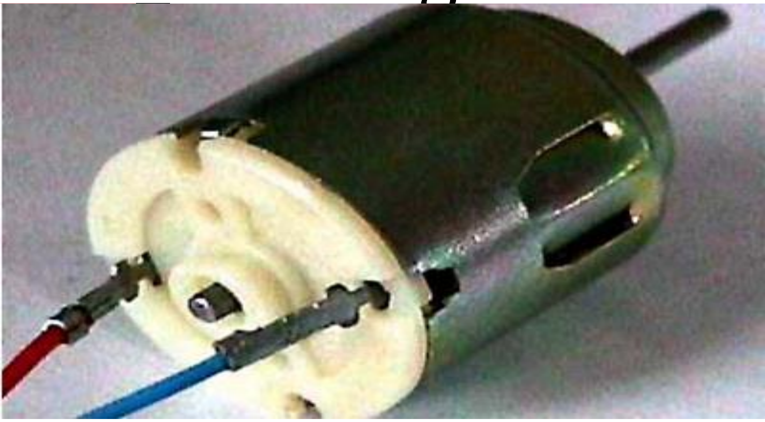
Chapter 2

D.C. MOTORS

D.C. Motor Principle

A machine that converts d.c. Electrical 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 = B .I. L newtons



*DC motors are everywhere! In a house, almost every mechanical movement that you see around you is caused by an DC (direct current)

*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.

Working of D.C. Motor

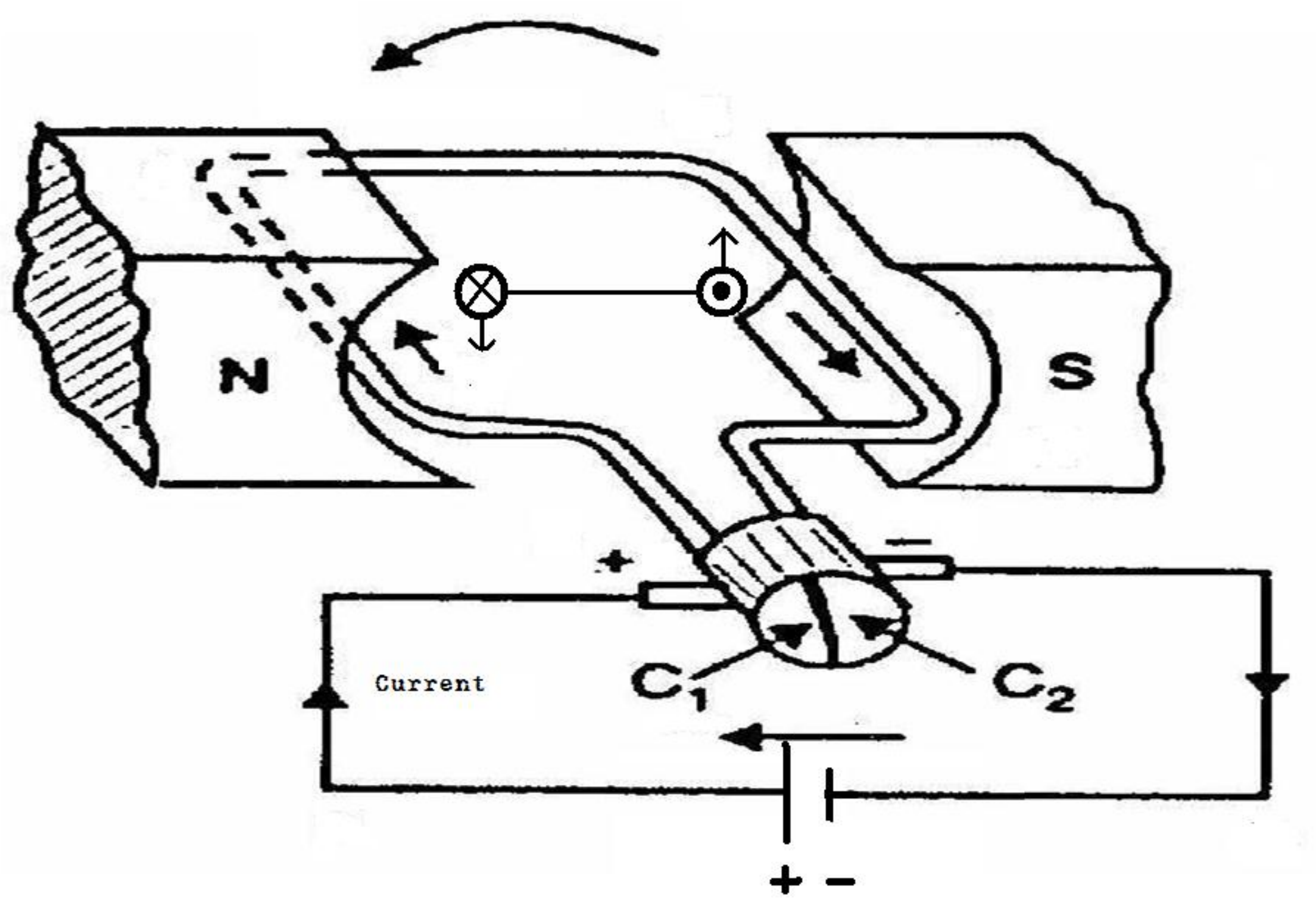
When the terminals of the motor are connected to an external source of d.c. supply:

(i) the field magnets are excited developing alternate N and S poles;

(ii) the armature conductors carry currents. All conductors under N-pole carry currents in one direction while all the conductors under S-pole carry currents in the opposite direction.

Suppose the conductors under N-pole carry currents into the plane of the paper and those under S-pole carry currents out of the plane of the paper. By applying **Fleming's left hand rule,** it is clear that force on each conductor is tending to rotate the armature in **anticlockwise** direction. All these forces add together to produce a driving torque which sets the armature rotating.

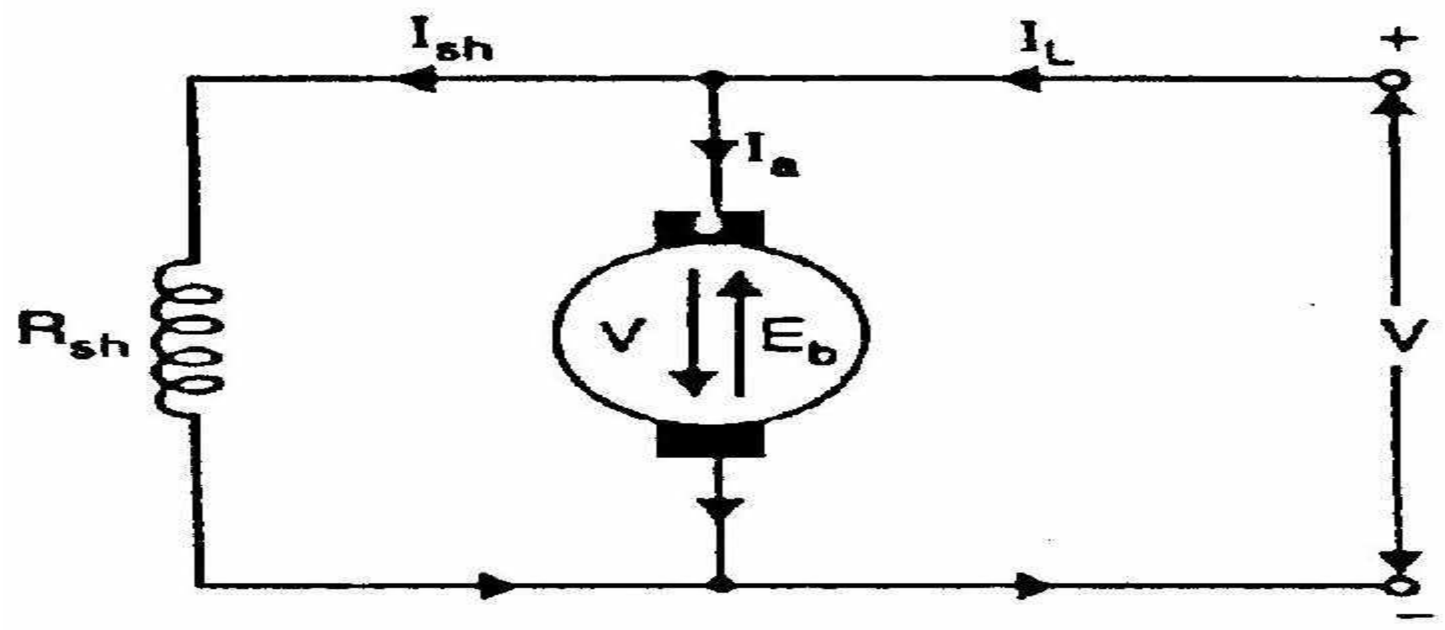
When the conductor moves from one side of a brush to the other, the current in that conductor is reversed and at the same time it comes under the influence of next pole which is of opposite polarity. Consequently, the direction of force on the conductor remains the same.


N
S
+
−
Current
C1
C2
+ −

Back or Counter E.M.F. E_b

When the armature of a d.c. motor **rotates**, 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. Eb.**

The back e.m.f. E_b(= P Φ ZN/60 A) is always less than the applied voltage V, although this difference is small when the motor is running under normal conditions.



Significance of Back E.M.F.

The presence of back e.m.f. makes the d.c. motor a **self-regulating machine** i.e., **it makes the motor to draw as much armature current as is just sufficient to develop the torque required by the load.**

Armature current, $I_a = V - E_b / R_a$

(i) When the motor is running **on no load**, small torque is required to overcome the friction and windage losses. Therefore, the armature current I_a is small and the back e.m.f. is nearly equal to the applied voltage.

(ii) **If the motor is suddenly loaded**, the first effect is to cause the **armature to slow down**. Therefore, the speed at which the armature conductors move through the field is reduced and hence the **back e.m.f. E_b falls**. The decreased back e.m.f. allows a **larger current** to flow through the armature and larger current means **increased driving torque**. Thus, the **driving torque increases as the motor slows down**. The motor will **stop slowing down when the armature current is just sufficient** to produce the increased torque required by the load.

(iii) **If the load on the motor is decreased**, the driving **torque** is momentarily in excess of the requirement so that **armature is accelerated**. As the armature speed increases, the back e.m.f. Eb also increases and causes the armature current Ia to decrease. The motor will stop accelerating when the armature current is just sufficient to produce the reduced torque required by the load.

It follows, therefore, that back e.m.f. in a d.c. motor **regulates** the flow of armature current i.e., it automatically changes the armature current to meet the load requirement.

Voltage Equation of D.C. Motor

Let in a d.c. motor if

V = applied voltage

E_b = back e.m.f.

R_a = armature resistance

I_a = armature current

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;

$$\mathbf{I_a = (V - E_b) / R_a}$$

or

$$\mathbf{V = E_b + I_a R_a}$$

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

Power Equation

If the equation $V = E_b + I_a R_a$ is multiplied by I_a 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 power)

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

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

Thus out of the armature input, a small portion (about 5%) is wasted as a $I^2 R_a$ and the remaining portion $E_b I_a$ is converted into **mechanical power** within the armature and denoted by $\mathbf{P_m}$

Condition For Maximum Power developed

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, dP_m/dI_a should be zero.

$$\therefore \quad \frac{dP_m}{dI_a} = V - 2I_a R_a = 0$$

or

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

Now,

$$V = E_b + I_a R_a = E_b + \frac{V}{2} \qquad \left[\because \; I_a R_a = \frac{V}{2}\right]$$

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

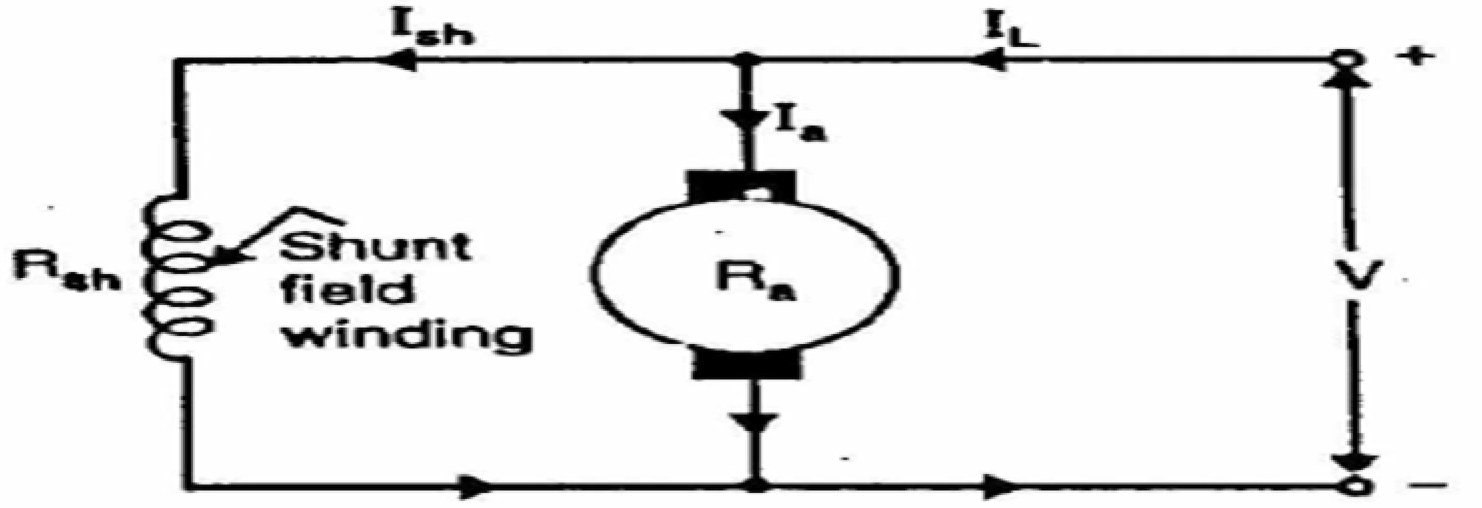
Hence mechanical power developed by the motor is maximum when back e.m.f. is equal to half the applied voltage.

Types of D.C. Motors

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

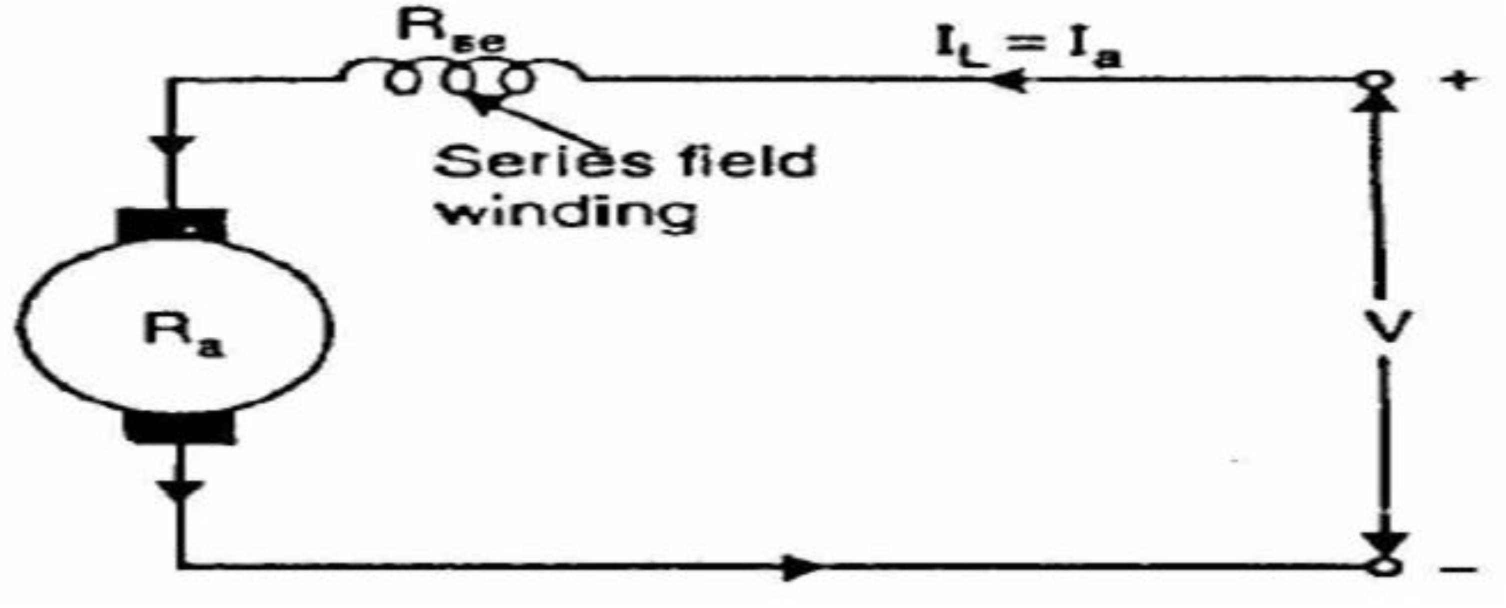
(i) Shunt-wound motor

In which the field winding is connected in parallel with the armature 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.



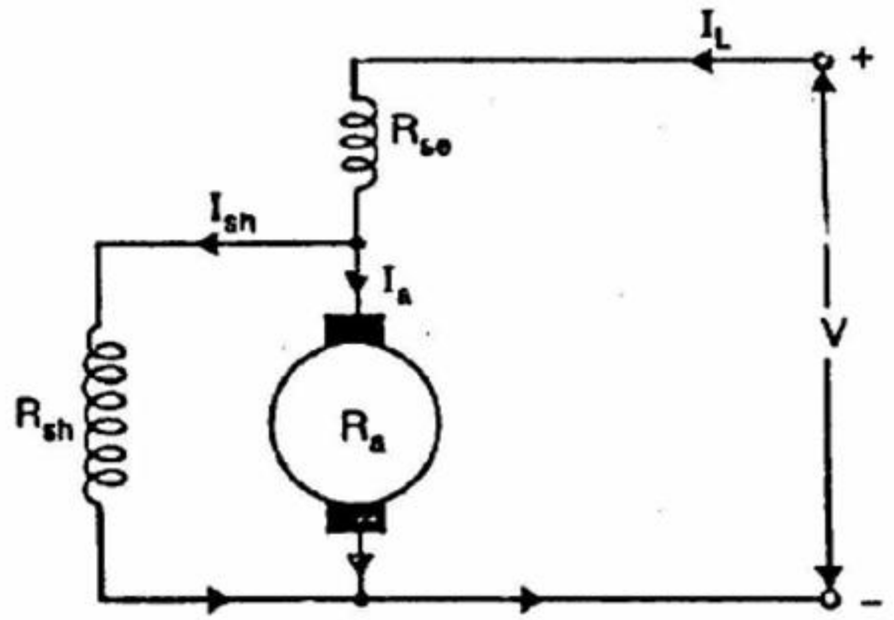
(ii) **Series-wound motor**

in which the field winding is connected in series with the armature, 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.

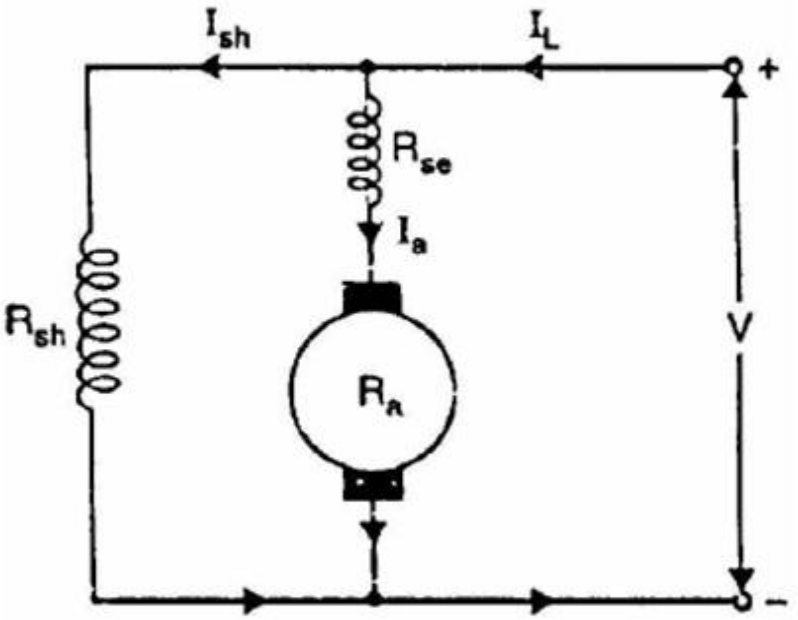


(iii) **Compound-wound motor**

In 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 ,it is called short-shunt connection. When the shunt winding is so connected that it shunts the series combination of armature and series field, it is called long-shunt connection.



Short-shunt connection



Long-shunt connection

Armature Torque of D.C. Motor

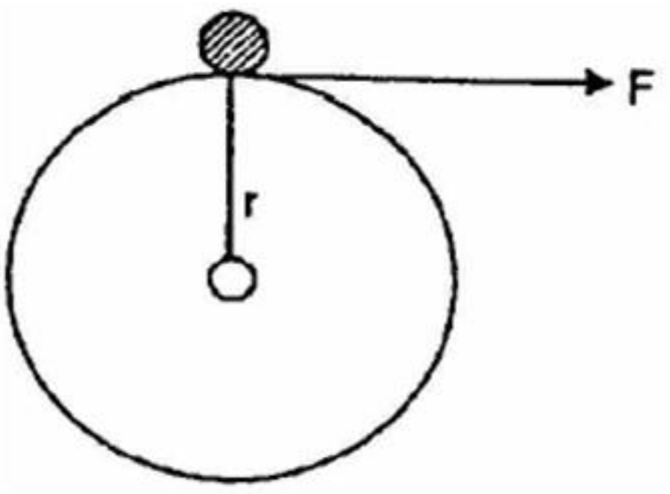
Torque is the moment of a force about an axis and is measured by the product of force (F) and radius (r) at right angle to which the force acts i.e.

$T = F * r$

In a d.c. motor, each conductor is acted upon by a 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 (Ta).

Let in a d.c. motor

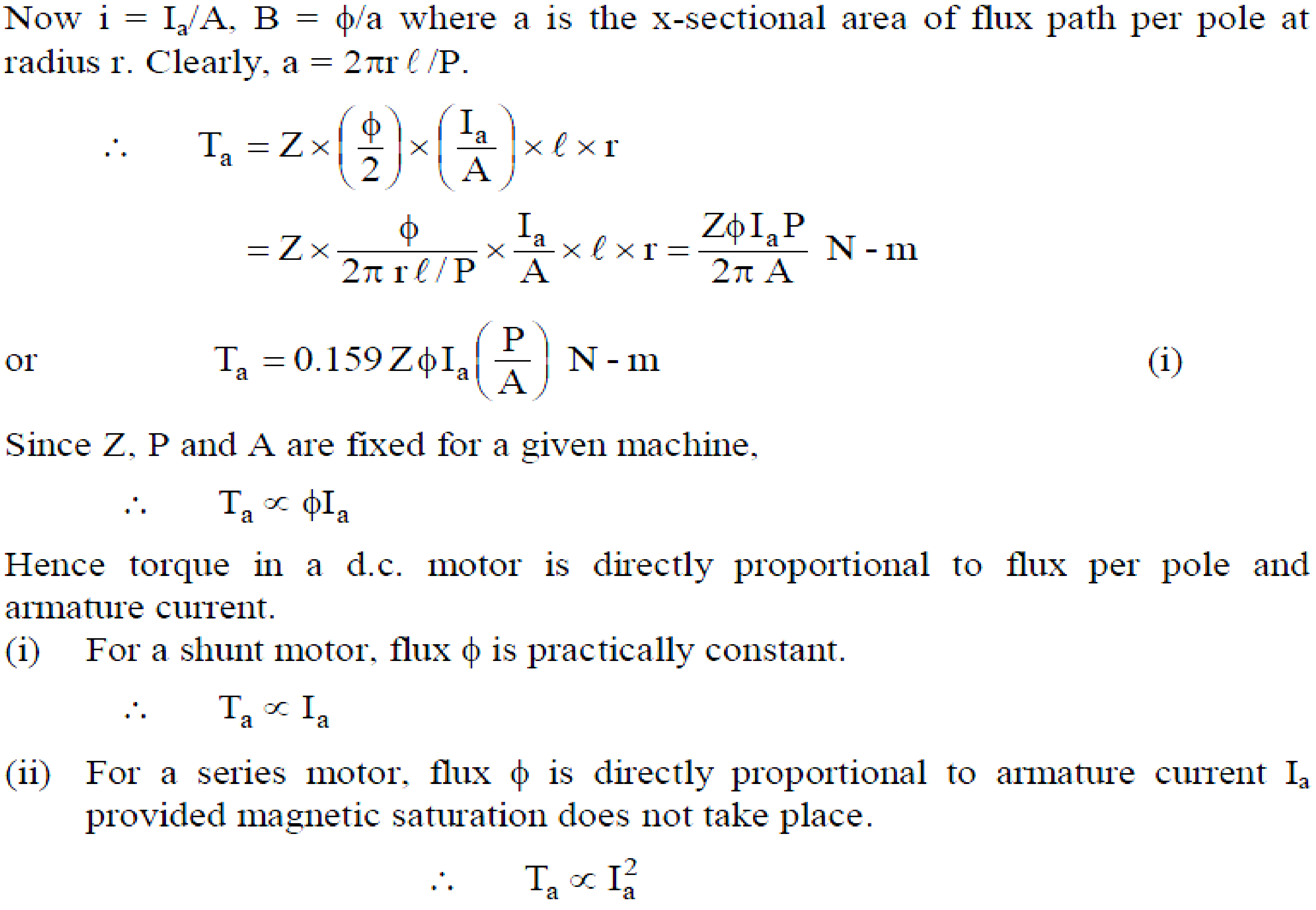


r = average radius of armature in m
l = effective length of each conductor in m
Z = total number of armature conductors
A = number of parallel paths
i = current in each conductor = Ia/A
B = average flux density in Wb/m2
Φ = flux per pole in Wb
P = number of poles
Force on each conductor, F = B I L newtons

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

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

= Z B I L r



Now $i = I_a/A$, $B = \phi/a$ where a is the x-sectional area of flux path per pole at radius r. Clearly, $a = 2\pi r \ell / P$.

$$\therefore \qquad T_a = Z \times \left(\frac{\phi}{2}\right) \times \left(\frac{I_a}{A}\right) \times \ell \times r$$

$$= Z \times \frac{\phi}{2\pi\, r\, \ell / P} \times \frac{I_a}{A} \times \ell \times r = \frac{Z\phi I_a P}{2\pi\, A} \ \text{N - m}$$

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

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

$$\therefore \qquad T_a \propto \phi I_a$$

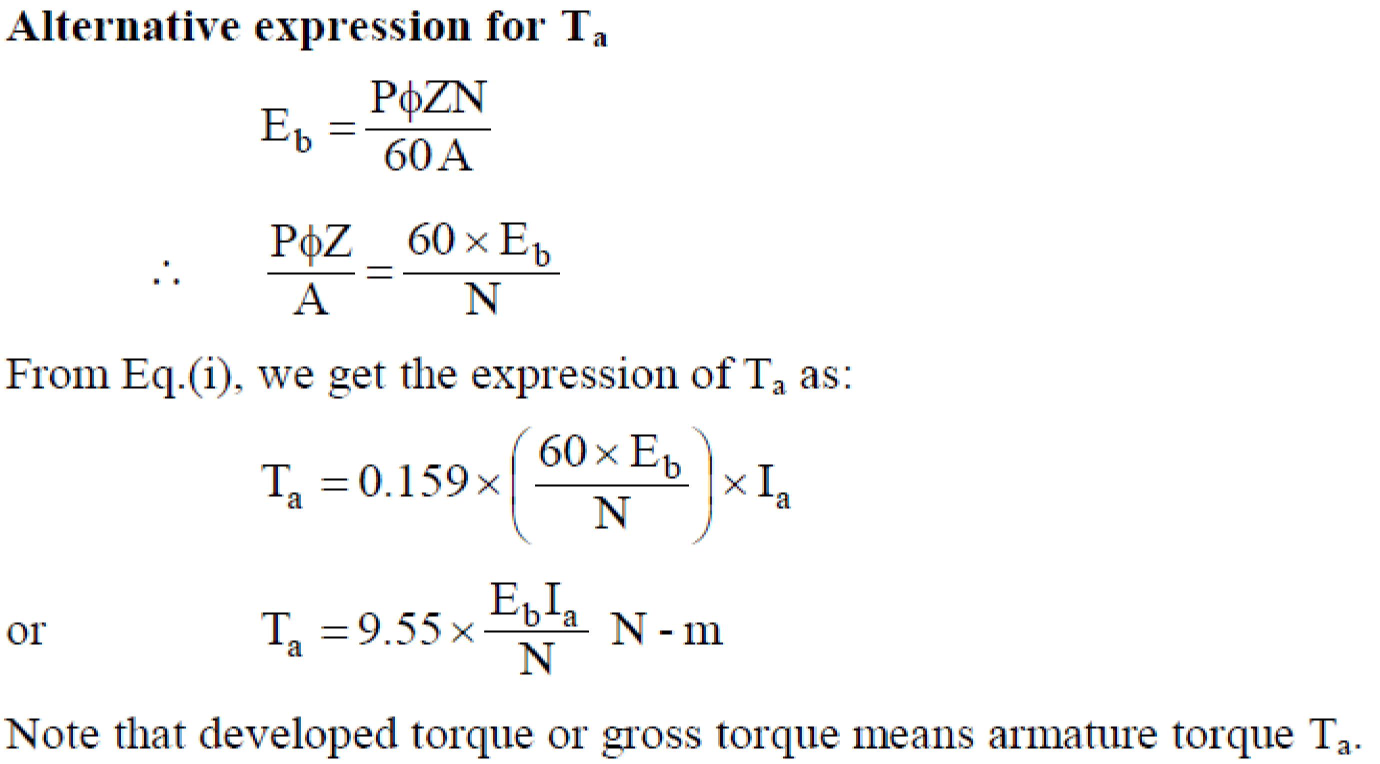
Hence torque in a d.c. motor is directly proportional to flux per pole and armature current.

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

$$\therefore \qquad T_a \propto I_a$$

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

$$\therefore \qquad T_a \propto I_a^2$$



Alternative expression for T_a

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

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

From Eq.(i), we get the expression of T_a as:

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

or $$T_a = 9.55 \times \frac{E_b I_a}{N} \ \text{N - m}$$

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

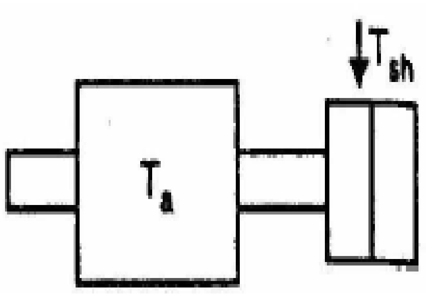


Fig. (4.9)

Shaft Torque (T_{sh})

The torque which is available at the motor shaft for doing useful work is known as shaft torque. It is represented by T_{sh}. Fig. (4.9) 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 Tsh is somewhat less than the armature torque Ta. The difference T_a - T_{sh} is called lost torque.

Speed of a D.C. Motor

$$E_b = V - I_aR_a$$

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

$$\therefore \quad \frac{P\phi ZN}{60\ A} = V - I_aR_a$$

or $$N = \frac{(V - I_aR_a)}{\phi}\,\frac{60\ A}{PZ}$$

or $$N = K\frac{(V - I_aR_a)}{\phi} \qquad \text{where} \qquad K = \frac{60\,A}{PZ}$$

But $$V - I_aR_a = E_a$$

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

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 Relations

If a d.c. motor has initial values of speed, flux per pole and back e.m.f. as N_1, ϕ_1 and E_{b1} respectively and the corresponding final values are N_2, ϕ_2 and E_{b2}, then,

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

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

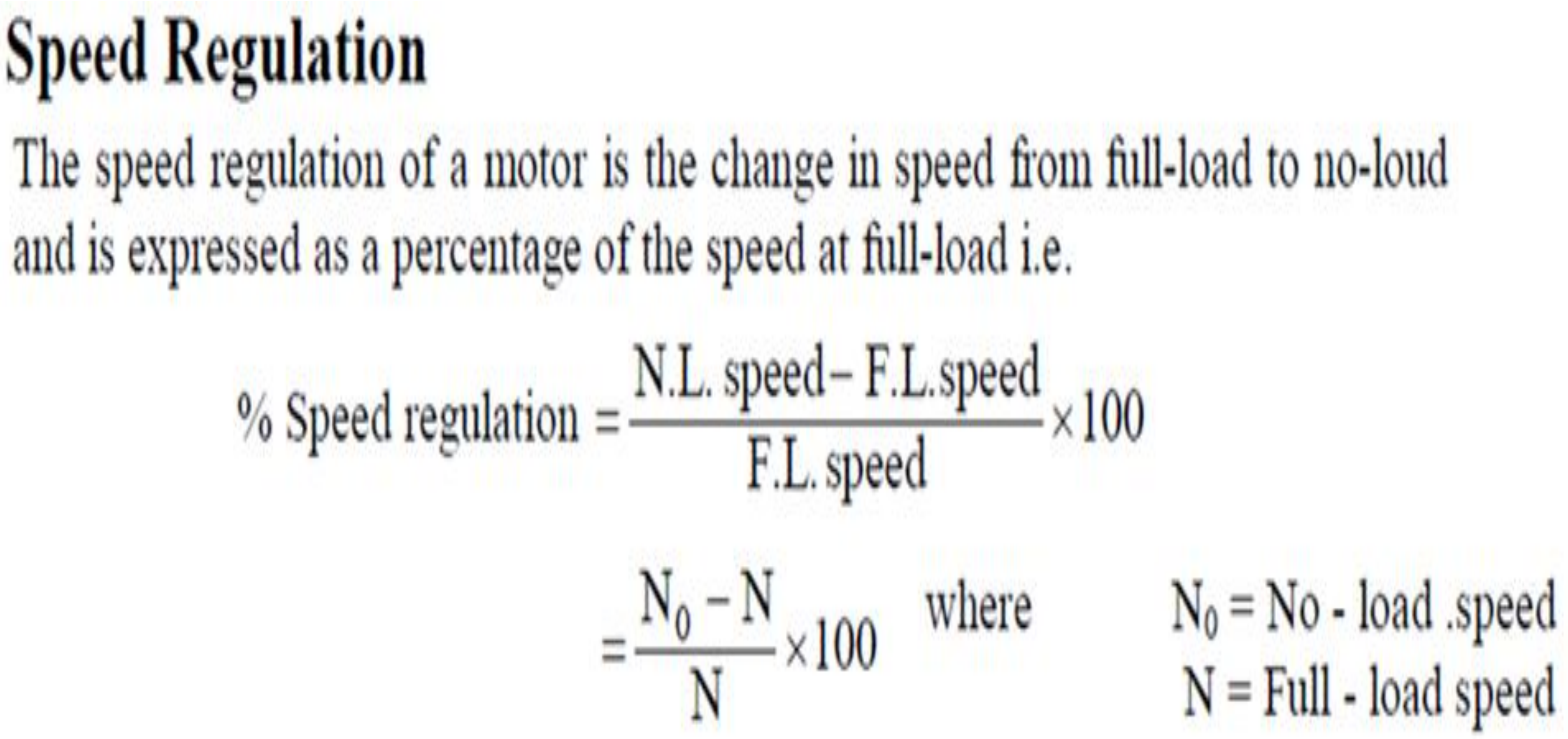
(i) For a shunt motor, flux practically remains constant so that $\phi_1 = \phi_2$.

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

(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-loud and is expressed as a percentage of the speed at full-load i.e.

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

$$= \frac{N_0 - N}{N} \times 100 \quad \text{where}$$

N_0 = No - load .speed

N = Full - load speed

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:

(i) 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.

(ii) 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.

(iii) 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.

Characteristics of Shunt Motors

Fig. (4.13) shows the connections of a d.c. shunt motor. The field current I_{sh} is constant since the field winding is directly connected to the supply voltage V which is assumed to be constant. Hence, the flux in a shunt motor is approximately constant.

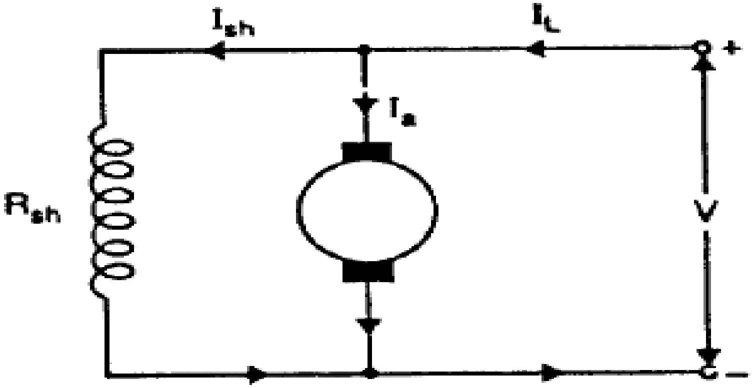


Fig. (4.13)

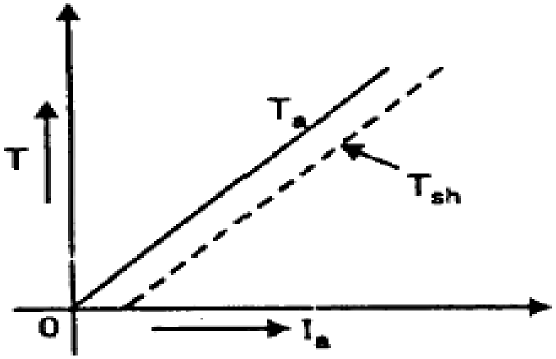


Fig. (4.14)

(i) T_a/I_a Characteristic. We know that in a d.c. motor,

$$T_a \propto \phi I_a$$

Since the motor is operating from a constant supply voltage, flux ϕ is constant (neglecting armature reaction).

$$\therefore \quad T_a \propto I_a$$

Hence T_a/I_a characteristic is a straight line passing through the origin as shown in Fig. (4.14). The shaft torque (T_{sh}) is less than T_a and is shown by a dotted line. It is clear from the curve that a very large current is required to start a heavy load. Therefore, a shunt motor should not be started on heavy load.

(ii) **N/I$_a$ Characteristic.** The speed N of a. d.c. motor is given by;

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

The flux ϕ and back e.m.f. E_b in a shunt motor are almost constant under normal conditions. Therefore, speed of a shunt motor will remain constant as the armature current varies (dotted line AB in Fig. 4.15). Strictly speaking, when load is increased, E_b (= $V - I_aR_a$) and ϕ decrease due to the armature resistance drop and armature reaction respectively. However, E_b decreases slightly more than ϕ so that the speed of the motor decreases slightly with load (line AC).

(iii) **N/T$_a$ Characteristic**. The curve is obtained by plotting the values of N and T_a for various armature currents (See Fig. 4.16). It may be seen that speed falls somewhat as the load torque increases.

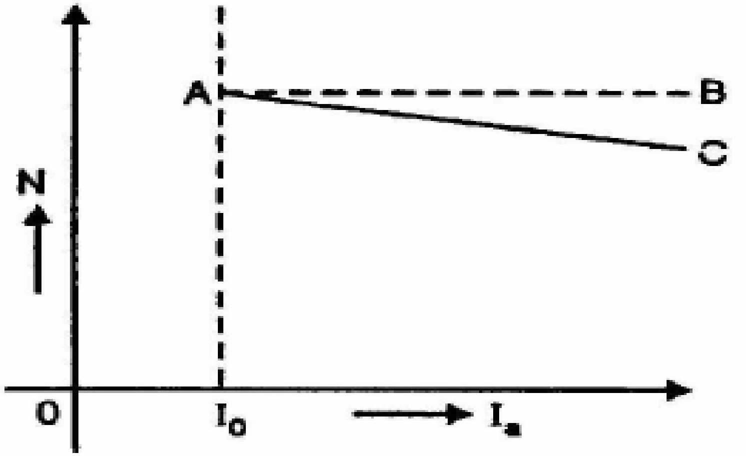


Fig. (4.15)

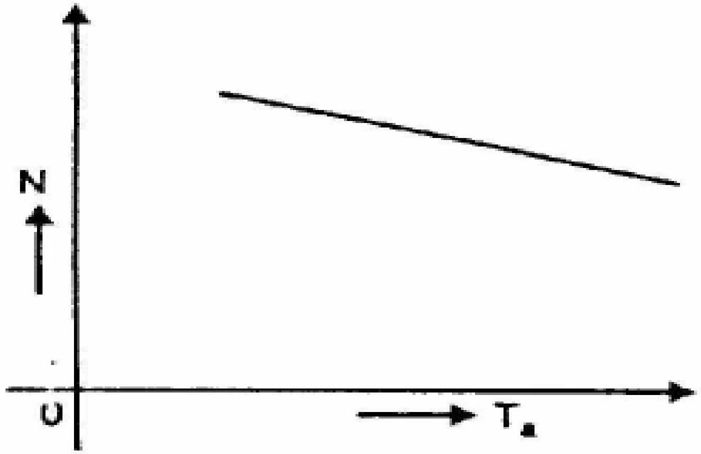


Fig. (4.16)

Characteristics of Series Motors

Fig. (4.17) shows the connections of a series motor. Note that current passing through the field winding is the same as that in the armature. If the mechanical load on the motor increases, the armature current also increases. Hence, the flux in a series motor increases with the increase in armature current and vice-versa.

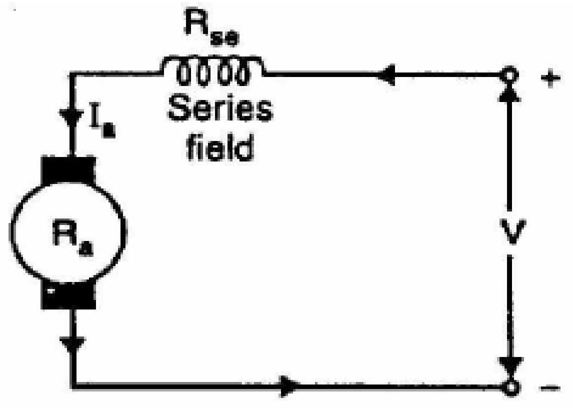


Fig. (4.17)

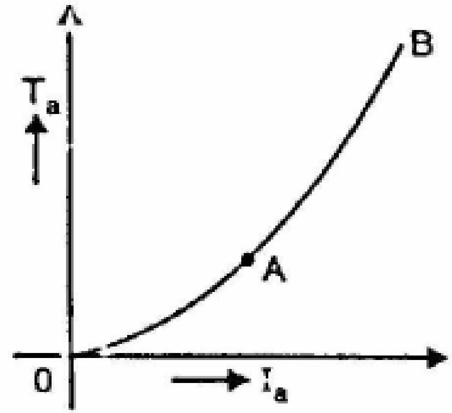


Fig. (4.18)

(i) **T_a/I_a Characteristic**. We know that:

$$T_a \propto \phi I_a$$

Upto magnetic saturation, $\phi \propto I_a$ so that $T_a \propto I_a^2$

After magnetic saturation, ϕ is constant so that $T_a \propto I_a$

Thus upto magnetic saturation, the armature torque is directly proportional to the square of armature current. If I_a is doubled, T_a is almost quadrupled. Therefore, T_a/I_a curve upto magnetic saturation is a parabola (portion OA of the curve in Fig. 4.18). However, after magnetic saturation, torque is directly proportional to the armature current. Therefore, T_a/I_a curve after magnetic saturation is a straight line (portion AB of the curve).

It may be seen that in the initial portion of the curve (i.e. upto magnetic saturation), $T_a \propto I_a^2$. This means that starting torque of a d.c. series motor will be very high as compared to a shunt motor (where that $T_a \propto I_a$).

(ii) **N/I_a Characteristic.** The speed N of a series motor is given by;

$$N \propto \frac{E_b}{\phi} \qquad \text{where} \qquad E_b = V - I_a(R_a + R_{se})$$

When the armature current increases, the back e.m.f. E_d decreases due to $I_a(R_a + R_{se})$ drop while the flux ϕ increases. However, $I_a(R_a + R_{se})$ drop is quite small under normal conditions and may be neglected.

$$\therefore \quad N \propto \frac{1}{\phi}$$

$$\propto \frac{1}{I_a} \quad \text{upto magnetic saturation}$$

Thus, upto magnetic saturation, the N/I_a curve follows the hyperbolic path as shown in Fig. (4.19). After saturation, the flux becomes constant and so does the speed.

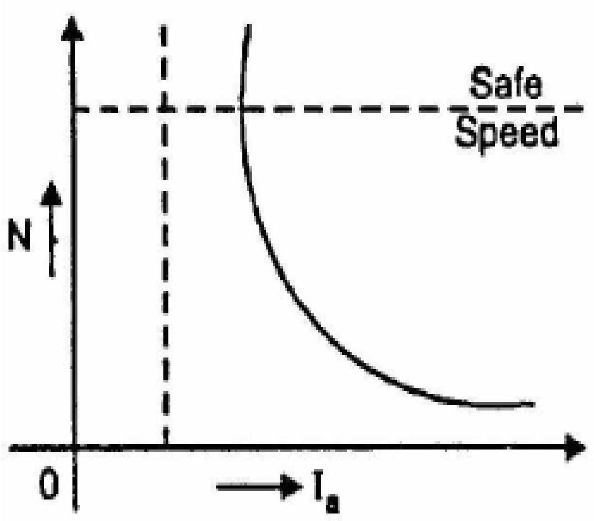


Fig. (4.19)

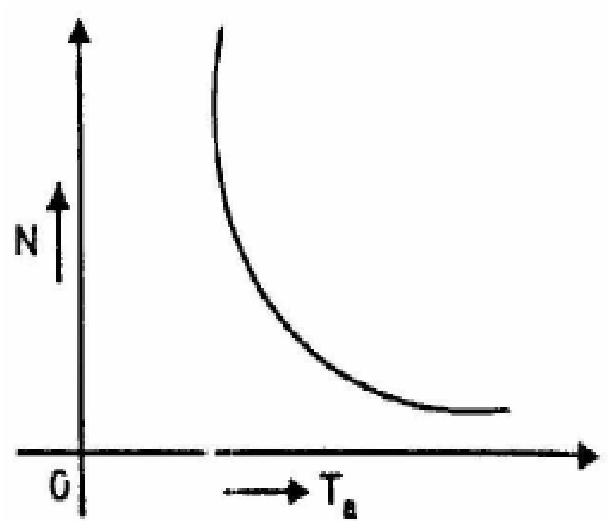


Fig. (4.20)

(iii) **N/T_a Characteristic**. The N/T_a characteristic of a series motor is shown in Fig. (4.20). It is clear that series motor develops high torque at low speed and vice-versa. It is because an increase in torque requires an increase in armature current, which is also the field current. The result is that flux is strengthened and hence the speed drops ($\because$ $N \propto 1/\phi$). Reverse happens should the torque be low.

Compound Motors

A compound motor has both series field and shunt field. The Compound motors are of two types:

(i) *Cumulative-compound motors in which series field aids the shunt field.*

(ii) *Differential-compound motors in which series field opposes the shunt* field.

Differential compound motors are rarely used due to their poor torque characteristics at heavy loads.

Characteristics of Cumulative Compound Motors

Fig. (4.21) shows the connections of a cumulative-compound motor. Each pole carries a series as well as shunt field winding; the series field aiding the shunt field.

(i) **T_a/I_a Characteristic**. As the load increases, the series field increases but shunt field strength remains constant. Consequently, total flux is increased and hence the armature torque ($\because\ T_a \propto \phi I_a$). It may be noted that torque of a cumulative-compound motor is greater than that of shunt motor for a given armature current due to series field [See Fig. 4.22].

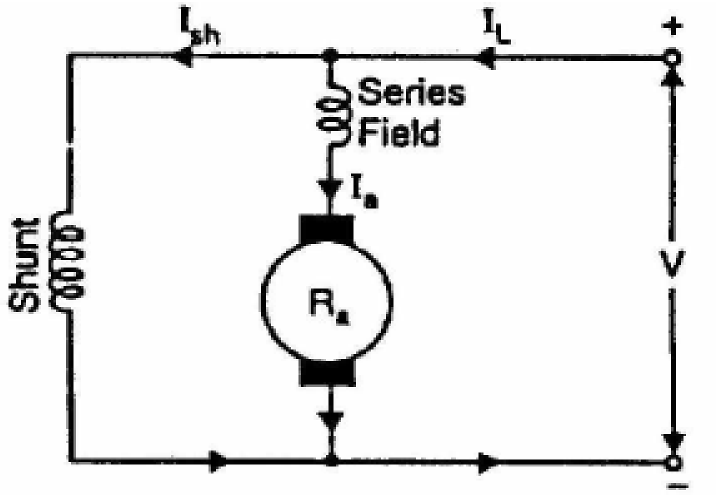


Fig. (4.21)

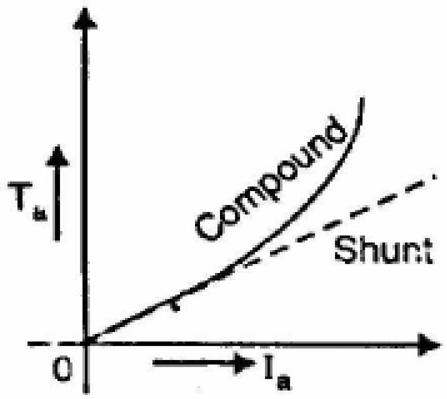


Fig. (4.22)

(ii) **N/I_a Characteristic**. As explained above, as the lead increases, the flux per pole also increases. Consequently, the speed ($N \propto 1/\phi$) of the motor tails as the load increases (See Fig. 4.23). It may be noted that as the load is added, the increased amount of flux causes the speed to decrease more than does the speed of a shunt motor. Thus the speed regulation of a cumulative compound motor is poorer than that of a shunt motor.

Note: Due to shunt field, the motor has a definite no load speed and can be operated safely at no-load.

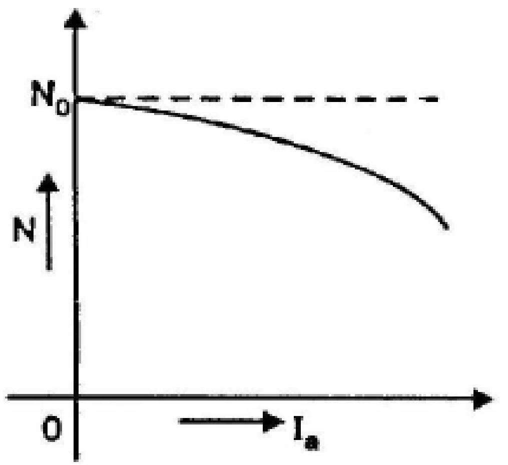


Fig. (4.23)

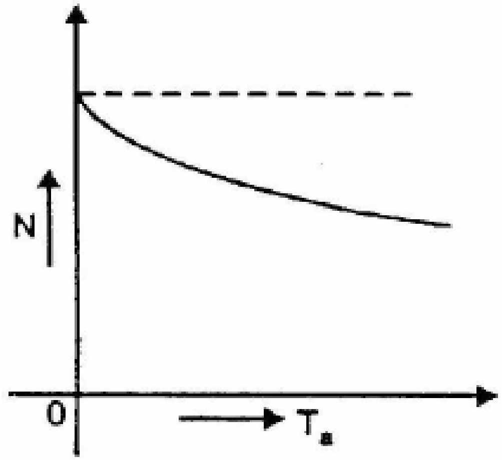


Fig. (4.24)

(iii) **N/Ta Characteristic.**

Fig. (4.24) shows N/Ta characteristic of a cumulative compound motor. For a given armature current, the torque of a cumulative compound motor is more than that of a shunt motor but less than that of a series motor.

Speed Control of D.C. Motors

The speed of a d.c. motor is given by:

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

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

where $R = R_a$ for shunt motor

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

From exp. (i), 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

It is based on the fact that by varying the flux ϕ, the motor speed ($N \propto 1/\phi$) 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. (5.1).

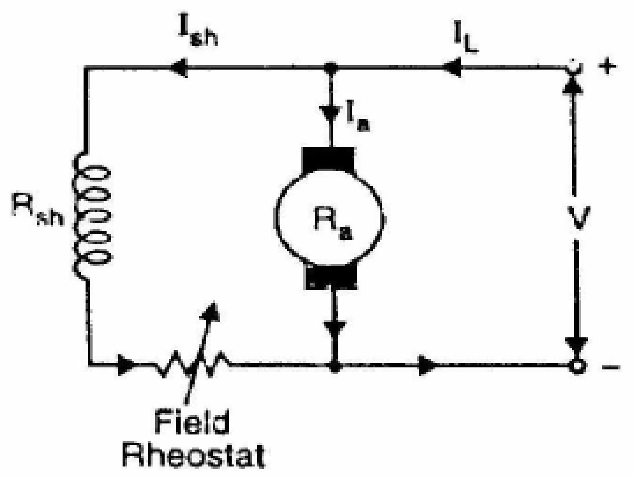


Fig. (5.1)

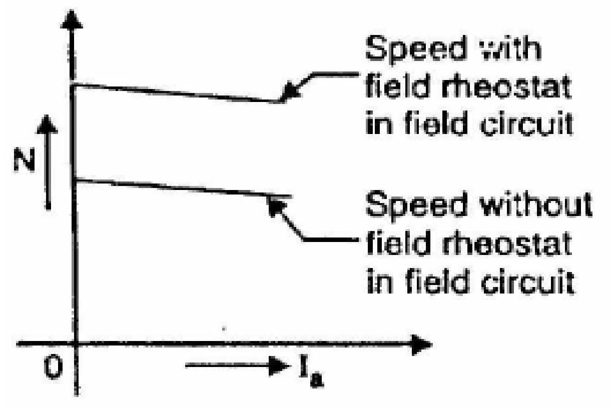


Fig. (5.2)

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 Fig. 5.2). 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 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. (5.3).

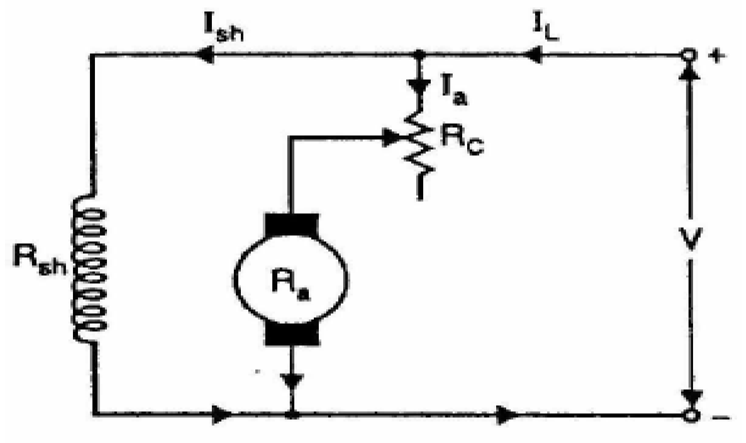


Fig. (5.3)

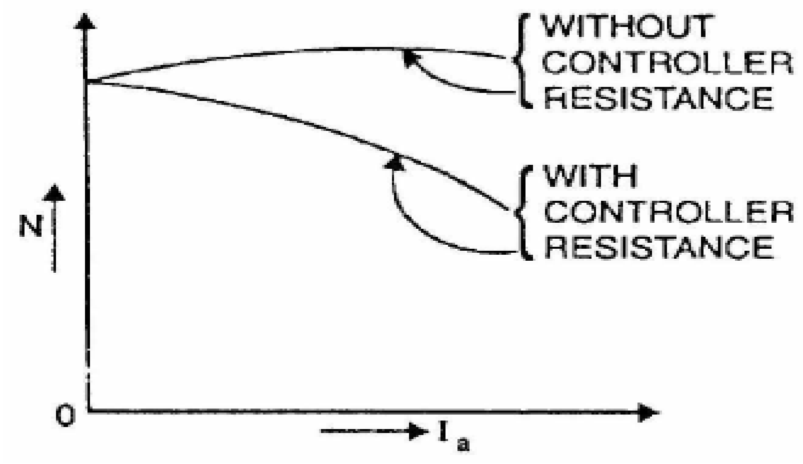


Fig. (5.4)

$$N \propto V - I_a(R_a + R_C)$$

where R_C = controller resistance

Due to voltage drop in the controller resistance, the back e.m.f. (E_b) is decreased. Since $N \propto E_b$, 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 (Fig. 5.4).

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.

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

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. (5.6). Its effect is to shunt some portion of the line current from the series field winding, thus weakening the field and increasing the speed ($\because \quad N \propto 1/\phi$). 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.

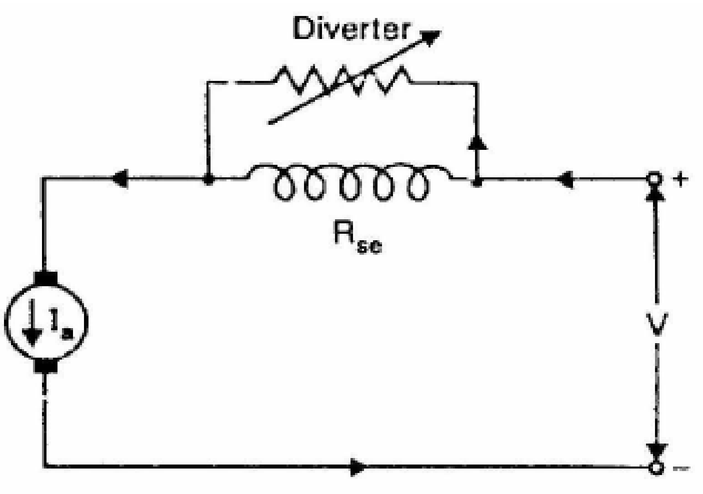


Fig. (5.6)

(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. (5.7). The diverter causes more current flows i.e. the flux ϕ must increase .Since $N \propto 1/\phi$, the motor speed is decreased. By adjusting the armature diverter, any speed lower than the normal speed can be obtained.

(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. (5.8). The switch S 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.

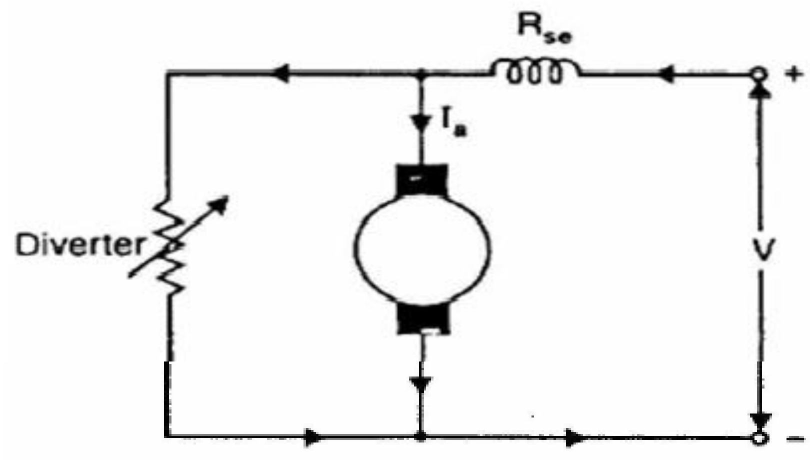


Fig. (5.7)

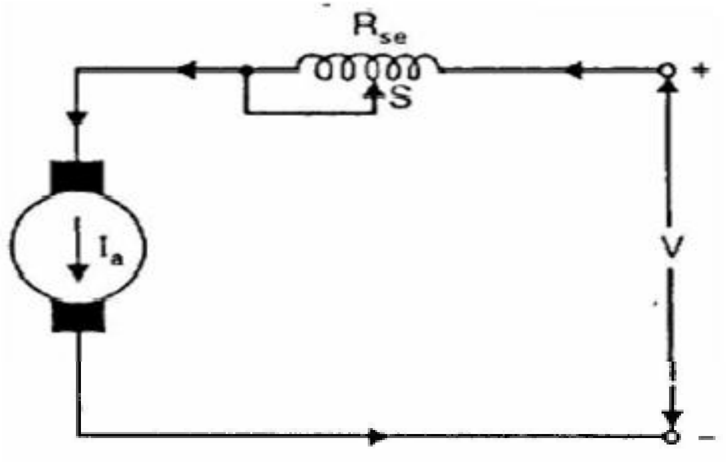
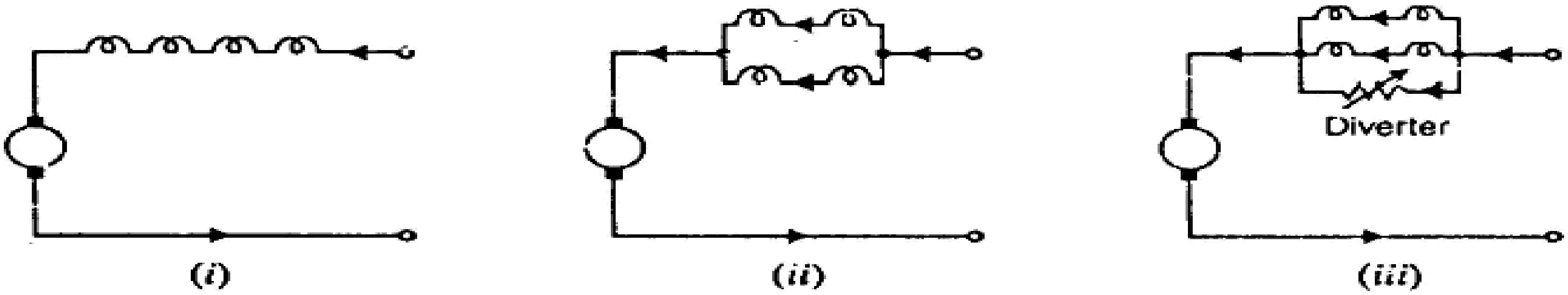


Fig. (5.8)

(iv) **Paralleling field coils**. This method is usually employed in the case of fan motors. By regrouping the field coils as shown in Fig. (5.9), several fixed speeds can be obtained.



(*i*) (*ii*) (*iii*)

Fig. (5.9)

2. Armature-resistance control

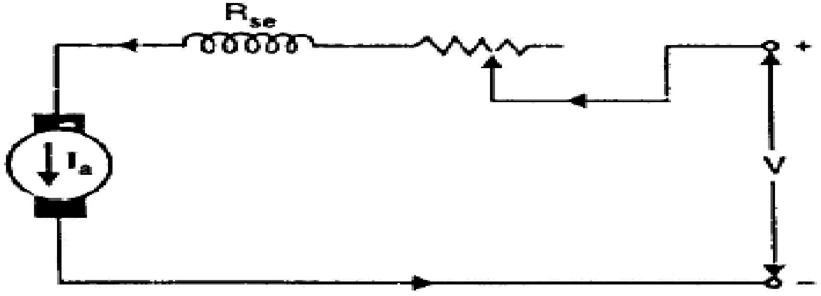


Fig. (5.10)

In this method, a variable resistance is directly connected in series with the supply to the complete motor as shown in Fig. (5.10). 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. 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.

Starting a DC Motor

If we apply full voltage to a stationary motor, the starting current in the armature will be very high (20-30 times the nominal load current) and we run the risk of:

- Burning out the armature
- Damaging the commutator and brushes, due to heavy sparking
- Overloading the supply
- Breaking the shaft due to mechanical shock
- Damaging the driven equipment due to the sudden torque surge

All DC motors must therefore be provided with a means to limit the starting current to reasonable values.

Electric Braking

Sometimes it is desirable to stop a d.c. motor quickly. This may be necessary in case of **emergency** or to **save time** if the motor is being used for frequently repeated operations. The motor and its load may be brought to rest by using either (i) mechanical (friction) braking or (ii) electric braking.

In mechanical braking, the motor is stopped due to the friction between the moving parts of the motor and the brake shoe i.e. kinetic energy of the motor is dissipated as heat.

Mechanical braking has several disadvantages including **non-smooth stop** and **greater stopping time**.

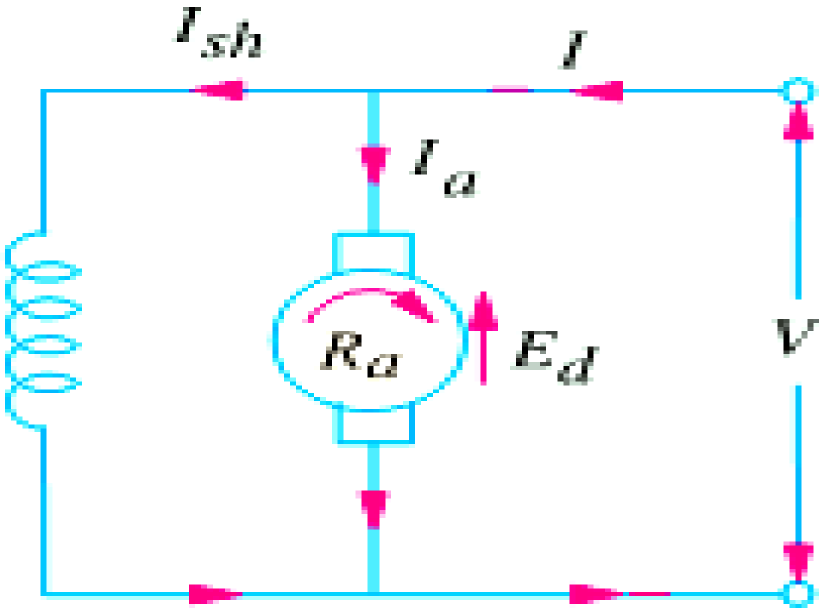
In electric braking, the kinetic energy of the moving parts (i.e., motor) is converted into electrical energy which is **dissipated in a resistance as heat or alternatively, it is returned to the supply source** (Regenerative braking). For d.c. shunt as well as series motors, the following three methods of electric braking are used:

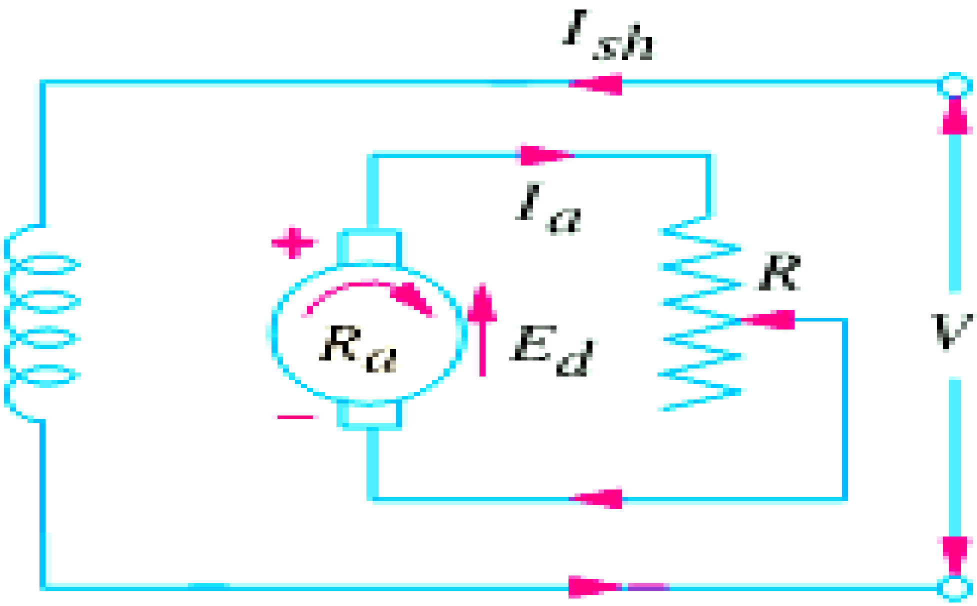
(i) Rheostatic or Dynamic braking

(ii) Plugging

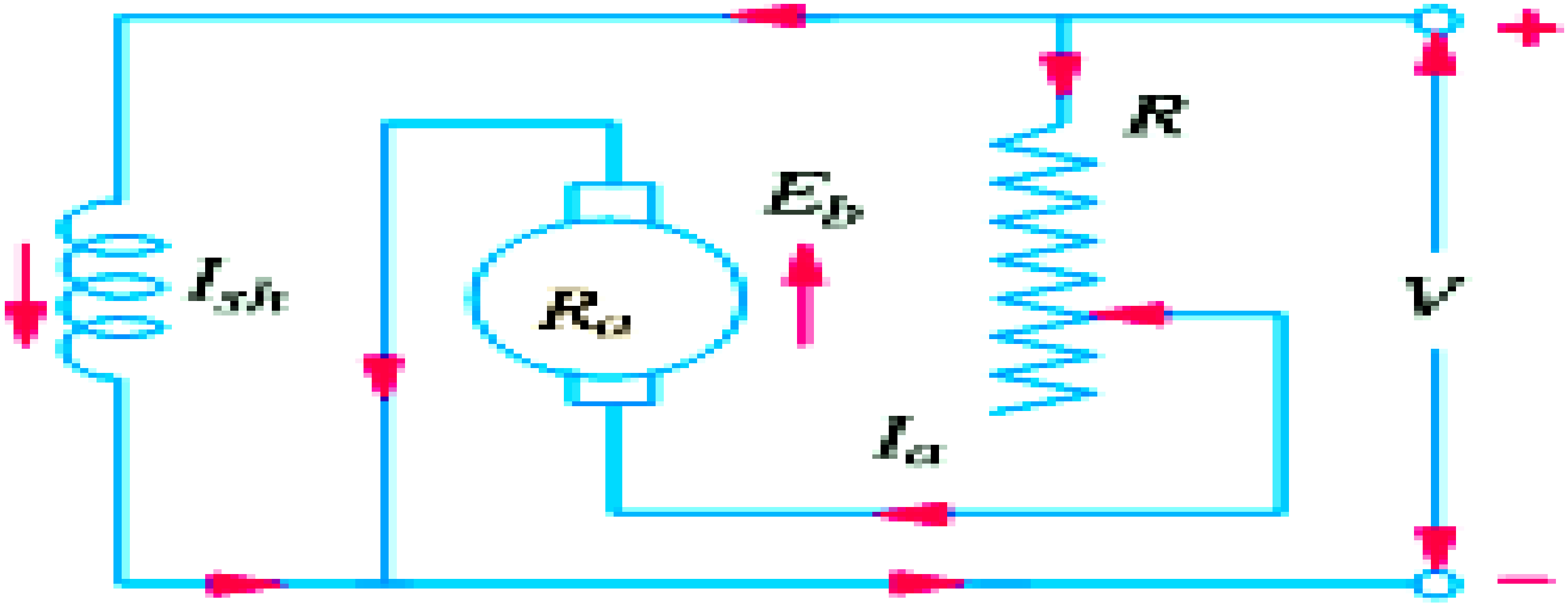
(iii) Regenerative braking

- **Rheostatic or Dynamic Braking(shunt motor)**: In this method, the armature of the shunt motor is disconnected from the supply and is connected across a variable resistance R. The field winding is left connected across the supply. The braking effect is controlled by varying the series resistance R.





- Plugging or Reverse Current Braking: In this method, connections to the armature terminals are reversed so that motor tends to run in the opposite direction. Due to the reversal of armature connections, applied voltage V and E start acting in the same direction around the circuit. In order to limit the armature current to a reasonable value, it is necessary to insert a resistor in the circuit while reversing armature connections.



- Regenerative Braking: This method is used when the load on the motor has over-hauling characteristic as in the lowering of the cage of a hoist or the downgrade motion of an electric train.

Regeneration takes place when Eb becomes grater than V. This happens when the overhauling load acts as a prime mover an so drives the machines as a generator. Consequently, direction of (Ia) & hence of armature torque is reversed and speed falls until E becomes lower than V. It is obvious that during the slowing down of the motor, power is returned to the line which may be use for supplying another train on an upgrade, thereby relieving the powerhouse of part of its load.

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),

Loss in interpoles winding = I_a^2 * Resistance of interpoles winding

Loss in compensating winding = I_a^2 *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.