D.C. Motors

Outline

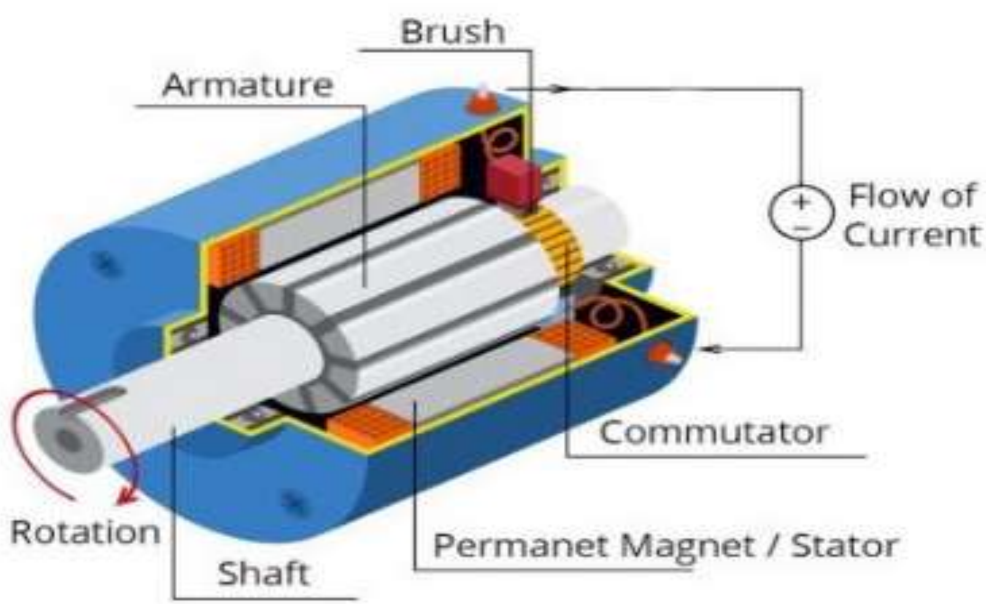
- **Introduction**
- **Working Principle and Torque Equation**
- **Back EMF**
- **Method of Excitation**
- **Types of DC Motor**
- **Performance Characteristics of DC Motors**
- **Starting of DC Motors: 3 Point and 4 Point Starters**
- **Speed Control of DC Motors: Field Control, Armature Control**
- **Losses and Efficiency**

Introduction

- D. C. motors are seldom used in ordinary applications because all electric supply companies furnish alternating current.
- However, for special applications such as in steel mills, mines and electric trains, it is advantageous to convert alternating current into direct current in order to use d.c. motors.
- The reason is that speed/torque characteristics of d.c. motors are much more superior to that of a.c. motors.
- Therefore, it is not surprising to note that for industrial drives, d.c. motors are as popular as 3-phase induction motors.
- An electric motor is a machine which converts electrical energy into mechanical energy whereas a generator is that machine which converts mechanical energy into electrical one.

Introduction

- As regards fundamental principles, the d.c. motors are identical with the d.c. 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 opened but those of motors should be either partly or totally enclosed.



D.C. Machine Fundamentals

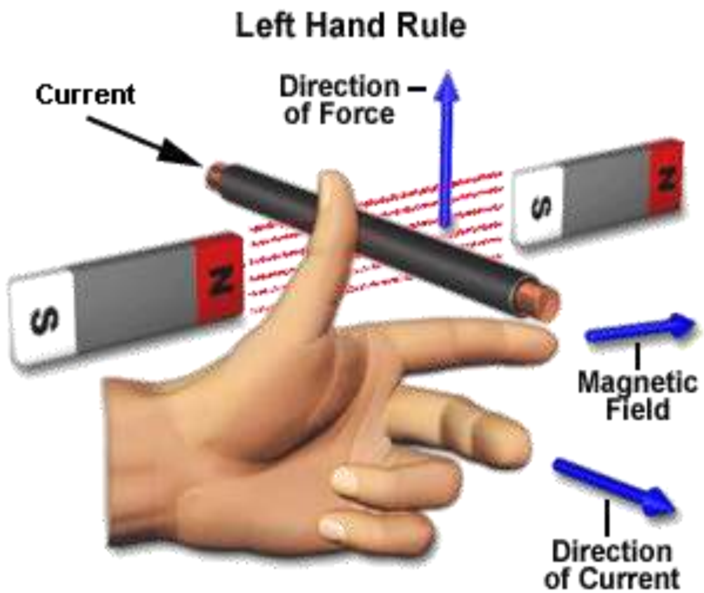
- **Generator action:**
  - An emf (voltage) is induced in a conductor if it moves through a magnetic field.
- **Motor action:**
  - A force is induced in a conductor that has a current going through it and placed in a magnetic field.

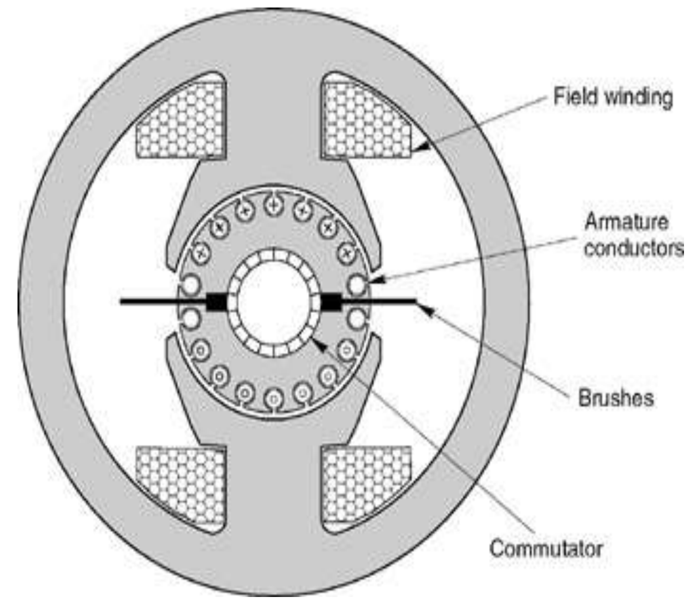
- Any DC machine can act either as a generator or as a motor.

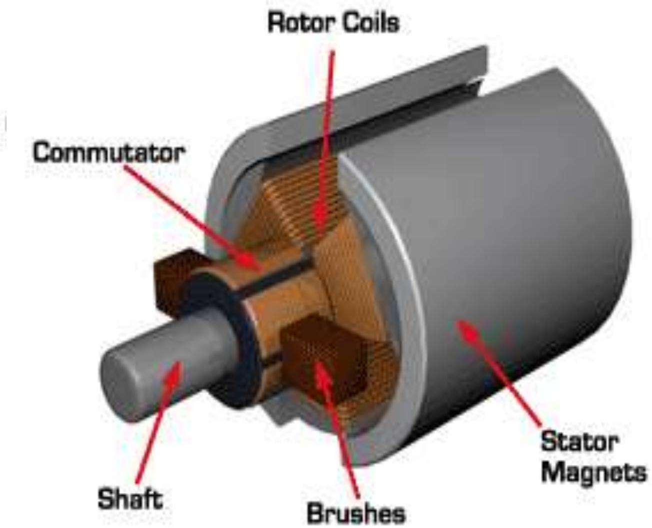
D.C. Motor Principle

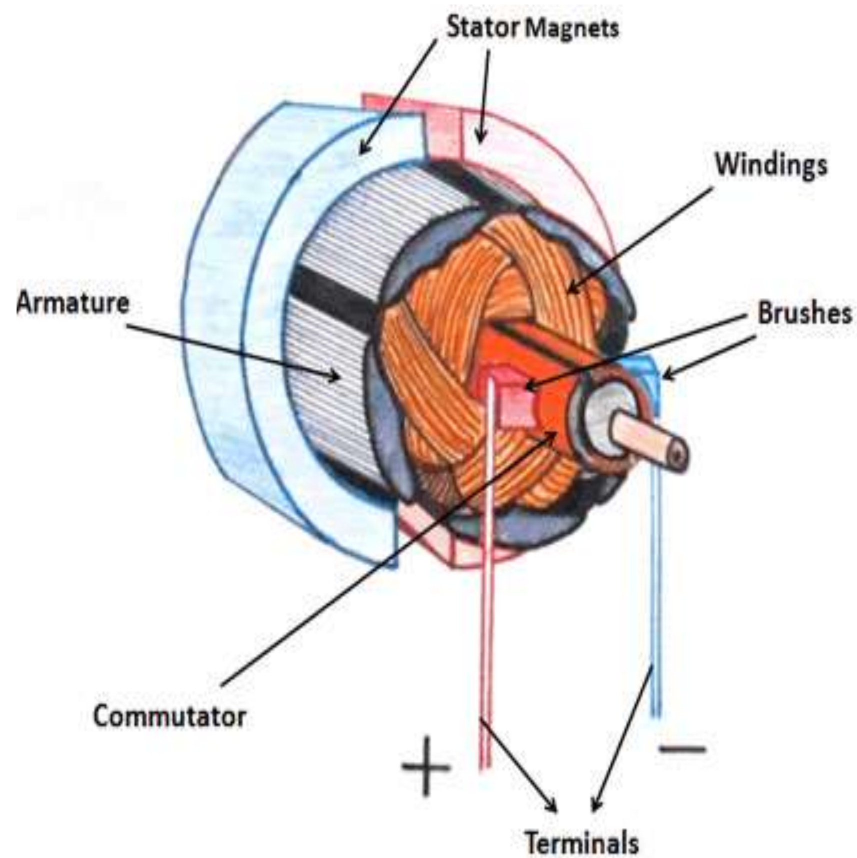
- A machine that converts d.c. power into mechanical power is known as a d.c. motor.
- Its operation is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force.
- The direction of this force is given by Fleming's left hand rule and magnitude is given by:

  $F = BIl$ (newtons) …… Eq.1
- Basically, there is no constructional difference between a d.c. motor and a d.c. generator. The same d.c. machine can be run as a generator or motor.






Rotor Coils
Commutator
Shaft
Brushes
Stator
Magnets


Stator Magnets
Windings
Armature
Brushes
Commutator
+
−
Terminals

Working Principle

- The principle upon which a d.c. motor works is very simple.
- Figure 2 shows a simpler form of a d.c. motor. In case of d.c. motor, the electrical energy is given across the armature and field windings and the armature produces the mechanical rotation.

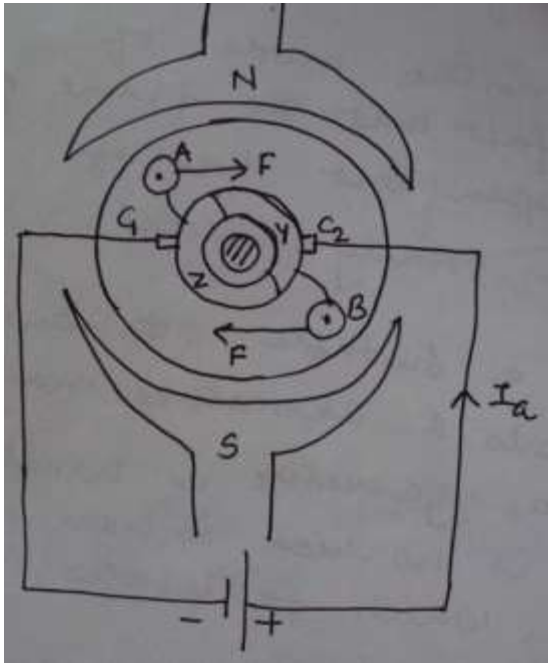


Figure 1: A DC Motor

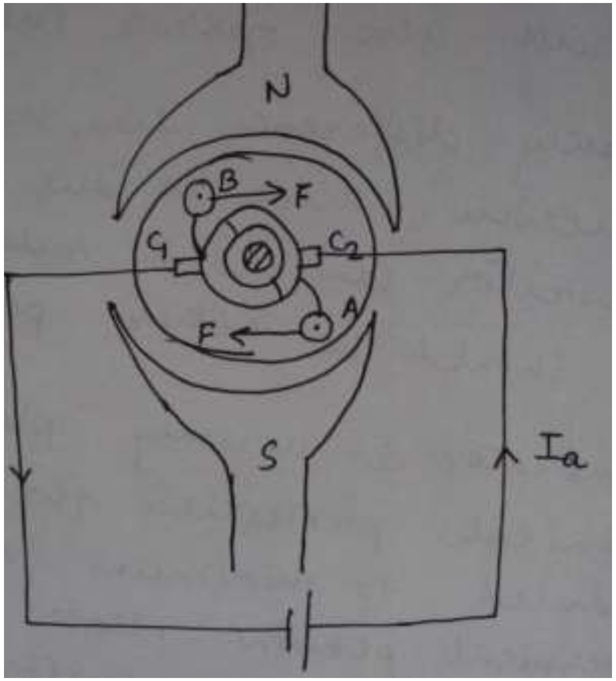


Figure 2: After 180° Rotation

Working Principle

- If a current carrying conductor is placed in a magnetic field, a mechanical force is experienced on the conductor, and hence the conductor moves in the direction of force.
- The magnitude of the mechanical force experienced on the conductor is given by equation 1.
- When the field winding is supplied by d.c. voltage, the field current I_f will flow through the field winding.
- This current will magnetize the field pole, resulting a magnetic field in the space between the two poles.
- When the armature conductors are also supplied by d.c. current through the carbon brushes, these armature conductors interacts with the magnetic field produced by the field poles and force will develop on the armature conductors. This force will produce continuous rotation of armature.

Working Principle

- After 180° rotation of the armature, the situation will be as shown in Figure 2. Here, the direction of current through the armature conductors has been changed due to the action of carbon brushes and commutator segments and the direction of force will be again same as before.
- When the armature conductors are supplied by d.c. current in the direction shown in Figure 1, the current is flowing inside through the conductor 'A'. Hence, the direction of force developed will be as shown in the figure as determined by the Fleming's left hand rule and the armature rotates in the clockwise direction.

Back E.M.F. in D.C. Motor

- When the armature of a d.c. motor rotates under the influence of the driving torque, the armature conductors move through the magnetic field and hence e.m.f. is induced in them as in a generator.
- The induced e.m.f. acts in opposite direction to the applied voltage V (Lenz's law) and in known as back or counter e.m.f.(E_b).
- The back e.m.f. E_b(= ZØNP/60A) is always less than the applied voltage V, although this difference is small when the motor is running under normal conditions.

Back E.M.F. in D.C. Motor

- Consider a shunt wound motor shown in Figure 3.
- When d.c. voltage V is applied across the motor terminals, the field magnets are excited and armature conductors are supplied with current. Therefore, driving torque acts on the armature which begins to rotate.
- As the armature rotates, back e.m.f. E_b is induced which opposes the applied voltage V.
- The applied voltage V has to force current through the armature against the back e.m.f. E_b.
- The electric work done in overcoming and causing the current to flow against E_b is converted into mechanical energy developed in the armature.
- It follows, therefore, that energy conversion in a d.c. motor is only possible due to the production of back e.m.f. E_b.

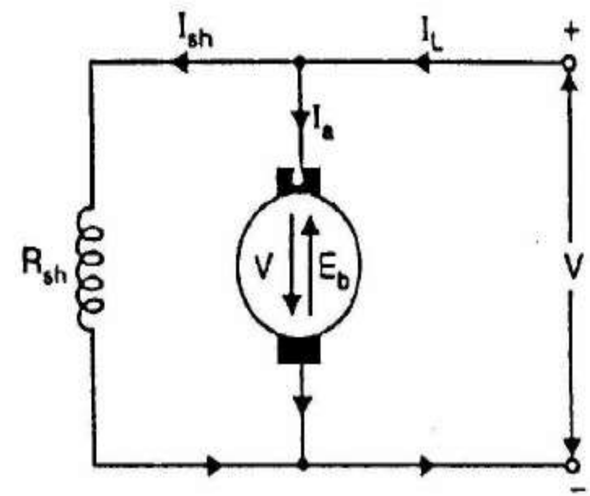


Figure 3: A Shunt Wound D.C. Motor

Back E.M.F. in D.C. Motor

- Net voltage across armature circuit = V- E_b
- If R_a is the armature circuit resistance, then,

$$I_a = \frac{V - Eb}{Ra}$$

- Since V and R_a are usually fixed, the value of E_b will determine the current drawn by the motor. If the speed of the motor is high, then back e.m.f. is large and hence the motor will draw less armature current and vice versa.

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

Significance of Back E.M.F.

1) The back e.m.f. protects the armature from short circuit during normal condition. As armature current,

$$I_a = \frac{V - Eb}{Ra}$$

-
- If there was no back emf i.e. E_b=0

$$I_a = V/R_a$$

- R_a is very low in DC motor so from above equation we can see that current Ia will be very large just like a short circuit.

2) Back emf acts as a current controlling agent:

- It helps to control the magnitude of armature current according to the load. When the mechanical load on the shaft increases, the speed of the armature will be decreased. Then, the magnitude of back emf E_b will decrease. Hence, more current will pass through the armature windings. Hence, the motor will be able to develop more torque to overcome the increased mechanical load

Significance of Back E.M.F.

- The induced emf in the armature of a motor, E_b depends upon other factors such as 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 will be 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 the development of large torque.
- Hence, the presence of the back emf makes the d.c. motor a self-regulating machine i.e. it makes the d.c. motor to draw as much armature current as is just sufficient to develop the required load torque.

3) Back emf also acts as an energy converting agent:

In any energy conversion system, there must be an opposing agent without which energy conversion is not possible. In case of dc motor back emf, E_b acts as an opposing agent due to which the d.c. motor is able to convert electrical energy into mechanical rotation.

Voltage Equation of D.C. Motor

- Let in a d.c. motor (See Figure 4),

  V = applied voltage

  Eb = back e.m.f.

  Ra = armature resistance

  Ia = armature current

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

$$I_a = \frac{V - Eb}{Ra}$$

Or, $$\boldsymbol{V = E_b + I_a \times R_a}$$

- This is known as the voltage equation of a D.C. Motor.

Power Equation

- If the voltage equation is multiplied by Ia, we get,

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

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

Where,

VI_a = electric power supplied to armature (armature input)

E_bI_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_bI_a is converted into mechanical power within the armature.

Condition for Maximum Power

- The mechanical power developed by the motor is $P_m = E_b I_a$.
- Now, $P_m = VI_a - I_a^2 R_a$
- Since, V and R_a are fixed, power developed by the motor depends upon armature current. For maximum power, $\frac{dP_m}{dI_a}$ should be zero.
- Therefore, $\frac{dP_m}{dI_a} = V - 2I_a R_a = 0$
- Now, $I_a R_a = \frac{V}{2}$

$$V = E_b + I_a R_a = E_b + \frac{V}{2}$$

$$E_b = \frac{V}{2}$$

- Hence, mechanical power developed by the motor is maximum when back e.m.f. is equal to half the applied voltage.

Condition for Maximum Power: Limitations

- In practice, we never aim at achieving maximum power due to the following reasons:
  - The armature current under this condition is very large (much excess of rated current of the machine).
  - Half of the input power is wasted in the armature circuit. In fact, if we take into account other losses (iron and mechanical), the efficiency will be well below 50%.

Types of DC Motor

- Like generators, there are three types of d.c. motors characterized by the connections of field winding in relation to the armature viz.:

- **Shunt-wound motor** in which the field winding is connected in parallel with the armature (See Figure 4). The current through the shunt field winding is not the same as the armature current. Shunt field windings are designed to produce the necessary m.m.f. by means of a relatively large number of turns of wire having high resistance. Therefore, shunt field current is relatively small compared with the armature current.

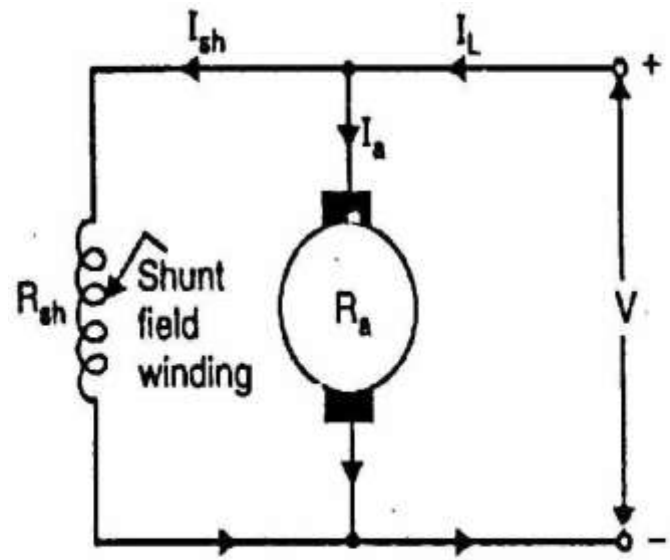


Figure 4: D.C. Shunt Motor

Types of DC Motor

- **Series-wound motor** in which the field winding is connected in series with the armature (see Figure 5). Therefore, series field winding carries the armature current. Since the current passing through a series field winding is the same as the armature current, series field windings must be designed with much fewer turns than shunt field windings for the same m.m.f. Therefore, a series field winding has a relatively small number of turns of thick wire and, therefore, will possess a low resistance.

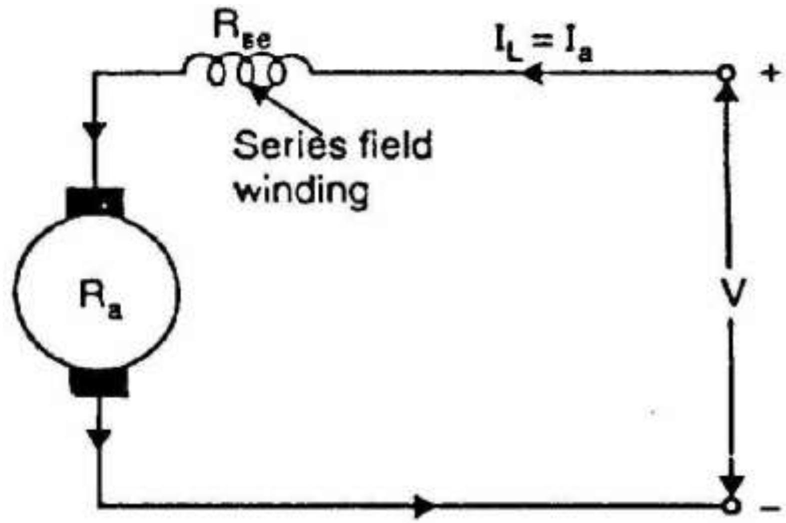


Figure 5: D.C. Series Motor

Types of DC Motor

- **Compound-wound motor** which has two field windings; one connected in parallel with the armature and the other in series with it. There are two types of compound motor connections (like generators).
  - When the shunt field winding is directly connected across the armature terminals (see Figure 6), it is called short-shunt connection.
  - When the shunt winding is so connected that it shunts the series combination of armature and series field (see Figure 7), it is called long-shunt connection.
  - The compound machines (generators or motors) are always designed so that the flux produced by shunt field winding is considerably larger than the flux produced by the series field winding. Therefore, shunt field in compound machines is the basic dominant factor in the production of the magnetic field in the machine.

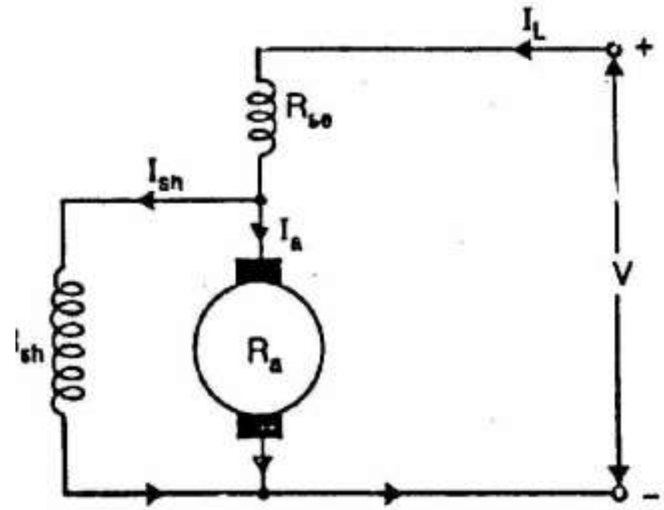


Figure 6: Short-shunt Connection

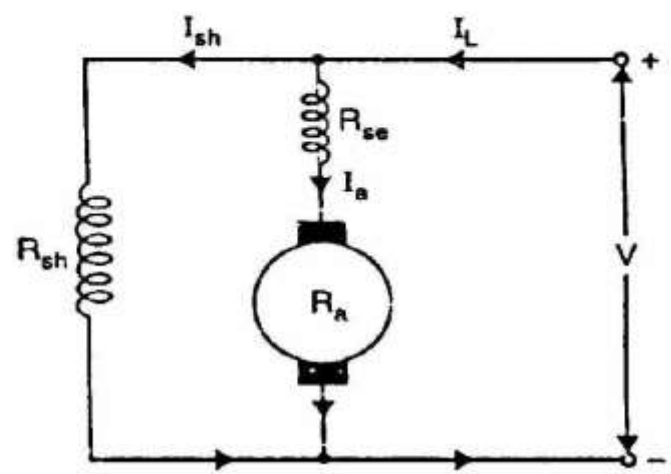


Figure 7: Long-shunt Connection

Torque

- The measure of causing the rotation of a wheel or the turning or twisting moment of a force about the axis is called the torque.
- Torque is measured by the product of force and the radius at which this force acts.
- Consider a wheel of radius r metres acted by circumferential force F newtons (see Figure 8). Let the force F cause the wheel to rotate at n rps.

$$Torque, T = F \times r \ \ newton - metres$$

$$Work\ done\ per\ revolution = F \times distance\ moved = F \times 2\pi r\ Joules$$

$$Work\ done\ per\ second = F \times 2\pi r \times n = F \times r \times 2\pi n\ \frac{Joules}{second} or\ watts$$

- Since F X r = Torque, T and 2πn =ω, angular velocity in radians per second,

$$Work\ done\ per\ second = T\omega\ Joules\ per\ second\ or\ watts$$

$$And\ power\ developed, P = T\omega = T \times \frac{2\pi N}{60} = 0.105\ NT\ watts$$

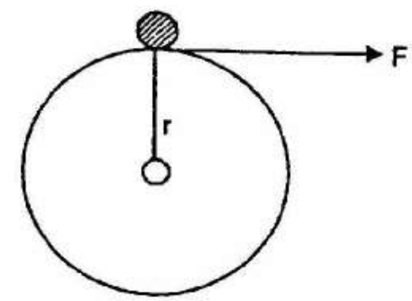


Figure 8

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.

$$T = F \times r$$

- In a d.c. motor, each conductor is acted upon by a circumferential force F at a distance r, the radius of the armature (see Figure 8). 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 (Ta).
- 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/m^2

f = flux per pole in Wb

P = number of poles

Force on each conductor, F = B i l newtons

Armature Torque of D.C. Motor

$$Torque\ due\ to\ one\ conductor = F \times r\ Newton - metre$$

$$Total\ armature\ torque, T_a = Z \times F \times r\ Newton - metre = ZBilr$$

$$Now, i = \frac{I_a}{A},$$

$$B = \frac{\emptyset}{a}\ where\ a\ is\ the\ cross\ sectional\ area\ of\ flux\ path\ per\ pole\ at\ radius\ r.$$

$$Clearly\ a = 2\pi rl/P$$

$$T_a = Z \times \left(\frac{\emptyset}{2}\right) \times \left(\frac{I_a}{A}\right) \times l \times r = Z \times \frac{\emptyset}{2\pi rl/P} \times \frac{I_a}{A} \times l \times r = \frac{Z\emptyset I_a P}{2\pi A}\ N - m$$

$$T_a \propto \emptyset I_a$$

$$or, T_a = 0.159 Z\emptyset I_a \left(\frac{P}{A}\right)\ N - m$$

Since Z, P and A are fixed for a given machine, $T_a \propto I_a$

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

For a shunt motor, flux Ø is practically constant.

$$T_a \propto I_a$$

Armature Torque of D.C. Motor

- For a series motor, flux Ø is directly proportional to armature current Ia provided magnetic saturation does not take place.

$$T_a \propto I_a^2$$

Alternative Expression for Ta

$$E_b = \frac{P\emptyset ZN}{60A} \qquad or, \frac{P\emptyset Z}{A} = \frac{60 \times E_b}{N}$$

From the expression of T_a,

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

$$Therefore, T_a = 9.55 \times \frac{E_b I_a}{N} \; N-m$$

It should be noted that developed torque or gross torque means armature torque, T_a.

Shaft Torque (Tsh)

- The torque which is available at the motor shaft for doing useful work is known as shaft torque. It is represented by T_{sh}.
- Figure 9 illustrates the concept of shaft torque.
- The total or gross torque T_a developed in the armature of a motor is not available at the shaft because a part of it is lost in overcoming the iron and frictional losses in the motor.
- Therefore, shaft torque T_{sh} is somewhat less than the armature torque T_a. The difference T_a - T_{sh} is called lost torque.

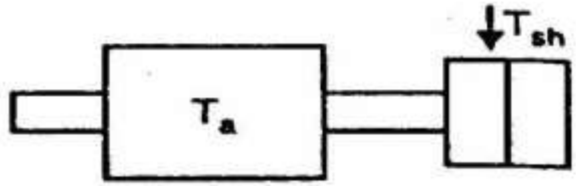


Figure 9: Shaft Torque

$$\text{Clearly}, T_a - T_{sh} = 9.55 \times \frac{\text{Iron and Frictional Losses}}{N}$$

For example, if the iron and frictional losses in a motor are 1600 W and the motor runs at 800 r.p.m., then,

$$T_a - T_{sh} = 9.55 \times \frac{1600}{800} = 19.1\ N-m$$

As stated above, it is the shaft torque Tsh that produces the useful output. If the speed of the motor is N r.p.m., then,

$$\text{Output in watts} = \frac{2\pi N T_{sh}}{60}$$

$$\text{or}, T_{sh} = \frac{\text{Output in watts}}{\frac{2\pi N}{60}}\ N-m$$

$$\text{or}, T_{sh} = 9.55 \times \frac{\text{Output in watts}}{N}$$

(since $60/2\pi = 9.55$)

D.C. Motor Characteristics

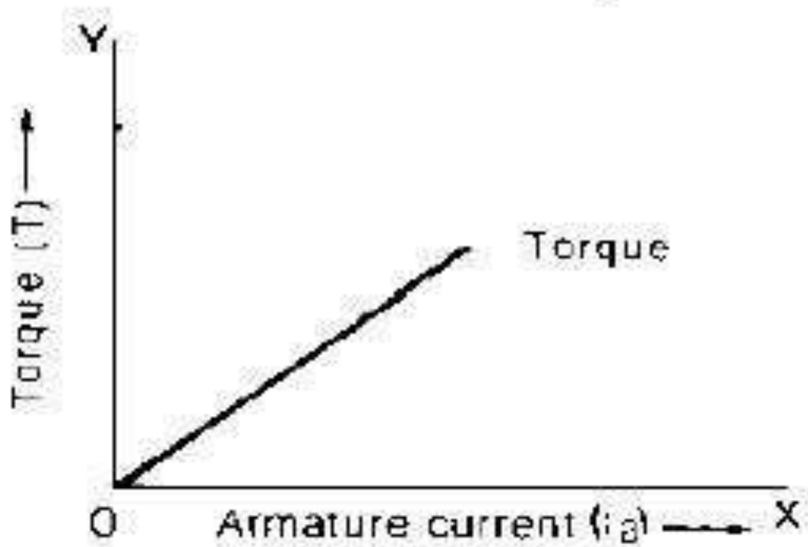
- There are three principal types of d.c. motors viz., shunt motors, series motors and compound motors.
- Both shunt and series types have only one field winding wound on the core of each pole of the motor.
- The compound type has two separate field windings wound on the core of each pole.
- The performance of a d.c. motor can be judged from its characteristic curves known as motor characteristics, following are the three important characteristics of a d.c. motor:
- **Torque and Armature current characteristic (T_a/I_a)**
  - It is the curve between armature torque T_a and armature current I_a of a d.c. motor. It is also known as electrical characteristic of the motor.
- **Speed and armature current characteristic (N/I_a)**
  - It is the curve between speed N and armature current I_a of a d.c. motor. It is very important characteristic as it is often the deciding factor in the selection of the motor for a particular application.It is also known as speed characteristics of the motor.
- **Speed and torque characteristic (N/T_a)**
  - It is the curve between speed N and armature torque T_a of a d.c. motor. It is also known as mechanical characteristic of the motor.

characteristics of DC Shunt motor
Torque Vs Armature current

This characteristic gives us information that, how torque of machine will vary with armature current, which depends upon load on the motor.

$$T \propto I_a$$

Thus,



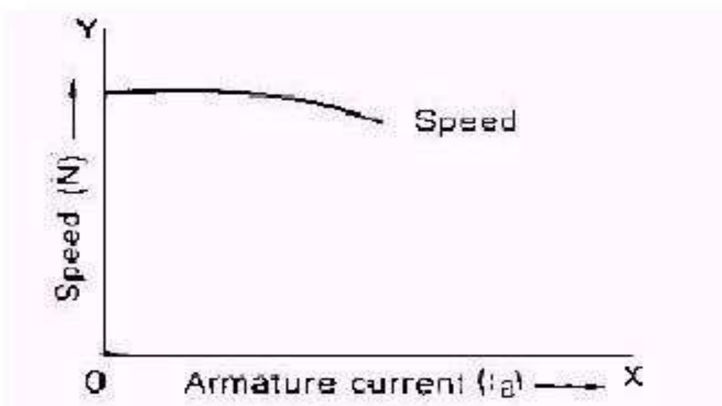
Characteristics of DC Shunt Motor
Speed Vs Armature current

The back emf of dc motor is $Eb = \dfrac{N\emptyset ZP}{A60} = V - I_a R_a$

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

where K = 60A/ ZP and it is constant. In dc shunt motor, when supply voltage V is kept constant the shunt field current and hence flux per pole will also be constant.

$$\therefore N \propto V - I_a R_a$$



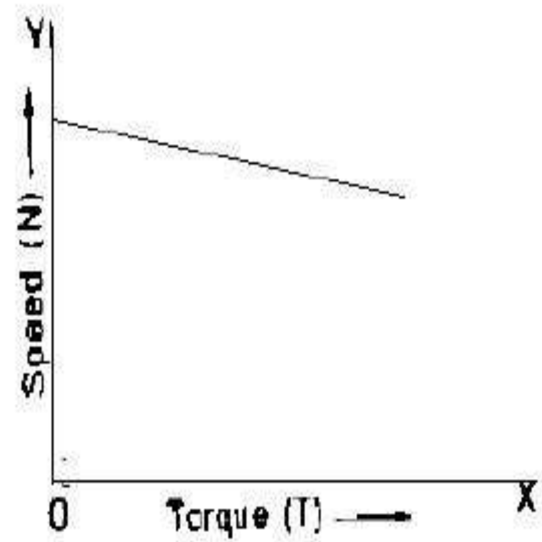
Therefore shunt motor is considered as constant speed motor.

Characteristics of DC Shunt motorSpeed Vs Torque

- From the above two characteristics of dc shunt motor, the torque developed and speed at various armature currents of dc shunt motor may be noted.

- If these values are plotted, the graph representing the variation of speed with torque developed is obtained.

- This curve resembles the speed Vs current characteristics as the torque is directly proportional to the armature current.



Applications of DC shunt Motor:

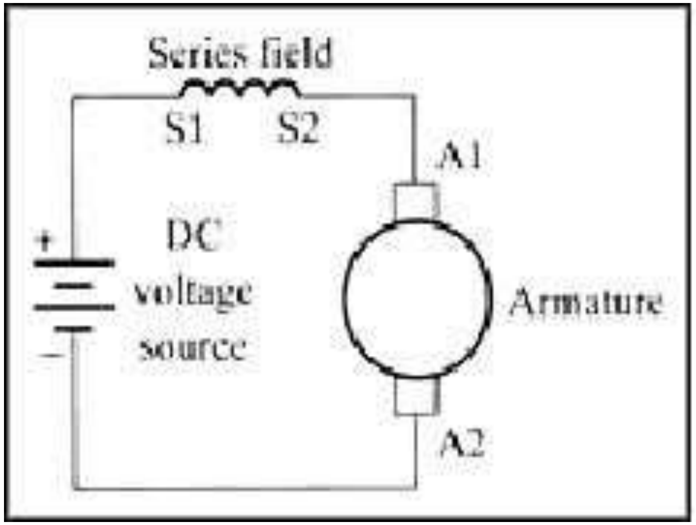
These motors are constant speed motors, hence used in applications requiring constant speed.

Like:

1) Lathe machine
2) Drilling machine
3) Grinders
4) Blowers
5) Compressors

DC Series Motor:

- In this type of DC motor the armature and field windings are connected in series.
- the resistance of the series field winding Rs is much smaller than the armature resistance Ra
- The flux produced is proportionalto the field current but in this



$I_f = I_a$ thus $\emptyset \propto I_a$

- Thus flux can never become constant in dc series motor as load changes I_f and I_a also gets changed
- Thus dc series motor is not a constant flux motor.

Torque and Speed equation of DC Series Motor:

As we have seen for dc motor

$$T \propto \emptyset I_a$$

But for dc series motor as $I_{f=}I_a$ $thus\ \emptyset \propto Ia$

So torque in dc series motor is

$$T \propto I_a^2$$

For dc motor

$$Eb = \frac{N\emptyset ZP}{A60}$$

Z , P, A and 60 are constants

Thus, $N \propto \frac{Eb}{\emptyset} \propto \frac{(V-IaRa)-I_sR_s}{\emptyset} = \frac{V-Ia(Ra+R_s)}{\emptyset}$ .... as I_a=I_s

for dc series motor

Characteristics of DC Series Motor:

- To study the performance of the DC series Motor various types of characteristics are to be studied.

1. Torque Vs Armature current characteristics.
2. Speed Vs Armature current characteristics.
3. Speed Vs Torque characteristics

Characteristics of DC Series Motor:

Torque Vs Armature current

- Torque developed in any dc motor is

$$T \propto \emptyset I_a$$

- In case of a D.C. series motor, as field current is equal to armature current, and for small value of I_a

$$\emptyset \propto I_a$$

Characteristics of DC Series Motor:
Torque Vs Armature current

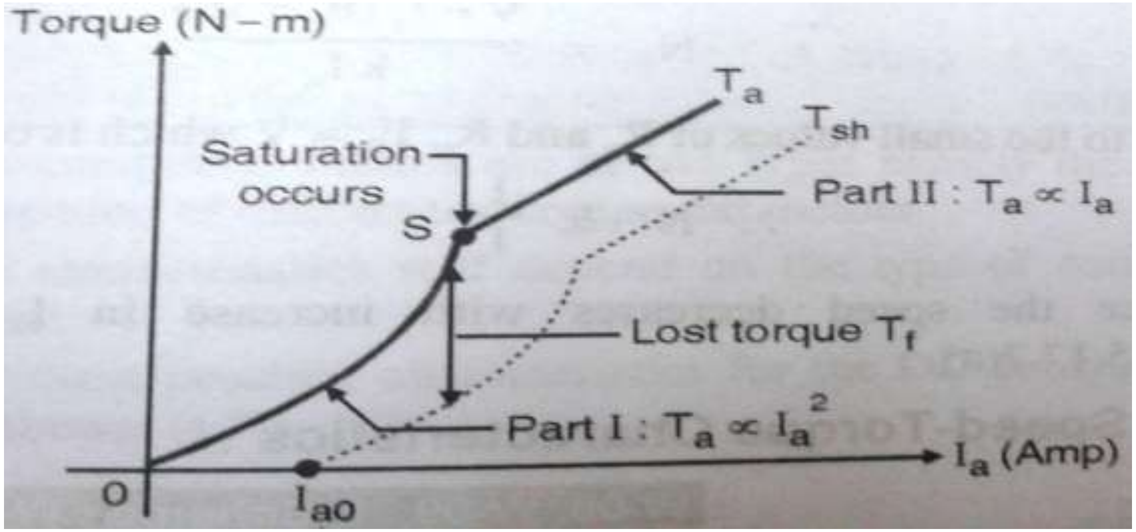
- Therefore the torque in the dc series motor for small value of I_a

$$T \propto {I_a}^2$$

- When I_a is large the $\emptyset$ remains the constant due to saturation, thus torque is directly proportional to armature current for large value of I_a

$$T \propto I_a$$

- Thus Torque Vs Armature current characteristics begin to raise parabolically at low value of armature current and when saturation is reached it become a straight line as shown below.



Caracteristics of DC Series Motor

Speed Vs Armature current

- Consider the following equation

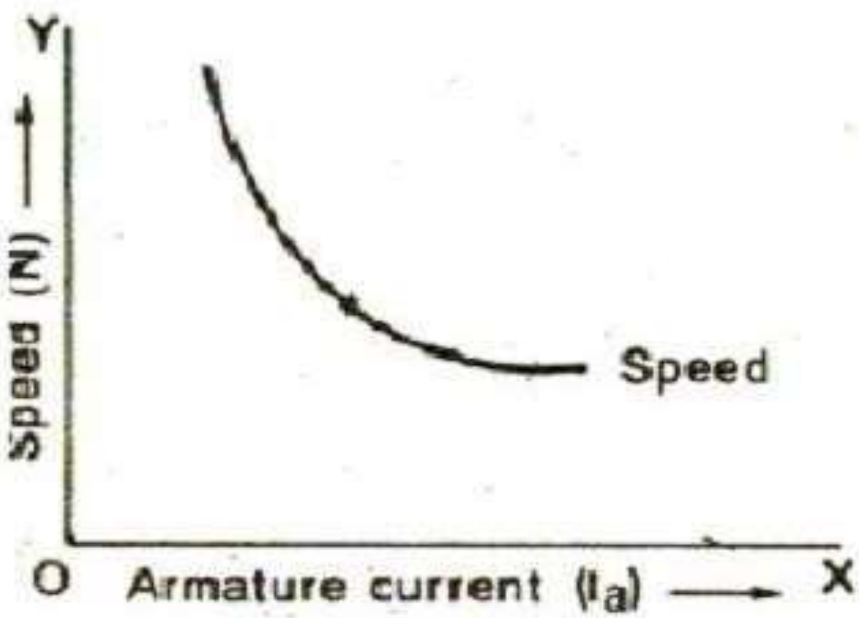
$$N = \frac{K(V - I_a R_a)}{\emptyset}$$

- When supply voltage V is kept constant, speed of the motor will be inversely proportional to flux. In dc series motor field exciting current is equal to armature current which is nothing but a load current. Therefore at light load when saturation is not attained, flux will be proportional to the armature current and hence speed will be inversely proportional to armature current. Hence speed and armature current characteristics is hyperbolic curve upto saturation.

Caracteristics of DC Series Motor

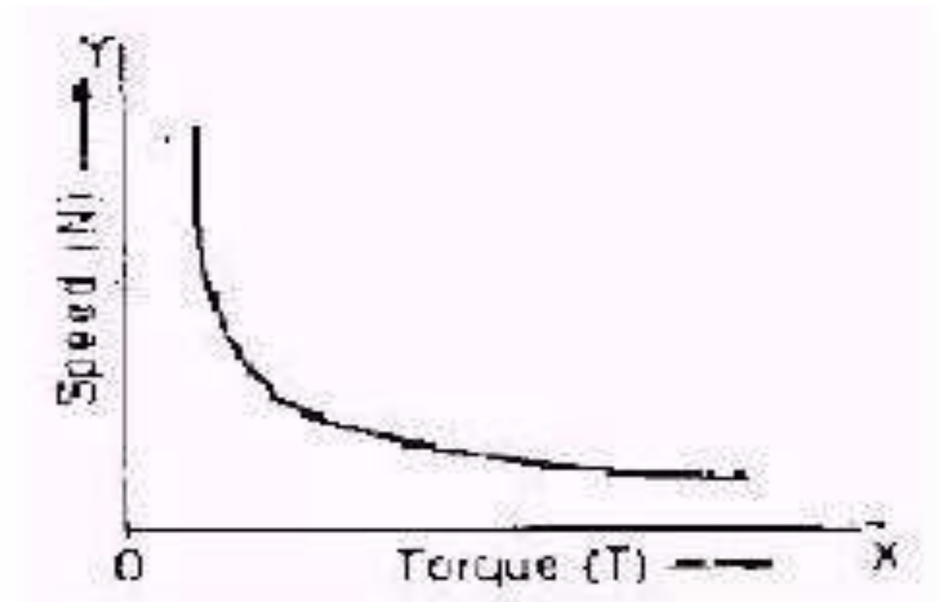
Speed Vs Armature current

- As the load increases the armature current increases and field gets saturated, once the field gets saturated flux will become constant irrespective of increases in the armature current. Therefore at heavy load the speed of the dc series motor remains constant.
- This type of dc series motor has high starting torque.



Characteristics of DC Series motorSpeed Vs Torque

- The Speed Vs Torque characteristics of dc series motor will be similar to the Speed Vs Armature current characteristics it will be rectangular hyperbola, as shown in the fig.



Applications of DC series Motor

These motors are useful in applications where starting torque required is high and quick acceleration. Like:

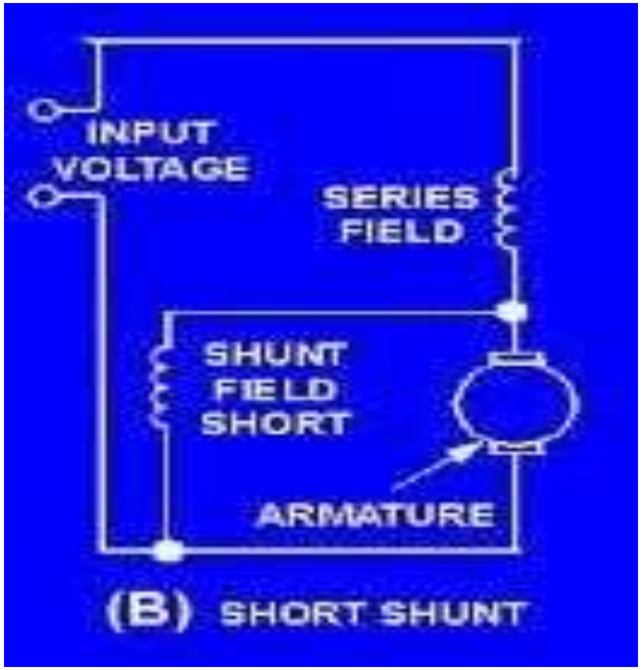
1) Traction
2) Hoists and Lifts
3) Crane
4) Rolling mills
5) Conveyors

DC Compound Motor:

- The DC compound motor is a combination of the series motor and the shunt motor. It has a series field winding that is connected in series with the armature and a shunt field that is in parallel with the armature. The combination of series and shunt winding allows the motor to have the torque characteristics of the series motor and the regulated speed characteristics of the shunt motor. Several versions of the compound motor are:
- Short shunt Compound Motors
- Long shunt Compound Motors

Short shunt compound motor:

When shunt field winding is connected in parallel with armature like dc shunt motor and this assembly is connected in series with the series field winding then this type of motor is called as short shunt compound motor.



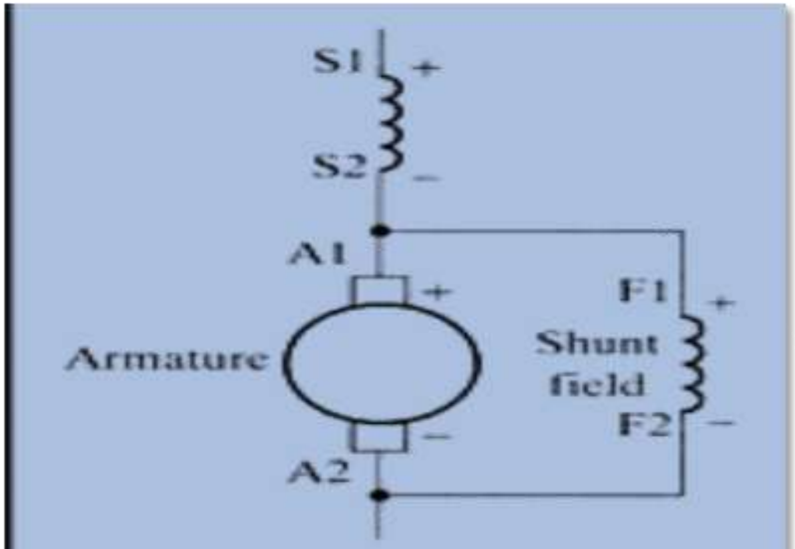
Short shunt compound motor:

- Depending on the polarity of the connection short shunt motor is classified as:

1. Cumulative compound motor.
2. Differential compound motor.

Cumulative compound motor (short shunt):

- Figure shows a diagram of the cumulative compound motor. It is so called because the shunt field is connected so that its coils are aiding the magnetic fields of the series field and armature.
- In this figure that the top of the shunt field is positive polarity and that it is connected to the positive terminal of the armature.



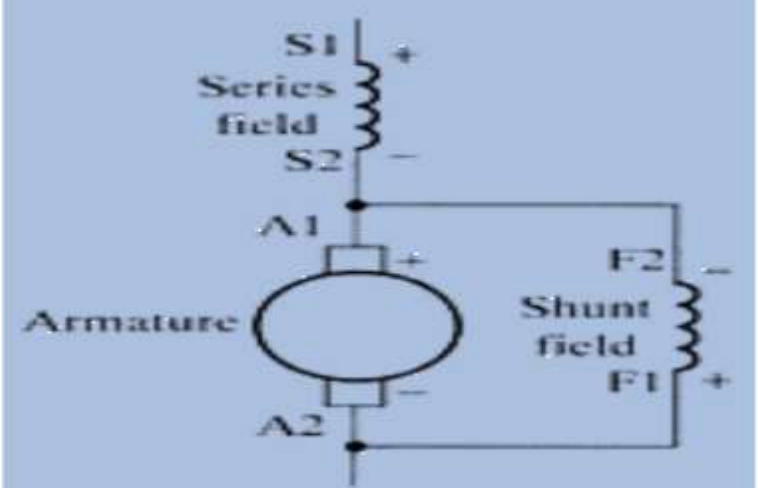
(a) Cummulative compound dc motor (short shunt)

- The cumulative compound motor is one of the most common DC motors because it provides high starting torque and good speed regulation at high speeds. Since the shunt field is wired with similar polarity in parallel with the magnetic field aiding the series field and armature field, it is called cumulative. When the motor is connected this way, it can start even with a large load and then operate smoothly when the load varies slightly.

- You should recall that the shunt motor can provide smooth operation at full speed, but it cannot start with a large load attached, and the series motor can start with a heavy load, but its speed cannot be controlled. The cumulative compound motor takes the best characteristics of both the series motor and shunt motor, which makes it acceptable for most applications.

Differential Compound Motor (short shunt):

- Differential compound motors use the same motor and windings as the cumulative compound motor, but they are connected in a slightly different manner to provide slightly different operating speed and torque characteristics. Figure shows the diagram for a differential compound motor with the shunt field connected so its polarity is reversed to the polarity of the armature. Since the shunt field is still connected in parallel with only the armature, it is considered a short shunt.



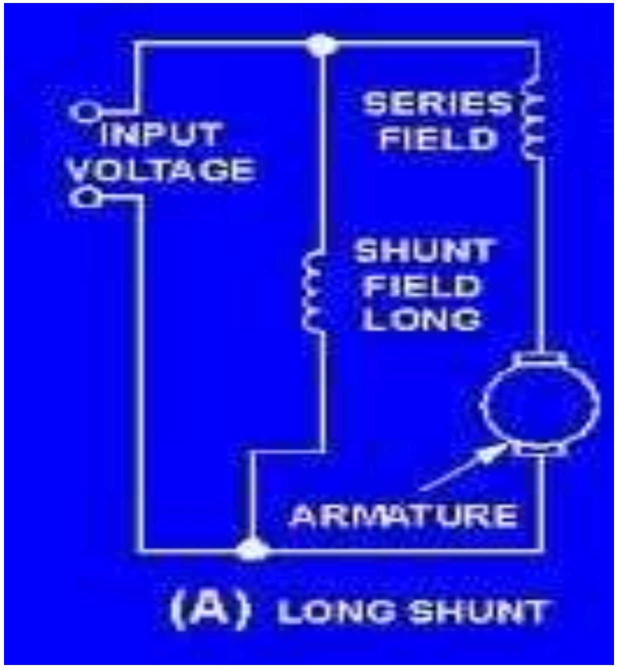
(b) Differential compound dc motor (short shunt)

- In the above diagram you should notice that F_1 and F_2 are connected in reverse polarity to the armature. In the differential compound motor the shunt field is connected so that its magnetic field opposes the magnetic fields in the armature and series field. When the shunt field's polarity is reversed like this, its field will oppose the other fields and the characteristics of the shunt motor are not as pronounced in this motor. This means that the motor will tend to overspeed when the load is reduced just like a series motor. Its speed will also drop more than the cumulative compound motor when the load increases at full rpm. These two characteristics make the differential motor less desirable than the cumulative motor for most applications.

Long shunt compound motor:

- when the shunt field is connected in parallel with both the series field and the armature then this type of motor is called as long shunt compound motor.
- Depending on the polarity of connection of shunt field winding, series field winding and armature, long shunt motor is classified as:

1. Cumulative Compound Motor.
2. Differential Compound Motor.



Characteristics of DC compound Motor:

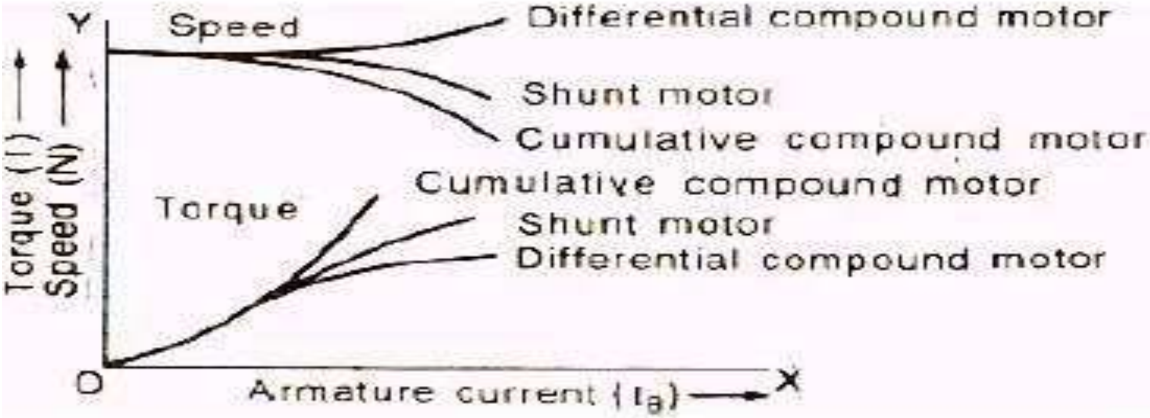
- To study the performance of the DC compound Motor various types of characteristics are to be studied.

1. Torque Vs Armature current characteristics.
2. Speed Vs Armature current characteristics.
3. Speed Vs Torque characteristics

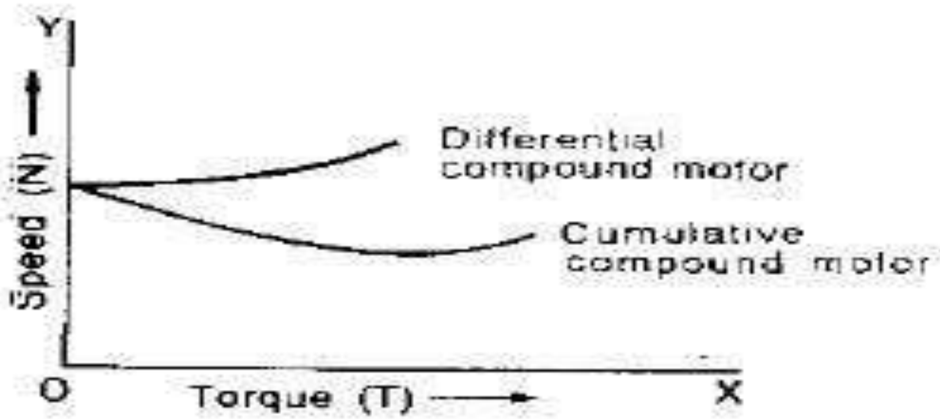
- In dc compound motors both shunt and series field acting simultaneously.
- In cumulative compound motor series field assist the shunt field.
- In such motors when armature current increases the field flux increases.
- So for given armature current the torque developed will be greater and speed lower when compared to a dc shunt motor.
- In differential compound motor series field opposes the shunt field, therefore when armature current decreases the field flux decreases, so for given armature current the torque developed will be lower and speed greater when compare to the dc shunt motor.

Torque Vs Armature current and Speed Vs Armature current

characteristics of dc compound motors



Speed Vs Torque characteristics are compared with that of shunt motor.



Applications of DC Compound Motor:

Cumulative Compound Motor:

- These motors have high starting torque.
- They can be operated even at no loads as they run at a moderately high speed at no load.
- Hence cumulative compound motors are used for the following applications.

❖ Elevators ,Rolling mills,Punches,Shears planers

Differential Compound Motor:

- The speed of these motors increases with increases in the load which leads to an unstable operation.
- Therefore we can not use this motor for any practical applications.

D.C. Motor Starter

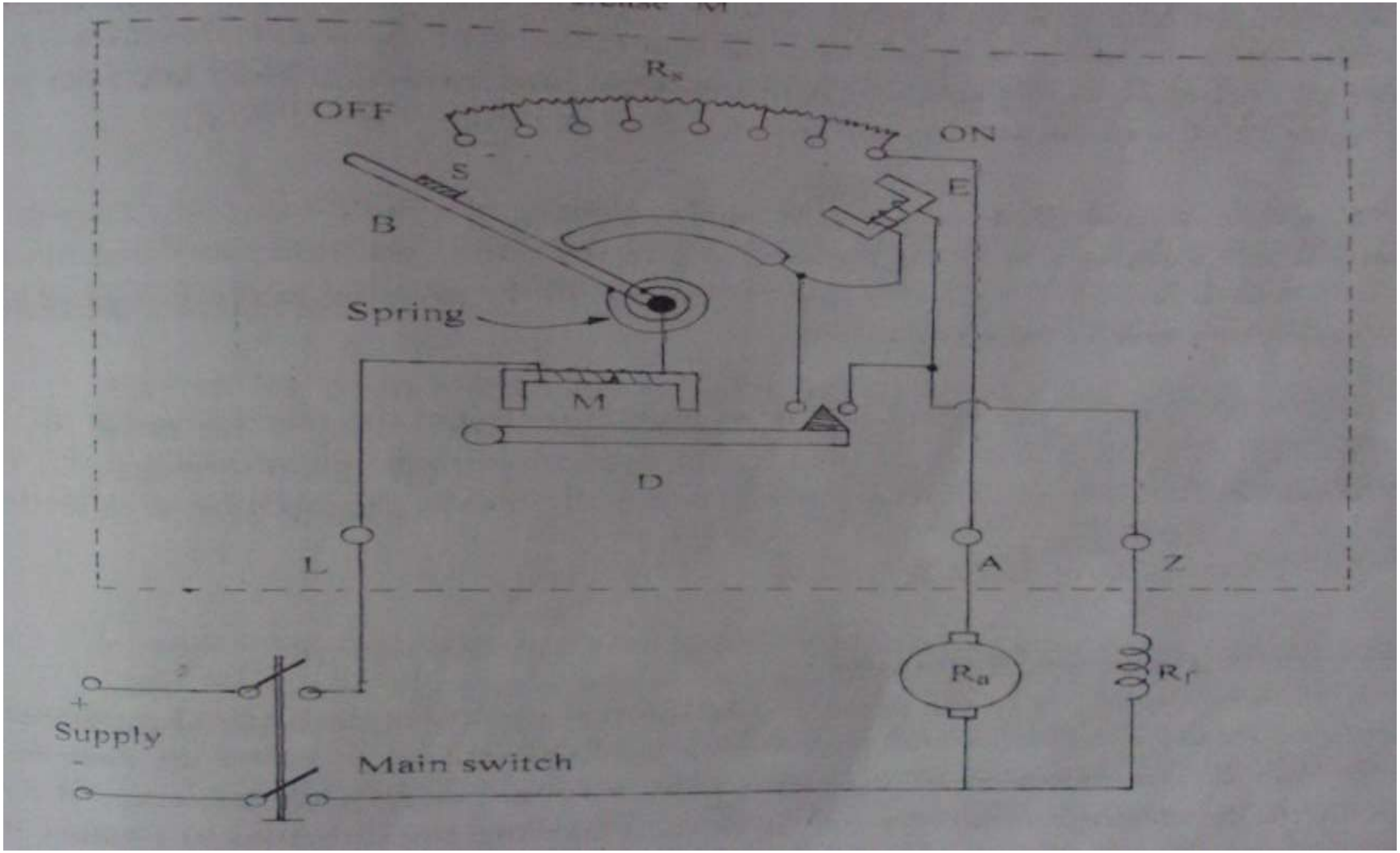
- It has been shown in the previous section that the current drawn by the armature circuit of a DC motor is given by
- $I_a = (V - E_b) / R_a$.
- At the instant of starting, there will be no back emf.
- If we apply full rated voltage to the motor at starting, the armature will draw a very high current which may be 20 – 30 times greater than its rated full load current.
- This high starting current will blow out the fuse and, prior to that it will damage the commutator and carbon brushes.
- To avoid this happening DC motor starter is necessary.
- A DC motor starter is a variable resistance connected in series with the armature winding (during the starting period only), which limits the starting current to a safe value.
- The starting resistance gradually cutout as the motor speeds up and develops back emf which in turn reduces the armature current.

D.C. Motor Starter

- When the armature rotates with full rated speed, the starting resistance will be completely cutout.
- Very small motors, however, can be started from the rest without starter because:
  - Such motors have a relatively higher armature resistance than the large motors; hence their starting current is not so high.
  - Being small, they have low moment of inertia, hence they speed up quickly.

- Figure shows the current diagram of a practical DC motor starter.
- It is called as three point starter.
- The three terminals of the starter are marked as L, A and Z.
- The negative line of supply is directly connected to the negative terminal of the armature which is also connected to the negative terminal of the field winding.
- The positive terminal of the supply line is connected to the terminal marked ‘L’ of the starter, which is further connected to the starting arm ‘B’ through over current release ‘M’.

D.C. Motor Starter

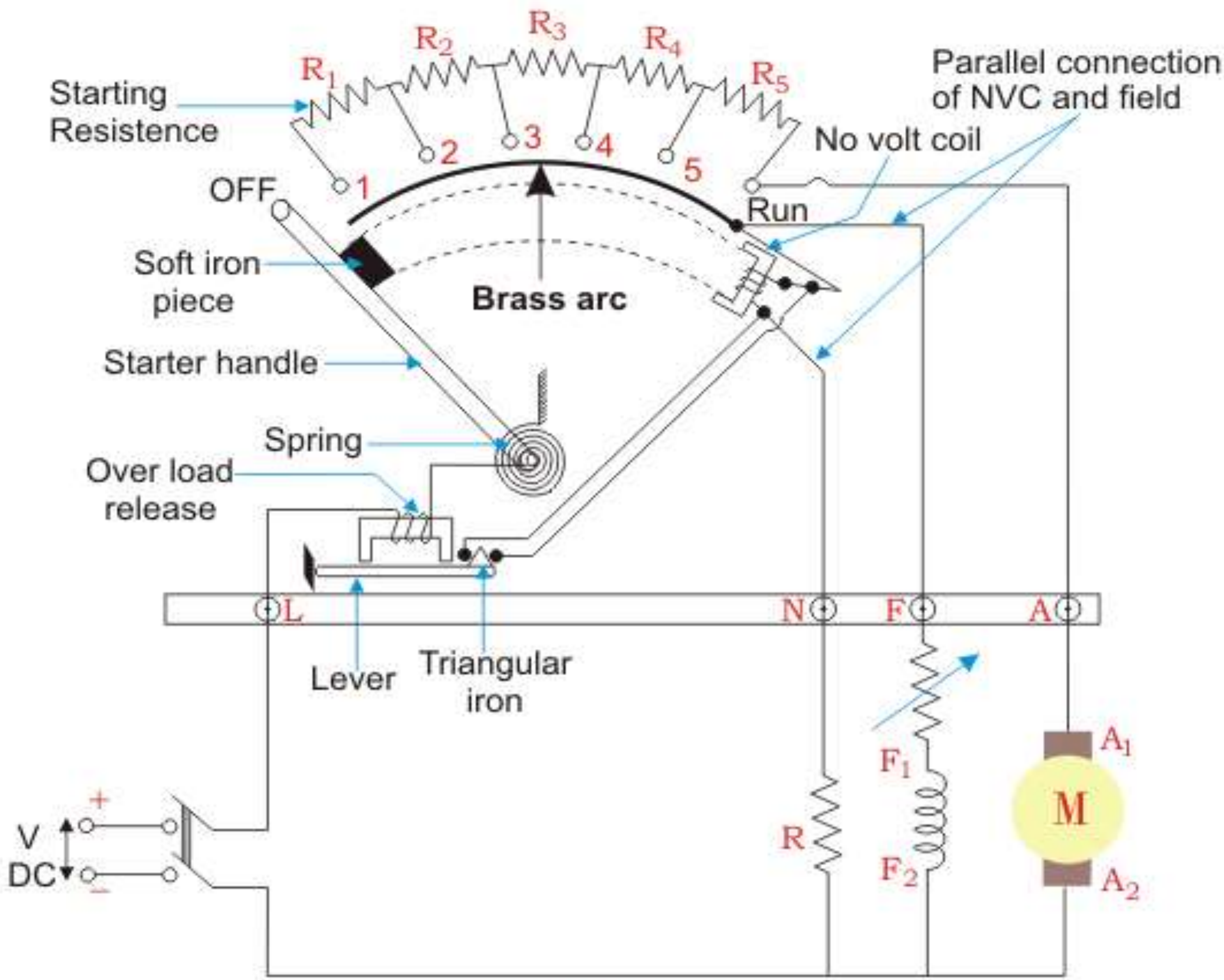


D.C. Motor Starter

- To start the motor, the main switch is first closed and starting arm 'B' is slowly moved to the stud no-1.
- As soon as the arm makes contact with stud no – 1, the field winding gets full supply voltage through the conductive arc and at the same time full starting resistance R_S is connected in series with the armature.
- The starting current drawn by the armature is given by:
  - $I_a = V / (R_a + R_s)$
- As the motor speeds up, arm is further moved and the starting resistance is gradually cut out.
- When the arm reach the position 'ON', the starting resistance R_S is completely cutout and at the same time the motor will have full rated speed, thus producing normal value of back emf to set armature current at normal value.

D.C. Motor Starter

- The arm moves over the various studs against a strong spring force which tends to pull back the arm to the 'OFF' position. But is a soft iron piece 'S' attached to the arm in which the 'ON' position is attracted and hold by an electromagnet 'E' (known as hold- on coil) energized by the shunt field current.
- When the motor is switched off by the main switch, the hold- on coil 'E' will get demagnetized and starting arm 'B' is thrown back to the 'OFF' position under the action of spring force. It also release the starting arm 'B' to the 'OFF' position at the instant of break in field winding and low voltage condition.
- If the motor is over loaded, the motor will draw high current and the electromagnet 'M' will be strong enough to lift up the liver 'D' and it will short circuits the electromagnet 'E'. Then the electromagnet 'E' will get de-energised and it will release the starting arm to 'OFF' position.



Four Point Starter

Speed of a D.C. Motor

$$E_b = V - I_a R_a$$

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

$$\therefore \quad \frac{P\phi Z N}{60\ A} = V - I_a R_a$$

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

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

But $$V - I_a R_a = E_a$$

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

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

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.

Speed of a D.C. Motor

Therefore the factors controlling the speed of DC motor are: Applied voltage 'V', Armature resistance 'Ra' and Flux per pole (ø)

Speed Relations

If a d.c. motor has initial values of speed, flux per pole and back e.m.f. as N_1, ϕ and E_{b1} respectively and the corresponding final values are N_2, ϕ_2 and E_{b2}, then,

$$N_1 \propto \frac{E_{b1}}{\phi_1} \quad \text{and} \quad N_2 \propto \frac{E_{b2}}{\phi_2}$$

$$\therefore \quad \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_1}{\phi_2}$$

(i) For a shunt motor, flux practically remains constant so that $\phi_1 = \phi_2$.

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

(ii) For a series motor, $\phi \propto I_a$ prior to saturation.

$$\therefore \quad \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{I_{a1}}{I_{a2}}$$

where I_{a1} = initial armature current
I_{a2} = final armature current

Speed Regulation

- The speed regulation of a motor is the change in speed from full-load to no-load and is expressed as a percentage of the speed at full-load i.e.

$$\% \text{ Speed regulation} = \frac{\text{N.L. speed} - \text{F.L. speed}}{\text{F.L. speed}} \times 100$$

$$= \frac{N_0 - N}{N} \times 100$$

where $N_0 = \text{No - load speed}$
$N = \text{Full - load speed}$

Speed Control of DC Shunt Motor

Speed of shunt motor can be controlled in two ways:

Flux Control Method &

Armature Control Method

<u>Flux Control Method:</u>

- It is clear that the speed of motor is inversely proportional to the flux per pole (ø).
- In this method of speed control, a variable resistance R_v is connected in series with the field winding to regulate the field current thereby regulates the flux per pole.

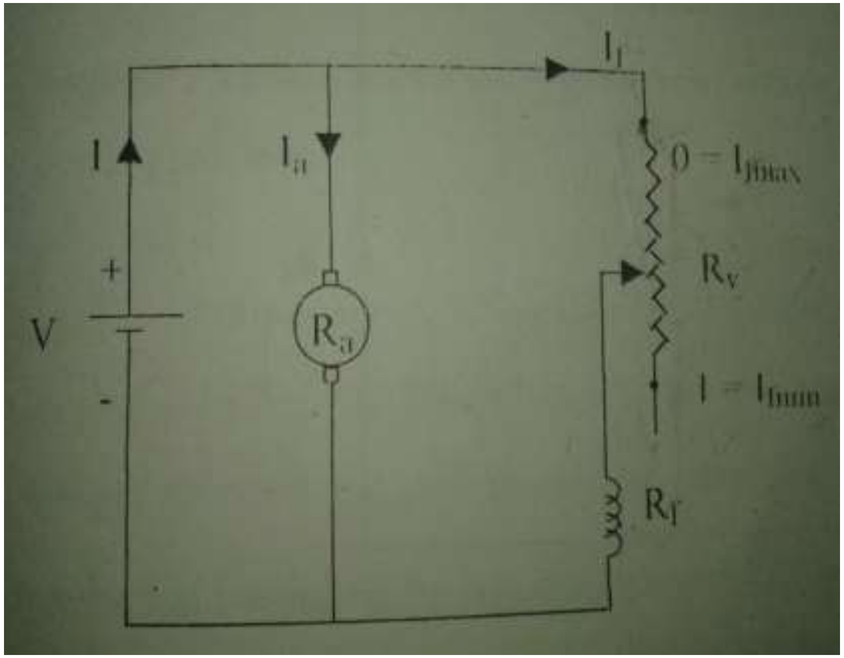


Figure: Flux Control Method of Speed Control

Speed Control of DC Shunt Motor – Flux Control Method

- The variable resistance R_v can only reduce the field current below its rated value.
- Therefore, this method is only suitable to control the speed above the rated speed.
- When R_v is reduced to '0' position, full rated field current ($I_f = V/R_f$) will flow and the motor rotates with normal rated speed.
- When full Rv is connected at position '1', the field current will reduce to $I_f = V/(R_f + R_v)$ thereby reducing the flux per pole, then the motor rotates with a speed higher than normal rated speed.
- Between the positions '0' and '1' many intermediate speed can be obtained by sliding the variable point contact.

Speed Control of DC Shunt Motor – Armature Control Method

- This method is used when speed below the normal rated speed is required.
- As the supply voltage is normally constant, the voltage across the armature is varied by inserting a variable resistance R_v in series with the armature circuit.
- As the field winding is directly proportional across the full supply voltage, the field current remains constant.

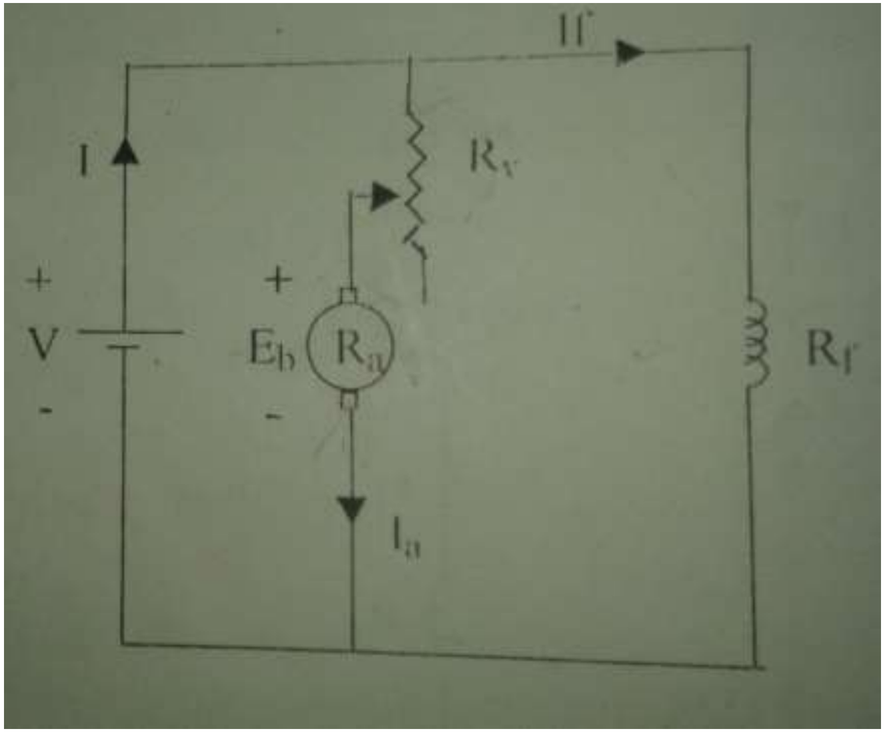


Figure: Armature Control Method

Speed Control of DC Shunt Motor – Armature Control Method

- Therefore, the flux per pole remains constant.
- The armature torque depends on the flux per pole and armature current $(T_a \propto \emptyset I_a)$.
- If the controller resistance R_v is increased keeping the load torque constant, the armature current remains constant, but the potential difference across the armature will decrease.
- Hence the speed of the armature will decrease.

Speed Control of DC Shunt Motor – Armature Control Method

- Let N_1 = speed of the motor when $R_v = 0$
- N_2 = speed of the motor when R_v is connected
- Since the flux per pole is constant and load torque is also constant

$I_{a1} = I_{a2}$ (since $T_a \propto \emptyset I_a$)

Then back emf

$E_{b1} = V - I_{a1} R_a$ and $E_{b2} = V - I_{a2}(R_a + R_v)$

$Now, \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\emptyset_1}{\emptyset_2}$ $but\ \emptyset_2 = \emptyset_1$

Therefore,

$$\frac{N_2}{N_1} = \frac{V - I_{a2}(R_a + R_v)}{V - I_{a1} R_a}$$

Speed control of DC series motors

Flux control method: Variation of flux in DC series motors can be done by anyone of the following methods.

Field diverter method:

- In this method, a variable resistance is connected across the series field winding as shown in the figure. When this variable resistance is connected some of the field current will get diverted and pass through R_V. Any desired amount of current can be passed through the field winding by adjusting the value of R_V. Hence, flux can be decreased and speed can be increased.

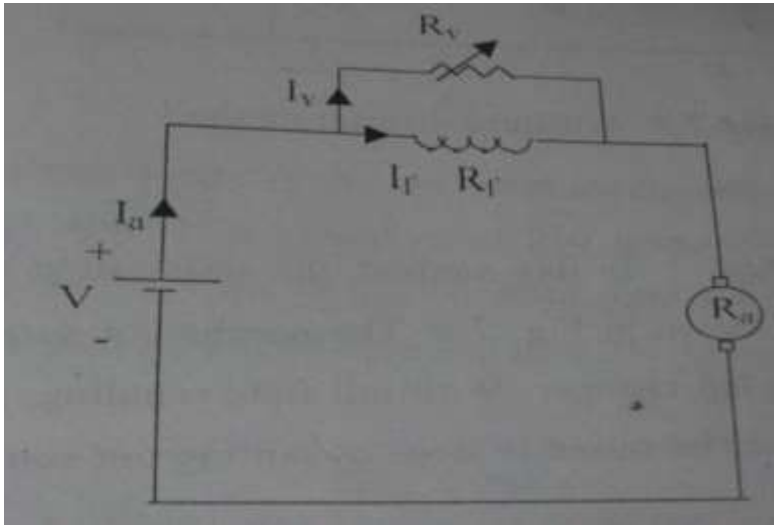


Figure: Field Diverter Method

Speed control of DC series motors

Armature diverter method:

- In this method, a variable resistance is connected across armature winding as shown in the figure. When this variable resistance is connected some of the armature current will be diverted and pass though R_V. For a constant load torque, if the armature current I_a is reduced due to diverted R_V, then the flux per pole must increase to produce constant torque.
- Hence, $T_a \propto \phi \, I_a$
- This results in a increase in main line current taken from the supply and a fall in speed (Hence, $N \propto 1/ø$). The variation in speed can be controlled by varying the value of diverter resistance R_V. This method is only suitable for controlling the speed below the normal rated speed.

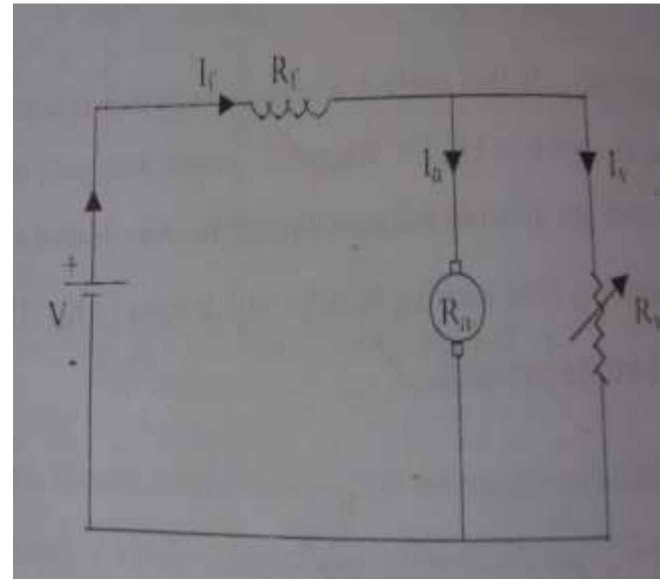


Figure: Armature Diverter Method

Speed control of DC series motors

Tapped field control method:

- In this method, the series field winding is provided with number of tappings as shown in the figure.
- The number of series turns in the circuit can be changed by the changer.
- With full field winding, the motor runs at its minimum speed. The speed can be raised in steps by cutting out some of the series turns.

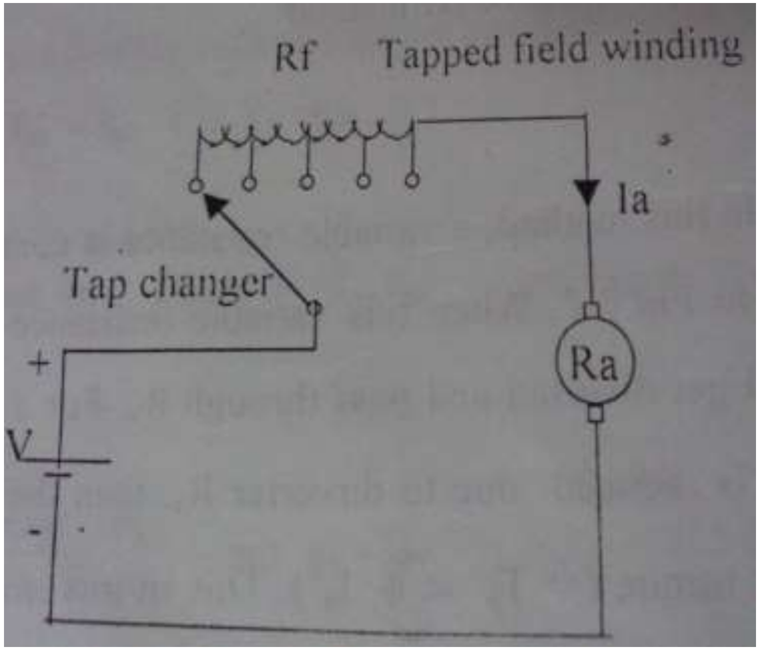


Figure: Tapped field control method

Reversal of Direction of Rotation:

- The direction of the magnetic flux in the air gap depends on the direction of the field current.
- And the direction of the force exerted on the armature winding depends on the direction of flux and the direction of armature current.
- Thus in order to reverse the direction of dc motor, we have to reverse the direction of force.
- This can be achieved either by changing the terminals of the armature or the terminals of the field winding.

Losses in a D.C. Motor

- The losses occurring in a d.c. motor are the same as in a d.c. generator .These are :

i. copper losses

ii. Iron losses or magnetic losses

iii. mechanical losses

As in a generator, these losses cause (a) an increase of machine temperature and (b) reduction in the efficiency of the d.c. motor.

The following points may be noted:

(i) Apart from armature Cu loss, field Cu loss and brush contact loss, Cu losses also occur in interpoles (commutating poles) and compensating windings. Since these windings carry armature current (I_a),

$$\text{Loss in interpole winding} = I_a^2 \times \text{Resistance of interpole winding}$$

$$\text{Loss in compensating winding} = I_a^2 \times \text{Resistance of compensating winding}$$

(ii) Since d.c. machines (generators or motors) are generally operated at constant flux density and constant speed, the iron losses are nearly constant.

(iii) The mechanical losses (i.e. friction and windage) vary as the cube of the speed of rotation of the d.c. machine (generator or motor). Since d.c. machines are generally operated at constant speed, mechanical losses are considered to be constant.

Efficiency of a D.C. Motor

- Like a d.c. generator, the efficiency of a d.c. motor is the ratio of output power to the input power i.e.

$$\text{Efficiency, } \eta = \frac{\text{output}}{\text{input}} \times 100 = \frac{\text{output}}{\text{output} + \text{losses}} \times 100$$

- As for a generator, the efficiency of a d.c. motor will be maximum when:

  Variable losses = Constant losses

- Therefore, the efficiency curve of a d.c. motor is similar in shape to that of a d.c.generator.

Power Stages

- The power stages in a d.c. motor are represented diagrammatically in Figure below.
- A - B = Copper losses
- B - C = Iron and friction losses
- Overall efficiency, hc = C/A
- Electrical efficiency, he = B/A
- Mechanical efficiency, hm = C/B

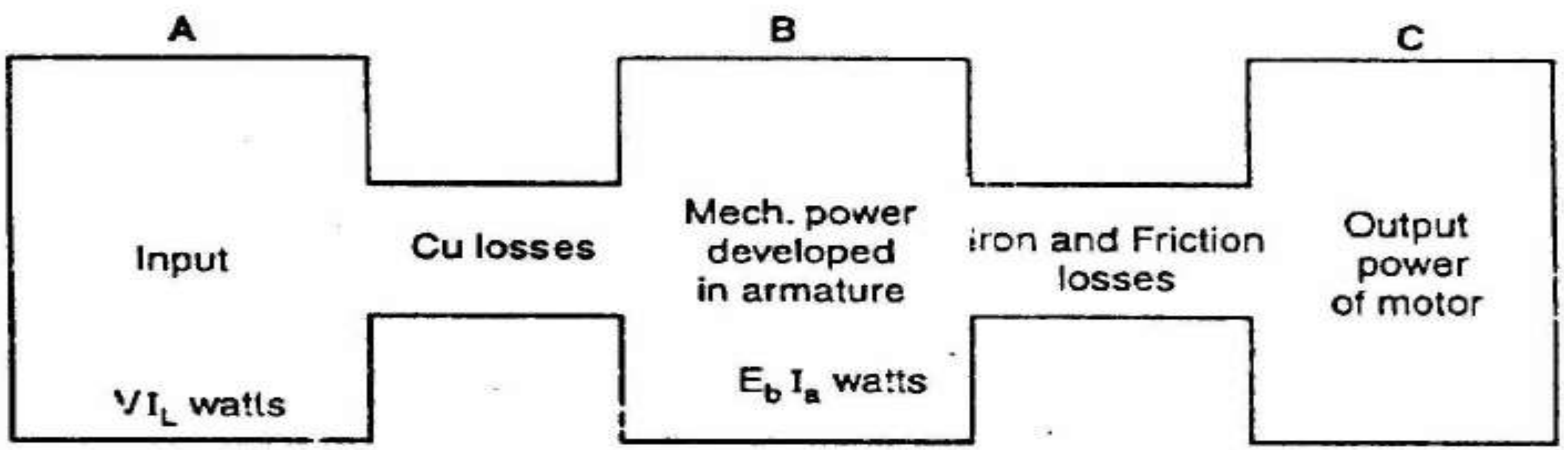


Figure : Power Stages