Chapter

12

DC Machines

Inside this Chapter

12.1 INTRODUCTION

DC machine is actually an *alternating current* machine, but furnished with a special device, called the *commutator,* which under certain conditions converts ac into dc and vice versa.

The term "generator" denotes that it generates electrical energy but actually it does not. It simply converts mechanical energy supplied to it into electrical energy. A dc generator may be compared with a water force pump to make operation of a dc generator more clear.

As the force pump does not produce water but causes a mechanical pressure which forces the existing water into an elevated reservoir against the back pressure due to its weight, in the same way the generator does not produce electricity but creates potential difference, which causes the electric current to flow from low pressure terminal to high pressure terminal in the machine and from high pressure terminal to low pressure terminal in the external circuit against the resistance of the circuit.

The generator operates on the principle of the production of dynamically induced emf *i.e.* whenever flux is cut by the conductor, dynamically induced emf is produced in it according to the laws of electromagnetic induction, which will cause a flow of current in the conductor if the circuit is closed.

For production of dynamically induced emf, three things are necessary, a magnetic field, a conductor and motion of the conductor with respect to the field. In dc generators the field is produced by the field magnets which are stationary. Permanent magnets are used for very small capacity machines and electromagnets are used for large machines to create magnetic flux. The conductors are situated on the periphery of the armature being rotated by the prime mover.

An electric motor is a machine which converts electrical energy into mechanical energy where as a generator is that machine which converts mechanical energy into electrical one. As regards fundamental principles the dc motors are identical with the dc generators which have the same type of excitation *i.e.* a machine that runs as a motor will also operate satisfactorily as a generator.

The only difference lies, however, in the mode of construction, which is due to the fact that the frame of the generator can as a rule be open but those of motors should be either partly or totally enclosed. A generator is usually placed in a suitable position and mechanical protection for the coils and armature may be reduced to minimum. Also the generator is handled by technical persons. Hence there is no risk in having the frame of the generator open, which facilitates cooling, inspection and repair. On the other hand, motors have to work in conditions of dampness, dirt, inflammable gases, chemical fumes and liability to mechanical damage and, therefore, protection must be adequate and motor frames are made flame-proof, partly enclosed or totally enclosed according to the requirements of service.

Both induced emfs and mechanical forces are developed in a machine whether it is a generator or motor. As such a dc generator and motor have identical construction. In this chapter dc machines used as generators, although much of what is said concerning generators is equally applicable to motors, are dealt with.

12.2 ESSENTIAL PARTS OF A DC MACHINE

DC machine (whether a generator or motor) with four poles is shown in Fig. 12.1. In construction, dc machine consists of four parts mainly 1. Field magnets 2. Armature 3. Commutator 4. Brush and brush gear. Disassembled dc machine is shown in Fig. 12.2.

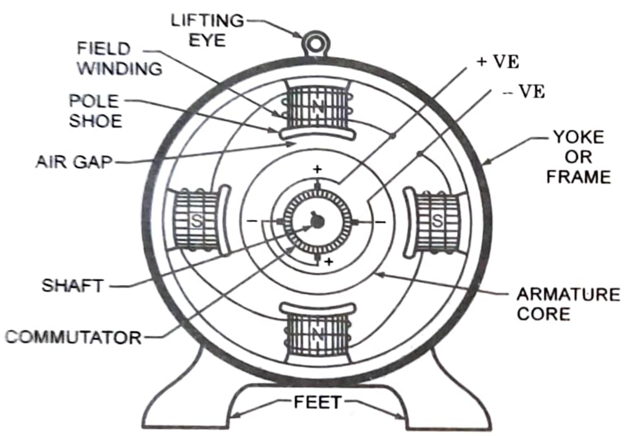


Fig. 12.1 *4-Pole DC Machine*

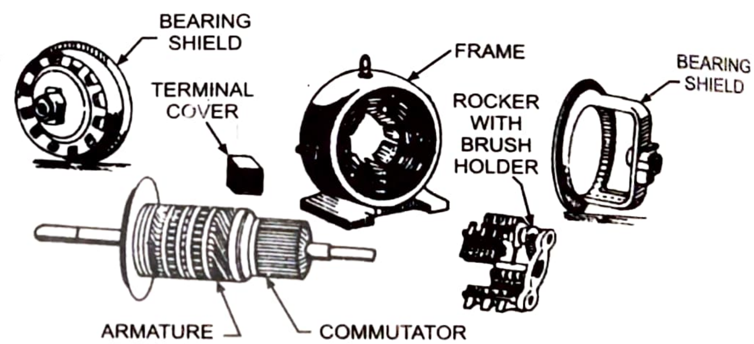


Fig. 12.2 *DC Machine (Disassembled)*

1. Field System. The object of the field system is to create a uniform magnetic field, within which the armature rotates.

Electromagnets are preferred in comparison with permanent magnets on account of its greater magnetic effect and its field strength regulation, which can be achieved by controlling the magnetising current.

Field magnet consists of four parts given below:

(*i*) Yoke or Frame (*ii*) Pole cores (*iii*) Pole shoes and (*iv*) Magnetising coils.

Cylindrical yoke is usually used which acts as a frame of the machine and carries the magnetic flux produced by the poles. In small machines, cast iron yokes are used, because of cheapness but yoke of a large machine is invariably made of fabricated steel due to its high permeability.

Pole core is usually of circular section and is used to carry the coils of insulated wires carrying the exciting (or field) current. The pole shoe acts as a support to the field coils and spreads out the flux over the armature periphery more uniformly and also being of larger cross section reduces the reluctance of the magnetic path.

The field poles are usually formed of laminations (thin sheets of steel) and are bolted to the frame or yoke to which are also fastened the end bells with their *bearings* and the *brush rigging*. In small machines the poles are cast integral with

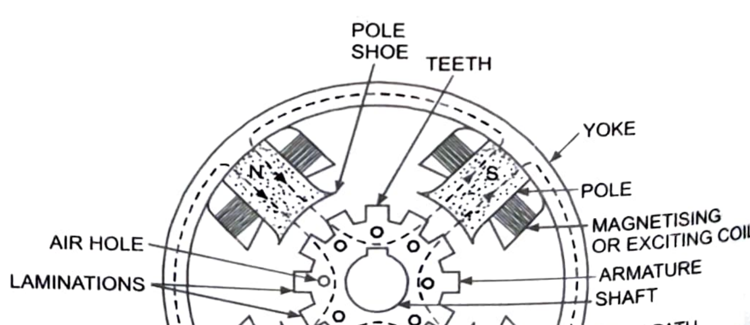


Fig. 12.3 *Cross Section of Field System of a DC Generator*

the yoke from cast iron due to its low cost and less machining required by individual parts. In some machines the yoke and pole cores are made in single casting and laminated pole shoes are attached to the pole cores. The pole faces or pole shoes are always laminated to avoid heating and eddy current losses caused by the fluctuations in the flux distribution on the pole face due to movement of armature slots and teeth.

The object of the magnetising or field coils is to provide, under the various conditions of operation, the number of ampere-turns of excitation required to give the proper flux through the armature to induce the desired potential difference. The magnetic flux produced by the mmf developed by the field coils pass through the pole pieces, the air gap, the armature core and the yoke or frame. In Fig. 12.3, the dotted lines indicate the mean flux path through the complete magnetic circuit. There are several field constructions adopted according to the type of excitation. In shunt field, many turns of fine wire are used, in series field few turns of large cross-sectional area are used and in compound field both shunt and series windings are used.

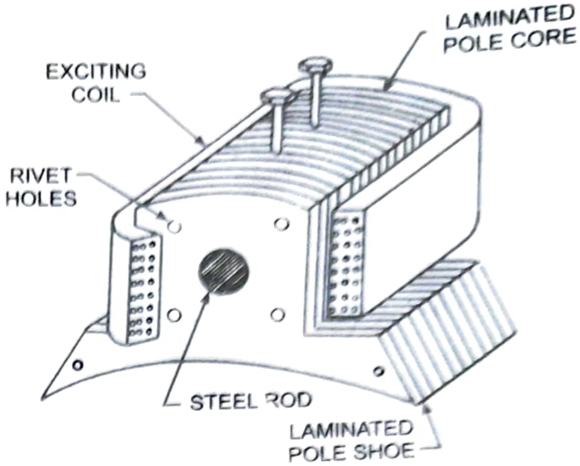
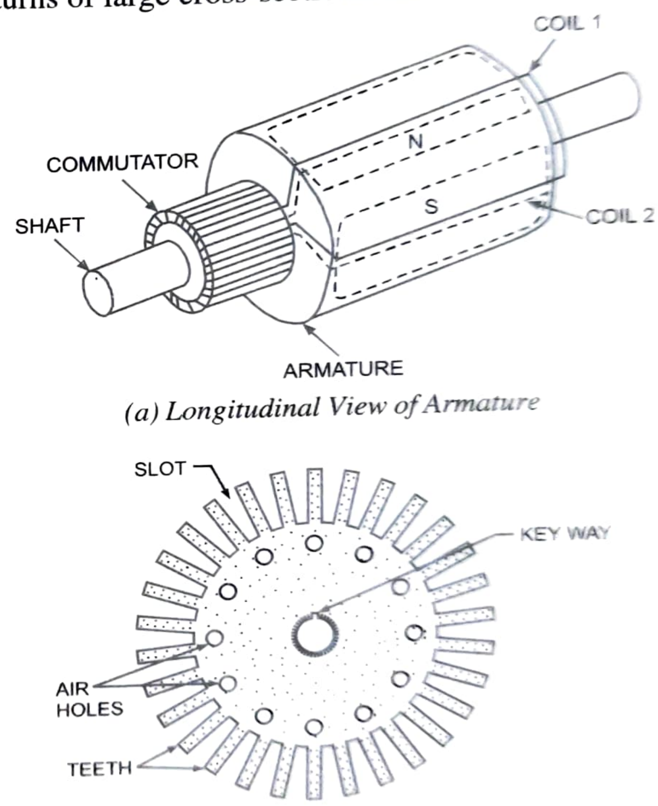


Fig. 12.4 *Laminated Pole Core and Pole Shoe*

2. Armature. It is a rotating part of a dc machine and is built up in a cylindrical or drum shape. The purpose of armature is to rotate the conductors in the uniform magnetic field. It consists of coils of insulated wires wound around an iron and so arranged that electric currents are induced in these wires when the armature is rotated in a magnetic field. In addition, its most important function is to provide a path of very low reluctance to the magnetic flux. The armature core is made from high permeability silicon-steel stampings, each stamping, being separated from its neighbouring one by thin paper or thin coating of varnish as insulation.

A small air gap exists between the pole pieces and the armature so that there will be no rubbing in the machine. However this gap is kept as small as possible, since larger the air gap greater is the mmf required to create the required flux. The air-gap length is about 1.0 mm to 6 mm (say 1 mm for a 1 kW machine, 1.5 to 1.75 mm for medium size machines and 6 mm for 800 kW machine).



(a) Longitudinal View of Armature

(b) Armature Lamination

Fig. 12.5 *Armature*

The use of high grade steel is made (*a*) to keep hysteresis loss low, which is due to cyclic change of magnetisation caused by rotation of the core in the magnetic field and (*b*) to reduce the eddy currents in the core which are induced by the rotation of the core in the magnetic field. By using stampings or laminations, the path of the eddy currents is cut into several units. The laminations must be in such a direction that they are perpendicular to the paths of eddy currents and parallel to the flux. Each lamination is about 0.3 to 0.6 mm thick.

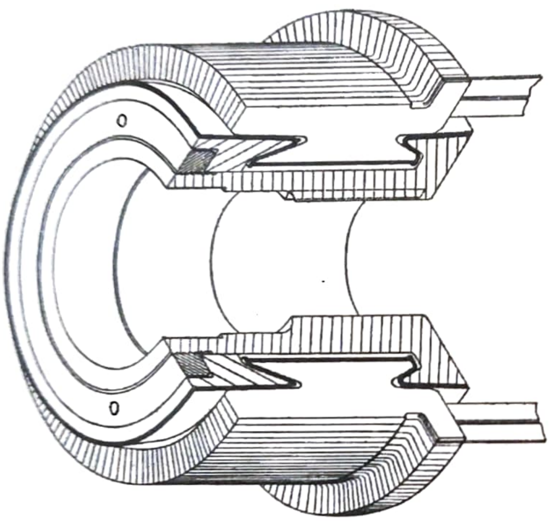
3. Commutator. The commutator is a form of rotating switch placed between the armature and the external circuit and so arranged that it will reverse the connections to the external circuit at the instant of each reversal of current in the armature coils.

It is very important part of a dc machine and serves the following purposes:

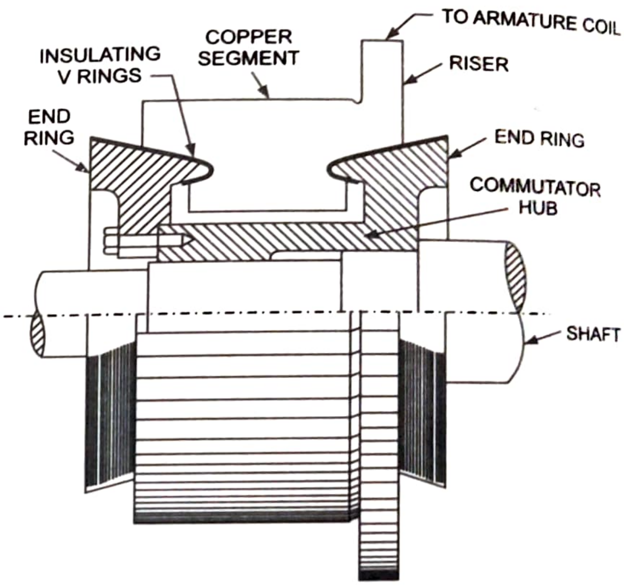
1. It provides the electrical connections between the rotating armature coils and the stationary external circuit.

2. As the armature rotates, it performs a switching action reversing the electrical connections between the external circuit and each armature coil in turn so that the armature coil voltages add together and result in a dc output voltage.
3. It also keeps the rotor or armature mmf stationary in space.

The commutator is essentially of cylindrical structure and is built up of wedge shaped segments of high conductivity hard drawn copper or drop forged copper. These segments are insulated from each other by thin layers of mica (usually of 0.5 to 1 mm thickness). Mica is to be preferred but cannot be used for large commutator because of the difficulty of obtaining large sheets, making the cost of large mica segments prohibitive. On account of cost also micanite is often used for small commutators. The segments are held together by means of two V-shaped rings that fit into the V-grooves cut into the segments.



(a) *Commutator*



(b) *Section View of Commutator Segments*

Fig. 12.6

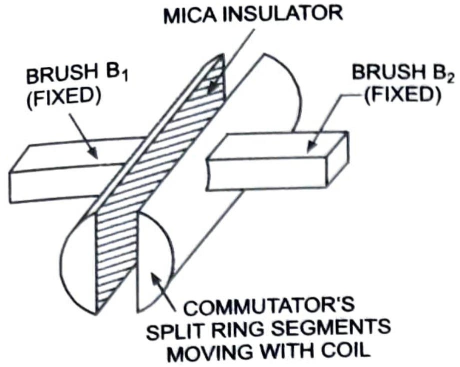
The commutator is pressed on to the armature shaft, and the outer periphery is then machined to provide a smooth surface with which a stationary carbon (or graphite or copper) brush can maintain continuous contact as the armature and commutator rotate. Great care is taken in building the commutator because even slight eccentricity will cause the brushes to bounce, causing undue sparking.

4. Brushes. The function of brushes is to collect current from the commutator and supply it to the external load circuit (the armature of the machine being connected to the external load circuit via the commutator and brushes). The brushes are rectangular in shape and rest on the commutator. Brushes are manufactured in a variety of compositions and degrees of hardness to suit the commutation requirements. They may be classified roughly as carbon, carbon graphite, graphite, metal graphite and copper. The allowable current density at the brush contact varies from 5 A per square cm in case of carbon to 23 A per square cm in the case of copper.

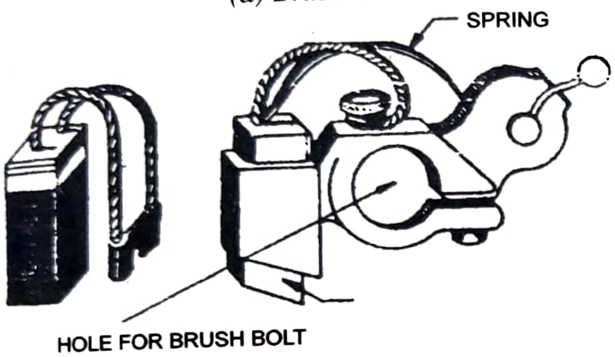
The brushes are housed in brushholders (usually of the box type) which are mounted on the brushholder studs or brackets.

5. Armature Winding. The insulated wires housed in armature slots are suitably connected. This is called the *armature winding*. Armature winding plays vital role in a dc machine. It is a place where conversion of power takes place *i.e.* conversion of mechanical power into electrical one in case of a generator and conversion of electrical power into mechanical one in case of motor. The armature windings most commonly used in drum type armature are of two types namely *lap winding* and *wave winding*.

In *lap winding* finish end of one coil is connected to a commutator segment and to the start end of the adjacent coil under the same pole and similarly all coils are connected. The winding is known as *lap winding* because the sides of successive coils overlap each other. Single turn lap winding is shown in Figs. 12.8(*a*) and

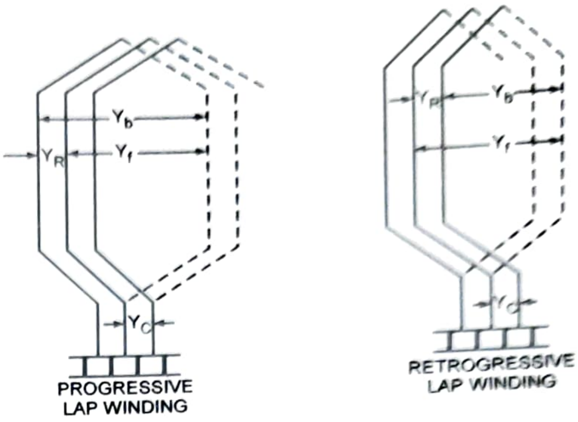


(a) Brushes



(b) Brush Holder

Fig. 12.7 *Brush and Brush Holder*



(a) *(b)*

Fig. 12.8

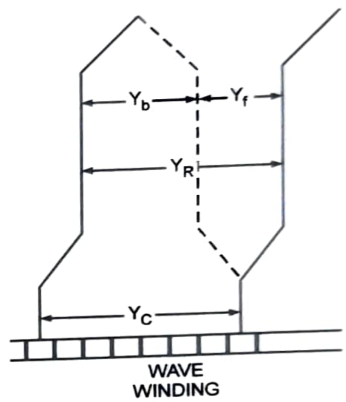


Fig. 12.9

12.8(*b*). In lap winding there are as many parallel paths or circuits through the winding as there are field poles on the machine. Lap winding because of larger number of parallel paths and lesser number of conductors per path is suitable for large current and low voltage machines.

Wave winding is also sometimes known as *series winding*. In wave winding finish end of one coil is connected to the start of another coil as shown in Fig. 12.9. Thus in wave winding, the winding progresses, passing every N pole and S pole till it returns to the coil side from where it was started. As the winding is wavy, the winding is, therefore, called *wave winding*. The wave winding gives always two parallel paths irrespective of number of poles and, therefore, for a given number of poles and armature conductors, it gives more emf than the lap winding. Hence it is used for high voltage and low current machines.

6. Bearings. With small machines, ball-bearings may be used at both ends. For larger machines, roller-bearings are used at the driving end, and ball-bearings may be used at the non-driving end, *i.e.* at the commutator end. Thrust bearings are used where excessive end thrust is anticipated. Sleeve-bearings, with ring lubrication are used for motors when very silent running is required. For large machines pedestal-bearings are generally used.

7. Shaft. The shaft is made of mild steel with a maximum breaking strength. The shaft is used to transfer mechanical power from or to the machine. The rotating parts such as armature core, commutator, cooling fan etc. are keyed to the shaft.

Sectional view of a dc rotor consisting of armature shaft, armature core, armature winding and commutator is illustrated in Fig. 12.10.

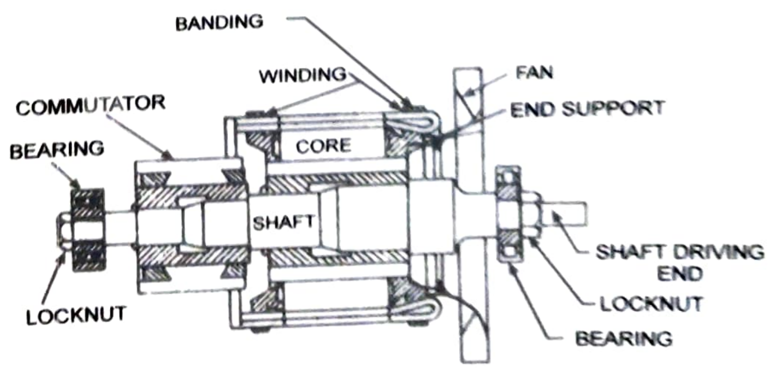


Fig. 12.10 *Sectional View of Rotor Assembly of a DC Machine*

12.3 FUNCTION OF COMMUTATOR FOR GENERATING AND MOTORING ACTION

As mentioned in Art. 12.1, commutator is a device which under certain conditions converts ac into dc and vice versa.

The commutator is a form of rotating switch placed between the armature and external circuit and so arranged that it reverses the connections to the external circuit at the instant of each reversal of the current in the armature coil, as already explained in Art. 12.2, and thus converts induced alternating currents in armature coils into direct currents in the external load circuit.

In case of a dc motor, a direct current passes through the brushes and commutator to the armature winding; while it passes through the commutator it is converted into ac so that the group of conductors under successive field poles carry currents in opposite directions.

12.4 EMF EQUATION

Let Φ be the flux per pole in webers, Z the total number of armature conductors or coil sides on the armature, P the number of poles, A the number of parallel paths in the armature and N be the rotational speed of armature in revolutions per minute (rpm).

As will be recalled, the induced emf is proportional to the time rate of change of the magnetic flux *i.e.*

$$e = \frac{d\phi}{dt}$$

During one revolution of armature in a P-pole generator each armature conductor cuts the magnetic flux P times, so flux cut by one conductor in one revolution = PΦ webers.

Since the number of revolutions made by the armature per minute is N so number of revolutions made per second is N/60 and, therefore, flux cut by each conductor per second = Flux cut by one conductor per revolution × number of revolutions of armature/second

$$= \Phi P \times \frac{N}{60} \text{ webers}$$

Consequently the average emf induced in one conductor will be

$$e = \Phi P \frac{N}{60} \text{ volts}$$

The number of conductors in series between a + ve brush and – ve brush is equal to the total number of conductors divided by the number of parallel paths *i.e.* number of armature conductors per parallel path = Z/A*

∴ The total emf generated between the terminals,

E = Average emf induced in one conductor × number of conductors in each circuit or parallel path

$$= \Phi P \frac{N}{60} \times \frac{Z}{A} \text{ volts} = \Phi Z \frac{N}{60} \times \frac{P}{A} \text{ volts} \quad \text{...(12.1)}$$

For a given machine the number of poles (P) and number of armature conductors per parallel path (Z/A) are constant, therefore,

$$\text{Generated emf, } E = K\Phi N \quad \text{...(12.2) where } K = \frac{PZ}{60\,A}$$

$$\text{or } E \propto \Phi N$$

$$\text{or } E \propto \Phi\omega \qquad \text{where } \omega = \frac{2\pi N}{60}\text{, the angular velocity in radians/second}$$

Thus we see that the induced emf is directly proportional to flux per pole Φ and speed N. Moreover, the polarity of the induced emf depends upon the direction of the magnetic field and the direction of rotation. If

* A = 2 in case of wave winding and = P in case of lap winding.

either of the two is reversed, the polarity of the induced emf *i.e* brushes is reversed, but when both are reversed, the polarity remains unchanged.

The induced emf is fundamental phenomenon to all dc machines whether they are operating as generators or motors. However, when the machine is operating as a generator, this induced emf is called the *generated emf, E_g* whereas in case of a machine operating as a motor it is called the *counter* or *back emf*, E_b.

Example 12.1. A dynamo has a rated armature current at 250 A. What is the current per path of the armature if the armature winding is simplex wave wound or simplex lap wound ? The machine has 12 poles.

Solution: Rated armature current, $I_a = 250$ A

Number of poles, $P = 12$

With simplex wave winding

Number of parallel paths, $A = 2$

$$\therefore \text{ Current per path, } I_c = \frac{I_a}{A} = \frac{250}{2} = 125 \text{ A} \textbf{ Ans.}$$

With simplex lap winding

Number of parallel paths, $A = P = 12$

$$\text{Current per path, } I_c = \frac{I_a}{A} = \frac{250}{12} = 20.833 \text{ A} \textbf{ Ans.}$$

Example 12.2. Derive emf equation of a dc generator. What will be change in emf induced if flux is reduced by 20% and the speed is increased by 20%. *[U.P. Technical Univ. Electrical Engineering Second Semester 2005-06]*

Solution: Since induced emf, $E \propto \Phi N$

$$\text{or } E_2 = E_1 \times \frac{\Phi_2}{\Phi_1} \times \frac{N_2}{N_1} = E_1 \times 0.8 \times 1.2 = 0.96\, E_1.$$

$$\text{So change in emf } = \frac{E_1 - E_2}{E_1} \times 100 = \frac{E_1 - 0.96E_1}{E_1} \times 100 = 4\% \text{ decrease } \textbf{Ans.}$$

Example 12.3. A six pole lap wound armature has 840 conductors and flux per pole of 0.018 webers. Calculate the emf generated when the machine is running at 600 rpm. *[R.G.T.U. Basic Elec. Engineering, December-2005]*

Solution: Flux per pole, $\Phi = 0.018$ Wb

Number of armature conductors, $Z = 840$

Speed or rotation of armature, $N = 600$ rpm

Number of poles, $P = 6$

Number of parallel paths, $A = P = 6$ $\quad\because$ armature is lap wound

$$\text{EMF generated, } E = \frac{\Phi Z N}{60} \times \frac{P}{A} \text{ volts} = 0.018 \times 840 \times \frac{600}{60} \times \frac{6}{6} = 151.2 \text{ V } \textbf{Ans.}$$

Example 12.4. A dc generator has an armature emf of 100 V when the useful flux per pole is 20 mWb, and the speed is 800 rpm. Calculate the generated emf (i) with the same flux and a speed of 1,000 rpm, (ii) with a flux per pole of 24 mWb and a speed of 900 rpm. *[U.P. Technical Univ. Electrical Engineering January 2003]*

Solution: Generated emf, $E_1 = 100$ V

Flux per pole, $\Phi_1 = 20$ m Wb $= 20 \times 10^{-3}$ Wb

Speed, $N_1 = 800$ rpm

Since induced emf is proportional to the product of flux per pole Φ and armature speed N for a given machine *i.e.*

$$E \propto \Phi N$$

$$\text{or } \frac{E_2}{E_1} = \frac{N_2}{N_1} \times \frac{\Phi_2}{\Phi_1}$$

$$(i) \text{ or } E_2 = \frac{N_2}{N_1} \times \frac{\Phi_2}{\Phi_1} \times E_1 = \frac{1{,}000}{800} \times 1 \times 100 = 125 \text{ V } \textbf{Ans.}$$

$\because N_2 = 1{,}000$ rpm and $\Phi_2 = \Phi_1$

$$(ii) \text{ and } E_3 = \frac{N_3}{N_1} \times \frac{\Phi_3}{\Phi_1} \times E_1$$

$$= \frac{900}{800} \times \frac{24 \times 10^{-3}}{20 \times 10^{-3}} \times 100 = 135 \text{ V } \textbf{Ans.} \quad \because N_3 = 900 \text{ rpm and } \Phi_3 = 24 \times 10^{-3} \text{ Wb}$$

Example 12.5. A 4-pole lap wound armature has 144 slots with two coil sides per slot, each coil having two turns. If the flux per pole is 20 mWb and armature rotates at 720 rpm, what is the induced voltage?

[U.P. Technical Univ. Electrical Engineering Second Semester, 2008-09]

Solution: Flux per pole, $\Phi = 20 \text{ mWb} = 20 \times 10^{-3}$ Wb

Number of armature conductors,

$$Z = \text{Number of slots} \times \text{number of coil sides per slot} \times \text{number of turns in each coil}$$
$$= 144 \times 2 \times 2 = 576$$

Number of parallel paths, $A = P = 4$

$$\text{Induced voltage, } E = \Phi \times Z \times \frac{N}{60} \times \frac{P}{A} = 20 \times 10^{-3} \times 576 \times \frac{720}{60} \times \frac{4}{4} = 138.24 \text{ V } \textbf{Ans.}$$

Example 12.6. Calculate the voltage induced in the armature winding of a 4-pole, wave wound, dc machine having 728 conductors and running at 1,800 rpm. The flux per pole is 35 mWb.

[Pb Technical Univ. Electrical Engineering, June-2000]

Solution: Flux per pole, $\Phi = 35 \text{ mWb} = 0.035$ Wb

Number of armature conductors, $Z = 728$

Speed, $N = 1{,}800$ rpm

Number of poles, $P = 4$

Number of parallel paths, $A = 2$ $\quad \because$ machine is wave-wound

$$\text{Voltage induced, } E = \frac{\Phi Z N}{60} \times \frac{P}{A} = \frac{0.035 \times 728 \times 1{,}800}{60} \times \frac{4}{2} = 1{,}528.8 \text{ V} \quad \textbf{Ans.}$$

Example 12.7. An 8-pole dc generator has 500 armature conductors and a useful flux of 0.05 Wb. What will be the emf generated, if it is lap-connected and runs at 1,200 rpm ? What must be the speed at which it is to be driven to produce the same emf, if it is wave wound. *[U.P. Technical Univ Elec. Engineering, February-2001]*

Solution: EMF generated when the generator is lap-connected,

$$E_g = \frac{\Phi Z N}{60} \times \frac{P}{A} = \frac{0.05 \times 500 \times 1{,}200}{60} \times \frac{8}{8} = 500 \text{ V } \textbf{Ans.}$$

$\because$ in lap-connected armature, number of parallel paths, $A = P = 8$

Speed of the generator, when wave-connected, to generate an emf of 500 V

$$\text{So } N' = \frac{E_g \times 60}{\Phi \times Z} \times \frac{A}{P} = \frac{500 \times 60}{0.05 \times 500} \times \frac{2}{8} = 300 \text{ rpm } \textbf{Ans.}$$

$\because$ in wave-connected armature $A = 2$.

Example 12.8. The armature of a four-pole dc machine has 100 turns and runs at 600 rpm. The EMF generated in open circuit is 220 V. Find the useful flux per pole when armature is

***(i)* lap connected** ***(ii)* wave connected.**

[G.B. Technical Univ. Electrical Engineering First Semester, 2010-11]

Solution: EMF generated in open circuit, $E = 220$ V

Speed, $N = 600$ rpm

Number of poles, $P = 4$

Number of armature conductors, $Z = 2 \times \text{number of turns} = 2 \times 100 = 200$

(i) When armature is lap connected

Number of parallel paths, $A = P = 4$

Flux per pole, $\Phi = E \times \frac{A}{P} \times \frac{60}{N} \times \frac{1}{Z}$ $\qquad \because \; E = \frac{\Phi Z N}{60} \times \frac{P}{A}$

$= 220 \times \frac{4}{4} \times \frac{60}{600} \times \frac{1}{200} = 0.11$ Wb **Ans.**

(*ii*) When armature is wave connected,

Number of parallel paths, $A' = 2$

and Flux per pole, $\Phi' = \frac{220 \times 2}{4} \times \frac{60}{600} \times \frac{1}{200} = 0.055$ Wb **Ans.**

12.5 TYPES OF DC GENERATORS

The mmf necessary to establish the flux in the magnetic circuit of a dc generator can be obtained by means of (*i*) permanent magnets (*ii*) field coils excited by some external source and (*iii*) field coils excited by the generator itself.

When permanent magnets are used for establishing the flux in the magnetic circuit, the generator is known as a *permanent magnet generator*. It consists of an armature and one or several permanent magnets encircling the armature. The field developed by the poles of such machines remains fairly constant. Although these machines are very compact but in view of the low power thus generated, permanent magnet generators have not found industrial applications. Such generators are employed only in small sizes like dynamos in motor cycles etc.

12.5.1. Separately-Excited DC Generators. Since the operation of a dc machine depends upon a fixed polarity of the poles which does not vary with time, the field coils need energization from a dc source.

A dc generator whose field winding is excited from an independent external dc source, such as a battery, the generator is called a *separately-excited generator*. The circuit diagram is illustrated in Fig. 12.11. In this case current flowing through the armature, I_a and load, I_L is the same and the terminal voltage (voltage across the load), V is equal to the generated emf, E_g less voltage drop in armature, $I_a R_a$ *i.e.*

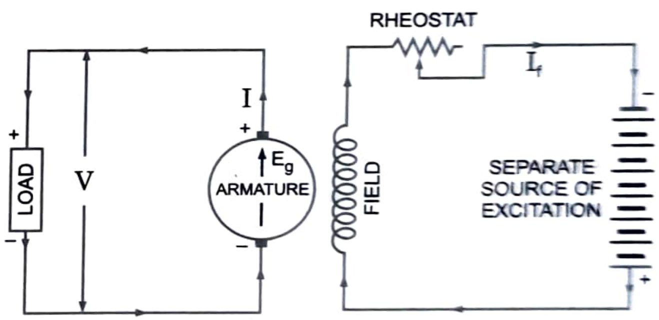


Fig. 12.11

$$I_a = I_L = I \text{ (say)} \qquad ...(12.3)$$

$$V = E_g - I R_a \qquad ...(12.4)$$ where R_a is the armature resistance

$$\text{Power developed, } P_g = E_g I \qquad ...(12.5)$$

$$\text{Power delivered to external load, } P_L = V I \qquad ...(12.6)$$

12.6 WORKING PRINCIPLE OF DC MOTOR

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

$$F = BI_c l_c \text{ newtons}$$

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

When the motor is connected to the dc supply mains, a direct current passes through the brushes and commutator to the armature winding; while it passes through the commutator it is converted into ac so that the group of conductors under successive field poles carry currents in the opposite directions, as shown in Fig. 12.20. Also the direction of current in the individual conductors reverses as they pass away from the influence of one pole to that of the next.

In Fig. 12.20, a 4-pole dc motor is shown when the field and armature circuits are connected across dc supply mains. Let the current in armature conductors be outwards under the N-poles (shown by dots) and inwards

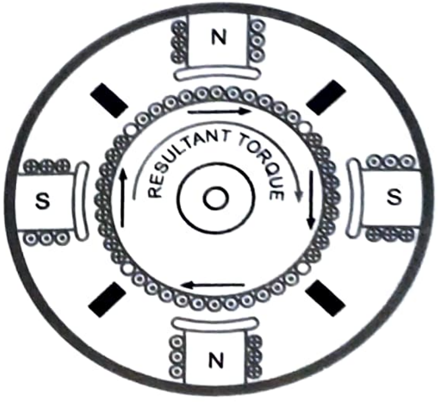


Fig. 12.20

under S-poles (shown by crosses). By applying Fleming's left hand rule, the direction of force on each conductor can be determined, which has been illustrated in Fig. 12.20. From Fig. 12.20. it is observed that each conductor experiences a force which tends to rotate the motor armature in clockwise direction. These forces collectively produce a driving torque.

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

Consider a single turn coil, whose leads are soldered to commutator segments *a* and *b*, each carrying a brush, as illustrated in Fig. 12.21. The positive side of the supply line is connected to left hand brush and negative side to the right hand brush. In position I the line current arrives at the commutator segment a, flows through the bottom side 1 of the coil away from the reader (as shown by cross in the circle) and then through the upper side 2 of the coil towards the reader (as shown by dot in the circle), reaches the commutator segment *b* and flows again into the line through the brush. The coil will tend to rotate in clockwise direction, as determined by Fleming's left hand rule.

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

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

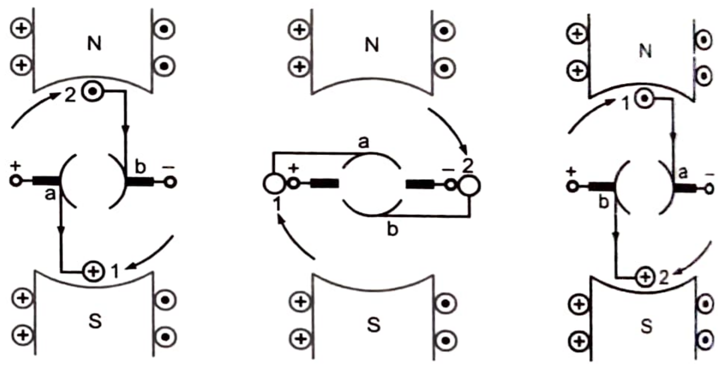


Fig. 12.21 *Commutation in a DC Motor*

12.7 IMPORTANCE OF BACK EMF

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

Since the back emf is induced due to the generator action, the magnitude of it is, therefore, given by the same expression as that for the generated emf in a generator

$$i.e.\ \text{Back emf, } E_b = \frac{\Phi ZN}{60} \times \frac{P}{A} \text{ volts} \qquad ...(12.28)$$

the symbols having their usual significance.

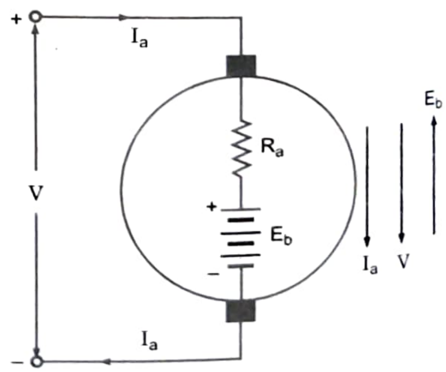


Fig. 12.22 *Equivalent Circuit of a Motor Armature*

The equivalent circuit of a motor is shown in Fig. 12.22. The armature circuit is equivalent to a source of emf, E_b in series with a resistance, R_a put across a dc supply mains of V volts. It is evident from Fig. 12.22 that the applied voltage V must be large enough to balance both the voltage drop in armature resistance and the back emf at all times *i.e.*

$$V = E_b + I_a R_a \qquad ....(12.29)$$

where V is the applied voltage across the armature, E_b is the induced emf in the armature by generator action, I_a is the armature current and R_a is the armature resistance.

The Eq. (12.29) may be rewritten as $I_a = \dfrac{V - E_b}{R_a}$ to give armature current in terms of applied voltage V, induced emf E_b and armature resistance R_a.

As obvious from Eqs (12.28) and (12.29) the induced emf in the armature of a motor, E_b depends among other factors upon the armature speed and armature current depends upon the back emf E_b for a constant applied voltage and armature resistance. If the armature speed is high, back emf E_b will be large and, therefore, armature current small. If the speed of the armature is low, then back emf E_b will be less and armature current I_a more resulting in development of large torque.

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

When the motor is operating on no load, small torque is required to overcome the friction and windage losses, therefore, back emf is nearly equal to the applied voltage and armature current is small. When the motor is loaded, the driving torque of the motor is not sufficient to counter the increased retarding torque due to load and the effect is to cause the armature to slow down. With the decrease in the speed of armature back emf falls. The reduced back emf allows a larger current to flow through the armature. The increase in armature current results in higher electromagnetic driving torque. The motor continues to slow down till the electromagnetic torque developed matches the load torque and the steady-state conditions are attained. The reverse phenomenon occurs when mechanical load on the motor falls.

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

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

12.10 SPEED EQUATION

As mentioned in Art. 12.7, the expressions for back emf developed in the armature of a dc motor are given as

$$E_b = \frac{\Phi ZN}{60} \times \frac{P}{A} \text{ volts} \quad \text{...(12.43)}$$

$$\text{and } E_b = V - I_a R_a \text{ volts} \quad \text{...(12.44)}$$

Comparing expressions (12.43) and (12.44) we get

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

$$\text{or } N = \frac{V - I_a R_a}{\Phi Z} \times \frac{60\,A}{P}$$

$$\text{or } N = K\frac{V - I_a R_a}{\Phi} = K\frac{E_b}{\Phi}$$ since Z, A and P are constant for a particular machine.

For a dc motor, if initial values of speed, armature current, back emf and flux per pole are N_1, I_{a1}, E_{b1} and Φ_1 respectively and corresponding final values are N_2, I_{a2}, E_{b2} and Φ_2 respectively, then

$$N_1 \propto \frac{E_{b1}}{\Phi_1} \quad \text{where } E_{b1} = V - I_{a1} R_a$$

$$N_2 \propto \frac{E_{b2}}{\Phi_2} \quad \text{where } E_{b2} = V - I_{a2} R_a$$

$$\text{and } \frac{N_2}{N_1} = \frac{E_{b2}/\Phi_2}{E_{b1}/\Phi_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\Phi_1}{\Phi_2} \qquad ...(12.45)$$

For a **dc shunt motor** (or a separately-excited dc motor) flux practically remains constant (*i.e.* $\Phi_2 = \Phi_1$) and

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} = \frac{V - I_{a2} R_a}{V - I_{a1} R_a} \qquad ...(12.46)$$

In above expression since applied voltage V is constant and the voltage drop in armature ($I_a R_a$) is negligible in comparison to supply voltage V, speed of a dc shunt motor remains almost constant.

For a **dc series motor**, prior to saturation,

$$\Phi \propto I_{se} \propto I_a$$

$$\text{or } \frac{\Phi_1}{\Phi_2} = \frac{I_{a1}}{I_{a2}} \text{ and } \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{I_{a1}}{I_{a2}} \qquad ...(12.47)$$

For a **dc series motor**, after saturation

Flux Φ is independent of field current I_{se} or armature current I_a

and speed $N \propto E_b$

$$\text{or } \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \qquad ...(12.48)$$

Example 12.19. A 6-pole lap wound shunt motor has 500 conductors in the armature. The resistance of armature path is 0.05 Ω. The resistance of shunt field is 25 Ω. Find the speed of the motor when it takes 120 A from dc mains of 100 V supply. Flux per pole is 2×10^{-2} Wb. *[M.D. Univ., December-2006]*

Solution: Shunt field current, $I_{sh} = \frac{V}{R_{sh}} = \frac{100}{25} = 4$ A

Armature current, $I_a = I_L - I_{sh} = 120 - 4 = 116$ A

Back emf, $E_b = V - I_a R_a = 100 - 116 \times 0.05 = 94.2$ V

Speed of motor, $N = \frac{E_b}{\Phi Z} \times \frac{60\,A}{P} = \frac{94.2 \times 60 \times 6}{2 \times 10^{-2} \times 500 \times 6} = 565$ rpm **Ans.**

Example 12.20. A 4-pole dc shunt motor working on 220 V dc supply takes a line current of 3 A at no load while running at 1,500 rpm. Determine the speed when the motor takes a line current of 50 A. Assume armature and field resistances as 0.2 ohm and 400 ohm respectively. *[U.P. Technical Univ. Electrical Engineering First Semester, 2003-04]*

Solution: Shunt field current, $I_{sh} = \frac{V}{R_{sh}} = \frac{220}{400} = 0.55$ A

No-load armature current, $I_{a0} = I_{L0} - I_{sh} = 3 - 0.55 = 2.45$ A

No-load back emf, $E_{b0} = V - I_{a0} R_x = 220 - 2.45 \times 0.2 = 219.51$ V

When loaded:

Armature current, $I_{af} = I_{Lf} - I_{sh} = 50 - 0.55 = 49.45$ A

Back emf, $E_{bf} = V - I_{af} R_a = 220 - 49.45 \times 0.2 = 210.11$ V

Speed, $N_f = N_0 \times \frac{E_{bf}}{E_{b0}} = 1{,}500 \times \frac{210.11}{219.51} = 1{,}436$ rpm **Ans.**

$\because$ flux is assumed to remain constant.

Example 12.21. A dc shunt motor runs at 600 rpm taking 60 A from a 230 V supply. Armature resistance is 0.2 ohm and field resistance is 115 ohms. Find the speed when the current through the armature is 30 A. *[Electrical Engineering U.P. Technical Univ. Second Semester, 2007-08; G.B. Technical Univ. Odd Semester, 2012-13]*

Solution: Shunt field current, $I_{sh} = \frac{V}{R_{sh}} = \frac{230}{115} = 2$ A

When line current $I_{L_1} = 60$ A

Armature current, $I_{a_1} = I_{L_1} - I_{sh} = 60 - 2 = 58$ A

$$\text{Back emf, } E_{b_1} = V - I_{a_1} R_a = 230 - 58 \times 0.2 = 218.4 \text{ V}$$

$$\text{Speed, } N_1 = 600 \text{ rpm}$$

When armature current $I_{a_2} = 30$ A

$$\text{Back emf, } E_{b_2} = V - I_{a_2} R_a = 230 - 30 \times 0.2 = 224 \text{ V}$$

$$\text{Speed, } N_2 = N_1 \times \frac{E_{b_2}}{E_{b_1}} = \frac{600 \times 224}{218.4} = 615.4 \text{ rpm} \quad \textbf{Ans.}$$

Example 12.22. A series motor runs at 600 rpm when taking a current of 110 A from a 230 volt supply. The useful flux per pole for 110 A is 24 mWb and that for 50 A is 16 mWb. The armature resistance and series field resistance are 0.12 ohms and 0.03 ohms respectively. Calculate the speed when the current has fallen to 50 A.

[R.G. Technical Univ. Basic Electrical and Electronics Engineering, June-2014]

Solution: Supply voltage, V = 230 V

For supply current of 110 A

$$\text{Flux per pole, } \Phi_1 = 24 \text{ mWb or } 0.024 \text{ Wb}$$

$$\text{Speed, } N_1 = 600 \text{ rpm}$$

$$\text{Back emf, } E_{b_1} = V - I(R_a + R_{se}) = 230 - 110 \times (0.12 + 0.03) = 213.5 \text{ V}$$

For supply current of 50 A

$$\text{Flux per pole, } \Phi_2 = 16 \text{ mWb} = 0.016 \text{ Wb}$$

$$\text{Back emf, } E_{b_2} = 230 - 50(0.12 + 0.03) = 222.5 \text{ V}$$

$$\text{Speed } N_2 = N_1 \times \frac{E_{b_2}}{E_{b_1}} \times \frac{\Phi_1}{\Phi_2} \qquad \because E_b \propto \Phi N$$

$$= 600 \times \frac{222.5}{213.5} \times \frac{0.024}{0.016} = 938 \text{ rpm} \quad \textbf{Ans.}$$

Example 12.23. A 230 V dc shunt generator has armature circuit resistance (including brushes) of 0.4 Ω and field circuit resistance of 120 Ω. If the machine run as a motor by connecting it a 230 V dc mains, find the ratio of speed as a generator to the speed as a motor. The line current in each case is 45 A.

[B.P. Univ. of Technology Electrical Machine-I, 2008]

Solution: Shunt field current, $I_{sh} = \frac{V}{R_{sh}} = \frac{230}{120} = 1.9$ A

As Generator Line current, $I_{Lg} = 45$ A

$$\text{Armature current, } I_{ag} = I_{Lg} + I_{sh} = 45 + 1.9 = 46.9 \text{ A}$$

$$\text{Generated emf, } E_g = V + I_{ag} R_a = 230 + 46.9 \times 0.4 = 248.76 \text{ V}$$

As motor Line current, $I_{Lm} = 45$ A

$$\text{Armature current, } I_{am} = I_{Lm} - I_{sh} = 45 - 1.9 = 43.1 \text{ A}$$

$$\text{Back emf developed, } E_b = V - I_{am} R_a = 230 - 43.1 \times 0.4 = 212.76 \text{ V}$$

Ratio of speed as a generator to speed as a motor,

$$\frac{N_g}{N_m} = \frac{E_g}{E_b} = \frac{248.76}{212.76} = 1.169 \textbf{ Ans.}$$

$\because$ Field current and therefore flux per pole is same in both cases.

12.11 ARMATURE TORQUE

Let T_e be the electromagnetic torque developed in newton-metres by the motor running at n rps.

$$\text{Power developed} = \text{Work done per second} = T_e\,\omega = T_e \times 2\pi n \text{ watts} \qquad \text{...(12.49)}$$

Electrical equivalent of mechanical power developed by the armature, as mentioned in Art 12.4, also

$$= E_b I_a \text{ watts} \qquad \text{...(12.50)}$$

Comparing expressions (12.49) and (12.50) we have

$$T_e \times 2\pi n = E_b I_a$$

$$\text{or } T_e = \frac{E_b I_a}{2\pi n} = 0.159 \frac{E_b I_a}{n} \text{ N-m} \quad \text{....(12.51)}$$

$$\text{Also } T_e = \frac{E_b I_a}{2\pi \frac{N}{60}} = 9.55 \frac{E_b I_a}{N} \text{ N-m} \quad \text{... (12.52) where N is speed in rpm}$$

Substituting $E_b = \Phi Z \frac{N}{60} \times \frac{P}{A}$ in Eq. (12.52) we have

$$T_e = 9.55 \times \Phi \times Z \times \frac{N}{60} \times \frac{P}{A} \times \frac{I_a}{N} = 0.159\, \Phi Z P \frac{I_a}{A} \text{ newton-metres} \quad \text{...(12.53)}$$

ALTERNATIVE PROOF. Quantitatively, the force on a straight section of conductor length *l* metres perpendicular to a magnetic field of density B webers per square metre and carrying I_c amperes is given as

$$F_c = B l I_c \text{ newtons} \quad \text{[Refer to Eq. (12.32)]}$$

If D is the diameter of the armature, the force F_c acts at a radial distance of D/2 metres and the associated torque per conductor is given as

$$T_c = \frac{B l I_c D}{2}$$

$$\text{The average flux density, } B_{av} = \frac{\Phi P}{\pi D l}$$

$$\text{So torque developed per conductor, } T_c = \frac{\Phi P}{\pi D l} \times \frac{l I_c D}{2} = \frac{1}{2\pi} \Phi P I_c$$

The torque associated with the entire winding is the summation of the torques for the individual conductors or coil sides. Torque developed by such electromagnetic action is called the electromagnetic torque and is given as

$$T = \frac{1}{2\pi} \Phi Z P I_c$$

where Z is the number of armature conductors on the armature surface.

$$= \frac{1}{2\pi} \Phi Z P \frac{I_a}{A} = 0.159\, \Phi Z P \frac{I_a}{A} \quad \because \text{ Current per conductor, } I_c = \frac{I_a}{A}$$

Since Z, P and A are constant for a particular machine,

$$T = K \Phi I_a \text{ where } K = \frac{1}{2\pi} \frac{PZ}{A}$$

$$\text{or } T \propto \Phi I_a$$

Thus it may be concluded that

(*i*) the electromagnetic torque developed by the armature is proportional to the product of flux per pole and armature current.

(*ii*) the direction of electromagnetic torque developed by armature depends upon the direction of flux or magnetic field and the direction of flow of current in armature conductors. If either of the two is reversed the direction of torque developed will be reversed and, therefore, the direction of rotation. When both (the direction of field as well as that of armature current) are reversed the direction of torque (or rotation) will not change. This has been explained in Art 12.6 also.

In case of a series wound motor flux Φ is directly proportional to armature current I_a (before saturation) because in a series wound motor field winding and armature winding currents are same, therefore,

$$T_e \propto I_a^2$$

In case of permanent magnet motors, separately-excited motors and shunt wound motors the field strength *i.e.* Φ is practically constant and, therefore,

$$T_e \propto I_a$$

On the basis of the same killowatt output and speed, a dc series motor develops the highest starting torque and the dc shunt motor the least, while the cumulative compound wound dc motor falls somewhere between the first two.

Example 12.24. A separately-excited dc motor develops an open-circuit emf of 250 volt at 1,500 rpm. Find its developed torque for an armature current of 20 amperes.

Solution: Open-circuit emf, $E_0 = 250$ V

Armature current, $I_a = 20$ A

Assuming back emf equal to open-circuit emf, though it may be slightly less due to armature reaction if field current remains unchanged.

$$\text{Torque developed, } T_e = \frac{9.55\, E_0\, I_a}{N} = \frac{9.55 \times 250 \times 20}{1{,}500} = 31.833 \text{ N-m } \textbf{Ans.}$$

Example 12.25. A 4-pole, 220 V dc shunt motor has armature and shunt field resistances of 0.2 Ω and 220 Ω respectively. It takes 20 A at 220 V from the source while running at a speed of 1,000 rpm. Find (*i*) field current, (*ii*) armature current (*iii*) back emf (*iv*) torque developed.

[*W.B. Univ. of Technology Basic Electrical Engineering, 2012-13*]

Solution: Supply voltage, $V = 220$ V

Line current, $I_L = 20$ A

Armature resistance, $R_a = 0.2\ \Omega$

Shunt field resistance, $R_{sh} = 220\ \Omega$

Speed, $N = 1{,}000$ rpm

(*i*) Shunt field current, $I_{sh} = \frac{V}{R_{sh}} = \frac{220}{220} = 1$ A **Ans.**

(*ii*) Armature current, $I_a = I_L - I_{sh} = 20 - 1 = 19$ A **Ans.**

(*iii*) Back emf, $E_b = V - I_a R_a = 220 - 19 \times 0.2 = 216.2$ V **Ans.**

(*iv*) Mechanical power developed, $P_{mech} = E_b I_a = 216.2 \times 19 = 4{,}107.8$ W

$$\text{Torque developed, } T = \frac{9.55 \times P_{mech}}{N} = \frac{9.55 \times 4{,}107.8}{1{,}000} = 39.23 \text{ N-m} \quad \textbf{Ans.}$$

Example 12.26. The armature resistance of a 200 V separately-excited dc motor is 0.12 Ω. It runs at 600 rpm at constant torque load and draws a current of 21 A. Calculate its new speed if the field current is reduced to 10%.

Solution: Supply voltage, $V = 200$ V

Line current, $I_{L1} = 21$ A

Armature current, $I_{a1} = I_{L1} = 21$ A neglecting shunt field current

Speed, $N_1 = 600$ rpm

Back emf, $E_{b1} = V - I_{a1} R_a = 200 - 21 \times 0.12 = 197.48$ V

Since torque is same

or $T_2 = T_1$

$$I_{a2}\Phi_2 = I_{a1}\Phi_1$$

$$\text{or } I_{a2} = I_{a1} \times \frac{\Phi_1}{\Phi_2} = I_{a_1} \times \frac{I_{sh_1}}{I_{sh_2}} \qquad \text{Assuming } \Phi \propto I$$

$$= 21 \times \frac{1}{0.9} = 23.333 \text{ A} \qquad \because I_{sh2} = 0.9\, I_{sh1}$$

$$\text{Back emf } E_{b2} = V - I_{a2} R_{a2} = 200 - 23.333 \times 0.12 = 197.2 \text{ V}$$

$$\text{Speed, } N_2 = \frac{E_{b2}}{E_{b1}} \times \frac{\Phi_1}{\Phi_2} \times N_1 = \frac{197.2}{197.48} \times \frac{1}{0.9} \times 600 = 665.7 \text{ rpm } \textbf{Ans.} \qquad \because E_b \propto \Phi N$$

Example 12.27. A separately-excited dc motor draws an armature current of 12 A from a 220 V dc supply when developing a gross torque of 20 N-m in the armature running at 1,200 rpm. What will be the induced back emf in the armature?

Solution: Gross torque developed, T = 20 N-m

Speed of armature, N = 1,200 rpm

Armature current, I_a = 12 A

$$\text{Back emf, } E_b = T \times \frac{2\pi N}{60} \times \frac{1}{I_a} \qquad \because E_b I_a = T \times \frac{2\pi N}{60}$$

$$= 20 \times \frac{2\pi \times 1{,}200}{60} \times \frac{1}{12} = 209.4 \text{ V } \textbf{Ans.}$$

Example 12.28. A dc shunt generator delivers 50 kW at 250 V when running at 500 rpm. The armature and field resistances are 0.05 ohm and 125 ohm respectively. Calculate the speed of the same machine and developed torque when running as a shunt motor and taking 50 kW at 250 V. Allow 1 volt per brush for contact drop.

[G.B. Technical Univ. Electrical Engineering First Semester 2009-10]

Solution: As Generator Generator output, P_G = 50 kW

Supply voltage, V_L = 250 V

Speed, N_G = 500 rpm

Armature resistance, $R_a = 0.05\ \Omega$

Shunt field resistance, $R_{sh} = 125\ \Omega$

$$\text{Line current, } I_L = \frac{P_G \times 1000}{V_L} = \frac{50 \times 1{,}000}{250} = 200 \text{ A}$$

$$\text{Shunt field current, } I_{sh} = \frac{V_L}{R_{sh}} = \frac{250}{125} = 2 \text{ A}$$

$$\text{Armature current, } I_{ag} = I_L + I_{sh} = 200 + 2 = 202 \text{ A}$$

$$\text{Generated emf. } E_g = V_L + I_{ag} R_a + 2 \times \text{volt per brush} = 250 + 202 \times 0.05 + 2 \times 1 = 262.1 \text{ V}$$

As Motor

$$\text{Load current, } I_L = \frac{50 \times 1{,}000}{250} = 200 \text{ A}$$

$$\text{Armature current, } I_{am} = I_L - I_{sh} = 200 - 2 = 198 \text{ A}$$

$$\text{Back emf developed, } E_b = V - I_{am} R_a - \text{brush contact drop} = 250 - 198 \times 0.05 - 2 \times 1 = 238.1 \text{ V}$$

$$\text{Speed of motor, } N_m = N_g \times \frac{E_b}{E_g} = \frac{500 \times 238.1}{262.1} = 454 \text{ rpm} \quad \textbf{Ans.}$$

$$\text{Motor torque, } T = \frac{E_b I_a}{2\pi N/60} = \frac{238.1 \times 198}{2\pi \times 454} \times 60 = 991.6 \text{ Nm} \quad \textbf{Ans.}$$

12.12 OPERATING CHARACTERISTICS OF DC MOTORS

The performance and, therefore, suitability of a dc motor is determined from its characteristics, known as *performance characteristics*. The important characteristics of dc motors are:

1. Torque-Armature Current Characteristic. This characteristic curve gives relation between torque developed in the armature, T and armature current I_a. This is also known as *electrical characteristic*.

2. Speed-Armature Current Characteristic. This characteristic curve gives relation between speed N and armature current I_a. This is also known *as speed characteristic*.

3. Speed-Torque Characteristic. This characteristic gives relation between speed N and torque developed in armature, T. This is also known as *mechanical characteristic*. This curve may be derived from the two characteristic curves mentioned above.

The important relations to be kept in mind while discussing motor characteristics are:

(*i*) $I_a = \frac{V - E_b}{R_a}$ (*ii*) $N \propto \frac{E_b}{\Phi}$ and (*iii*) $T \propto \Phi I_a$.

12.14 OPERATING CHARACTERISTICS OF DC SHUNT MOTORS

1. Speed - Armature Current Characteristic. If applied voltage V is kept constant, the field current will remain constant, hence flux will have maximum value on no load but will slightly decrease due to armature reaction as the load increases but for most purposes the flux is considered to be constant, neglecting armature reaction effect.

From speed equation, speed N is directly proportional to back emf E_b or $(V - I_a R_a)$ and inversely proportional to the flux Φ. Since flux is considered to be constant as mentioned above, with the increase in armature current the speed slightly falls due to increase in voltage drop in armature and the speed-armature current curve coincides with the back emf-armature current curve. Since voltage drop in armature at full load is very small as compared to applied voltage, drop in speed from no load to full load is very small. If demagnetising effect of armature reaction is considered, the drop in speed due to voltage drop in armature is compensated for up to some extent due to decrease in flux with the increase in armature current and speed-armature current characteristic is less drooping, as shown dotted in Fig. 12.30 or even be rising if demagnetisation is high. Thus the drop in speed from no load to full load is very small and for all practical purposes the dc shunt motor is taken as a constant speed motor.

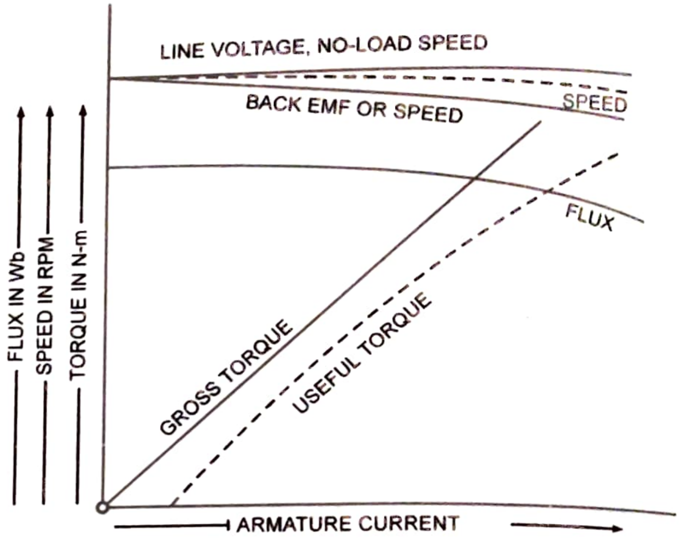


Fig. 12.30

There is a slight variation in speed of the shunt motor from no load to full load and this slight variation in speed can be made up by inserting resistance in the field circuit and so reducing the flux. Therefore, shunt motors can be used for the loads which are totally and suddenly thrown off without resulting in excessive speed. Shunt motors being constant speed motors are best suited for driving of line shafts, machine lathes, milling machines, conveyors, fans and for all purposes where constant speed is required. It is not suitable for use with flywheel or with fluctuating loads or for parallel operation due to its constant speed characteristic. It is also useful where a moderate degree of speed control is required.

2. Torque-Armature Current Characteristic. From the expression for the torque of a dc motor, torque is directly proportional to the product of flux per pole Φ and armature current I_a. Since in case of dc shunt motor the flux per pole Φ is considered to be constant, torque increases with the increase in load current following linear law, *i.e.* torque-armature current characteristic is a straight line passing through origin O (Fig. 12.30). But the weakening of field due to armature reaction causes the torque line to droop slightly, and the iron and friction losses cause it to be slightly lower than the line representing the electromagnetic developed torque corresponding to $T = 0.159\, \Phi\, Z\, P\, \frac{I_a}{A}$ Nm.

3. Speed-Torque Characteristic. This characteristic curve can be drawn from the above two characteristics and is shown in Fig. 12.31.

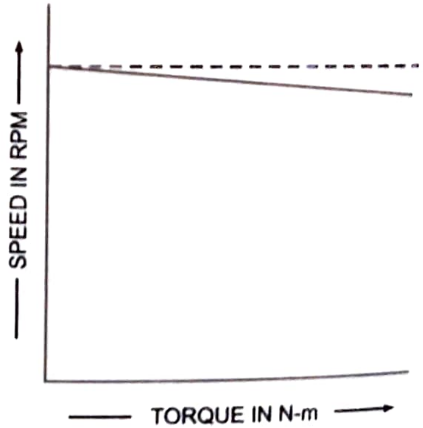


Fig. 12.31

This type of motor is used in applications requiring medium starting torque such as centrifugal pumps, blowers, fans, conveyors, boring mills, shapers, woodworking machines, spinning and weaving machines, printing presses, machine tools etc.

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

12.15 OPERATING CHARACTERISTICS OF SEPARATELY-EXCITED DC MOTORS

The torque-armature current, speed-armature current and speed-torque characteristics of separately-excited dc motors are similar to those of dc shunt motors.

12.17 SPEED CONTROL OF SEPARATELY-EXCITED DC MOTORS

Speed control means intentional change of the drive speed to a value required for performing the specific work process.

One of the attractive features the dc motor offers over all other types is the relative ease with which speed control can be achieved and, therefore, dc motors are indispensable for many adjustable speed drives. The various schemes available for speed control can be deduced from the expression of speed for a dc motor which is repeated here with one modification

$$N = K \frac{V - I_a (R + R_a)}{\Phi} \qquad \ldots(12.54)$$

The modification involves the inclusion of an external resistance in the armature circuit. The above expression reveals that the speed can be controlled by adjusting any one of the three factors appearing on the right hand side of the expression: (*i*) applied voltage to the armature terminals, V (*ii*) external resistance in the armature circuit, R and (*iii*) flux per pole, Φ. The first two possibilities involve adjustment affecting the armature circuit, whereas the third involves change in the magnetic field. Therefore, speed control methods are broadly classified as *armature control methods* and *field control methods*. Sometimes a combination of the two methods is employed. With armature control the speed decreases as the voltage applied to the armature terminals is reduced, whereas with field control the speed increases as the flux is reduced.

1. *Field Control Method.* In case of separately-excited dc motors the flux can be varied by inserting a variable resistance in series with the field winding (refer to Fig. 12.33). Since this resistance has to carry only a small current, it is made up of slide-wire type of resistor to have continuously variable speed over the range.

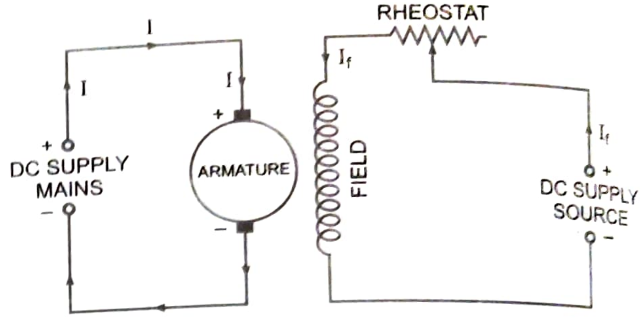


Fig. 12.33 *Field Control of Separately-Excited DC Motor*

Since the flux can be only decreased (not increased), the speeds only above normal one can be obtained by this method. The speed is minimum at the maximum value of flux and depends upon the design of the field and its saturation point. The speed is maximum at the minimum value of flux, which is governed by the demagnetizing effect of armature reaction on the field as at higher speeds the motor tends to be unstable and difficulties in commutation arise. The high speed is also restricted due to mechanical considerations as the centrifugal forces are set up at high speeds. Speed variation by this method is limited to ratio of 4 or 5 to 1. Creeping speeds cannot be obtained by this method. The power output being proportional to TN or VI_a remains constant. This method is, therefore, suitable only where power of the load remains constant. This method of speed control is very simple, convenient and most economical and is, therefore, extensively used in electric drives. The power wasted in the controlling resistance is very little, field current being very small. This method of speed control is independent of load on the motor and permits the remote control of speed.

2. *Armature Resistance Control Method.* In this method of speed control reduced speeds are obtained by inserting resistance in the armature circuit, as shown in Fig. 12.34.

An increase in resistance in the armature circuit will cause more voltage drop in the armature circuit, and, therefore, the speed will be reduced. Field current will remain unaffected as the field circuit is supplied from an independent source.

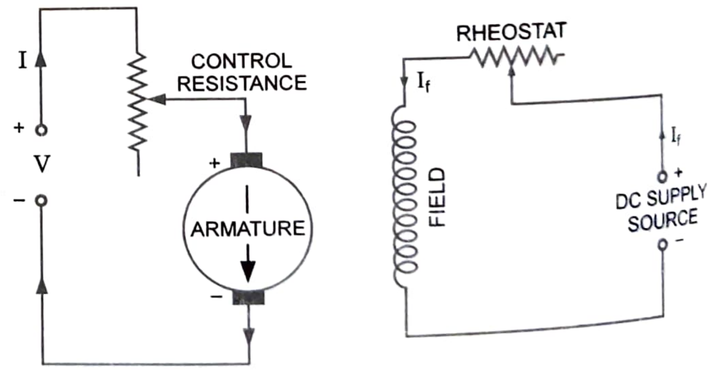


Fig. 12.34

For a constant torque load, the armature current remains the same so input to the motor remains the same but the output decreases in proportion to the speeds. Operating costs are, therefore, comparatively high for long time running at reduced speed. In case of fans and centrifugal pumps where the load torque decreases with the decrease in speed, the losses are considerably low and because of its low initial cost and simplicity this method may be quite convenient and economical for short-time or intermittent slowdowns. Wide range of speed (below normal one) can be obtained by this method and at the same time motor will develop any desired torque over its operating range. The main advantage of this method is that speeds below base speed down to creeping speeds of only a few rpm are easily available. This method of speed control, therefore, is employed where speeds lower than rated one are required for a short period only and also occasionally as in printing machines, cranes and hoists where the motor is frequently started and stopped. This method of speed control is also employed where the load drops off rapidly with the decrease in speed, as in fans and blowers.

3. ***Armature Voltage Control Method.*** This method avoids the disadvantages of poor speed regulation and low efficiency which are the characteristics of the armature–resistance control method but it is more expensive in initial cost. The adjustable voltage for the armature is obtained from an adjustable voltge generator or from an adjustable electronic rectifier*. This method provides a large speed range with any desired number of speed points. It is essentially a constant–torque system, because the output delivered by the motor decreases with a decrease in applied voltage and a corresponding decrease in speed.

12.18 APPLICATIONS OF DC MOTORS

The dc motor is often called upon to do the really tough jobs in the industry because of its high degree of flexibility and ease of control. These features cannot easily be matched by other electromechanical energy-conversion devices. The dc motor offers a wide range of control of speed and torque as well as acceleration and deceleration. The applications of the three types of dc motors are given below:

1. DC Series Motor. It is a variable speed motor *i.e.* very low speed at high torque and vice versa. However, at light or no load, the motor tends to attain dangerously high speed. The motor has a very high starting torque (up to 5 times of full-load torque). It is, therefore, used for drives requiring very high starting torque and where adjustable varying speed is satisfactory. Industrial uses are hoists, cranes, trolley cars, conveyors, electric locomotive, elevators, air-compressors, vacuum cleaners, sewing machines etc.

Loads must be positively connected, not belted. To prevent overspeed, lightest load should not be much less than 15 to 20% of full-load torque.

2. DC Shunt Motor. It is an approximately constant speed motor and has medium starting torque (usually limited to 2.5 times of full-load torque by a starting resistor).

DC shunt motor is, therefore, used essentially for constant speed applications requiring medium starting torque. May be used for adjustable speed not greater than 2 : 1 range.

Industrial applications are lathes, centrifugal pumps, reciprocating pumps, fans, blowers, conveyors, woodworking machines, machine tools, printing presses, spinning and weaving machines.

3. Compound Wound Motors. *Differential compound wound dc motors* are rarely used because of their poor torque characteristics and difficulties experienced during overloads and starting.

Cumulative compound wound dc motors are used in driving machines which are subject to sudden applications of heavy loads, such as occur in rolling mills, punching and shearing machines, lifts, mine-hoists etc. This type of motor is also used where a large starting torque is required but series motor cannot be conveniently used such as in cranes and elevators.