Chapter (4)

D.C. Motors

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. Like d.c. generators, d.c. motors are also of three types viz., series-wound, shunt-wound and compound-wound. The use of a particular motor depends upon the mechanical load it has to drive.

4.1 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;

$$F = BI^{a} \quad \text{newtons}$$

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.

4.2 Working of D.C. Motor

Consider a part of a multipolar d.c. motor as shown in Fig. (4.1). 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 as shown in Fig.(4.1). Since each armature conductor is carrying current and is placed in the magnetic field, mechanical force acts on it. Referring to Fig. (4.1) and 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.

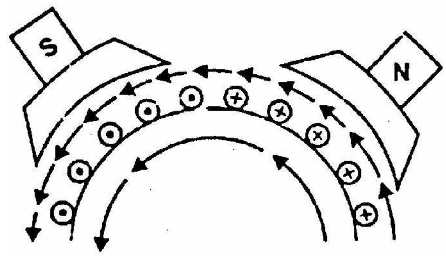


Fig. (4.1)

4.3 Back or Counter E.M.F.

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(= 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.

Consider a shunt wound motor shown in Fig. (4.2). 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.

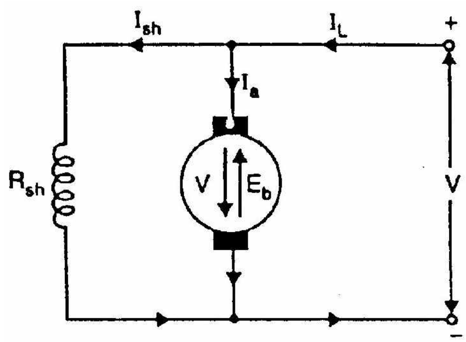


Fig. (4.2)

Net voltage across armature circuit = $V - E_b$

If R_a is the armature circuit resistance, then, $I_a = \frac{V - E_b}{R_a}$

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. E_b (= P ϕ

ZN/60 A) is large and hence the motor will draw less armature current and vice-versa.

4.4 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.

$$\text{Armature current, } I_a = \frac{V - E_b}{R_a}$$

(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. E_b also increases and causes the armature current I_a 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.

4.5 Voltage Equation of D.C. Motor

Let in a d.c. motor (See Fig. 4.3),

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

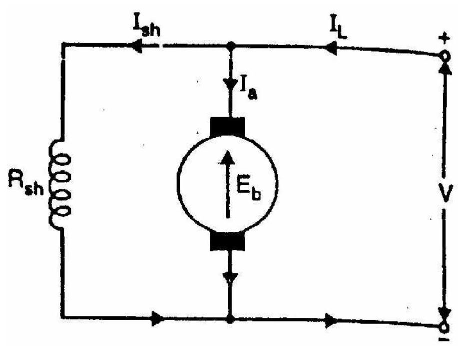


Fig. (4.3)

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

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

4.6 Power Equation

If Eq.(i) above is multiplied by ly 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.

4.7 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, 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, $$V = E_b + I_a R_a = E_b + \frac{V}{2} \qquad \left[\therefore\ I_a R_a = \frac{V}{2}\right]$$

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

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

Limitations

In practice, we never aim at achieving maximum power due to the following reasons:

(i) The armature current under this condition is very large—much excess of rated current of the machine.

(ii) 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%.

4.8 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 [See Fig. 4.4]. 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.

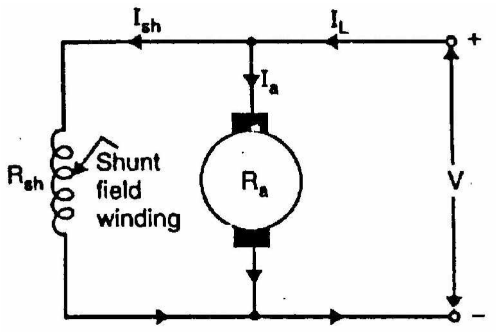


Fig. (4.4)

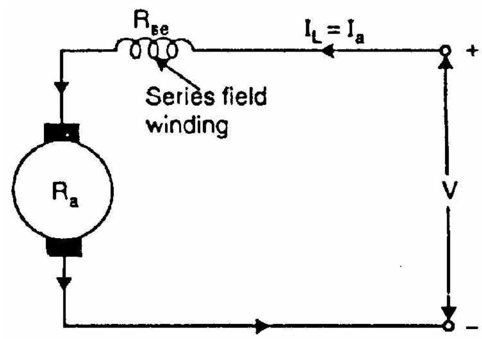
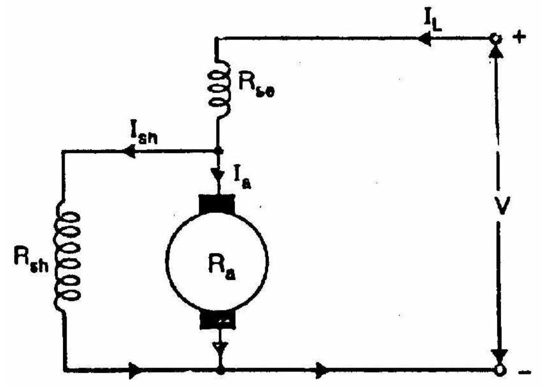


Fig. (4.5)

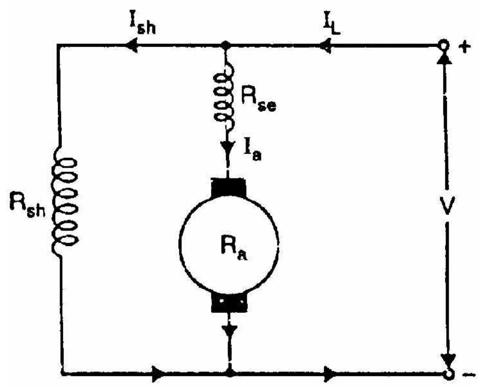
(ii) **Series-wound motor** in which the field winding is connected in series with the armature [See Fig. 4.5]. Therefore, series field winding carries the armature current. Since the current passing through a series field winding is the same as the armature current, series field windings must be designed 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.

(iii) **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 Fig. 4.6], 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 Fig. 4.7], it is called long-shunt connection.



Short-shunt connection

Fig. (4.6)



Long-shunt connection

Fig. (4.7)

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.

4.9 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.
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$$T = F \times r$$

In a d.c. motor, each conductor is acted upon by a circumferential force F at a distance r, the radius of the armature (Fig. 4.8). 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 (T_a).

Let in a d.c. motor

r = average radius of armature in m
ª = 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

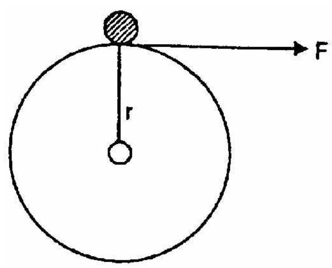

Fig. (4.8)

Force on each conductor, F = B i ª newtons

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

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

$= Z\,B\,i\,\mathbf{a}\,r$

Now i = I_a/A, B = φ/a where a is the x-sectional area of flux path per pole at radius r. Clearly, a = 2πr$\mathbf{a}$/P.

$$\therefore \quad T_a = Z \times \left(\frac{\phi}{2}\right) \times \left(\frac{I_a}{A}\right) \times \mathbf{a} \times r$$

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

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

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

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

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.

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

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

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

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Alternative expression for T_a

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

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

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.

4.10 Shaft Torque (T_{sh})

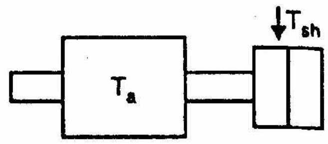

Fig. (4.9)

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 T_{sh} is somewhat less than the armature torque T_a. The difference $T_a - T_{sh}$ is called lost torque.

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,

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

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

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

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

or $$T_{sh} = 9.55 \times \frac{\text{Output in watts}}{N}\ \text{N - m} \qquad \left(\mathbf{n}\ \frac{60}{2\pi} = 9.55 \right)$$

4.11 Brake Horse Power (B.H.P.)

The horse power developed by the shaft torque is known as brake horsepower (B.H.P.). If the motor is running at N r.p.m. and the shaft torque is T_{sh} newton-metres, then,

W.D./revolution = force x distance moved in 1 revolution

$$= F \times 2\pi r = 2\pi \times T_{sh}\ J$$

$$\text{W.D./minute} = 2\pi\ N\ T_{sh}\ J$$

$$\text{W.D./sec.} = \frac{2\pi\ N\ T_{sh}}{60}\ Js^{-1} \text{ or watts} = \frac{2\pi\ N\ T_{sh}}{60 \times 746}\ \text{H.P.}$$

$$\therefore \quad \text{Useful output power} = \frac{2\pi\ N\ T_{sh}}{60 \times 746}\ \text{H.P.}$$

or $$\text{B.H.P.} = \frac{2\pi\ N\ T_{sh}}{60 \times 746}$$

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

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.

4.13 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

4.14 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.

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

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

where N_0 = No - load .speed
N = Full - load speed

4.15 Torque and Speed of a D.C. Motor

For any motor, the torque and speed are very important factors. When the torque increases, the speed of a motor increases and vice-versa. We have seen that for a d.c. motor;

$$N = K\frac{(V - I_a R_a)}{\phi} = \frac{K\,E_b}{\phi} \qquad \text{(i)}$$

$$T_a \propto \phi I_a \qquad \text{(ii)}$$

If the flux decreases, from Eq.(i), the motor speed increases but from Eq.(ii) the motor torque decreases. This is not possible because the increase in motor speed must be the result of increased torque. Indeed, it is so in this case. When the flux decreases slightly, the armature current increases to a large value. As a result, in spite of the weakened field, the torque is momentarily increased to a high value and will exceed considerably the value corresponding to the load. The surplus torque available causes the motor to accelerate and back e.m.f. ($E_a = P\,\phi\,Z\,N/60\,A$) to rise. Steady conditions of speed will ultimately be achieved when back e.m.f. has risen to such a value that armature current [$I_a = (V - E_a)/R_a$] develops torque just sufficient to drive the load.

Illustration

Let us illustrate the above point with a numerical example. Suppose a 400 V shunt motor is running at 600 r.p.m., taking an armature current of 50 A. The armature resistance is 0.28 Ω. Let us see the effect of sudden reduction of flux by 5% on the motor.

Initially (prior to weakening of field), we have,

$$E_a = V - I_a R_a = 400 - 50 \times 0.28 = 386 \text{ volts}$$

We know that $E_b \propto \phi N$. If the flux is reduced suddenly, $E_b \propto \phi$ because inertia of heavy armature prevents any rapid change in speed. It follows that when the flux is reduced by 5%, the generated e.m.f. must follow suit. Thus at the instant of reduction of flux, $E'_b = 0.95 \times 386 = 366.7$ volts.

Instantaneous armature current is

$$I'_a = \frac{V - E'_b}{R_a} = \frac{400 - 366.7}{0.28} = 118.9 \text{ A}$$

Note that a sudden reduction of 5% in the flux has caused the armature current to increase about 2.5 times the initial value. This will result in the production of high value of torque. However, soon the steady conditions will prevail. This will depend on the system inertia; the more rapidly the motor can alter the speed, the sooner the e.m.f. rises and the armature current falls.

4.16 Armature Reaction in D.C. Motors

As in a d.c. generator, armature reaction also occurs in a d.c. motor. This is expected because when current flows through the armature conductors of a d.c. motor, it produces flux (armature flux) which lets on the flux produced by the main poles. For a motor with the same polarity and direction of rotation as is for generator, the direction of armature reaction field is reversed.

(i) In a generator, the armature current flows in the direction of the induced e.m.f. (i.e. generated e.m.f. E_g) whereas in a motor, the armature current flows against the induced e.m.f. (i.e. back e.m.f. E_b). Therefore, it should be expected that for the same direction of rotation and field polarity, the armature flux of the motor will be in the opposite direction to that of the generator. Hence instead of the main flux being distorted in the direction of rotation as in a generator, it is distorted opposite to the direction of rotation. We can conclude that:

Armature reaction in a d.c. generator weakens the jinx at leading pole tips and strengthens the flux at trailing pole tips while the armature reaction in a d. c. motor produces the opposite effect.

(ii) In case of a d.c. generator, with brushes along G.N.A. and no commutating poles used, the brushes must be shifted in the direction of rotation (forward lead) for satisfactory commutation. However, in case of a d.c. motor, the brushes are given a negative lead i.e., they are shifted against the direction of rotation.

With no commutating poles used, the brushes are given a forward lead in a d.c. generator and backward lead in a d.c. motor.

(iii) By using commutating poles (compoles), a d.c. machine can be operated with fixed brush positions for all conditions of load. Since commutating poles windings carry the armature current, then, when a machine changes from generator to motor (with consequent reversal of current), the polarities of commutating poles must be of opposite sign.

Therefore, in a d.c. motor, the commutating poles must have the same polarity as the main poles directly back of them. This is the opposite of the corresponding relation in a d.c. generator.

4.17 Commutation in D.C. Motors

Since the armature of a motor is the same as that of a generator, the current from the supply line must divide and pass through the paths of the armature windings.

In order to produce unidirectional force (or torque) on the armature conductors of a motor, the conductors under any pole must carry the current in the same direction at all times. This is illustrated in Fig. (4.10). In this case, the current flows away from the observer in the conductors under the N-pole and towards the observer in the conductors under the S-pole. Therefore, when a conductor moves from the influence of N-pole to that of S-pole, the direction of current in the conductor must be reversed. This is termed as commutation. The function of the commutator and the brush gear in a d.c. motor is to cause the reversal of current in a conductor as it moves from one side of a brush to the other. For good commutation, the following points may be noted:

(i) If a motor does not have commutating poles (compoles), the brushes must be given a negative lead i.e., they must be shifted from G.N.A. against the direction of rotation of, the motor.

(ii) By using interpoles, a d.c. motor can be operated with fixed brush positions for all conditions of load. For a d.c. motor, the commutating poles must have the same polarity as the main poles directly back of them. This is the opposite of the corresponding relation in a d.c. generator.

Note. A d.c. machine may be used as a motor or a generator without changing the commutating poles connections. When the operation of a d.c. machine changes from generator to motor, the direction of the armature current reverses. Since commutating poles winding carries armature current, the polarity of commutating pole reverses automatically to the correct polarity.

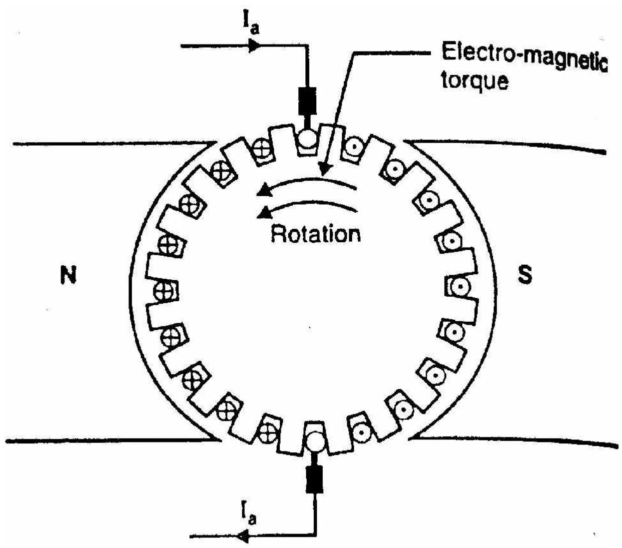

Fig. (4.10)

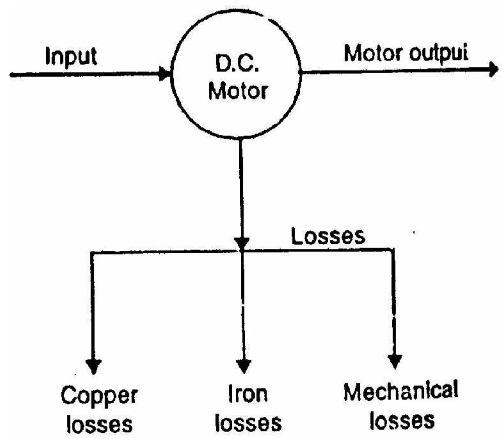

Fig. (4.11)

4.18 Losses in a D.C. Motor

The losses occurring in a d.c. motor are the same as in a d.c. generator [See Sec. 1.26]. These are [See Fig. 4.11]:

(i) copper losses (n) Iron losses or magnetic losses
(ii) 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 interpole winding = $I_a^2 \times$ Resistance of interpole winding

Loss in compensating winding = $I_a^2 \times$ 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.

4.19 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 (See Sec. 1.29), 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.

4.20 Power Stages

The power stages in a d.c. motor are represented diagrammatically in Fig. (4.12).

A – B = Copper losses

B – C = Iron and friction losses

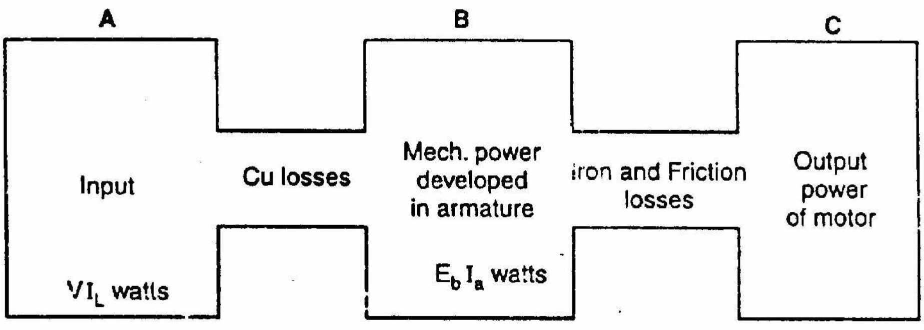

Fig. (4.12)

Overall efficiency, η_c = C/A
Electrical efficiency, η_e = B/A
Mechanical efficiency, η_m = C/B

4.21 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.

4.22 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.

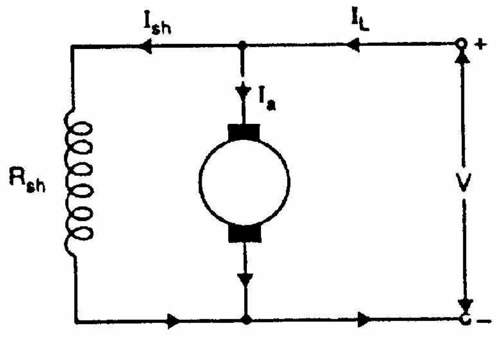

Fig. (4.13)

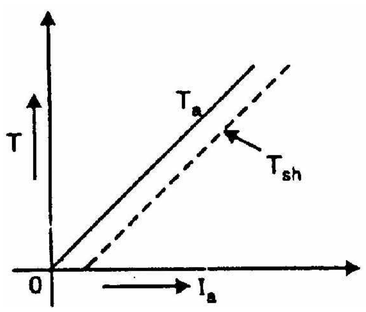

Fig. (4.14)

(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.

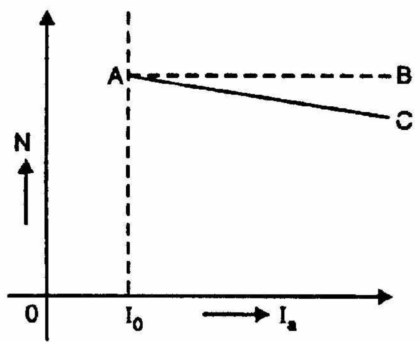

Fig. (4.15)

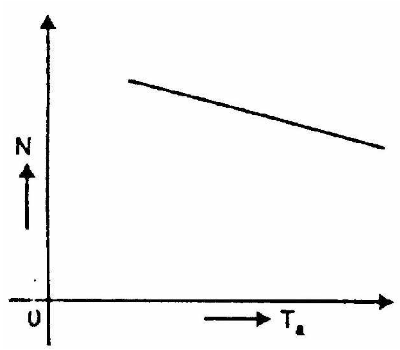

Fig. (4.16)

Conclusions

Following two important conclusions are drawn from the above characteristics:

(i) There is slight change in the speed of a shunt motor from no-load to full-load. Hence, it is essentially a constant-speed motor.

(ii) The starting torque is not high because $T_a \propto I_a$.

4.23 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.

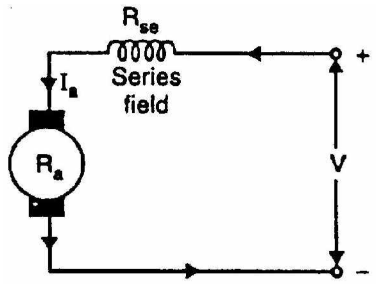

Fig. (4.17)

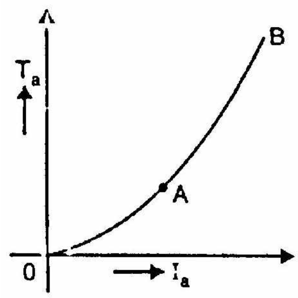

Fig. (4.18)

(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.

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

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

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.

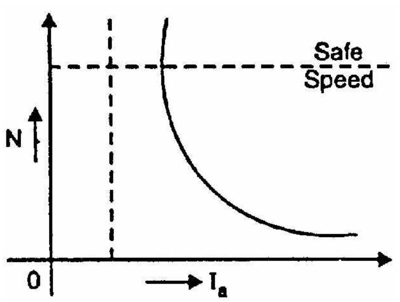

Fig. (4.19)

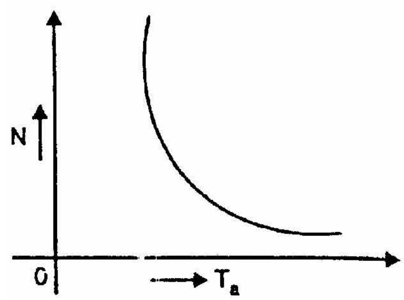

Fig. (4.20)

(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 (**n** $N \propto 1/\phi$). Reverse happens should the torque be low.

Conclusions

Following three important conclusions are drawn from the above characteristics of series motors:

(i) It has a high starting torque because initially $T_a \propto I_a^2$.

(ii) It is a variable speed motor (See N/I_a curve in Fig. 4.19) i.e., it automatically adjusts the speed as the load changes. Thus if the load decreases, its speed is automatically raised and vice-versa.

(iii) At no-load, the armature current is very small and so is the flux. Hence, the speed rises to an excessive high value (**n** $N \propto 1/\phi$). This is dangerous for the machine which may be destroyed due to centrifugal forces set up in the rotating parts. Therefore, a series motor should never be started on no-load. However, to start a series motor, mechanical load is first put and then the motor is started.

Note. The minimum load on a d.c. series motor should be great enough to keep the speed within limits. If the speed becomes dangerously high, then motor must be disconnected from the supply.

4.24 Compound Motors

A compound motor has both series field and shunt field. The shunt field is always stronger than the series field. 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.

4.25 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 (**n** $T_a \propto \phi I_a$). 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].

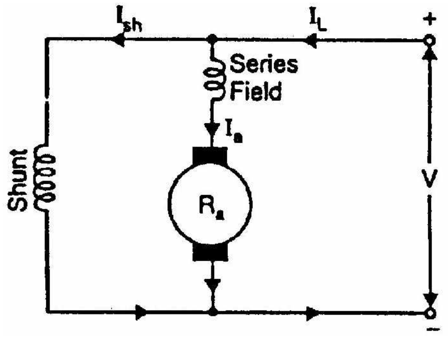

Fig. (4.21)

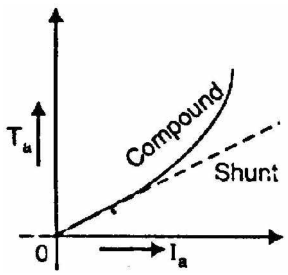

Fig. (4.22)

(ii) **N/I_a Characteristic**. As explained above, as the lead increases, the flux per pole also increases. Consequently, the speed (N ∝ 1/ϕ) 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.

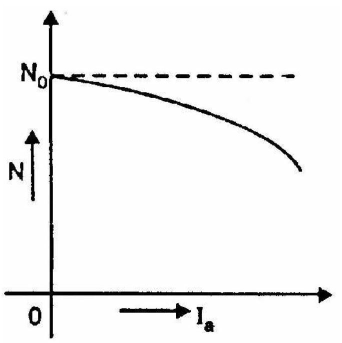

Fig. (4.23)

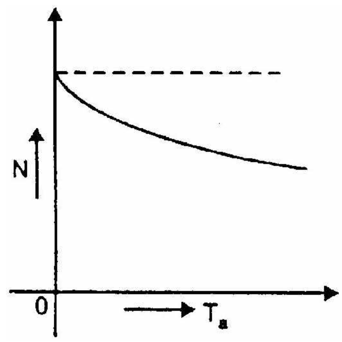

Fig. (4.24)

(iii) **N/T_a Characteristic**. Fig. (4.24) shows N/T_a 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.

Conclusions

A cumulative compound motor has characteristics intermediate between series and shunt motors.

(i) Due to the presence of shunt field, the motor is prevented from running away at no-load.

(ii) Due to the presence of series field, the starting torque is increased.

4.26 Comparison of Three Types of Motors

(i) The speed regulation of a shunt motor is better than that of a series motor.

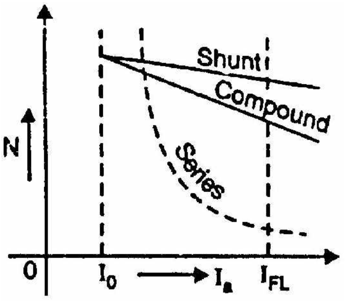

Fig. (4.25)

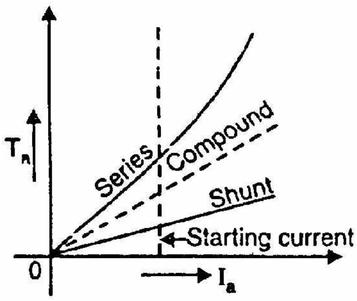

Fig. (4.26)

However, speed regulation of a cumulative compound motor lies between shunt and series motors (See Fig. 4.25).

(ii) For a given armature current, the starting torque of a series motor is more than that of a shunt motor. However, the starting torque of a cumulative compound motor lies between series and shunt motors (See Fig. 4.26).

(iii) Both shunt and cumulative compound motors have definite no-load speed. However, a series motor has dangerously high speed at no-load.

4.27 Applications of D.C. Motors

1. Shunt motors

The characteristics of a shunt motor reveal that it is an approximately constant speed motor. It is, therefore, used

(i) where the speed is required to remain almost constant from no-load to full-load

(ii) where the load has 10 be driven at a number of speeds and any one of which is required to remain nearly constant

Industrial use: Lathes, drills, boring mills, shapers, spinning and weaving machines etc.

2. Series motors

It is a variable speed motor i.e., speed is low at high torque and vice-versa. However, at light or no-load, the motor tends to attain dangerously high speed. The motor has a high starting torque. It is, therefore, used

(i) where large starting torque is required e.g., in elevators and electric traction

(ii) where the load is subjected to heavy fluctuations and the speed is automatically required to reduce at high torques and vice-versa

Industrial use: Electric traction, cranes, elevators, air compressors, vacuum cleaners, hair drier, sewing machines etc.

3. Compound motors

Differential-compound motors are rarely used because of their poor torque characteristics. However, cumulative-compound motors are used where a fairly constant speed is required with irregular loads or suddenly applied heavy loads.

Industrial use: Presses, shears, reciprocating machines etc.

4.28 Troubles in D.C. Motors

Several troubles may arise in a d.c. motor and a few of them are discussed below:

1. Failure to start

This may be due to (i) ground fault (ii) open or short-circuit fault (iii) wrong connections (iv) too low supply voltage (v) frozen bearing or (vi) excessive load.

2. Sparking at brushes

This may be due to (i) troubles in brushes (ii) troubles in commutator (iii) troubles in armature or (iv) excessive load.

(i) Brush troubles may arise due to insufficient contact surface, too short a brush, too little spring tension or wrong brush setting.

(ii) Commutator troubles may be due to dirt on the commutator, high mica, rough surface or eccentricity.

(iii) Armature troubles may be due to an open armature coil. An open armature coil will cause sparking each time the open coil passes the brush. The location of this open coil is noticeable by a burnt line between segments connecting the coil.

3. Vibrations and pounding noises

These maybe due to (i) worn bearings (ii) loose parts (iii) rotating parts hitting stationary parts (iv) armature unbalanced (v) misalignment of machine (vi) loose coupling etc.

4. Overheating

The overheating of motor may be due to (i) overloads (ii) sparking at the brushes (iii) short-circuited armature or field coils (iv) too frequent starts or reversals (v) poor ventilation (vi) incorrect voltage.