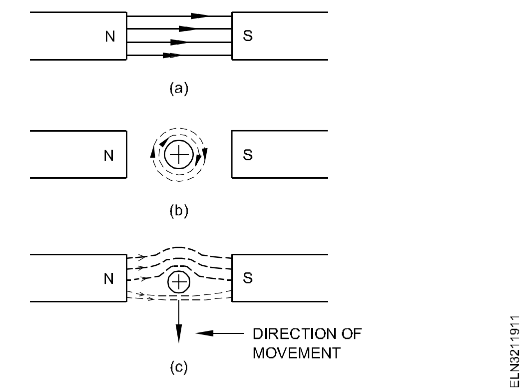
DC motor - principle and types

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. The DC motor needs frequent care and maintenance by qualified electricians. Hence more job opportunities exist in this area for an electrician.

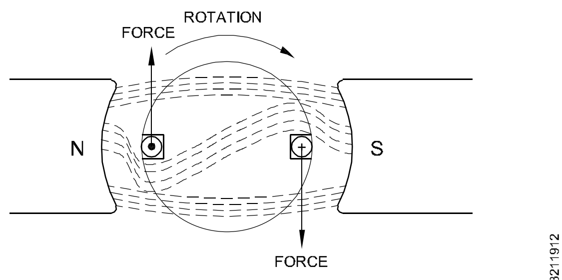
Principles of a DC motor: It works on the principle that whenever a current-carrying conductor is kept in a uniform magnetic field, a force will be set up on the conductor so as to move it at right angles to the magnetic field. It can be explained as follows. Fig 1a shows the uniform magnetic field produced 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.

Fig 1



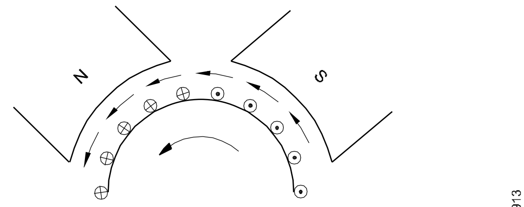
If the conductor in Fig 1 is replaced by a loop of wire as shown in Fig 2, the resultant field makes one side of the conductor move upwards and the other side move downwards. It forms a twisting torque over the conductors, and they tend to rotate, if they are free to rotate. But in a practical motor, 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.

Fig 2



REACTION OVER A CURRENT CARRYING LOOP BY THE MAGNETIC FIELD

Fig 3



REACTION OVER THE ARMATURE CURRENT CARRYING CONDUCTORS BY THE MAGNETIC FIELD

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.

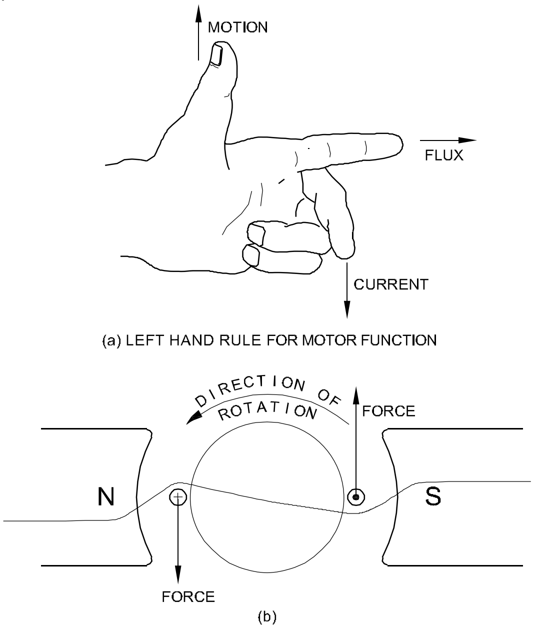
Fleming's Left Hand Rule: The direction of force produced on a current-carrying conductor placed in a magnetic field can be determined by this rule. As shown in Fig 4a, hold the thumb, forefinger and middle finger of the left hand mutually at right angles to each other, such that the forefinger is in 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.

Fig 4

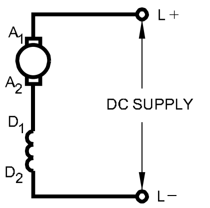


(a) LEFT HAND RULE FOR MOTOR FUNCTION

(b)

FLEMING'S LEFT HAND RULE

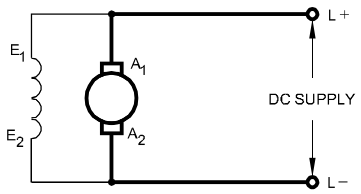
Fig 5



SERIES MOTOR

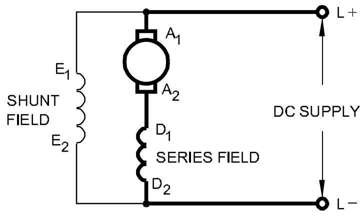
When the motor has two field coils, one in series with the armature and the other in parallel with the armature, as shown in Fig 7, it is called a compound motor.

Fig 6



SHUNT MOTOR

Fig 7



COMPOUND MOTOR

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

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

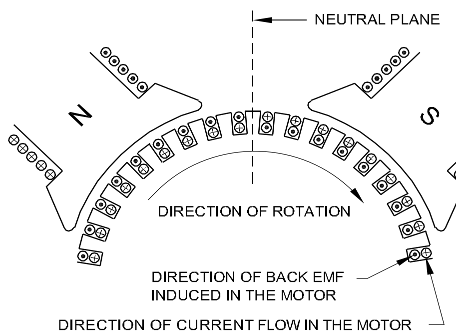
$$E_b = \frac{\varnothing ZNP}{60A} \text{ volts}$$

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_aR_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

Fig 1



$V = E_b + I_aR_a$.

Alternatively, $I_aR_a = V – E_b$.

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

$$E_b = V - I_a R_a$$

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

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

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

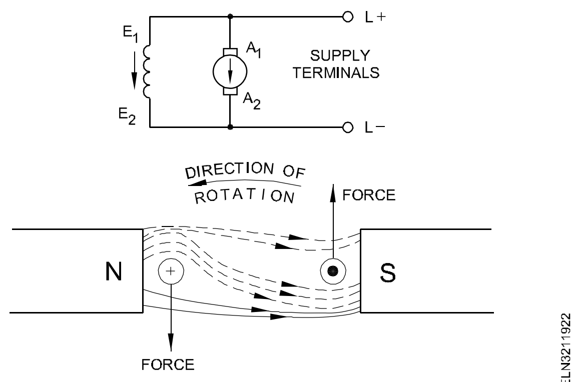
$$\text{where } K = \frac{60A}{ZP}$$

Therefore $N = K\, E_b/\varnothing$.

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

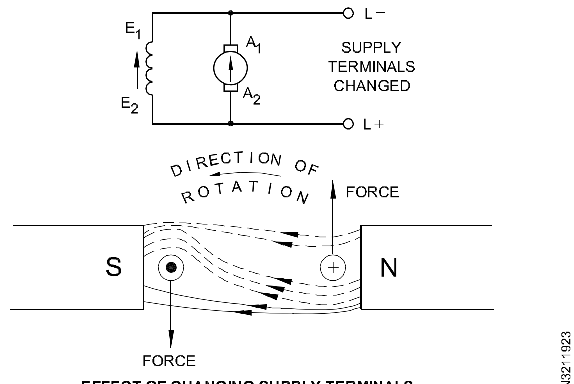
Reversing the direction of rotation of DC motors: The direction of rotation of a DC motor can be changed either by changing the direction of the armature current or by changing the direction of the field current. The direction of rotation of a DC motor cannot be changed by interchanging the supply connections because this changes the direction of the field as well as the armature current. Its effect is as shown in Figs 2 and 3.

Fig 2



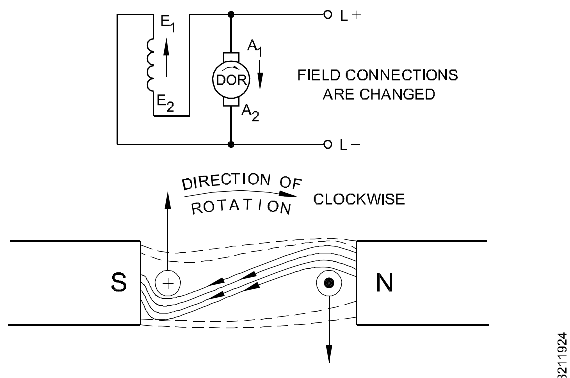
But when the field current direction alone is changed, the direction of rotation changes as shown in Fig 4. When the armature current direction alone is changed, the direction of rotation changes as shown in Fig 5.

Fig 3



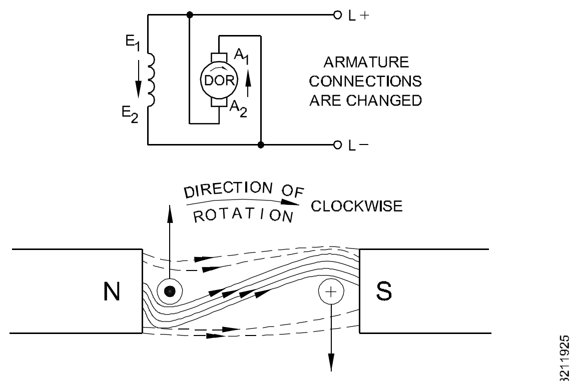
EFFECT OF CHANGING SUPPLY TERMINALS

Fig 4



EFFECT OF CHANGING THE FIELD CURRENT DIRECTION

Fig 5



EFFECT OF CHANGING THE ARMATURE CURRENT DIRECTION

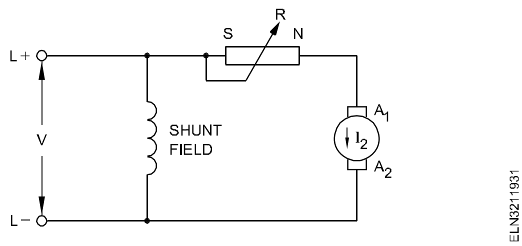
To reverse the direction of rotation of a compound motor without changing its characteristics, the best method is to change only the armature current direction. In case, changing the direction of rotation needs to be done by changing the field terminals, it is essential to change the current direction in both the shunt and series windings. Otherwise, the machine, which was running as cumulatively compounded, will change its characteristic as differentially compounded or vice versa.

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.

Fig 1



In addition to the automatic inclusion of resistance at the time of starting, the starters may protect the motor from overload and will switch `off' the motor, when supply fails. These starters are named according to the number of connecting terminals as explained subsequently.

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

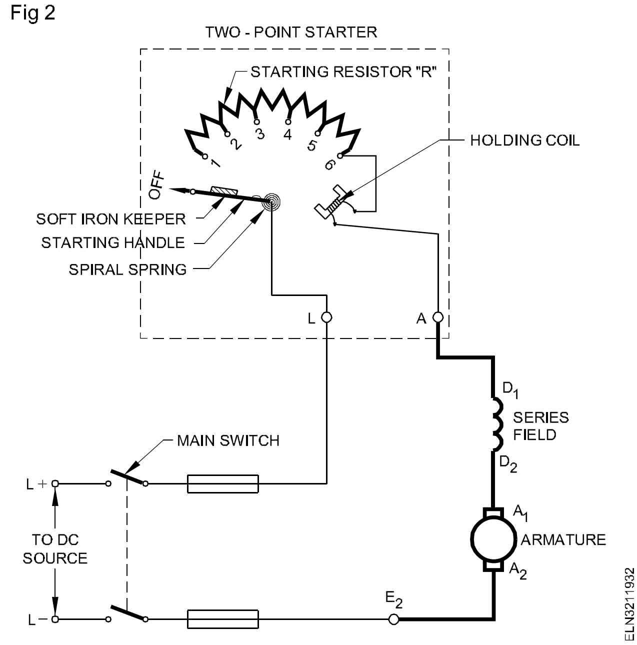
- Two-point starter
- Three-point starter
- Four-point starter

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.

Fig 2

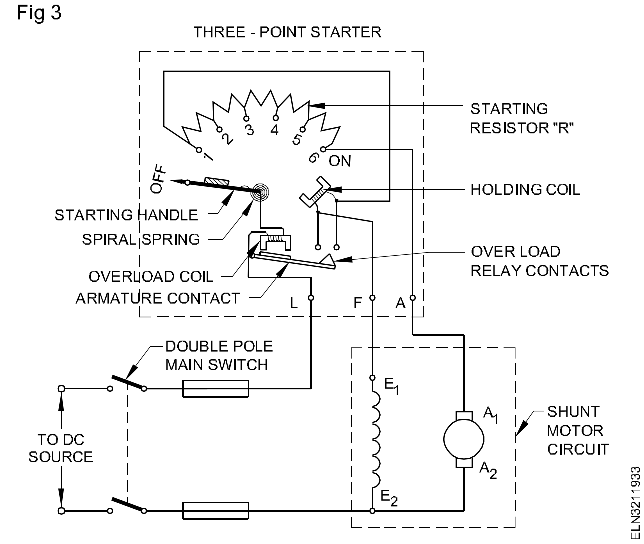


When the arm is moved to the first contact point, the circuit is completed, and the armature begins to rotate. As the armature speed increases, the arm is slowly moved towards the right side electromagnet, thereby the starter resistance is reduced. When the arm is against the electromagnet, complete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

The electromagnet is wound with a thick gauge wire to carry the rated armature current of the motor. This holds the handle in the `ON' position when the motor is working. The handle comes back to the `OFF' position, due to spring action when the electromagnet demagnetises due to failure of supply. This starter in general will not have protection against overloads.

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.

Fig 3



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.

The holding coil is connected in series with the shunt field to provide a `no-field release'. If the field circuit opens by accident, the motor speed will become excessive should the armature remain connected across the line. To prevent this increase in speed, the holding coil is connected in series with the field. In case of an open circuit in the field, there will be no current through the holding coil, and hence, it will be demagnetized, and the spring action returns the arm to the `off' position.

An overload coil is provided to prevent damage to the motor from overload. Under normal load condition, the flux produced by the O/L 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 O/L 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.

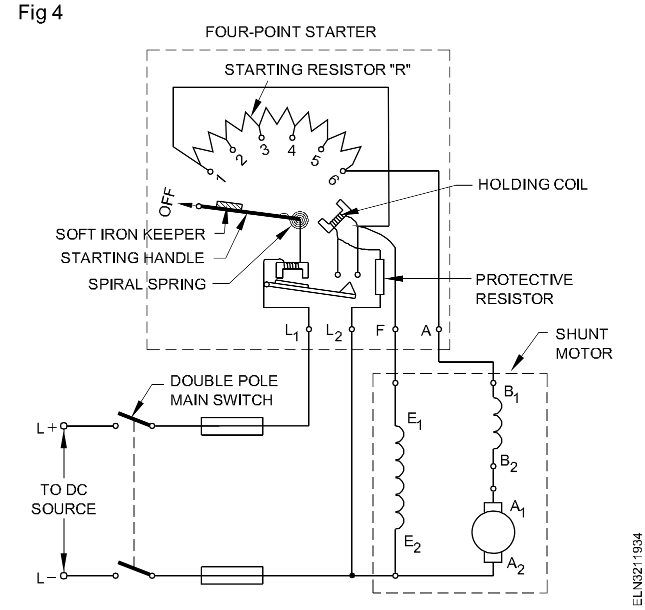
This type of starter can be used to start both shunt and compound motors.

However, a 3-point starter will be found to be tripping when the motor speed is controlled through the field regulator. The reason could be explained as stated below.

When the speed of a shunt or compound motor is to be increased beyond its rated speed, the resistance is increased in the field regulator to reduce the field current, and thereby, the field flux. While doing so, the holding coil which is in series with the field gets very low current and produces less holding force on the handle armature against the tension of the spiral spring. When the current reduces below a certain value, the handle is pulled out from the `ON' position to the `OFF' position. This is an undesirable effect. To avoid this, the 3-point starter circuit is modified, and the holding coil circuit is made independent of the field circuit. Such a starter is called a 4-point starter.

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.

Fig 4



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

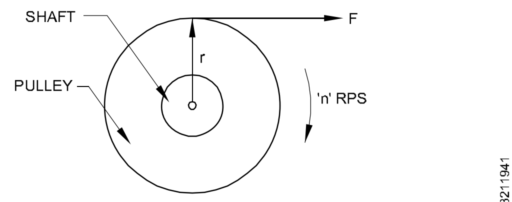
Objectives: At the end of this lesson you shall be able to
- **explain the relation between torque, flux and armature current**
- **solve problems pertaining to metric HP; load current, rated voltage, torque and speed of DC motors.**

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.

Fig 1



TORQUE PRODUCTION IN A MOTOR

Then torque T = F x r Newton-metres(N-m)

Work done by this force in one revolution = Force x distance

= F x $2\pi r$ joules.

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

= (Fxr)$2\pi n$ watts

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

(F x r) = Torque T

Power developed = T x ω watts

P = $T\omega$ watts.

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

We get $E_b I_a = T_a 2\pi n$

Since $E_b = \dfrac{\varnothing ZnP}{A}$ volts (By taking `n' in r.p.s.)

$$T_a \times 2\pi n = \frac{\varnothing ZnP}{A} \times I_a$$

By cross multiplication we get

$$T_a = \frac{\varnothing ZP \times I_a}{2\pi A} \text{ Newton - metre}$$

$$\text{or } T_a = \frac{0.159\ \varnothing ZP}{A} \times I_a \text{ Newton - metre}$$

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

$\dfrac{0.159\ ZP}{A}$ can be reagrded as constant 'K'

Then $T_a = K\varnothing I_a$

where Ø is the flux pole in weber

I_a is the armature current

$$K = \frac{0.159\ ZP}{A}$$

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

$$T_a \text{ is } = \frac{9.55 \times E_b I_a}{N} \text{ Newton - metre}$$

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.

$$\text{One H.P. metric} = \frac{2\pi n T_{sh}}{735.5} = \frac{2\pi N T_{sh}}{60 \times 735.5} \text{ HP}$$

where 'n' is the speed is 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.

Newton metre = Kg. metre x 9.81

Example 1: A 250V, 4 pole, wave-wound DC series motor has 782 conductors in its armature. It has a combined armature and series field resistance of 0.75 ohms. The motor takes a current of 40 A. Estimate its speed, armature torque and H.P. if the flux per pole is 25 milli-weber.

$E_b = V - I_a R_a$

= 250 – (40 x 0.75)

= 250 – 30 = 220 volts

Therefore, $E_b = \frac{\varnothing ZnP}{A}$ volts

$$N = \frac{E_b \times 60 \times A}{\varnothing ZP} = \frac{220 \times 60 \times 2}{25 \times 10^{-3} \times 782 \times 4}$$

$$= \frac{220 \times 60 \times 2 \times 10^3}{25 \times 782 \times 4} = 338 \text{ rpm.}$$

$$T_a = \frac{9.55 \times E_b I_a}{N} = \text{Nm}$$

$$T_a = \frac{9.55 \times 220 \times 40}{338} = 248.64 \text{ Nm.}$$

Assuming armature Torque T_a = Shaft torque T_{sh}

$$\text{Metric H.P.} = \frac{2\pi NT_{sh}}{60 \times 735.5} = \frac{2 \times 22 \times 338 \times 248.64}{7 \times 60 \times 735.5}$$

$= 11.97$ HP metric.

Example 2: A 220V DC shunt motor runs at 500 r.p.m. when the armature current is 50A. It has an armature resistance of 0.2 ohm. Calculate the speed if the torque is doubled.

The torque is proportional to I_a and Ø. But Ø is constant for shunt motor T a I_a.

Therefore, T_{a1} a I_{a1} and T_{a2} a I_{a2}.

Therefore, $\frac{T_{a2}}{T_{a1}} = \frac{I_{a2}}{I_{a1}}$

As T_{a2} is double of T_{a1} we have $\frac{T_{a2}}{T_{a1}} = 2$

$$2 = \frac{I_{a2}}{I_{a1}} = \frac{I_{a2}}{50}$$

Therefore I_{a2} = 50 x 2 = 100 amps.

$E_{b1} = V - I_aR_a$

= 220 – (50 x .2)

= 220 – 10 = 210 volts

$E_{b2} = V - I_aR_a$

E_{b2} = 220 – (100 x .2)

= 220 – 20 = 200 volts.

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

$$= \frac{N_2}{500} = \frac{200}{210}$$

$$\text{Therefore, } N_2 \; \frac{200 \times 500}{210} = 476 \text{ rpm.}$$

Service and maintenance of DC motor starters

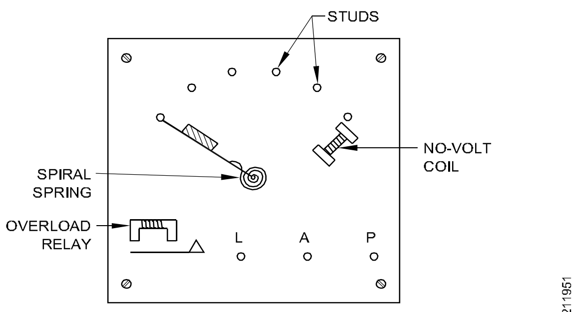
Objectives: At the end of this lesson you shall be able to
- **explain the procedure of service and troubleshoot the DC motor starter**
- **state how to check the handle for its spring tension and contact pressure against the studs**
- **state how to check the no-volt coil assembly**
- **explain the 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 semi- 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.

Figs 2 and 3 show the schematic diagrams of 3 and 4 point starters respectively.

Handle: The handle of the face plate starter consists of a movable arm attached with a spiral spring which acts against the magnetic action of the no volt coil. In case the spring becomes weak, the arm will not come to the off position even though the supply fails.

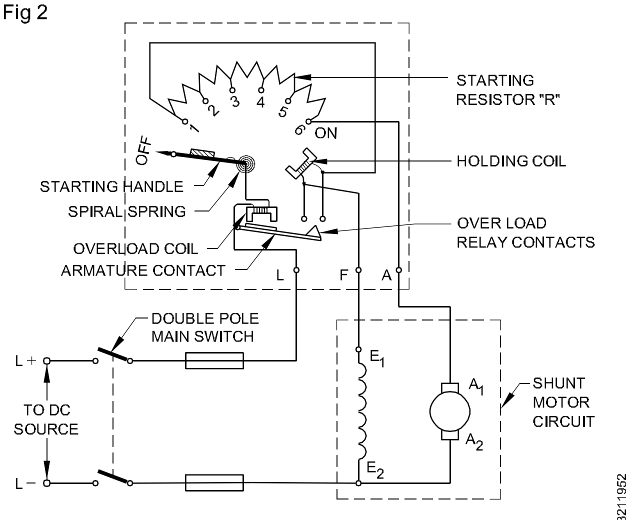
Fig 1



FACE PLATE ARRANGEMENT

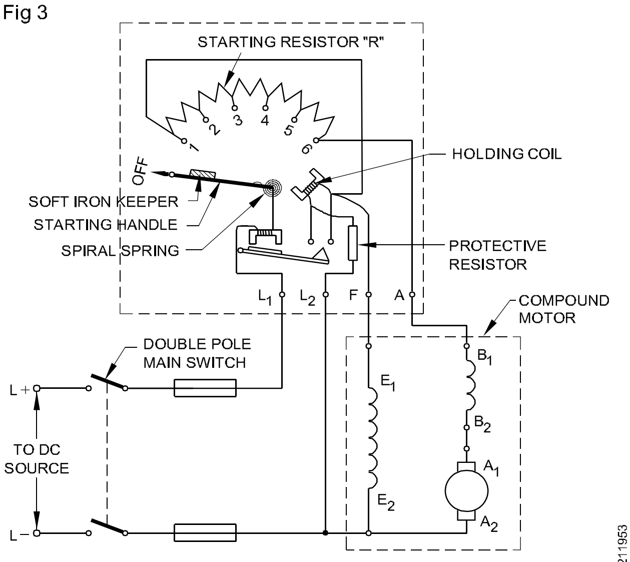
During the course of maintenance these points have to be checked. If the starter handle does not come to the off position in case of power failure, it is necessary to replace the spring as per the manufacturer specification. Also ensure during maintenance, proper pressure of the movable contact of the arm is available against the brass studs of the face place. 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 4.

Fig 2



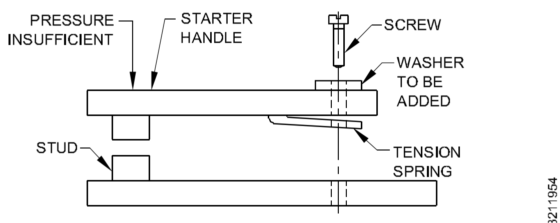
THREE - POINT STARTER

Fig 3



FOUR – POINT STARTER

Fig 4

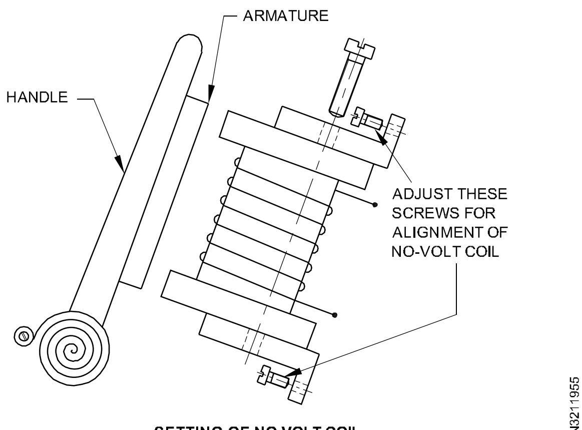


ADJUSTING THE STUD PRESSURE

Maintenance and servicing of no-volt coil assembly: The no-volt coil is connected in series with the field winding in the case of 3-point starter and in parallel with the supply through a limiting resistance in the case of 4 point starter. The no-volt coil is wound with a thin insulated wire and has a few number of turns.

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 5).

Fig 5

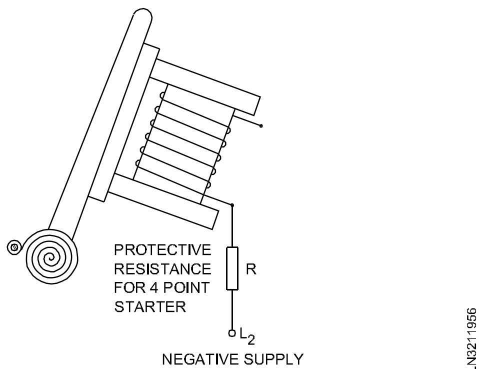


SETTING OF NO-VOLT COIL

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. Periodically check these values and compare these with original manufacturer's data. In any case, at any time if the value falls below 80% of the normal value, then replace it with a new no-volt coil of the same specification.

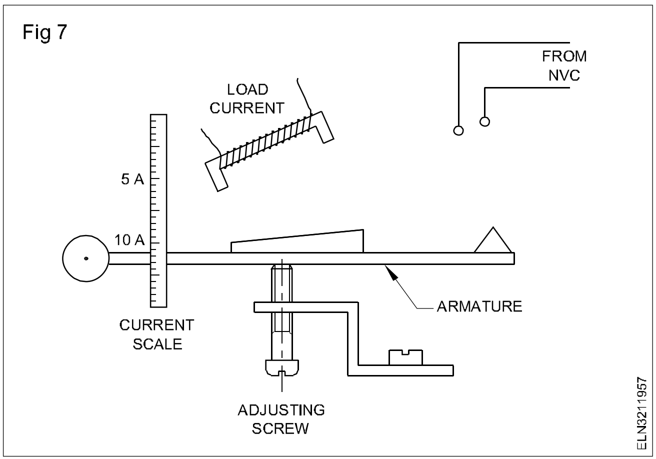
In the case of 4-point starter, the no-volt coil should be checked as mentioned above. If found OK, then the protective resistance should be checked with a multimeter. If found defective it has to be replaced with a resistance of same specification. (Fig 6.)

Fig 6



The overload relay coil is wound with thick gauge insulated wire suitable to carry the load current and has less turns. When the load current exceeds the set current, the magnetic strength of the overload coil assembly will be sufficient to attract the armature. The upward movement of the armature short-circuits the tapped contacts of the no-volt coil, thereby bypasses the current in the no-volt coil resulting in the demagnetisation of the no volt coil and releasing the handle to off position.

Maintenance of overload relay (Fig 7)**:** 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.

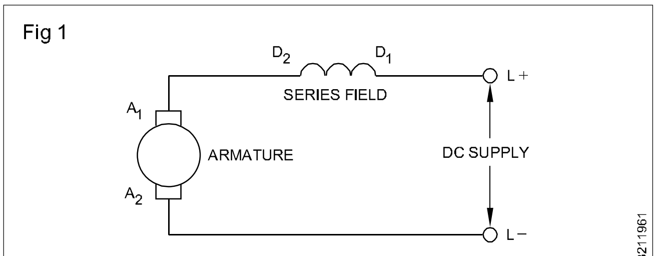
In the case of chattering noise observed at the no-volt coil the surfaces of the core assembly and armature need to be cleaned.

For the troubleshooting procedure follow the chart given in the trade practical exercise.

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**
- **explain the method of changing the direction of rotation of a DC series motor**
- **state the method of loading the motor and explain the brake test.**

DC series motors: The DC series motor, like the DC series generator, has its field connected in series with the armature as shown in Fig 1. Due to this mode of connection, all the current that flows through the armature must also flow through the field, and hence, the field strength varies with the change in the load.

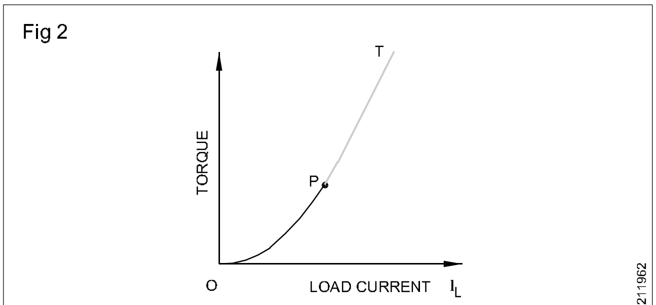


DC SERIES MOTOR CONNECTION

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.

Characteristics of DC series motors: The torque `T' in a DC motor is proportional to the flux `Ø' 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 V_s load and torque V_s 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 proportional to armature current and field flux. T a I_a Øse as $Ø_{se}$ is proportional to I_{se} and, further, I_{se} is proportional to the armature current. We have



TORQUE-LOAD CHARACTERISTIC

T a $I_a I_{se}$

T a $I_a I_a$

T a 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 (1.5^2) 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