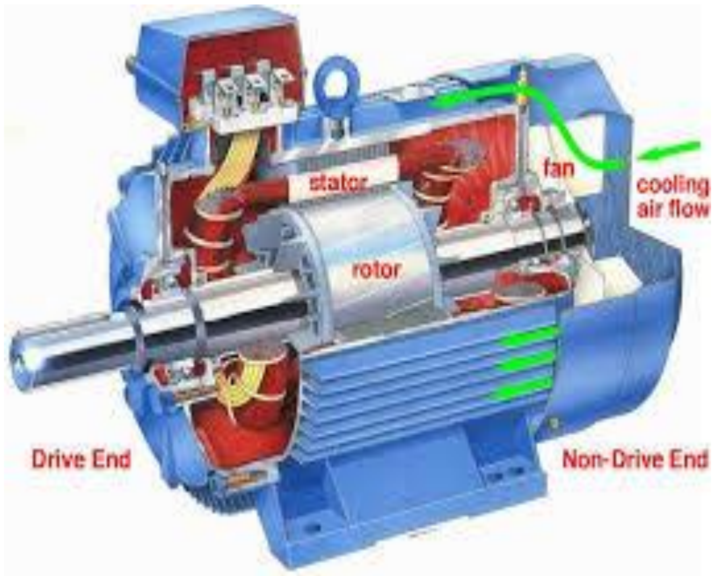


UNIT – III

DC Motors: Working principle – types of DC motors -Torque and Power developed by armature – characteristics of DC motors – Applications & numerical problems - Starting of DC motors - Constructional details of three point and four point starters – numerical problems - Speed control of DC motors – numerical problems.

INTRODUCTION

An electric motor is a machine which converts electrical energy into mechanical energy where as a generator is that machine which converts mechanical energy into electrical energy.

As regards fundamental principles the dc motors are identical with the dc generators which have the same type of excitation i.e. a machine that operates as a motor will also operate satisfactorily as a generator.

The only difference lies, however, in the mode of construction, which is due to the fact that the **frame of the generator can as a rule, be open but those of motors should be either partly or totally enclosed.**

A generator is usually placed in a suitable position and mechanical protection for the coils and armature may be reduced to minimum. Also the generator is handled by technical persons. Hence there is no risk in having the frame of the generator open, which facilitates cooling, inspection and repair.

On the other hand, **motors have to work in conditions of dampness; dirt, inflammable gases, chemical fumes and are liable to mechanical damage and, therefore, protection must be adequate** and motor frames are made flame proof, partly enclosed or totally enclosed according to the requirements of service.

The need for motive power has prompted the development of various kinds of electric motors. Since early electric power systems were direct current, the first motors were dc types: With the development of ac power systems. **The popularity of dc motor**

declined, mainly because of its higher cost and its need for more frequent and careful maintenance.

However, it never entirely disappeared partly because the **dc motor was inherently the most stable for smooth efficient, wide-range speed control and quick reversal** and partly because it was the only type that could be employed for **automotive and aircraft applications.**

WORKING PRINCIPLE OF DC MOTOR

The principle upon which a dc motor works is very simple. **If a current carrying conductor is placed in a magnetic field mechanical force is experienced on the conductor,** the direction of which is given by Fleming's left hand rule (also called motor rule) and hence the conductor moves in the direction of force. The magnitude of the mechanical force experienced on the conductor is given by

$F = BI_C l_C$ newtons

where B is the field strength in teslas (Wb/m^2), I_C is the current flowing through the conductor in amperes and l_C is the length of conductor in metres.

When the motor is connected to the dc supply mains, **a direct current passes through the brushes and commutator to the armature winding; while it passes through the commutator it is converted into ac** so that the group of conductors under successive field poles carry currents in the opposite directions, as shown in Fig. 3.1.

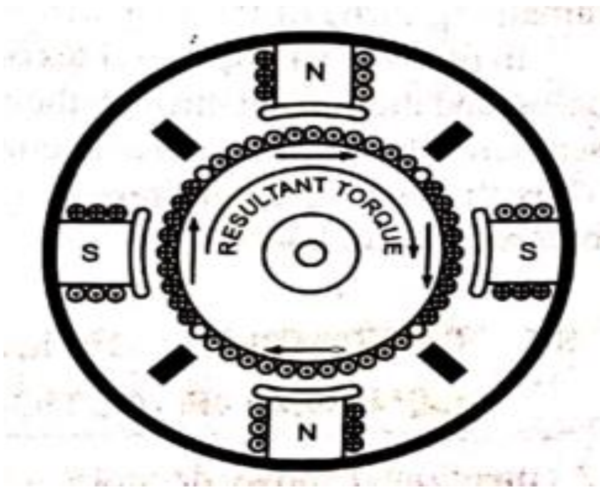
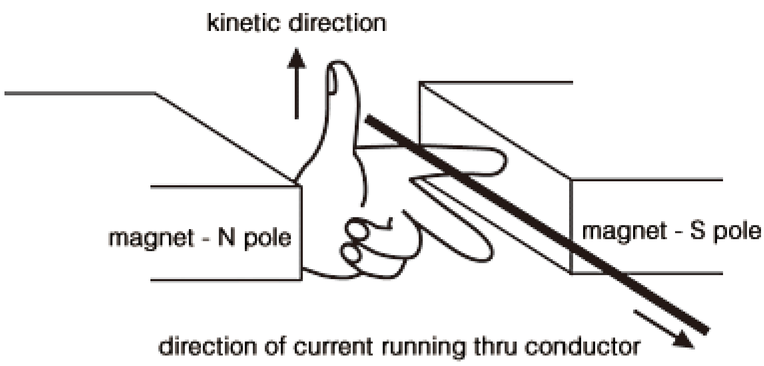


Fig 3.1.

Also the **direction of current, in the individual conductors reverses as they pass away from the influence of one pole to that of the next**.

In Fig 3.1, a 4-pole de motor is shown when the field and armature circuits are connected across de supply mains. Let the **current in armature conductors be outwards(coming out) under the N poles (shown by dots) and inwards (going in) under S-poles (shown by crosses).** By applying Fleming's left hand rule, the direction of force on each conductor can be determined,

From above figure, it is observed that **each conductor experiences a force which tends to rotate the motor armature in clockwise direction. These forces collectively produce a driving torque.Fleming's left hand rule.**The direction of force (motion) of a current carrying conductor in a magnetic field is given by Fleming's left hand rule.



It states that if we hold the thumb, index finger and middle finger of the left hand perpendicular to each other such that **the index finger points in the direction of magnetic field, the middle finger points in the direction of current, then the thumb shows the direction of force(motion) of the conductor**.

COMMUTATOR ACTION IN A DC MOTOR.

In the case of a dc motor, it is necessary that the **current through the coils of the armature winding be reversed** as a particular coil leaves one pole (say, the north pole), crosses the neutral line and comes under the influence of next pole which is of opposite polarity (i.e. the south pole), The operation of the commutator, that serves the above purpose is given below:

Consider a single turn coil whose leads are soldered to commutator segments a and b, each carrying a brush, as illustrated in Fig. 3.2.

The positive side of the supply line is connected to left hand brush and negative side to the right hand brush.

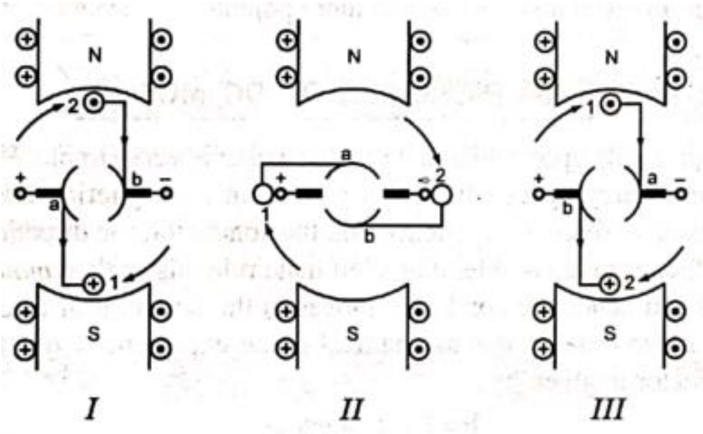


Fig 3.2.

In position (I) the line current arrives at the commutator segment a, flows through the **bottom side 1 of the coil away from the reader** (as shown by cross in the circle) and **then through the upper side 2 of the coil towards the reader** (as shown by dot in the circle), reaches the commutator segment b and flows again into the line through the brush. The coil will tend to rotate in **clockwise direction**, as determined by Fleming's left hand rule.

In position (II) the coil is on the magnetic neutral line; there in no contact between the commutator segments and brushes, and there is no flow of current through the coil. The coil crosses the neutral line by inertia. In case of a multi-turn coil, remaining turns of the coil will supply the necessary torque.

In position (III), the two sides of the coil 1and 2 have changed poles, and the current through them has reversed. The commutator segments, however, have also changed contact with the brushes. Thus the coil will continue to rotate in the same direction as before, i.e. clockwise.

COMPARISON OF MOTOR AND GENERATOR ACTION

As mentioned above dc motor and the dc generator are the same devices at least theoretically. **The machine operating as a generator is driven by some external driving force and dc output is obtained from it whereas the machine operating as a motor is supplied by electric current and mechanical rotation is produced**.

If the excitation of a dc machine (working as a dc shunt generator) operating in parallel with dc line is gradually reduced to an extent that the emf generated by it is less than the line voltage, the machine will start drawing current from the line and working as a motor.

Let us first consider generator operation. In Fig. 3.3 a dc machine driven in a clockwise direction, by its prime mover and supplying direct current to external load circuit is shown. The machine is working as a generator and the direction of the generated emf and current flowing through the armature conductors, as determined by Fleming's right hand rule, are shown in the figure.

Since the armature is carrying current and rotating in a magnetic field, electromagnetic forces will be developed between the conductors and field, the direction of the forces so developed will be given by Fleming's left hand rule. These electromagnetic forces acting on the **armature conductors will collectively result in a torque acting on the armature in a counter clockwise direction.**

This electromagnetic torque, therefore, opposes the outside driving torque, which is causing the rotation of the machine and called the backward torque or magnetic drag on the conductors.

The prime mover has to work against this magnetic drag and the work so done is converted into electrical energy. The **larger the output current, more will be the backward torque and, therefore, more mechanical energy will be required to be supplied to the generator.**

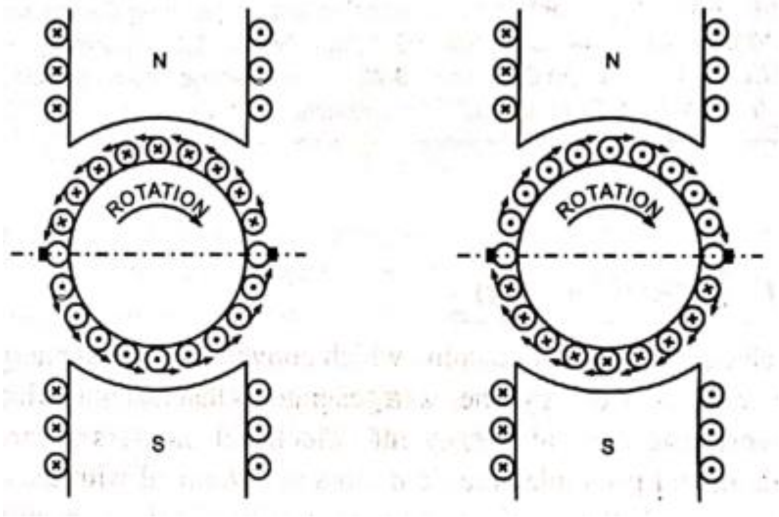


Fig 3.3. Fig 3.4.

In the Fig. 3.4 the same machine operating as a motor is shown. This operation takes place when the prime mover is uncoupled from the machine and the machine is connected to the dc supply mains.

With the direction of field and armature current shown in the figure, the torque developed by **electromagnetic action will rotate the machine in a clockwise direction** (as determined by Fleming's left hand rule).The friction of the machine and the mechanical load that the motor is driving will excert a torque in counter-clockwise direction, opposing the rotation of the motor.

Since the armature conductors are revolving in the magnetic field, emf is induced in the armature conductors. The direction of emf so induced, as determined by Fleming's right hand rule, is in direct opposition to the applied voltage. That is why **the induced emf in a motor is often called the counter emf or back emf, Eb.**

The applied voltage must be large enough to overcome this back emf and to send the current through the resistance of the armature. The electrical energy supplied to overcome this opposition is converted into mechanical energy developed in the armature.

Thus we see that an emf is generated in both generator and motor, therefore, there is a generator action in both motor and generator operations. However, in generator operation, the generated emf produces the armature current, whereas, **in motor operation the generated emf opposes the conduction.**

We also observe that electromagnetic torque is developed in generator as well as motor i.e. there is a motor action in both generator and motor operations. However, in motor operation the electromagnetic torque developed causes the armature rotation, **whereas in a generator operation the electromagnetic torque produced opposes the armature rotation**.

IMPORTANCE OF BACK EMF

As already explained, **when the motor armature continues to rotate due to motor action, the armature conductors cut the magnetic flux and, therefore, emfs are induced in them. The direction of this induced emf, known as back emf, is such that it opposes the applied voltage.**
Since the back emf is induced due to the generator action, the magnitude of it is, therefore, given by the same expression as that for the generated emf in a generator.

i.e. Back emf $Eb = \frac{\varphi ZN}{60} X \frac{P}{A}$ volts---(1)

The equivalent circuit of a motor is shown in Fig. 3.5. The armature circuit is equivalent to a source of emf, E_b in series with a resistance, R_a and brush contact drop V_b put across, a dc supply mains of V volts. It is evident from Fig. 3.5 that the applied voltage V must be large enough to balance the voltage drop in armature resistance brush contact drop and the back emf at all times i.e.

$V = E_b + I_aR_a + V_b$ .... (2)

where V is the applied voltage across the armature,
E_b is the induced emf in the armature by generator action,
I_a is the armature current
R is the armature resistance and
V_b is the brush contact drop.
The Eq. (2) may be rewritten as $Ia = \frac{V - Eb}{Ra}$ to give armature current in terms of applied voltage V, induced emf E_b and armature resistance R_a.

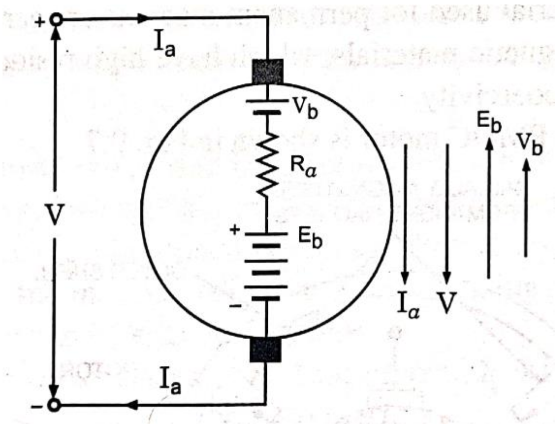


Fig.3.5 Equivalent Circuit of a Motor Armature

As obvious from Eqs. (1) and (2) the induced emf in the armature of a motor, E_b depends among other factors upon the armature speed and **armature current depends upon the back emf E_b for a constant applied voltage and armature resistance**.

If the armature speed is high, back emf E_b will be large and, therefore, armature current small. If the speed of the armature is low, then back emf E_b will be less and armature current I_a more resulting in development of large torque.

The presence of back emf makes the de motor a self-regulating machine i.e. it makes the de motor to draw as much armature current as is just sufficient to develop the required load torque. This is explained below:

When the motor is operating on no load, small torque is required to overcome the friction and windage losses, therefore, back emf is nearly equal to the applied voltage and armature current is small.
When the motor is loaded, the driving torque of the motor is not sufficient to counter the increased retarding torque due to load and the effect is to cause the armature to slow down.

With the decrease in the speed of armature, back emf falls. The reduced back emf allows a larger current to flow through the armature. The increase in armature current results in higher electromagnetic driving torque. The motor continues to slow down till the electromagnetic torque developed matches the load torque and the steady state conditions are attained. The reverse phenomenon occurs when mechanical load on the motor falls.

When the load on the motor falls, the electromagnetic torque developed is momentarily in excess of the load requirement and, therefore, the motor armature accelerates. With the increase in armature speed, back emf increases causing armature current to decrease. The decrease in armature current causes decrease in electromagnetic torque and the steady-state conditions are attained when the electromagnetic torque developed matches the load torque.

Thus it is evident that back emf E_b acts like a governor i.e. it makes a motor self-regulating so that it draws as much current as just required.

VOLTAGE EQUATION OF D.C. MOTOR

Let in a d.c. motor (See Fig. 3.6),

V = applied voltage

E_b = back e.m.f

R_a = armature resistance

I_a = armature current

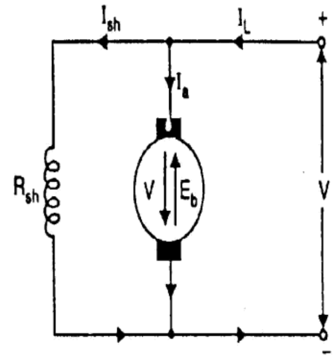


Fig 3.6.

Since back e.m.f. E_b acts in opposition to the applied voltage V, the net voltage across the armature circuit is V - E_b. The armature current I_a is given by;

$$I_a = \frac{V - E_b}{R_a}$$

or

$$V = E_b + I_a R_a \qquad \text{---------} \ (2)$$

This is known as voltage equation of the c. motor.

POWER EQUATION

$V = E_b + I_a R_a$

If above equation is multiplied by la throughout, we get,

$VI_a = E_b I_a + I_a^2 R_a$

This is known as power equation of the d.c. motor.

VI_a = electric power supplied to armature (armature input)

$E_b I_a$ = power developed by armature (armature output)

$I_a^2 R_a$ = electric power wasted in armature (armature Cu loss)

Thus out of the armature input, a small portion (about 5%) is wasted as $I_a^2 R_a$ and the remaining portion $E_b I_a$ is converted into mechanical power within the armature.

TYPES OF DC MOTORS

Similar to de generators, the de motors can also be classified as (1) permanent magnet, (2) separately excited, (3) series wound (4) shunt wound and (5) compound wound dc motors.

1. Permanent Magnet DC Motor

A permanent magnet dc (PMDC) motor is a de motor whose poles are made of permanent magnets i.e. field flux required in the air gap of a PMDC motor is developed by a set of permanent magnets fixed to the stator.

The permanent magnets of a PMDC motor are radially magnetized and mounted on the inner periphery of the cylindrical steel stator. The stator also serves as a return path for the magnetic flux. Field coils are usually not required. However, some of these motors do have coils wound on the poles. If they exist, these coils are intended only for recharging the magnets in the event they lose their strength.

Equivalent circuit of a PMDC motor is shown in Fig. 9.8. Since the field flux in a PMDC motor is developed by permanent magnets, the field winding is not shown in the equivalent circuit.

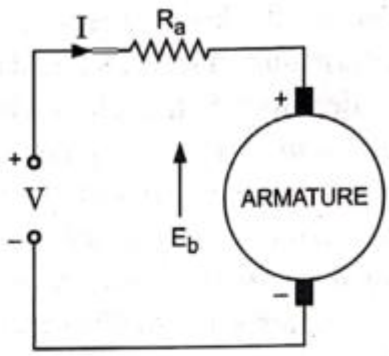


Fig 3.7. Equivalent Circuit of a PMDC Motor

The major advantage of PMDC motor is that they do not have any field winding, so they require no excitation current. Thus there is no continuous loss of energy in the field. Because of absence of field windings, there is saving in space and PMDC motors are smaller in size and cheaper in cost in comparison to corresponding rated conventional dc motors.

The limitation of PMDC motors is that the excessive current in the armature winding may demagnetize the permanent magnets and also the flux density produced in the air gap by permanent magnets is limited.

PMDC motors are used extensively in automobiles as starter motors and for windshield wipers and washers, for blowers used heaters and air-conditioners, to raise and lower windows, in slot cars and electric tooth brushes, in personal computer disc drives etc.

2. Separately-Excited DC Motors.

These motors have field coils similar to those of a shunt wound machine, but the armature and field coils are fed from different supply sources, as illustrated in Fig. 3.8 and may have different voltage ratings.

In a separately excited dc motor,

Armature current, I_a = Line current, I_L = I (say)

Back emf developed, $E_b = V - IR_a$

Power drawn from the supply mains

P=VI

where V is supply voltage ---(1)

Mechanical Power developed,

Pm= Power input to armature – power lost in armature

$= VI - I^2R_a = I(V - IR_a) = E_bI$ --- (2)

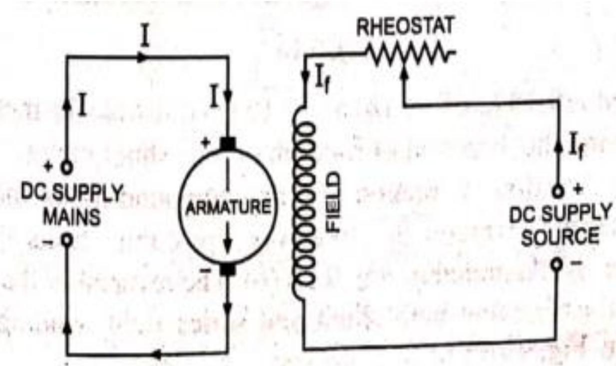


Fig 3.8 Separately Excited DC Motor

3.Series Wound DC Motors.

As the name implies, the field coils, consisting of few turns of thick wire, are connected in series with the armature, as illustrated in Fig. 9.10. The cross-sectional area of the wire used for field coils has to be fairly large to carry the armature current, but owing to the higher current, the number of turns of wire in them need not be large. In a dc series motor,

Armature current, I_a = Series field current I_{se}

= Line current, I_L=I (say) --(1)

Back emf developed, $E_b = V-I(R_a + R_{se})$ ---(2)

Power drawn from supply mains V I ---(3)

Mechanical power developed,

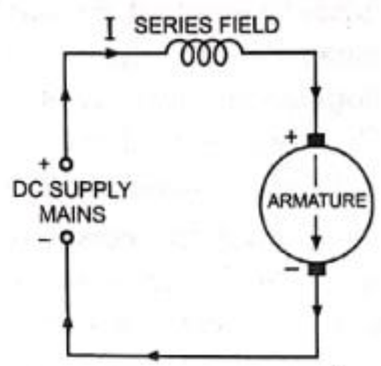


Fig 3.9 Series Wound DC Motor

Pm = Power input - losses in armature and field

$= VI-I^2(R_a + R_{se})$

$=I[V-I(R_a+R_{se})]=E_bI$ ...(4)

4. Shunt Wound DC Motors.

The word "shunt" means "parallel". These motors are so named because they basically operate with the field coils connected in parallel with the armature. The field winding consists of a large number of turns of comparatively fine wire so as to provide large resistance. The field current is much less than the armature current, sometimes as low as 5%.

The connection diagram is shown in Fig.3.1O. The current supplied to the motor is divided into two paths, one through the field winding and second through the armature i.e.,

Input line current, $I_L = I_a + I_{sh}$

where l_a is the armature current and I_{sh} is the shunt field current,

and is given by, the equation

$I_{sh}=(V/R_{sh})$

Where V is the Supply voltage and Rsh is the shunt field resistance.

Back emf developed $E_b=V-I_aR_a$

Power drawn from supply mains, $P=VI_L$

Mechanical Power developed,

Pm=Power Input-losses in armature and shunt field

$=VI_L-VI_{sh}-I_a^2Ra$

$=V(I_L-I_{sh})-I_a^2Ra$

$= VI_a-I_a^2Ra= (V-I_aR_a)\ I_a=E_bI_a$

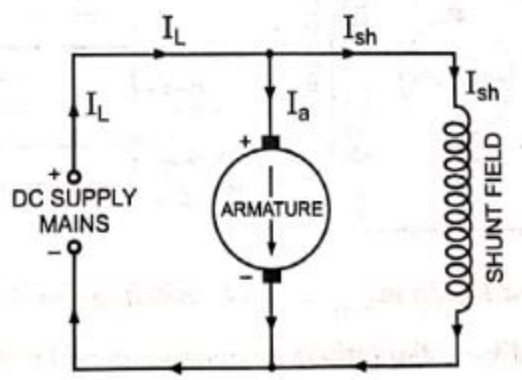
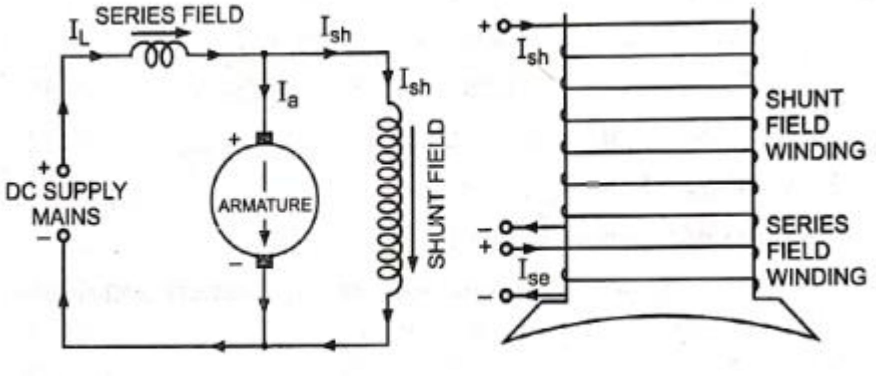


Fig. 3.10 Shunt Wound DC Motor

5. Compound Wound DC Motors.

A compound wound dc motor has both shunt and series field coils. The shunt field is normally the stronger of the two (i.e., has more ampere-turns). Compound wound motors are of two types namely cumulative compound wound and differential compound wound motors.

Cumulative compound wound motor is one in which the field windings are connected in such a way that the direction of flow of current is same in both of the field windings, as illustrated in Fig. 3.11. In the motor of this type the flux due to series field winding strengthens the field due to the shunt field winding.



(a) Circuit Diagram (b)Winding Connection Diagram

Fig.3.11 Cumulative Compound Wound DC Motor

Differential compound wound motor is one in which the field windings are connected in such a way that the direction of flow of current is opposite to each other in the two field windings, as illustrated in Fig. 9.13. In this type of motor the flux due to series field winding weakens the field due to shunt field winding.

Compound wound de motors, like compound wound dc generators, may be either long-shunt connected or short-shunt connected. In long-shunt connected (or long-shunt) compound wound motors, series field and armature are connected in series with each other and in parallel with the shunt field. In short-shunt connected (or short-shunt) compound wound motors, the armature and shunt field are in parallel with each other and the pair is in series with the series field. Long-shunt connection sometimes results in simpler wiring. Changing from long- to short-shunt, or vice versa, has little effect on motor performance.

$$V = E_b + I_a R_a + I_{se} R_{se} + BrushDrop$$

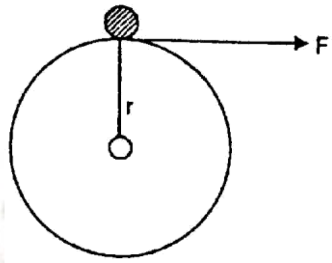
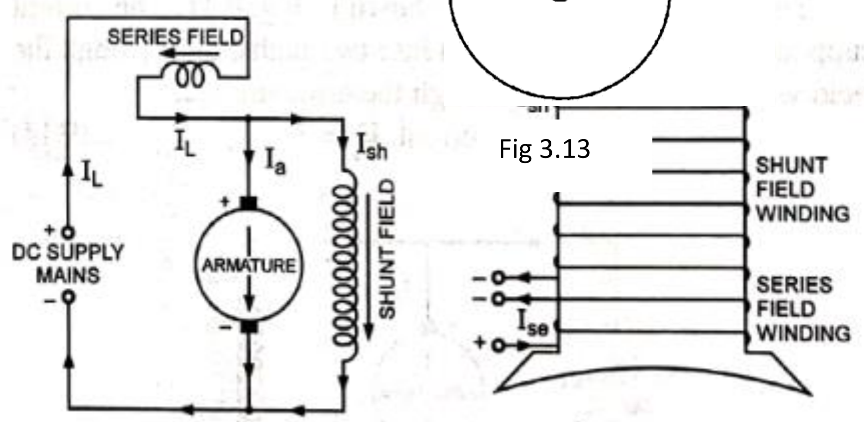


Fig 3.13



(a) Circuit Diagram (b)Winding Connection Diagram

Fig.3.12 Differential Compound Wound DC Motor

ARMATURE TORQUE OF D.C. MOTOR

Torque is the turning moment of a force about an axis and is measured by the product of force (F) and radius (r) at right angle to which the force acts i.e.T = F X r

In a d.c. motor, each conductor is acted upon by a circumferential force F at a distance r, the radius of the armature . Therefore, each conductor exerts a torque, tending to rotate the armature.

The sum of the torques due to all armature conductors is known as gross or armature torque (T_a).

Let in a d.c. motor

r = average radius of armature in m

l = effective length of each conductor in m

Z = total number of armature conductors

A = number of parallel paths

i = current in each conductor = I_a/A

B = average flux density in Wb/m2

φ= flux per pole in Wb

P = number of poles

Force on each conductor, F = B i l newtons

Torque due to one conductor = F * r newton- metre

Total armature torque, T_a = Z F r newton-metre

= Z B i l r

Now i=Ia/A, B=φ/a where a is the x-sectional area of flux path per pole at radius r. Clearly, a=2πrl/P.

$$T_a = Z \times (\phi / a) \times (I_a / A) \times l \times r$$

$$= Z \times \frac{\phi}{2\pi r l / P} \times \frac{I_a}{A} \times l \times r$$

$$= \frac{Z\phi I_a P}{2\pi A}$$

$$T_a = 0.159 Z\phi I_a (P/A) \quad \text{N-m ------(3)}$$

Sincce, Z, P and A are fixed for a given machine,

$$T_a \propto \phi I_a$$

Hence, torque in a DC motor is directly proportional to flux per pole and armature current.

(i) For a shunt motor, flux is practically constant,

$$T_a \propto I_a$$

(ii) For a series motor, flux is directly proportional to armature current I_a provided magnetic saturation does not take place.

$$T_a \propto I_a^2$$

Alternate expression for T_a

$$E_b = \frac{P\phi ZN}{60A}$$

$$\frac{P\phi Z}{A} = \frac{60 \times E_b}{N}$$

From eq (3), we get the expression of T_a as:

$$T_a = 0.159 \times \left(\frac{60 \times E_b}{N}\right) \times I_a$$

$$T_a = 9.55 \times \left(\frac{E_b \times I_a}{N}\right) \quad \text{N-m}$$

Note that developed torque or gross torque means armature torque T_a.

SPEED OF A D.C.MOTOR

$$E_b = V - I_a R_a$$

$$E_b = \frac{P\phi ZN}{60A}$$

$$\frac{P\phi ZN}{60A} = V - I_a R_a$$

$$N = \frac{(V - I_a R_a)}{\phi}\frac{60A}{PZ}$$

$$N = K\frac{(V - I_a R_a)}{\phi} \quad \text{where} \quad K = \frac{60A}{PZ}$$

But $(V - I_a R_a) = E_b$

$$N = K\frac{E_b}{\phi}$$

$$N \propto \frac{E_b}{\phi}$$

Therefore, in a d.c. motor, speed is directly proportional to back e.m.f E_b and inversely proportional to flux per pole φ.

CHARACTERISTICS OF DC MOTORS

Generally, three characteristic curves are considered important for DC motors which are, (i) Torque vs. armature current, (ii) Speed vs. armature current and (iii) Speed vs. torque. These are explained below for each type of DC motor.

These characteristics are determined by keeping the following two relations in mind.
T_a ∝ ϕ.I_a and **N ∝ E_b/ϕ**
These above equations can be studied at - emf and torque equation of dc machine. For a DC motor, magnitude of the back emf is given by the same emf equation of a dc generator i.e. E_b = PϕNZ / 60A. For a machine, P, Z and A are constant, therefore, N ∝ E_b/ϕ.

1.Characteristics Of DC Series Motors

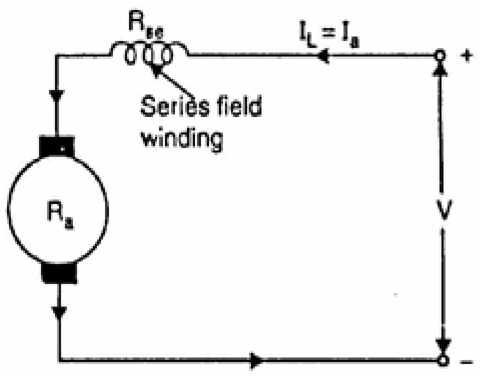
1. Torque Vs. Armature Current (T_a-I_a)
This characteristic is also known as **electrical characteristic**. We know that torque is directly proportional to the product of armature current and field flux, T_a ∝ ϕ.I_a.

In DC series motors, field winding is connected in series with the armature, i.e. $I_a = I_f$. Therefore, before magnetic saturation of the field, flux ϕ is directly proportional to Ia. Hence, before magnetic saturation Ta α Ia^2. Therefore, the Ta-Ia curve is parabola for smaller values of Ia.

After magnetic saturation of the field poles, flux ϕ is independent of armature current Ia. Therefore, the torque varies proportionally to Ia only, T ∝ Ia. Therefore, after magnetic saturation, Ta-Ia curve becomes a straight line.

The shaft torque (Tsh) is less than armature torque (Ta) due to stray losses. Hence, the curve Tsh vs Ia lies slightly lower.

In DC series motors, (prior to magnetic saturation) torque increases as the square of armature current, these motors are used where high starting torque is required.



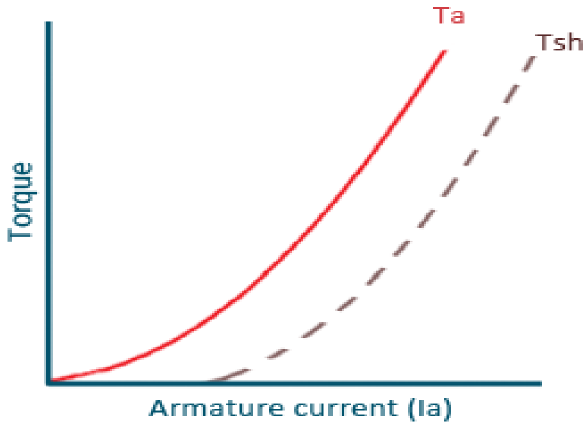
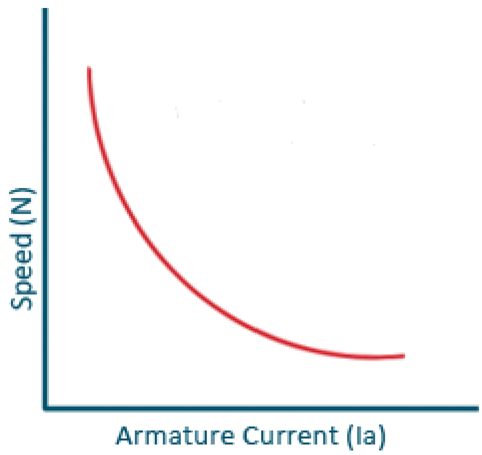


fig. 3.14

2. Speed Vs. Armature Current (N-Ia)

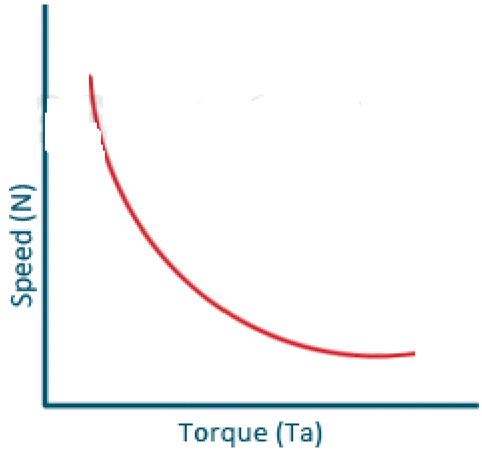
We know the relation, N ∝ E_b/ϕ



For small load current (and hence for small armature current) change in back emf Eb is small and it may be neglected. Hence, for small currents speed is inversely proportional to ϕ. As we know, flux is directly proportional to Ia, speed is inversely proportional to Ia. Therefore, when armature current is very small the speed becomes dangerously high. That is **why a series motor should never be started without some mechanical load**.

But, at heavy loads, armature current Ia is large. And hence, speed is low which results in decreased back emf Eb. Due to decreased Eb, more armature current is allowed.

3. Speed Vs. Torque (N-Ta)



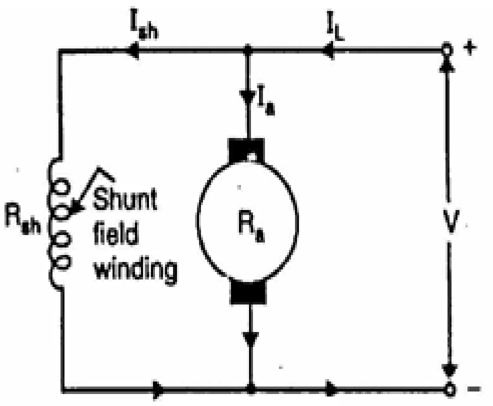
This characteristic is also called as **mechanical characteristic**. From the above two **characteristics of DC series motor**, it can be found that **when speed is high, torque is low and vice versa.**

2.Characteristics Of DC Shunt Motors

1.Torque Vs. Armature Current (Ta-Ia)

In case of DC shunt motors, we can assume the field flux ϕ to be constant. Though at heavy loads, ϕ decreases in a small amount due to increased armature reaction. As we are neglecting the change in the flux ϕ, we can say that torque is proportional to armature current. Hence, the Ta-Ia characteristic for a dc shunt motor will be a straight line through the origin.

Since heavy starting load needs heavy starting current, **shunt motor should never be started on a heavy load**.



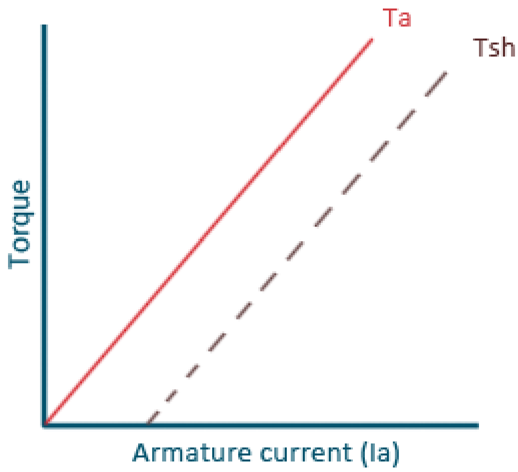


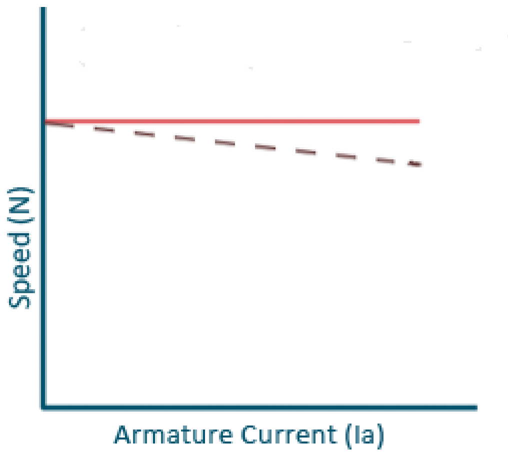
Fig. 3.15

2. Speed Vs. Armature Current (N-Ia)

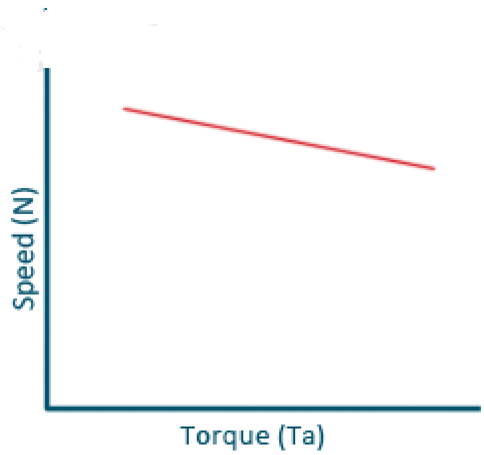
As flux ϕ is assumed to be constant, we can say N ∝ Eb. But, as back emf is also almost constant, the speed should remain constant.

But practically, ϕ as well as Eb decreases with increase in load. Back emf Eb decreases slightly more than ϕ, therefore, the speed decreases slightly.

Generally, the speed decreases only by 5 to 15% of full load speed. Therefore, **a shunt motor can be assumed as a constant speed motor**.



In speed vs. armature current characteristic in the following figure, the straight horizontal line represents the ideal characteristic and the actual characteristic is shown by the dotted line.



3. Speed Torque characteristics.

This characteristics can be drawn from the above two characteristics.

Dc shunt motors should never be started on heavy loads because such loads need heavy starting current.

3.Characteristics Of DC Compound Motor

DC compound motors have both series as well as shunt winding. In a compound motor, if series and shunt windings are connected such that series flux is in direction as that of the shunt flux then the motor is said to be cumulatively compounded.

And if the series flux is opposite to the direction of the shunt flux, then the motor is said to be differentially compounded. Characteristics of both these compound motors are explained below.

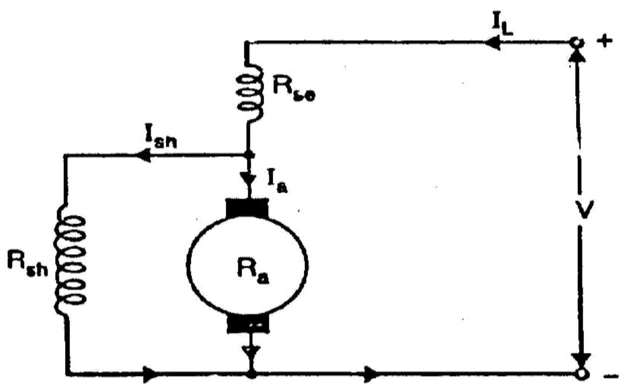
(a) Cumulative compound motor

Cumulative compound motors are used where series characteristics are required but the load is likely to be removed completely. Series winding takes care of the heavy load, whereas the shunt winding prevents the motor from running at dangerously high speed when the load is suddenly removed.

These motors have generally employed a **flywheel, where sudden and temporary loads are applied like in rolling mills.**

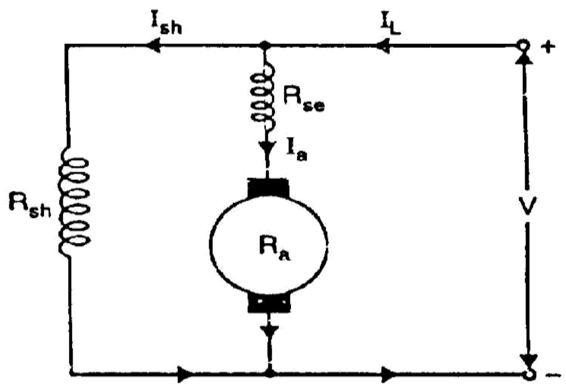
(b) Differential compound motor

Since in differential field motors, series flux opposes shunt flux, the total flux decreases with increase in load. Due to this, the speed remains almost constant or even it may increase slightly with increase in load ($N \propto E_b/\phi$). Differential compound motors are not commonly used, but they find **limited applications in experimental and research work.**



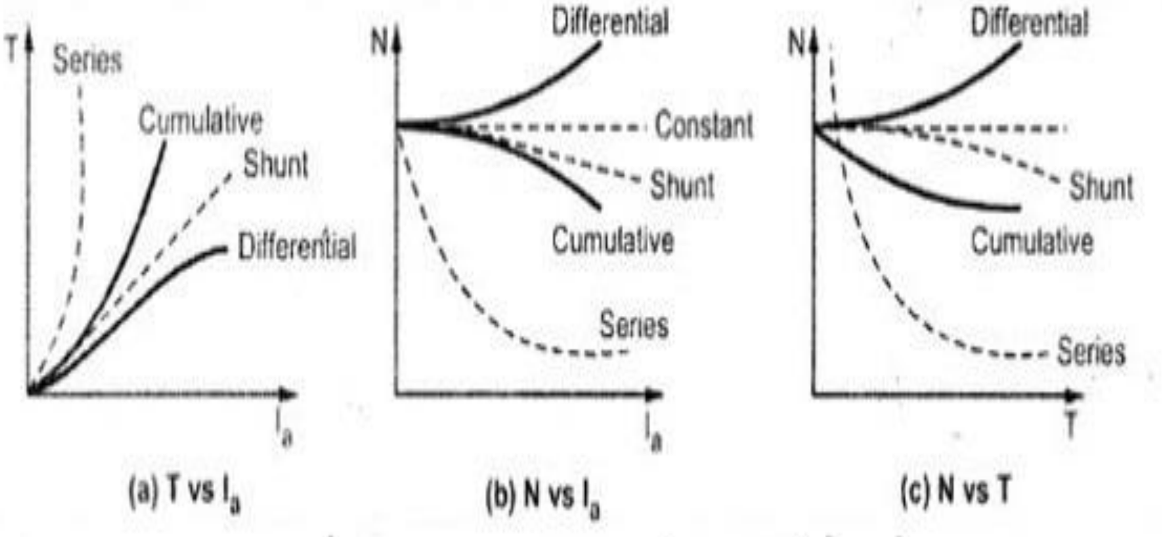
Short-shunt connection

Fig 3.16



Long-shunt connection

Fig 3.17



Characteristics of compound motor

APPLICATION OF DC MOTOR

1. ***Shunt DC Motor***

Characteristics:

- Speed is fairly constant and medium starting torque.

Applications:

1. Blowers and fans
2. Centrifugal and reciprocating pumps
3. Lathe machines
4. Machine tools
5. spinning and weaving machines
6. Drilling machines

2. ***Series DC Motor***

Characteristics:

- Series High starting torque.
- No load condition is dangerous.
- Variable speed.

Applications:

1. Cranes
2. Hoists, Elevators
3. Trolley cars
4. Conveyors
5. Electric locomotives

3.Cumulative compound DC Motor

Characteristics:

- High starting torque.
- No load condition is allowed.

Applications:

1. Rolling mills
2. Printing presses
3. Air compressors
4. Heavy planers
5. Elevators

4.Differential compound DC Motor

Characteristics:

- Speed increases as load increases.

Applications:

- Not suitable for any practical applications. For experimental and research work.

STARTING METHODS OF DC MOTOR

NECESSITY OF A STARTER

When the motor is at rest the speed of the motor is zero, therefore, back emf Eb is zero and if a dc motor is connected directly to the supply mains, a heavy current will flow through the armature conductors because from the emf equation for armature circuit (Eb = V - Ia Ra) armature current Ia is given as (V – Eb)/Ra and armature resistance Ra is very small.

For example consider a 400 V, 20 kW dc motor having a total resistance of 0.5 ohms. If switched directly on to the supply, it would draw a current of (400/0.5) =800 A while the full-load current would probably be about 64 A. The starting current thus would be (800/64) i.e. 12.5 times the full-load current and would give rise to heating effects and mechanical forces 150 times the full-load values. When running, of course, the applied voltage V is opposed by the induced back emf and, therefore, a much smaller current flows.

Heavy inrush of current at the starting instant may cause

- **heavy sparking at the commutator and even flash-overs,**
- **damage to the armature winding,** either by the heat developed in the windings, or by the mechanical forces set up by electromagnetic action.
- **damage to the rotating parts of the motor** and load due to development of large starting torque and quick acceleration and
- large dip in the supply voltage.

Hence for the protection of the motor against the flow of excessive current during starting period (say 5 to 10 seconds), it is necessary that a **high resistance be connected in series with the armature of the motor at the instant of starting and gradually cut in steps as the motor gains speed and develops back emf and ultimately when the motor attains its normal speed,** the additional resistance from the armature circuit is totally disconnected.

If this additional resistance inserted is left in the armature circuit, it would cause (i) additional loss of energy resulting in reduced operating efficiency and (ii) reduction in operating speed of the motor.

However, a very small motor (fractional kW motor) may be started simply by closing the switch which connects it to the supply mains. The reasons for it are given below.

1. The resistance and inductance of the armature winding in-case of small motors are generally sufficiently huge to limit the initial inrush of current to values that are not particularly serious.
2. The inertia of a small armature is generally so low that it comes up to speed very quickly, thereby minimizing the detrimental effects that might otherwise result from the excessive sustained current.

STARTERS FOR DC SHUNT AND COMPOUND WOUND MOTORS

Motor starters are generally manufactured in convenient sizes and styles for use as auxiliaries with dc shunt and compound motors. **Their primary function is to limit the current in the armature circuit during the starting or accelerating period.** They are always rated on the basis of output power and voltage of the motors with which they are to be employed. The simplest type of starter consists of an additional resistance (a rheostat) inserted in series with the armature alone (not with the motor as a whole), as illustrated in Fig. 3.18.

This starter is, however, modified to include a few protective devices, such as no-volt release, overload release etc. There are two standard types of motor starters for de shunt and compound motors, the three point type and the four point type starters.

The four point starter is employed when wide range of speed by shunt field control is required. When no (or little) speed control is required, either type of starter may be used.

In this context it is pertinent to note that while starting dc shunt and compound motors, it is advantageous to keep the field excitation at its maximum value.

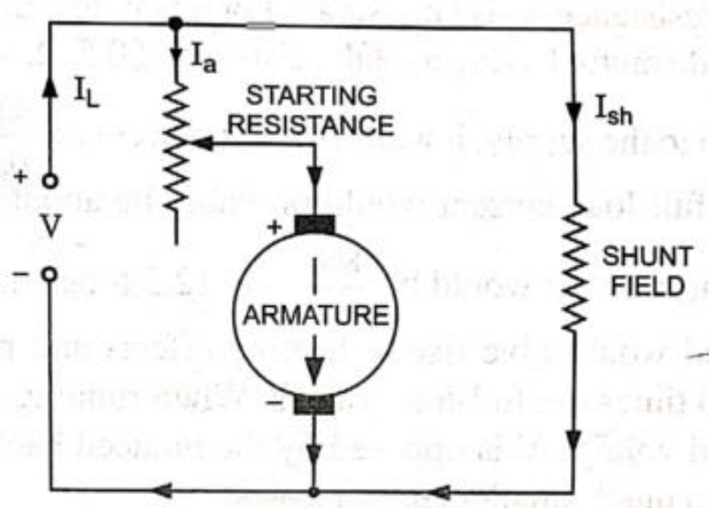


Fig. 3.18

A large field current, therefore, a higher value of flux will result in a low operating speed and in higher motor torque for a particular value of starting current because motor torque is proportional to the product of flux per pole and armature current. Thus the rheostat, in series with the shunt field winding, should be at zero resistance position at the time of starting of the dc shunt and compound motors.

THREE POINT STARTER.

The three point starter with its electrical connections and protective devices (no-volt release and overload release) is illustrated in Fig, 3.19. It consists of a series starting resistance divided into several sections and connected to brass studs, brass arc by which the connection to shunt field, no-volt release and overload release is made.

Since only three terminals (L, F and A) are available from the starter, it is called a three point starter. The last stud of the starting resistance is connected to terminal A to which one terminal of the armature is connected.

The + ve supply line is connected to the line terminal L through main switch. From line terminal L, supply is connected to the starter arm through overload release.

A spiral spring S is placed over the lever to bring the starter arm to the OFF position in case of failure of supply. A soft Iron keeper is attached to the starter arm which is pulled by the holding Coil or no-volt release under normal running condition.

The far end of the brass arc is connected to the terminal F through the no-volt release and to the terminal F one terminal of the field is connected. The -ve supply line is connected directly to the remaining ends of armature and field winding of the dc shunt motor.

Operation.

When the motor is at rest, the starter arm is in the OFF position due to action of strong spiral spring S. For starting the motor the de supply is switched on by closing the main switch keeping starter arm in OFF position.

The starter arm (or handle) is then turned clockwise to the first stud and brass arc (or strip). As soon as it comes in contact with first stud, whole of the starting resistance R is inserted in series with the armature, the field winding is directly connected across the supply through the brass arc and the holding coil is also energized.

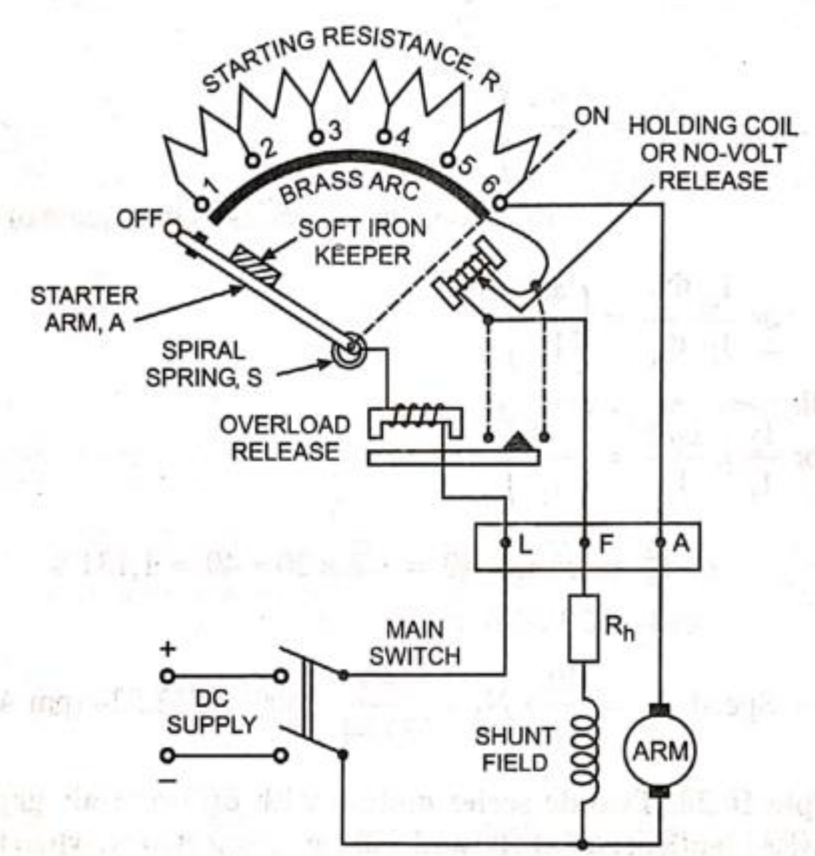


Fig. 3.19 Three Point Starter

As the starter arm is turned further the starting resistance is cut out of the armature circuit in steps and finally entire starting resistance R is cut out of armature circuit. When the starter arm reaches the ON position, it is held against the action of spiral spring S by the force of attraction between holding coil magnet and soft iron keeper attached to the starter arm. The starter arm should not be held for an unduly long time in an intermediate position as it is likely to burn out the starting resistor.

No- Volt Release.

When the starter arm reaches “ON” position, the resistance is completely cut off and motor starts running at normal speed. If the supply gets interrupted or disconnected, the starting arm will remain in the same position i.e. "ON" position and when the supply is switched on or gets restored, no back emf will be acting in circuit, the armature being directly across the supply mains, and resistance of armature being low, the motor will draw excessive current and will get damaged.

Hence for the protection of the motor, some device must be provided, so that starter arm may reach the "OFF" position automatically as soon as the supply is cut off or disconnected or fails and for this purpose "no-volt" release coil is provided.

No-volt release coil consists of an electromagnet connected in series with shunt field which holds the arm in the "ON" position. Now when the supply fails or gets disconnected the electromagnet demagnetizes and so releases the starting arm A, which goes back to "OFF" position due to the spring attached to it and gets disconnected from the supply mains.

The other important advantage of connecting the no-volt release in series with the shunt field winding is that it prevents the motor from running away owing to an open shunt field because open-circuited shunt field will demagnetise the electromagnet and release the starter arm A and, thus the starter arm will go back to its OFF position and the supply will be disconnected.

Overload Release Coil.

This coil is provided for the protection of the motor against the flow of excessive current due to overload. This coil is connected in series with motor so carries full-load current. When the motor is overloaded, it draws heavy current, which also flows through this coil and magnetises it to such an extent, that it pulls its armature upwards and so short circuits the no-volt release coil.

The no-volt release coil, being short circuited, demagnetises and releases the starting arm, which goes back to "OFF" position with the action of spring attached to it and the motor is automatically disconnected from the supply mains. Thus the motor is disconnected from the supply and is protected against overloading.

The starters for motors up to 15 kW are provided with overload release to disconnect the motor from the supply mains in the event of an overload. Larger motors are provided with separate automatic circuit breakers.

FOUR POINT STARTER.

In three point starter (shown in Fig. 3.20) no-volt release coil is connected in series with the shunt field and the field rheostat and, therefore, the current flowing through the field is the same current that flows through the holding coil.

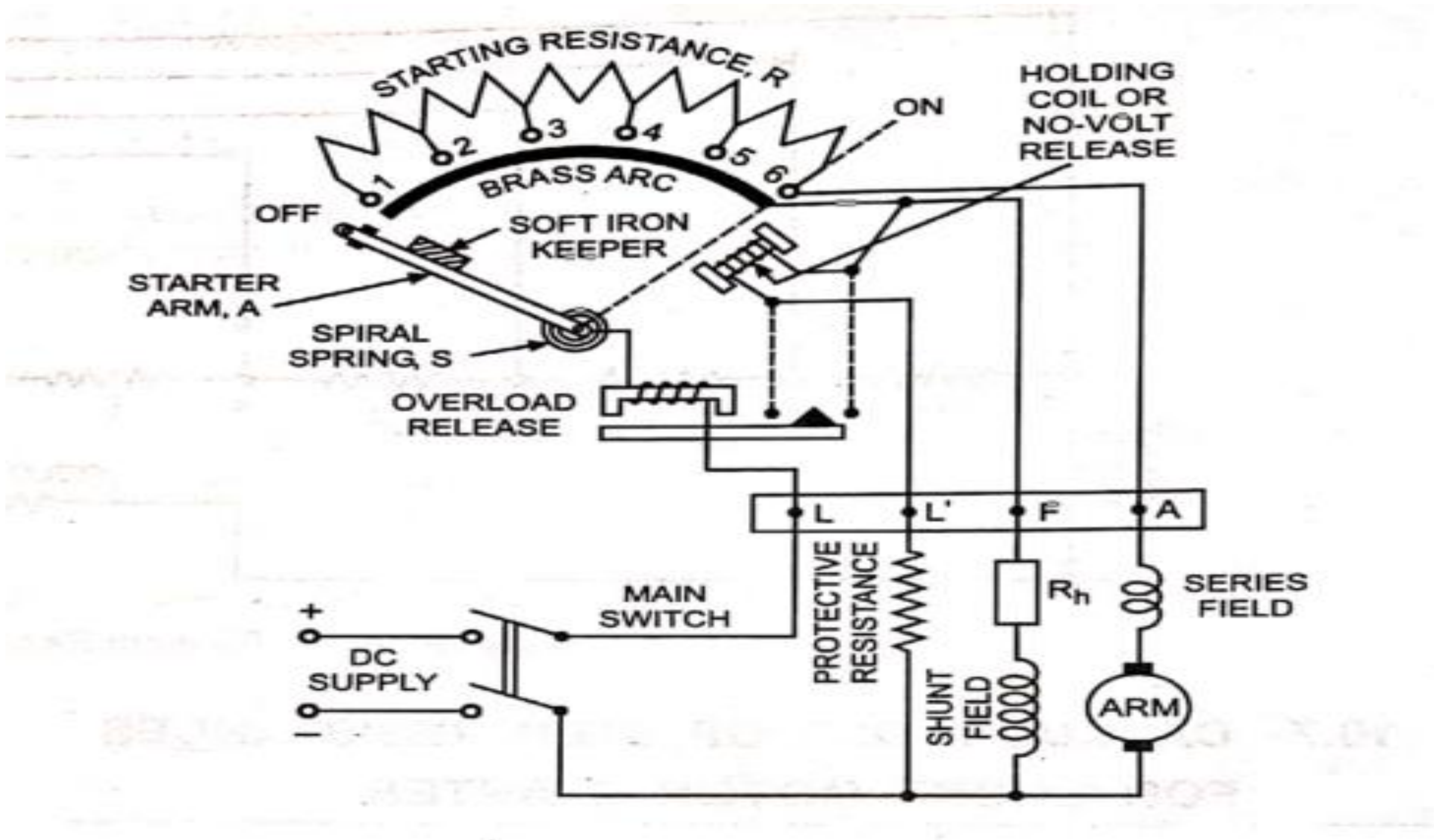


Fig. 3.20 Four Point Starter

Thus if sufficient resistance is cut in by the field rheostat so that holding coil current is no longer able to create sufficient electromagnetic pull to overcome the spring tension, the starter arm will fall back to the "OFF" position. **It is this undesirable feature of the three point starter that makes it unsuitable for use with speed-controlled motors and that has resulted in the wide spread application of four point starters.**

A four point starter with its internal wiring connected to a long shunt compound wound motor is shown in Fig. 3.20. It is obvious that when the arm touches stud no 1, line current divides into three parts:

1. One part passes through starting resistance, armature and series field.
2. Second part passes through the shunt field winding.
3. The third part passes through no-volt release coil and protective resistance.

Since in this arrangement, "no-volt release coil" circuit is independent of shunt field circuit, it will not be affected by the change of the current in the shunt field circuit. It means that the electromagnetic pull exerted by the holding coil will always be sufficient and will prevent the spiral spring from restoring the arm to the "OFF" position, no matter how the field rheostat is adjusted.

The possibility of accidently opening the field circuit is quite remote; hence there is greater acceptance of the four point starter over the three point starter.

A motor is started with a four terminal starter in the same way as with a three terminal starter. Any desired speed, above normal, of the motor can be obtained by adjustment of the field rheostat in series with the shunt field.
It is necessary to ensure, before starting a dc motor that the field circuit is closed, the rheostat in series with the shunt field winding is at zero resistance position and starting resistance in series with the armature circuit is at maximum value.
For stopping the motor, the line switch should always be opened rather than throwing back the starting arm.
In shunt motors, the line switch can be opened without any appreciable arc, since the motor develops a back emf nearly equal to applied line voltage and the net voltage across the switch contact is small.
The electromagnetic energy stored in the field does not appear at the switch but is discharged gradually through the armature. On the other hand if the starting arm is thrown back the field circuit is broken at the last contact button. Owing to the inductive nature of the field, this will cause a hot arc and burn the contact.

Precaution.
While stopping the motor, all the resistance in the field rheostat is cut out, so that motor speed-falls to its normal value; then the line switch is opened. This procedure ensures that, the next time the motor is started, it will be with a strong field and resultant strong starting torque.

SPEED CONTROL OF D.C. MOTORS

INTRODUCTION

Although a far greater percentage of electric motors in service are a.c. motors, the d.c. motor is of considerable industrial importance. The principal advantage of a d.c. motor is that its speed can be changed over a wide range by a variety of simple methods. Such a fine speed control is generally not possible with a.c. motors. In fact, fine speed control is one of the reasons for the strong competitive position of d.c. motors in the modem industrial applications. In this chapter, we shall discuss the various methods of-speed control of d.c. motors.

SPEED CONTROL OF D.C.MOTORS

The speed of a D.C. motor is given by:

$$N \alpha \frac{E_b}{\phi}$$

$$N = K\frac{(V - I_a R)}{\phi} \text{ r.p.m} \quad \text{----(1)}$$

$where R = R_a$ for shunt motor

$R = R_a + R_{se}$ for series motor

From exp. (1), it is clear that there are three main methods of controlling the speed of a d.c. motor, namely:

(i) By varying the flux per pole (φ). This is known as flux control method.

(ii) By varying the resistance in the armature circuit. This is known as armature control method.

(iii) By varying the applied voltage V. This is known as voltage control method.

SPEED CONTROL OF D.C. SHUNT MOTORS

The speed of a shunt motor can be changed by (i) flux control method (ii) armature control method (iii) voltage control method. The first method (i.e. flux control method) is frequently used because it is simple and inexpensive.

1. FLUX CONTROL METHOD(FIELD CURRENT CONTROL METHOD)

It is based on the fact that by varying the flux, the motor speed ($N \alpha 1/\varphi$) can be changed and hence the name flux control method. In this method, a variable resistance (known as shunt field rheostat) is placed in series with shunt field winding as shown in Fig. (1.44).

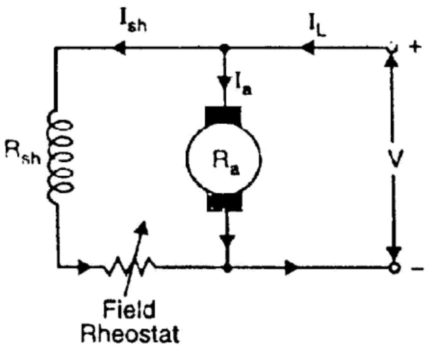


Fig 3.21

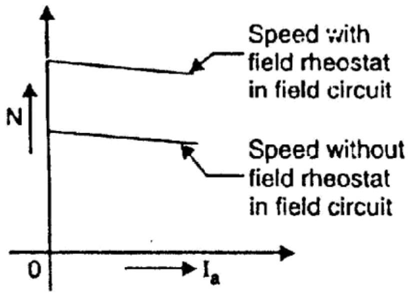


Fig 3.22

The shunt field rheostat reduces the shunt field current I_{sh} and hence the flux φ. Therefore, we can only raise the speed of the motor above the normal speed .Generally, this method permits to increase the speed in the ratio 3:1. Wider speed ranges tend to produce instability and poor commutation.

Advantages:

(i) This is an easy and convenient method.

(ii) It is an inexpensive method since very little power is wasted in the shunt field rheostat due to relatively small value of I_{sh}.

(iii)The speed control exercised by this method is independent of load on the machine.

Disadvantages:

(i)Only speeds higher than the normal speed can be obtained since the total field circuit resistance cannot be reduced below R_{sh} the shunt field winding resistance.

(ii)There is a limit to the maximum speed obtainable by this method. It is because if the flux is too much weakened, commutation becomes poorer.

Note. The field of a shunt motor in operation should never be opened because its speed will increase to an extremely high value.

2. ARMATURE VOLTAGE CONTROL METHOD

This method is based on the fact that by varying the voltage available across the armature, the back e.m.f and hence the speed of the motor can be changed. This is done by inserting a variable resistance R_C (known as controller resistance) in series with the armature as shown in Fig.

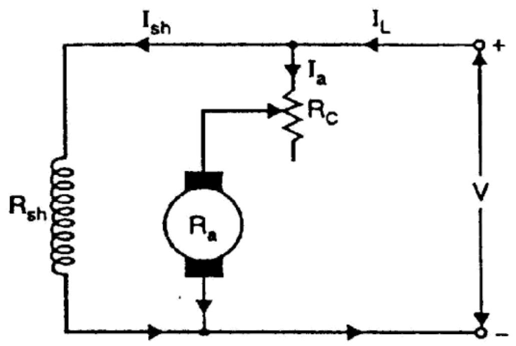


Fig 3.23

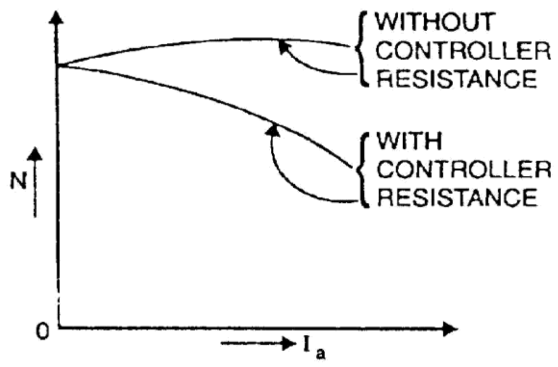


Fig 3.24

$$N \alpha V - I_a(R_a + R_c)$$

Where R_c=controller resistance

Due to voltage drop in the controller resistance, the back e.m.f. (E_b) is decreased. Since N α E_b, the speed of the motor is reduced. The highest speed obtainable is lhat corresponding to R_C = 0 i.e., normal speed. Hence, this method can only provide speeds below the normal speed .

Disadvantages:

(i) A large amount of power is wasted in the controller resistance since it carries full armature current I_a.

(ii) The speed varies widely with load since the speed depends upon the voltage drop in the controller resistance and hence on the armature current demanded by the load.

(iii) The output and efficiency of the motor are reduced.

(iv) This method results in poor speed regulation.

Due to above disadvantages, this method is seldom used to control tie speed of shunt motors.

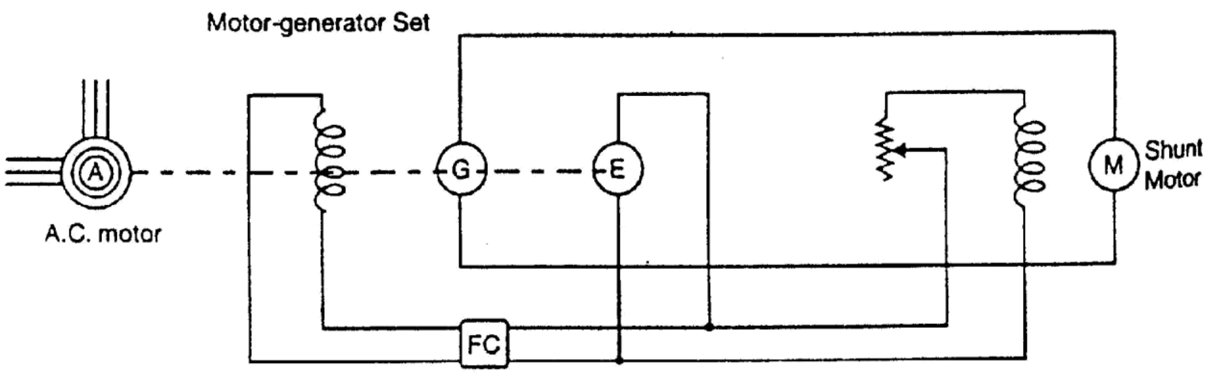
Note. The armature control method is a very common method for the speed control of d.c. series motors. The disadvantage of poor speed regulation is not important in a series motor which is used only where varying speed service is required.

3. VOLTAGE CONTROL METHOD

In this method, the voltage source supplying the field current is different from that which supplies the armature. This method avoids the disadvantages of poor speed regulation and low efficiency as in armature control method. However, it is quite expensive. Therefore, this method of speed control is employed for large size motors where efficiency is of great importance.

(i) **Multiple voltage control**. In this method, the shunt field of the motor is connected permanently across a-fixed voltage source. The armature can be connected across several different voltages through a suitable switchgear. In this way, voltage applied across the armature can be changed. The speed will be approximately proportional to the voltage applied across the armature. Intermediate speeds can be obtained by means of a shunt field regulator.

(ii) **Ward-Leonard system**. In this method, the adjustable voltage for the armature is obtained from an adjustable-voltage generator while the field circuit is supplied from a separate source. This is illustrated in Fig. (1.48). The armature of the shunt motor M (whose speed is to be controlled) is connected directly to a d.c. generator G driven by a constant-speed a.c. motor A. The field of the shunt motor is supplied from a constant-voltage exciter E. The field of the generator G is also supplied from the exciter E. The voltage of the generator G can be varied by means of its field regulator. By reversing the field current of generator G by controller FC, the voltage applied to the motor may be reversed. Sometimes, a field regulator is included in the field circuit of shunt motor M for additional speed adjustment. With this method, the motor may be operated at any speed up to its maximum speed.



Ward-Leonard speed-control system.

Fig 3.25

Advantages

(a) The speed of the motor can be adjusted through a wide range without resistance losses which results in high efficiency.

(b) The motor can be brought to a standstill quickly, simply by rapidly reducing the voltage of generator G. When the generator voltage is reduced below the back e.m.f. of the motor, this back e.m.f. sends current through the generator armature, establishing dynamic braking. While this takes place, the generator G operates as a motor driving motor A which returns power to the line.

(c) This method is used for the speed control of large motors when a d.c. supply is not available.

The disadvantage of the method is that a special motor-generator set is required for each motor and the losses in this set are high if the motor is operating under light loads for long periods.

Applications

The ward-Leonard system of speed control is expensive but is used where an unusually wide and very sensitive speed control is desired. This arrangement offers an excellent speed control and is well suited for such applications as passenger elevators, electric excavators etc.

SPEED CONTROL OF D.C. SERIES MOTORS

The speed control of d.c. series motors can be obtained by (i) flux control method (ii) armature-resistance control method. The latter method is mostly used.

1. FLUX CONTROL METHOD (FIELD CURRENT CONTROL METHOD)

In this method, the flux produced by the series motor is varied and hence the speed. The variation of flux can be achieved in the following ways:

(i) **Field diverters**. In this method, a variable resistance (called field diverter) is connected in parallel with series field winding as shown in Fig. . Its effect is to shunt some portion of the line current from the series field winding, thus weakening the field and increasing the speed (N α 1/φ).

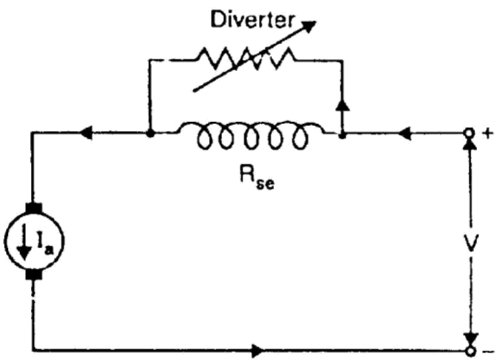


Fig 3.26

The lowest speed obtainable is that corresponding to zero current in the diverter (i.e. diverter is open). Obviously, the lowest speed obtainable is the normal speed of the motor. Consequently, this method can **only provide speeds above the normal speed**. The series field diverter method is often employed in traction work.

(ii)**Armature diverter**. In order to obtain speeds below the normal speed, a variable resistance (called armature diverter) is **connected in parallel with the armature** as shown in Fig. (3.27). The diverter shunts some of the line current, thus reducing the armature current. Now for a given load, if I_a is decreased, the flux φ must increase (T α φI_a). Since Nα (1/φ), the motor speed is decreased. By adjusting the armature diverter, any speed lower than the normal speed can be obtained.

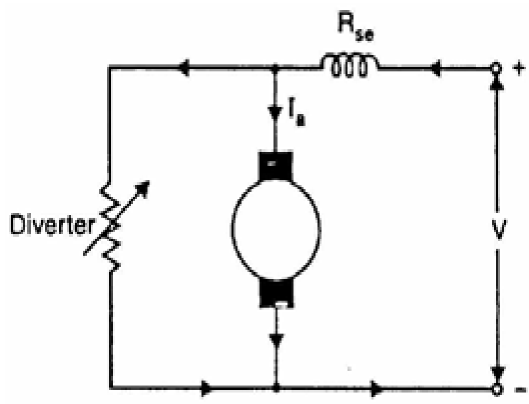


Fig. 3.27

(iii) **Tapped field control**. In this method, the flux is reduced (and hence speed is increased) by decreasing the number of turns of the series field winding as shown in Fig. The switch can short circuit any part of the field winding, thus decreasing the flux and raising the speed. **With full turns of the field winding, the motor runs at normal speed and as the field turns are cut out, speeds higher than normal speed are achieved.**

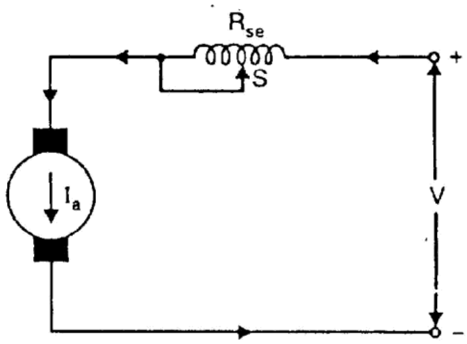


Fig 3.28

(iv) **Paralleling field coils**. This method is usually employed in the case of fan motors. By regrouping the field coils as shown in Fig., several fixed speeds can be obtained.

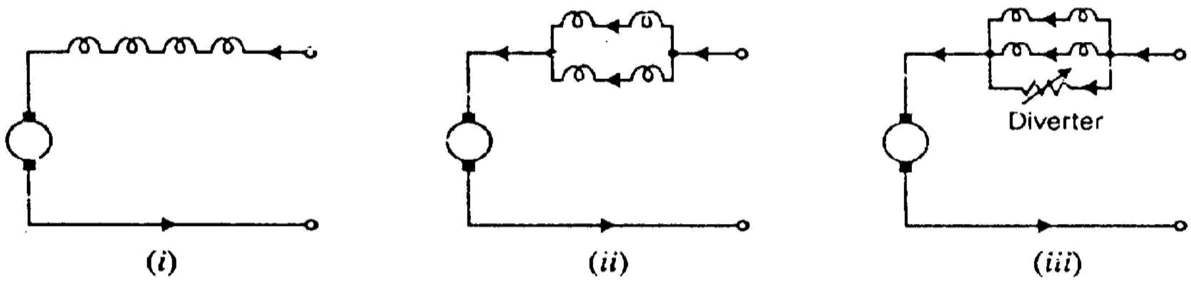


Fig 3.29

2. Armature-resistance control

In this method, a variable resistance is directly connected in series with the supply to the complete motor as shown in Fig. (3.30). This reduces the voltage available across the armature and hence the speed falls. By changing the value of variable resistance, any speed below the normal speed can be obtained. This is the most common method employed to control the speed of d.c. series motors.

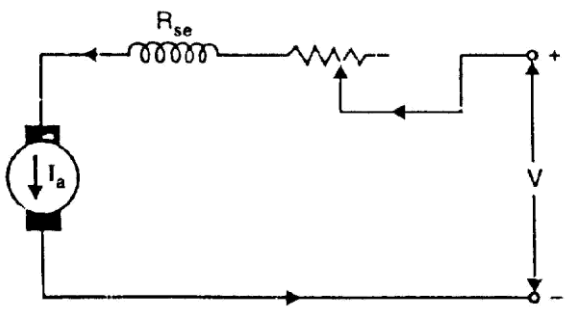


Fig 3.30

Although this method has poor speed regulation, this has no significance for series motors because they are used in varying speed applications. The loss of power in the series resistance for many applications of series motors is not too serious since in these applications the control is utilized for a large portion of the time for reducing the speed under light-load conditions and is only used intermittently when the motor is carrying full-load.