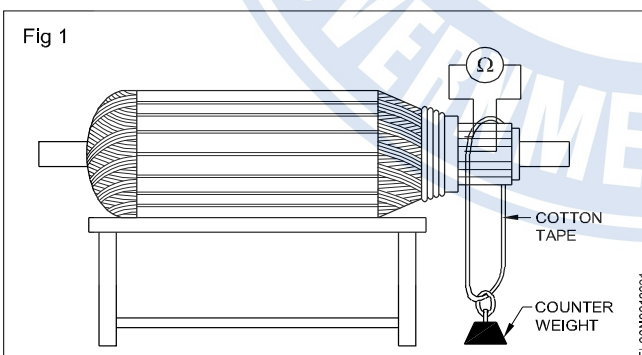
Testing of armature winding

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

- describe the methods of testing armature, such as the
 - winding resistance test
 - insulation resistance test
 - growler test
 - voltage drop test.

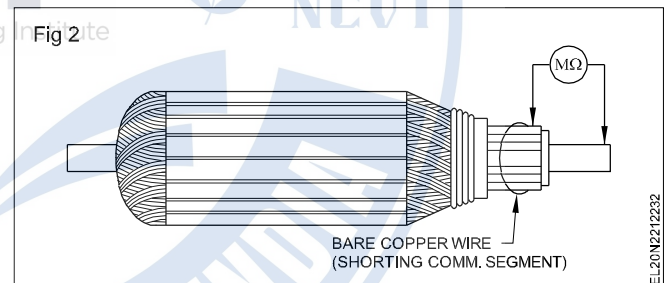
Testing the winding : After an armature is wound and the leads are connected to the commutator, a test should be conducted. From this test, defects may be revealed, which might have occurred during winding. The common defects in armature windings are grounding, shorts in the coils, open in the coil and reversal in the coil connection. These defects can be located by different test procedures.

Armature winding resistance test : Resistance of the armature coil is measured by using a low range ohmmeter and preferably with the Kelvin bridge. Resistance between consecutive segments in the case of simplex lap winding (for wave and multiplex windings at a distance of commutator pitch Y_c) is measured. Fig 1 shows a simple arrangement to measure the resistance between the successive commutator segments.



As shown in Fig 1, a cotton tape with a counterweight is passed around the commutator to hold the connecting leads to the segments. Measurement of resistance is done in all the coils by changing the position of the connecting leads to successive commutator segments. The resistance measured should be the same in all coils. Lower resistance shows short in turns, while a higher resistance shows higher numbers of turns or open in the coil.

Insulation resistance test : With a bare copper wire short all the commutator segments. (Fig 2) Test the insulation resistance between the body and the commutator segments by a 500V Megger, for armatures rated up to 250 volts. The IR so measured shall be greater than 1 megohm. If the value is less than 1 megohm, moisture in the winding or a weak insulation is to be suspected.



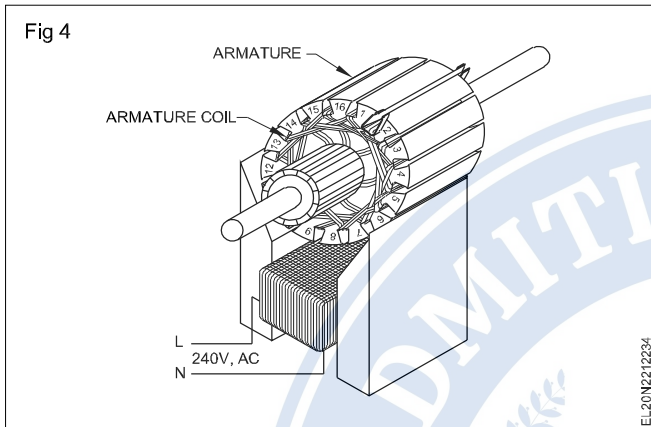
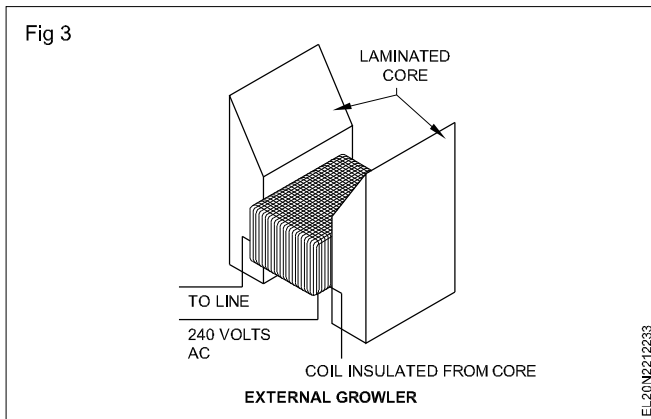
This test is sometimes conducted by a series test lamp and is called the 'ground test'. It will only indicate if any coil is grounded, and not the insulation resistance.

Growler test : A simple and most common method to test armature winding for short and open coils is by a growler.

Growler : There are two types of growlers - 1) internal and 2) external growlers. An external growler is used for testing small armatures and an internal growler for large DC armatures and AC motor stator windings.

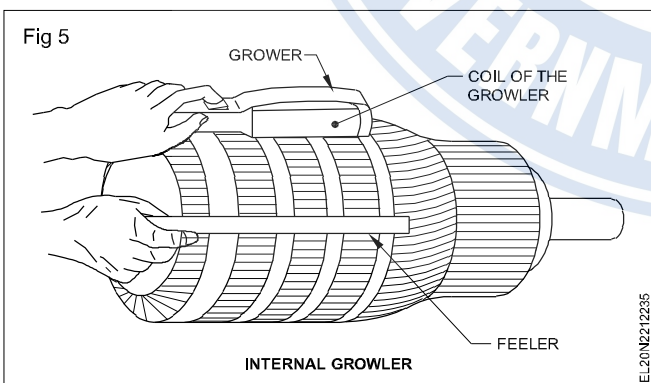
External growler : An external growler, shown in Fig 3, is an electromagnetic device that is used to detect and locate grounded, shorted and open coils in an armature.

This growler consists of a coil wound around an iron core and is connected to a 240 volt AC line. The core is generally H shaped and cut out on top so that the armature will fit on it, as shown in Fig 4.



When an alternating current is applied to the growler coil, the voltage will be induced in the armature coils by transformer action.

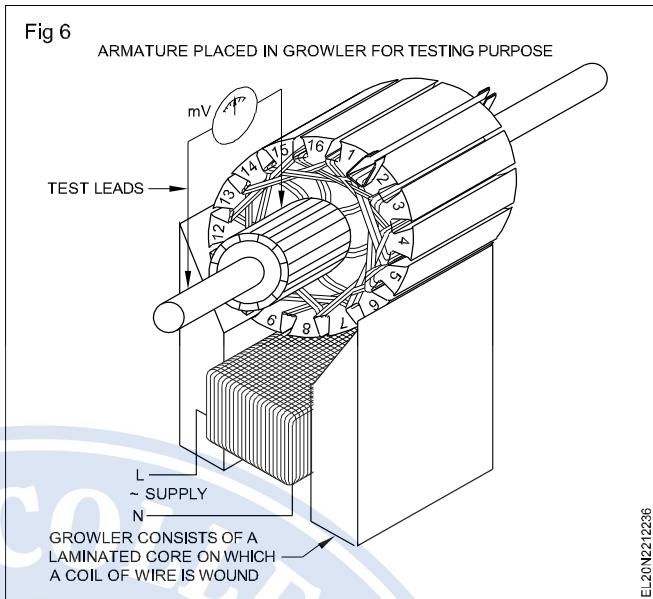
Internal growler : An internal growler, such as the one used for stators, may be used for armatures as well. These are made with or without built-in feelers. The growler with a built-in feeler has a flexible blade attached to the growler so that a hacksaw blade or similar instrument is not necessary. This type is especially desirable in smaller stators that have no room for a separate feeler. Fig 5 shows an internal growler with a separate feeler, used for large armatures.



Growler test for grounded coil : The armature to be tested is placed on the growler and then the growler is switched 'ON'. Place one lead of an AC milli-volmeter on the top commutator bar and the other meter lead on the shaft, as shown in Fig 6.

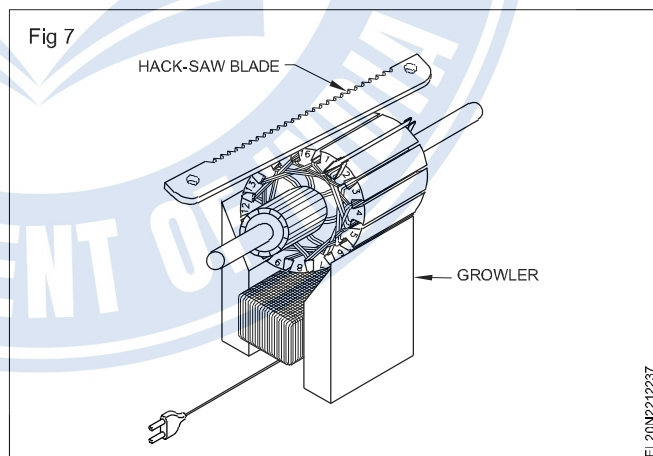
If a reading is noticed on the meter, turn the armature so that the next commutator bar is in the same position as the earlier one, and test as before. Continue in this manner

until all the bars are tested. Where the meter gives no deflection, it is an indication that the grounded coil is connected to this particular bar.



Growler test for shorted coil : The procedure to test for short circuits in an armature is as follows.

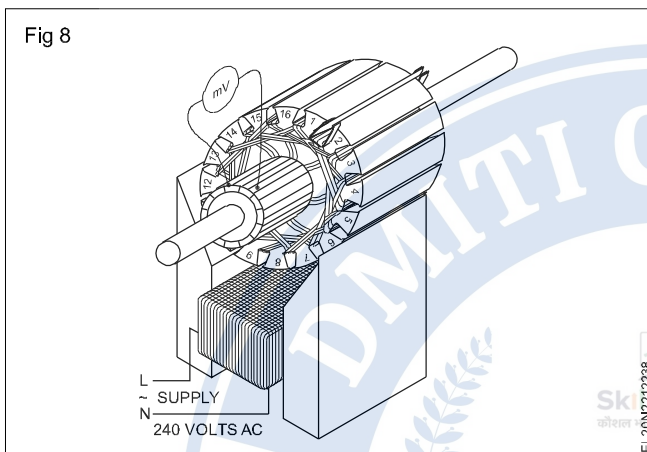
The armature to be tested is placed on the growler and then the growler is switched on. A thin piece of metal, such as a hacksaw blade, is held over the top slot of the armature as shown in Fig 7. In case of short in the winding, the blade will vibrate rapidly and create a growling noise. If the blade remains stationary, it is an indication that no short exists in the coil under test. After several top slots have been given the hacksaw blade test, turn the armature so that the next few slots are on top. Test as before and continue this procedure for the entire armature.



An armature having cross connections or equalizers cannot be given the hacksaw blade test. This type of armature will cause the blade to vibrate at every slot, which would seem to indicate that possibly every coil is shorted.

Test for open coil : Growlers are also provided with meters (milli-volt or ammeter) on the panel with variable resistance. In this case an open in the armature coil can be found out as follows.

Growler test for an open coil : To locate an open coil with a growler, set up the armature on the growler in the usual manner. Test the top two adjacent bars with an AC milli-voltmeter as shown in Fig 8. Rotate the armature and continue testing the adjacent bars. When the milli-voltmeter bridges the two bars connected to the open coil, the meter pointer will not deflect. All the other bars will give a deflection. This test for an open coil can be made without the meter by shorting the two top bars with a piece of wire. Absence of a spark indicates that the coil is open. The open may be either at the commutator bar or in the coil itself. The procedure may be used to determine the location of the leads of a shorted coil. However, the hacksaw blade test is the most satisfactory method of determining a shorted coil.



Drop test : The most accurate method of testing the armature for correct resistance, number of turns, short and open and reversed coil connection is by the drop test. Connect a low voltage DC supply across the commutator segments at a distance of pole pitch. Insert a variable resistance in series with the circuit. Switch 'ON' the DC supply and connect a milli-voltmeter to the adjacent segments as in Fig 9a and b.

Adjust the readings to a specified value, by using a variable rheostat. Record the milli-voltmeter readings on the consequent commutator segments by rotating the armature

in one direction. The position of the segments and the connection should be the same as in the first set up. The result could be concluded as enumerated below.

- If all the readings are the same, the winding is correct.
- If the milli-voltmeter reads zero or low voltage, the coil connected to the segment is short.
- If the milli-voltmeter reads high voltage, the coil connected to the segment is open.
- If the milli-voltmeter deflects in the reverse direction as shown in Fig 9b, the coil connected with the segment is reversed.

Generally armatures are tested as a routine for insulation resistance and for shorted coils. Only when a fault in the armature winding is suspected, a drop test is conducted.

