CHAPTER - 7

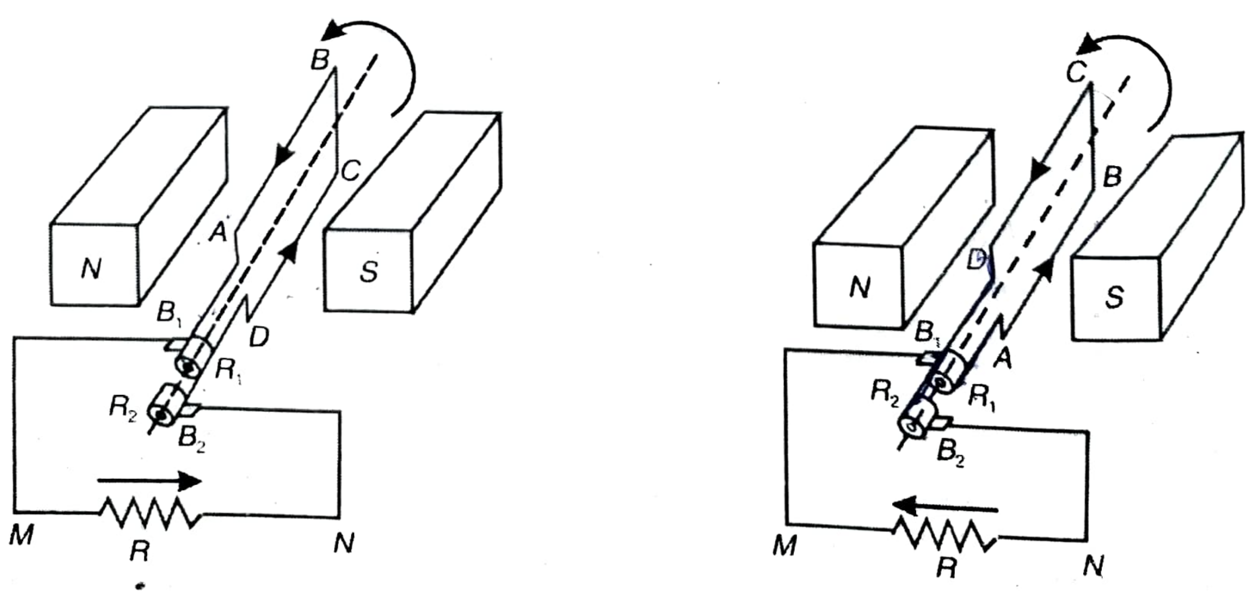
D.C. GENERATORS

7.1 Introduction:

A D.C. generator is an electrical machine which converts mechanical energy into electrical energy. The electrical energy is generated in the form of an alternating voltage in the windings of the D.C. generator. This alternating voltage is converted into direct or constant voltage by commutator. Hence, when a load is connected to the terminals of a D.C. generator, direct current flows through the load. The principle used for the generation of voltage is electromagnetic induction.

7.2 Working Principle:

A D.C. generator works on the principle of Faraday's laws of electromagnetic induction. The nature of the e.m.f. induced is dynamically induced e.m.f., which is an established fact. In a D.C. generator, the conductors connected to one another rotate in a circular path in such a way that, when one conductor is rotating under the influence of a north pole, the conductor connected to it moves under the influence of a south pole, so that even though the directions of e.m.f.s induced in them are in opposite directions, they are additive. This is best illustrated in Fig.7.1, in which, two conductors AB and CD, are connected together at the backside and connected to two separate copper slip rings R_1 and R_2 on the front side. The two rings rotate along with the conductors. Two brushes B_1 and B_2, just sit on the two rings and collect the current flowing through the load resistance R which is connected to these brushes.



(a) (b)

Fig.7.1

The two conductors which are connected together form a coil ABCD. When this coil starts rotating at a uniform speed in the anti-clockwise direction, conductor AB rotates under the influence of north pole and conductor CD rotates under the influence of south pole. According to Fleming's right hand rule, the direction of the e.m.f.s induced in AB and CD are as shown. Hence, the current flows from M to N through the resistance R as shown in Fig. 7.1 (a). This direction of current remains the same, when the coil rotates through 180°. For the rotation of the coil from 180° to 360°, the conductor CD rotates under the influence of north pole and the conductor AB rotates under the influence of south pole. Hence, the e.m.f.s induced in them gets reversed and now the current flows from N to M through the resistance R as shown in Fig 7.1 (b). The whole process repeats for the subsequent revolutions of the coil. During one revolution, each of the conductors cut the flux from zero value to maximum value and again zero value, when it is moving under a pole. The nature of the e.m.f. induced is alternating in nature.

If the pole faces are so shaped that the flux produced by them is radial and the air gap is uniform, by having more number of alternate north and south poles and a large number of conductors distributed uniformly on the outer periphery of a circular cylindrical drum, the nature of the e.m.f. induced in the conductors is sinusoidal in nature, which is shown in Fig. 7.2.

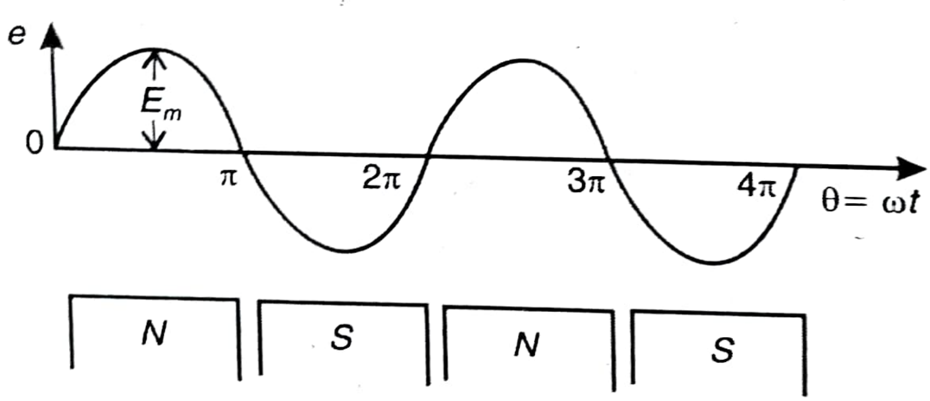


Fig. 7.2

The equation for the e.m.f. induced in each conductor is given by,

$$e = B\,l\,v \sin\theta = E_m \sin\theta$$

Where, B = flux density produced by the poles in Wb/m^2 or Tesla.

l = length of the conductor in metres

v = velocity with which the conductor is moving in m/s

To convert this alternating current voltage into a direct current voltage, instead of using two separate rings R_1 and R_2, a split ring is used as shown in Fig. 7.3.

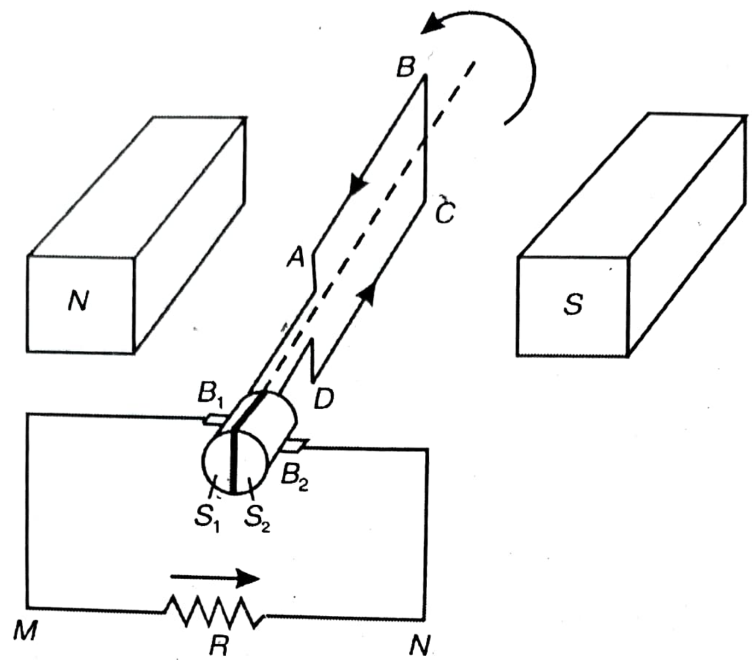


Fig.7.3

The ring has two segments S_1 and S_2, separated by an insulating medium. B_1 and B_2 are the two brushes, which just slide on the split ring. When the coil rotates through an angular displacement of 180°, the conductor AB is moving under the influence of north pole and conductor CD is moving under the influence of south pole. The direction of the e.m.f.s induced in AB and CD and the current flowing through the resistance R are as shown in Fig. 7.3.

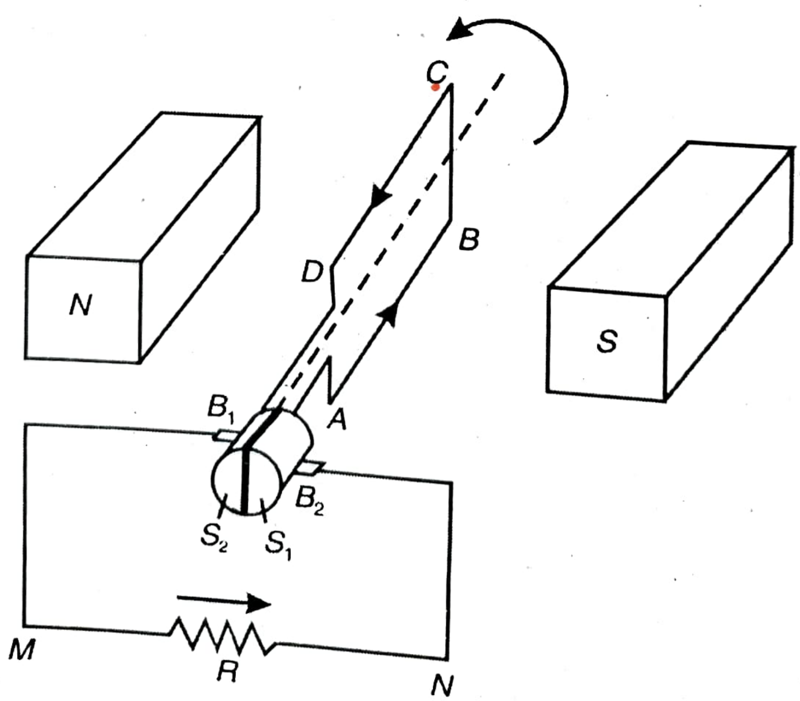


Fig.7.4

In the next half rotation i.e. when the coil rotates through 180° to 360°, the conductor AB rotates under the influence of south pole and the conductor CD rotates under the influence of north pole and the directions of the e.m.f.s induced in them are reversed as shown in Fig. 7.4. But the direction of current flowing through the resistance R remains the same, as shown in Fig. 7.4.

Even though, the nature of the e.m.f. induced in the coil is sinusoidal in nature, the voltage applied across the external resistance or the current flowing through it is as shown in Fig. 7.5.

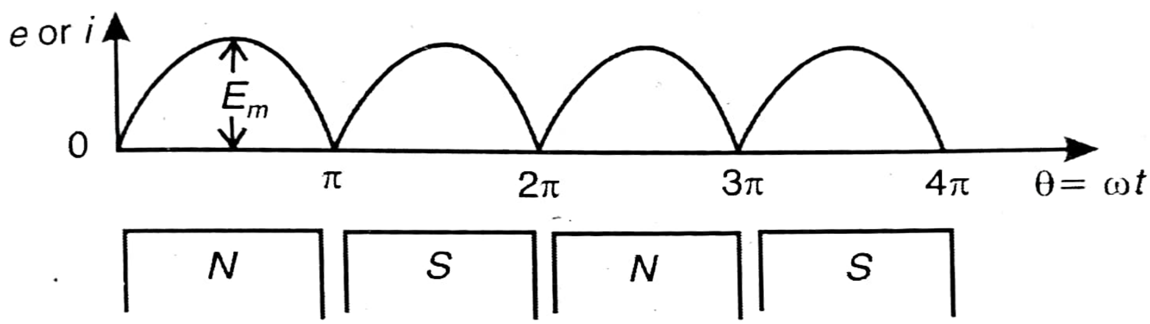


Fig. 7.5

Hence, the split ring S_1S_2 converts the alternating e.mf. into unidirectional voltage across the load. Instead of splitting the ring into only two parts, if it is split into a large number of wedge shaped segments, which are insulated from one another, the voltage delivered by the generator to the load resistance and hence the current flowing through it, will not only be unidirectional, but also of almost a constant magnitude as shown in Fig.7.6.

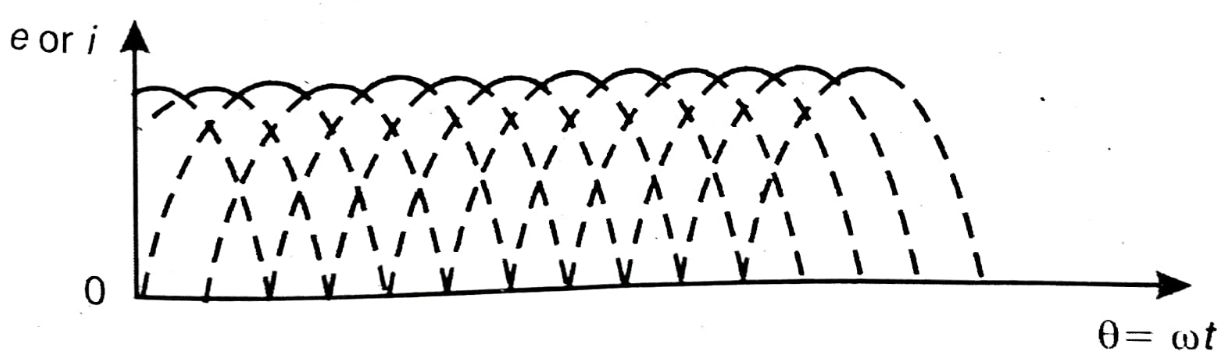


Fig.7.6

Such a circular split ring is known as the *commutator*, which converts alternating e.m.f. induced in the conductors to a direct current voltage across the load.

7.3 Construction:

Fig.7.7 shows the various parts of a D.C. generator.

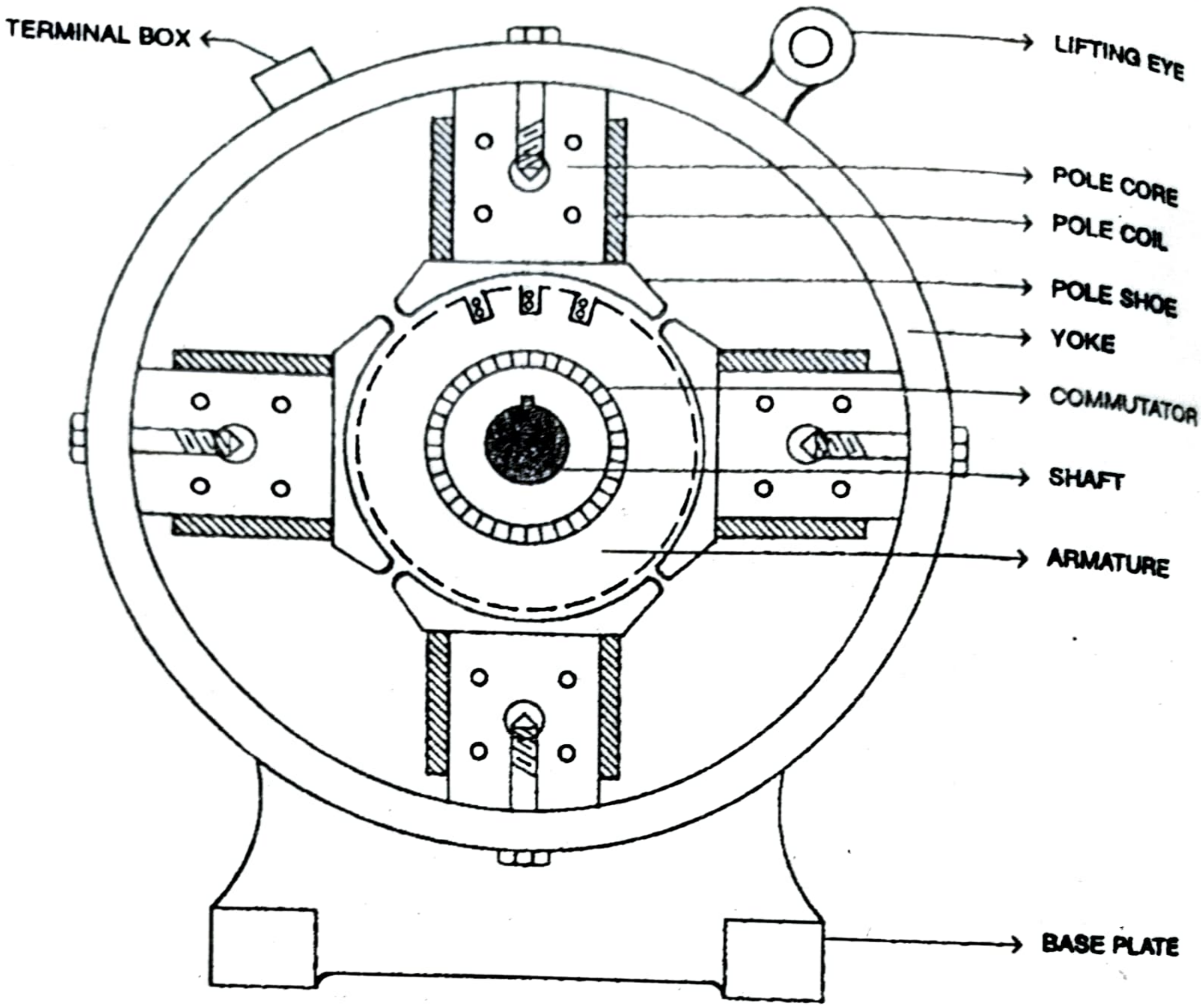


Fig.7.7

A D.C. generator mainly consists of two parts (i) Stationary part and (ii) Rotating part. The stationary part produces a constant magnetic flux and the rotating part converts the mechanical energy into electrical energy. The stationary part and the rotating part are separated by a small air gap.

The stationary part consists of (i) Yoke or magnetic frame (ii) Main poles along with pole shoes and pole coils (iii) Base plate (iv) Lifting eye (v) Brush box with brushes and (vi) Terminal box.

The rotating part consists of the (i) Armature (ii) Armature windings (iii) Commutator and (iv) Shaft. The construction of the various parts and the purpose they serve in the D.C. generator are described in the following sections:

7.4 Yoke or Magnetic Frame:

Yoke forms the outer cover for the D.C. generator and is cylindrical in shape as shown in Fig.7.8. For small generators, yoke is made of cast iron, whereas for large generators, it is made of cast steel. Cast iron gets saturated at about 0.8 Wb/m^2, whereas, cast steel gets saturated at 1.5 Wb/m^2. If the flux density is more than 0.8 Wb/m^2, as in the case of large machines, for the same flux density, the cross section of cast iron has to be nearly double the cross section of cast steel frame.

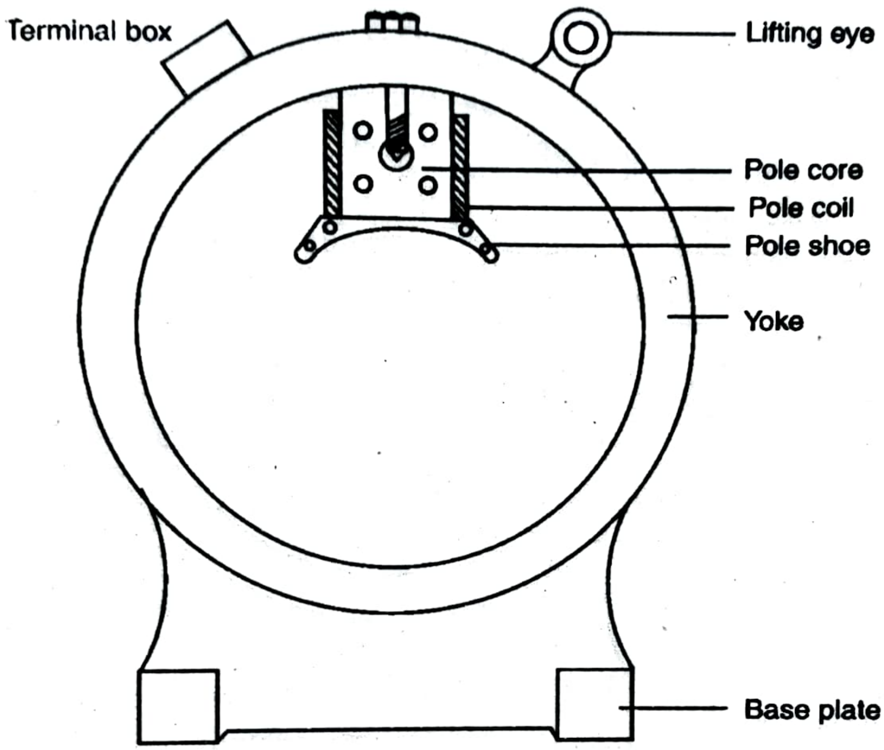


Fig.7.8

Another disadvantage of cast iron is that, its mechanical and magnetic properties are uncertain due to the presence of blow holes in the casting. Hence, in order to reduce the weight and also to have better magnetic properties, yokes of large generators are made of cast steel. For small generators, cast iron yokes are used, as they are cheap. The yoke supports the field system and also forms the part of the magnetic circuit. The lifting eye, the base plate and the terminal box are cast integral with the yoke.

7.5 Main Poles, Pole Shoes and Pole Coils:

The main poles are made of an alloy steel of high relative permeability. The pole core is laminated to reduce eddy current losses. Thin sheets of alloy steel are insulated from one another and pressed together to form the core. The laminations are held tightly with the help of end plates, which are rivetted together. The poles are fixed to the yoke with the help of bolts. The tail end of the bolt is screwed into the threaded holes of the steel bar, so that, the poles are held tightly to the yoke. The pole core supports the field coils.

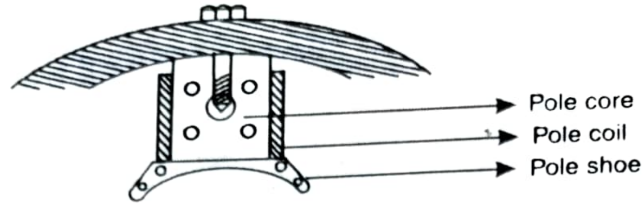


Fig.7.9

For small machines, the laminations of pole core and pole shoe are cast together as a single piece. For large machines the laminations of pole core and pole shoes are cast as different pieces, but are made of the same material. The pole shoes are also laminated, each lamination being insulated from one another, pressed together and riveted, so that, they are held together very tightly. The pole shoe is fixed to the pole core by means of counter sunk screws. The shape of the pole shoe is cylindrical at the bottom, so that, the flux produced is spread out uniformly in the air gap and also it reduces the reluctance of the magnetic path, because of the larger area of cross section. The pole shoe supports the field coils, which are former wound and fixed on the pole cores. When a direct current is passed through the field coils, the pole core becomes an electromagnet and produces the main flux required for the generation of e.m.f. The field coil and the pole shoe are also shown in Fig. 7.9.

The base plate, the lifting eye, the terminal box and the brush box are cast integral with the yoke. The base plate enables the generator to be placed conveniently on the ground or any platform. The lifting eye is used to lift the generator and to transfer it from one place to the other. The terminal box contains the output terminals of the D.C. generator, to which, any load can be connected. The brush box carries the brushes inside them, which are made of carbon or graphite. The brushes are held on the commutator segments by means of a latch or a spring, whose tension is adjustable, so that, the brush is in contact with the rotating commutator all the time. The brushes are connected to the terminals of the terminal box by means of stranded conductors, usually called as pigtails. The brushes collect current from the armature conductors via commutator segments and deliver it to the external load.

7.6 Armature:

The armature consists of armature core and armature winding. The armature core is made of high permeability and low loss silicon steel laminations, which are usually 0.4 to 0.5 mm thick and are insulated from one another by varnish. The laminations are clamped together tightly between two flanges. There are slots cut uniformly on the outer periphery of the armature core and armature conductors are placed in these slots as shown in Fig.7.10.

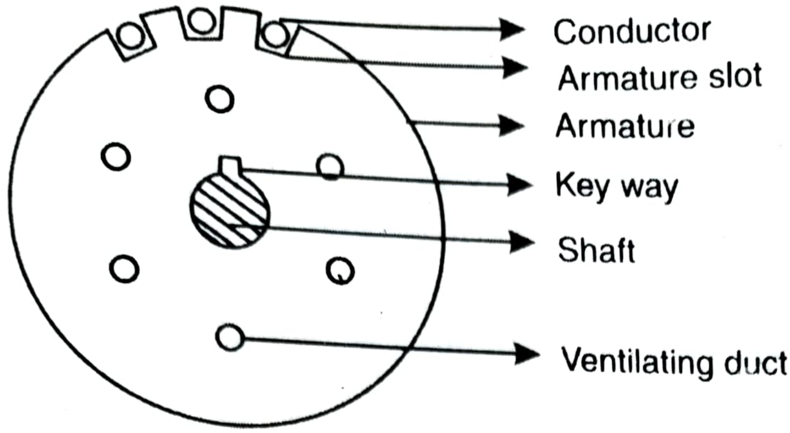


Fig. 7.10

The conductors placed in the slots are not only insulated from one another but also from the slots of the armature core. The armature laminations are directly keyed to the shaft and hence, the armature also rotates, when the shaft is rotated. Axial ventilating ducts are provided through the armature core, so that, free air can circulate through them and cool the armature. For small generators, each lamination is a single piece. But for large generators, each lamination is made of two or more segments, which form parts of a complete circular lamination. Key ways are provided on each segment, which are wedge or dove-tail shaped, so that, when placed in position, they are secured tightly to the armature shaft.

7.7 Armature Windings:

The armature conductors are placed in the slots of the armature. The conductors are not only insulated from one another but also from the armature slots. The armature conductors are connected together either as a *lap winding* or a *wave winding*. More discussion is made on armature windings in the later sections of this chapter.

7.8 Commutator:

As already explained in section 7.2 of this chapter, the commutator converts the alternating e.m.f. generated in the armature windings into direct current voltage in the external circuit. The cross sectional view of the commutator is shown in Fig.7.11.

The commutator is cylindrical in shape and is built of wedge shaped segments made of hard drawn copper, which are insulated from one another and from the shaft by mica strips. The segments are connected to the armature conductors through risers. The risers have air spaces between one another, so that, air can circulate in the spaces and cool the commutator.

7.9 Shaft and Bearings:

The shaft of the D.C. generator is rotated by a prime mover, due to which, the armature fixed to it also rotates. For small generators, roller bearings are used at both ends of the shaft. For large generators, roller bearings are used for driving end and ball bearings are used at the other end of the shaft. For still larger generators, pedestal bearings are used.

7.13 E.M.F. Equation:

Let Z = Total number of armature conductors.

ϕ = Useful flux per pole in webers.

N = Speed of the armature in revolutions per minute. (r.p.m.).

P = Number of poles

A = Number of parallel paths.

The flux cut by a conductor in one revolution = $\phi P = d\phi$.

The time taken by the conductor to make one revolution = $60/N$ Sec = dt. Hence,

The E.M.F. induced in one conductor $= \dfrac{d\phi}{dt} = \dfrac{\phi P}{60/N} = \dfrac{\phi PN}{60}$ volts

The E.M.F. induced per parallel path = E.M.F. induced per conductor x Number of conductors per parallel path.

$$E = \frac{\phi PN}{60} \times \frac{Z}{A} = \frac{\phi ZNP}{60A} \text{ volts} \qquad (7.2)$$

Equation (7.2) is the E.M.F. Equation of a D.C. generator.

For lap winding , $A = P$

$$\therefore E = \frac{\phi Z N}{60} \text{ Volts} \qquad (7.3)$$

For wave winding , $A = 2$

$$\therefore E = \frac{\phi Z N P}{120} \text{ Volts} \qquad (7.4)$$

7.14 D.C. Generat

7.15 Types of D.C generators:

Depending on the nature of excitation provided to the field windings, D.C generators are broadly classified as,

a) *Separately excited D.C generator* and
b) *Self excited D.C generator*

The self excited D.C generator is further classified as (i) *D.C shunt generator* (ii) *D.C series generator* and (iii) *D.C compound generator.*

The D.C compound generator is further classified as *cumulatively* compounded and *differentially* compounded generators. Depending on the way in which the field windings are connected to the armature, the cumulatively compounded and differentially compounded generators are further classified *as long shunt* and *short shunt* generators.

7.16 Separately excited D.C generator:

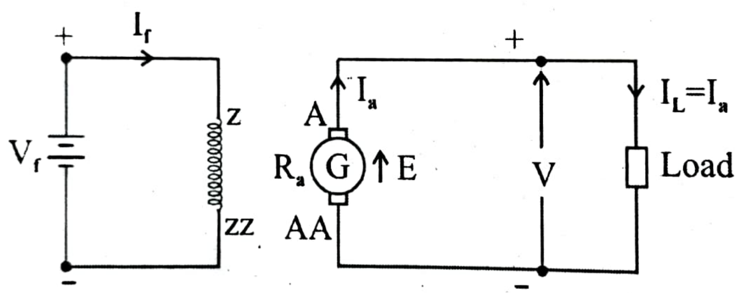


Fig.7.16

In this type of generator, which is represented as shown in Fig.7.16, the excitation to the field winding is provided by a separate D.C voltage source of voltage V_f. This voltage drives a current I_f through the field winding due to which, a magnetic flux is produced. When the armature is rotated by a prime mover, the armature conductors cut the magnetic flux and hence an E.M.F E is induced, which is nothing but the generated voltage. When the load is connected across the armature terminals, a current I_L flows through the load. If V is the terminal voltage of the D.C generator, then

$$I_a = I_L \tag{7.6}$$

And $$V = E - I_a R_a - A.R.D - B.C.D \tag{7.7}$$

A and AA represent the positive and negative terminals of the armature respectively. Z and ZZ represent positive and negative terminals of the shunt field winding respectively.

7.17 Self-excited D.C generator:

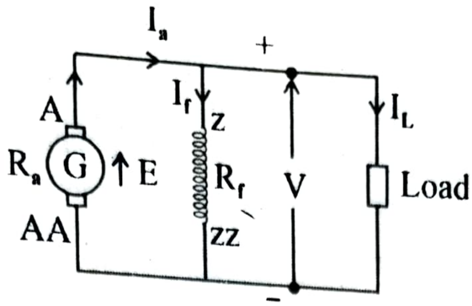


Fig.7.17

In this type of generator which is shown in Fig.7.17, the excitation to the field winding is provided by the generator itself. For self excitation, it is necessary that the pole cores should have some residual flux ϕ_r. When the armature is rotated by a prime mover, the armature conductors cut the residual flux, a small amount of E.M.F is induced. This e.m.f sends a small current through the field winding. Hence, the flux produced increases due to which, the E.M.F induced also increases. Thus the increase of induced E.M.F and the increase of flux, help each other and the voltage is built up to its rated value. In this case, we have,

$$I_a = I_L + I_f \qquad (7.8)$$

And $$V = E - I_a R_a - A.R.D - B.C.D \qquad (7.9)$$

As already mentioned, there are three types of self-excited D.C generators, which are discussed in the following sections.

7.18 D.C shunt generator:

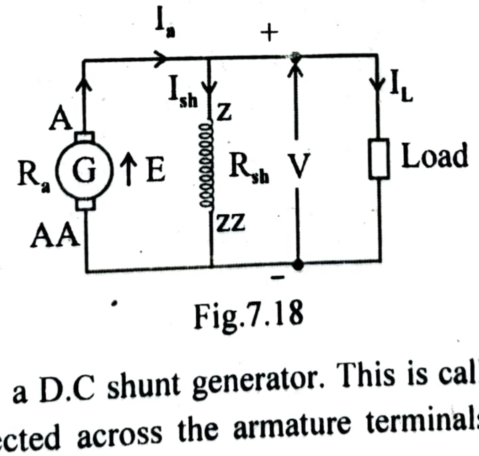


Fig.7.18

The Fig.7.18 represents a D.C shunt generator. This is called shunt generator because, the field winding is connected across the armature terminals. I_{sh} is the current flowing through the shunt field winding. In this case

$$I_a = I_L + I_{sh} \qquad (7.10)$$

$$I_{sh} = \frac{V}{R_{sh}} \qquad (7.11)$$

Where R_{sh} = Resistance of the shunt field winding

$$V = E - I_a R_a - A.R.D - B.C.D \tag{7.12}$$

The shunt field winding consists of a large number of very thin turns of copper, so that, its resistance is quite high and I_{sh} is very small. This is necessary because, the load current should not be drastically reduced due to a large current I_{sh} drawn by the shunt field winding. I_{sh} and hence the flux produced remains almost constant, irrespective of the load current, over the operating range of the generator.

7.19 D.C series generator:

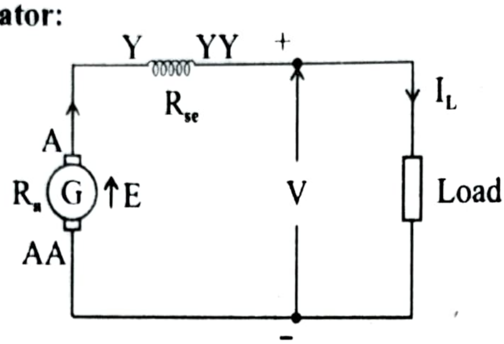


Fig.7.19

Fig.7.19 represents a D.C series generator. This is called series generator because, the field winding is connected in series with the armature. The voltage drop across this winding has to be very small and hence its resistance has to be very less. Therefore, it is made of a few thick turns of copper. Whatever current flows through the load, same current flows through the armature and the field winding.

$$I_a = I_{se} = I_L \tag{7.13}$$

Where I_{se} = current through the series field winding

$$V = E - I_a (R_a + R_{se}) - A.R.D. - B.C.D \tag{7.14}$$

The flux produced depends on $I_{se} = I_L$, the load current.

Y and YY represent the positive and negative terminals of the series field winding respectively.

7.20 D.C compound generator:

A D.C compound generator contains both shunt field winding and series field winding. If the two field windings are connected in such a way that the fluxes produced by them are in the same direction and are additive, then the generator is said to be cumulatively compounded. If the field windings are connected in such a way that the fluxes produced by them are in opposite direction and the resultant flux is the difference between the two, then the generator is said to be differentially compounded.

Depending on how the series field winding is connected to the shunt field winding, we have long shunt compound generator and short shunt compound generator.

7.21 Cumulative compounded D.C generator:

a) **Long shunt:**

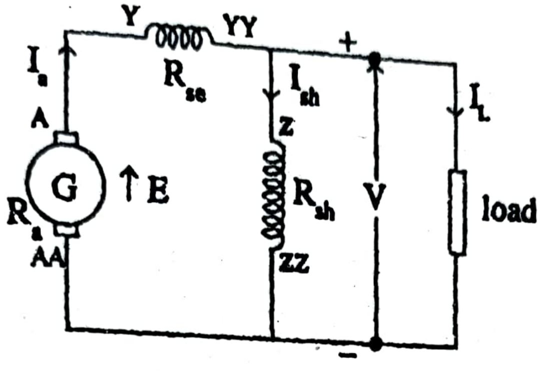


Fig.7.20

Fig.7.20 represents a long shunt cumulatively compounded D.C generator. Current I_a enters the positive terminal of the series field winding and current I_{sh} enters the positive terminal of the shunt field winding. Hence the fluxes produced by them will have the same direction and they are additive. The total flux is given by,

$$\phi = \phi_{sh} + \phi_{se}$$

Where ϕ = total flux

ϕ_{sh} = flux produced by the shunt field winding

ϕ_{se} = flux produced by the series field winding

$$I_{sh} = \frac{V}{R_{sh}}$$

$$I_a = I_L + I_{sh} \quad (7.15)$$

and

$$V = E - I_a (R_a + R_{se}) - A.R.D - B.C.D \quad (7.16)$$

b) **Short shunt:**

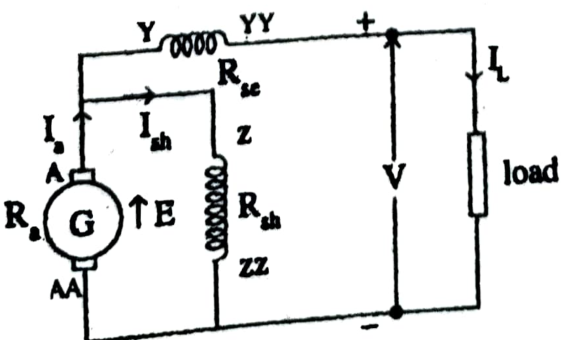


Fig.7.21

Fig.7.21 represents a short shunt cumulatively compounded D.C generator. For this generator,

$$I_{sh} = \frac{V + I_L R_{se}}{R_{sh}} \quad (7.17)$$

$$I_a = I_L + I_{sh} \quad (7.18)$$

and $V = E - I_a R_a - I_L R_{se} - A.R.D - B.C.D$ (7.19)

7.22 Differentially compounded D.C generator:

a) Long shunt:

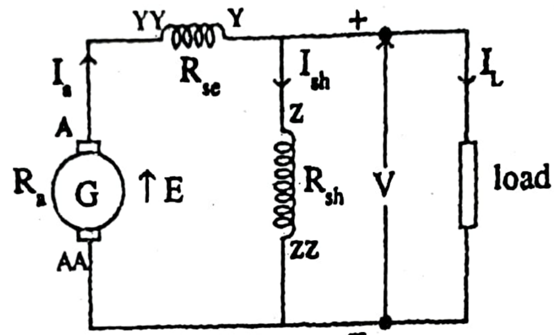


Fig.7.22

Fig.7.22 represents a long shunt differentially compounded D.C generator. Current I_a enters the negative terminal of the series field winding and current I_{sh} enters the positive terminal of the shunt field winding. Hence, the fluxes produced by them are in opposite directions. Hence the resultant flux is given by,

$$\phi = \phi_{sh} - \phi_{se} \quad (7.20)$$

$$I_{sh} = \frac{V}{R_{sh}} \quad (7.21)$$

$$I_a = I_L + I_{sh} \quad (7.22)$$

and $V = E - I_a (R_a + R_{se}) - A.R.D - B.C.D$ (7.23)

b) Short shunt:

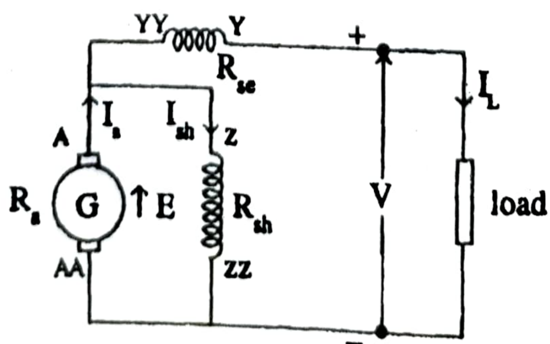


Fig.7.23