Module 5

DC Generators and Motors

7

Syllabus : Construction, Working principle, EMF equation, Classification and applications.

7.1 Introduction :

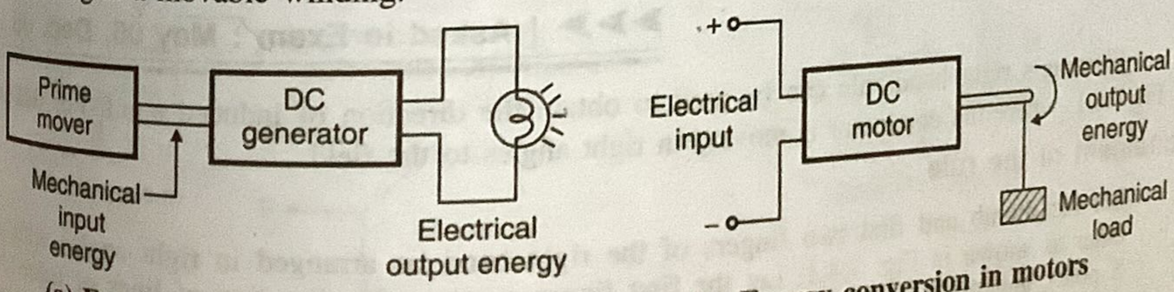
- In the field of electrical engineering we come across conversion of energy from one form to the other. For example, electrical to mechanical or vice versa.
- The electrical machine which converts the electrical energy into mechanical energy is called as the **electric motor,** whereas the machine that converts the mechanical energy into an electrical energy is called as the **electric generator.**
- A DC generator is a machine that produces DC voltage when rotated mechanically.

7.2 Types of DC Machines :

- DC machines are basically of two types :
  1. D.C. generator
  2. D.C. motor.
- A dc generator is rotated by a prime mover and produces a dc voltage. So it converts mechanical energy into electrical energy.
- A dc motor receives energy from a d.c. voltage source and rotates at a speed proportional to the applied voltage. So a dc motor converts the electrical energy into a mechanical energy.

7.3 Windings of a DC Machine :

- In any dc machine, (motor or generator) there are two windings :
  1. Field winding
  2. Armature winding.
- Out of these, the field winding is stationary which does not move at all and the armature winding is a movable winding.



(a) Energy conversion in generators

(b) Energy conversion in motors

Fig. 7.3.1

- The armature winding is mounted on a shaft. So it can rotate freely.
- The construction of a dc generator and dc motor is the same. That means we can use the same dc machine either as a generator or as a motor.
- As shown in Fig. 7.3.1(a), a prime mover supplies mechanical energy to the DC generator which generates electrical output energy.
- Fig. 7.3.1(b) shows the operating principle of a DC motor. It accepts the energy in the electric form from D.C. source and converts it into mechanical energy at its output (shaft).

7.3.1 Connection of Windings for Operation as Generator :

- To operate the dc machine as a generator, the **field winding is connected across the dc power supply.** A dc current starts flowing through the field winding, called as field current.
- The field winding then produces a **magnetic field** in the air gap between the armature and field windings.
- The armature winding is a rotating winding which is mounted on the shaft. The shaft is mechanically coupled to another machine called prime mover as shown in Fig. 7.3.1(a).
- And the connection of the armature winding are brought out. A load such as electric lamp is connected across the armature winding.
- The dc generator thus takes the mechanical energy as an input energy from the prime mover and delivers an electrical energy to the load.

7.4 Principle of Operation of a DC Generator :

- **The DC generator operates on the principle of dynamically induced emf in a conductor.**
- According to this principle, if the flux linked with a conductor is changed, then an emf is induced into the conductor.
- In case of a DC generator, when armature winding is rotated by the prime mover, the flux linked with it changes and an emf is dynamically induced into the armature winding.
- This is the principle of operation of a generator.
- **The prime mover can be a water turbine, steam engine, steam turbine or diesel engine etc.**
- The direction of induced voltage in the armature winding is given by the **Fleming's Right handrule.**

7.4.1 Fleming's Right Hand Rule :

➤➤➤ [Asked in Exam : May 05, Dec. 05 !!!]

Fleming's right hand rule can be used to obtain the direction of induced e.m.f. For that refer to Fig.7.4.1, where the conductor is moving in right angles to the field.

Statement of the rule :

- Let the thumb and first two fingers of the right hand be arranged in right angles with each other as shown in Fig. 7.4.1. Let the first finger point in the direction of lines of force (N to S pole), and the outstretched thumb point the direction of conductor motion. Then the second finger indicates the direction of the induced e.m.f. (or current).

- Fig. 7.4.1(a) can be used to verify the Fleming's right hand rule. With the thumb indicating the direction of conductor movement and first finger indicating the direction of flux, the induced current I comes out of the conductor in the direction indicated by the second finger.

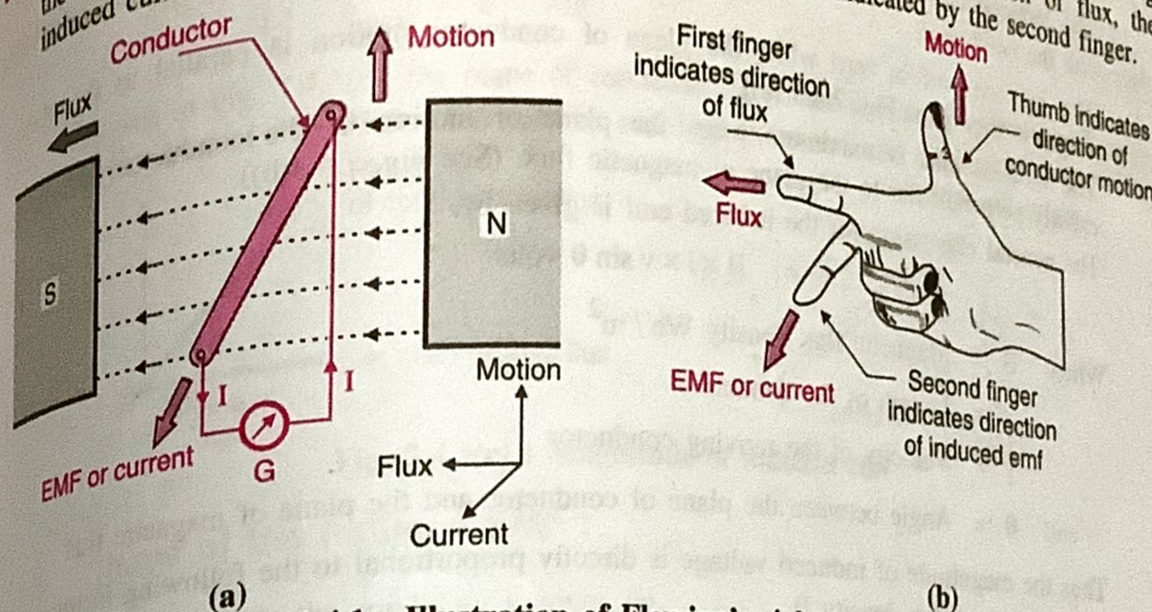


Fig. 7.4.1 : Illustration of Fleming's right hand rule

- The rule can be verified for various possible working conditions as shown in Fig. 7.4.2.

Fleming's rule under various operating conditions :

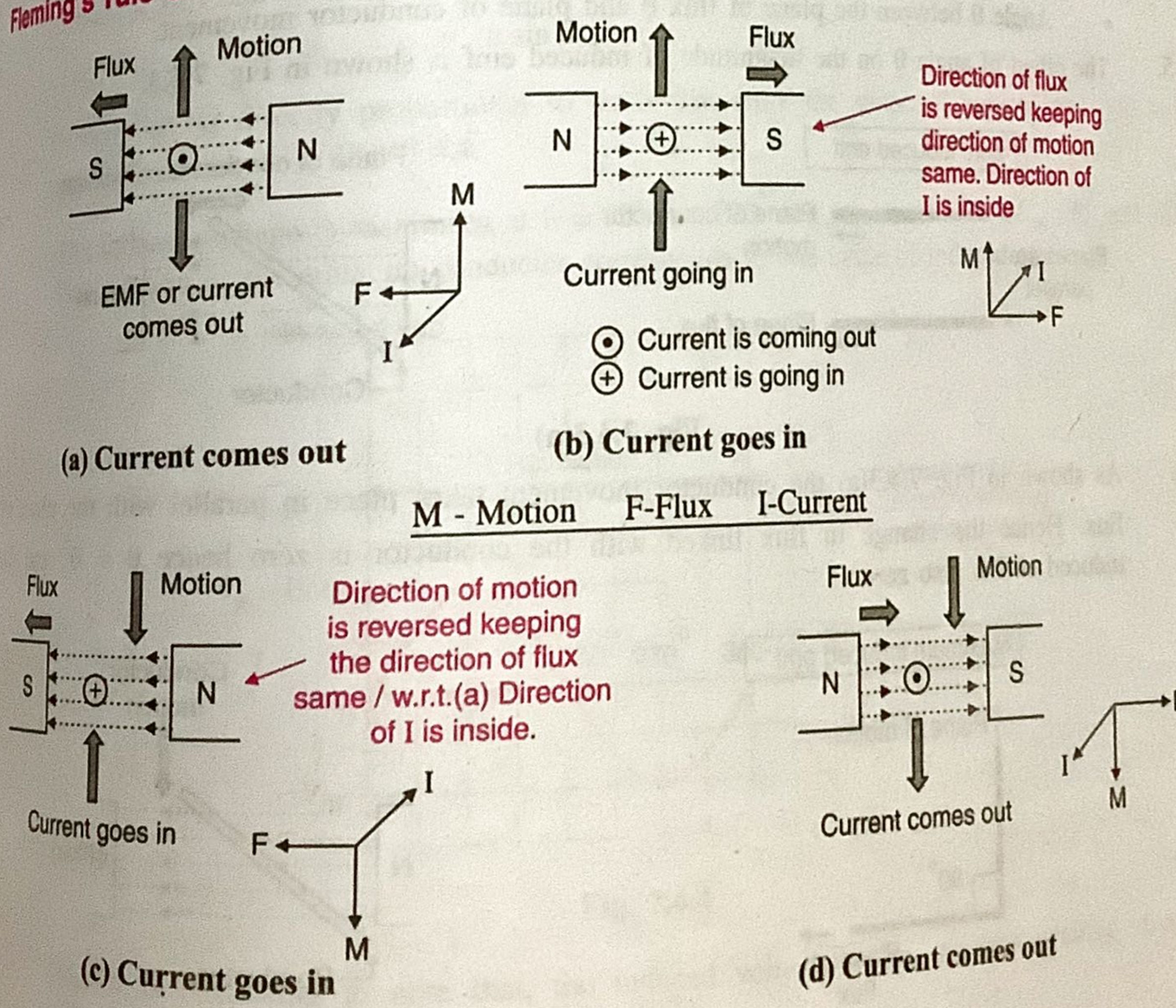


Fig. 7.4.2 : Verification of Fleming's right hand rule

7.4.2 Magnitude of Induced EMF :

The induced emf in the armature is dependent on the rate of change of flux linkage taking place with the conductor.

1. The induced emf is zero when the plane of conductor motion is parallel to the plane of magnetic flux. (See Fig. 7.4.3 (a)).
2. The induced emf is maximum when the plane of motion of the conductor (armature) is exactly perpendicular to the plane of magnetic flux. (See Fig. 7.4.3(b)).
3. The general expression for the induced emf is given by,

$$e = B \times l \times v \sin \theta \text{ volts}$$

Where B = Magnetic flux density Wb/m^2

l = Length of the conductor

v = Velocity of the moving conductor

and θ = Angle between the plane of conductor and the plane of magnetic flux

4. Thus the magnitude of induced voltage is directly proportional to the following factors :
   - Magnetic flux density B.
   - Length of the conductor l.
   - Velocity of the conductor v.
   - Angle θ between the plane of flux ϕ and plane of conductor movement.
5. The effect of angle θ on the magnitude of induced emf is shown in Fig. 7.4.3.

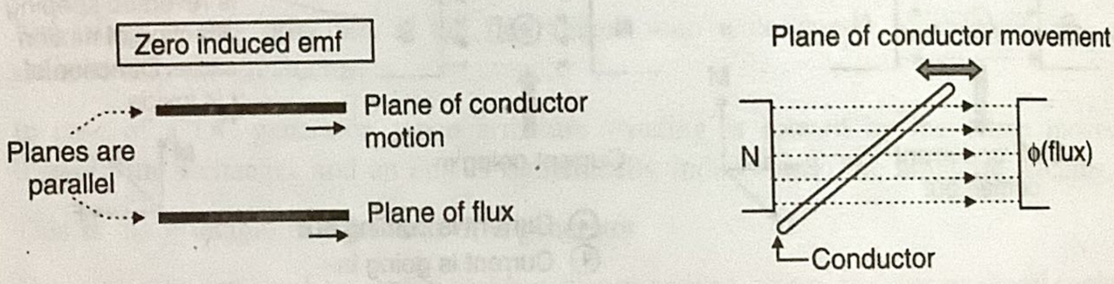


Fig. 7.4.3(a)

6. As shown in Fig. 7.4.3(a) the conductor movement takes place in parallel with the plane of flux. Hence the change in flux linked with the conductor is zero hence $\theta = 0^\circ$ and the induced emf is also zero.

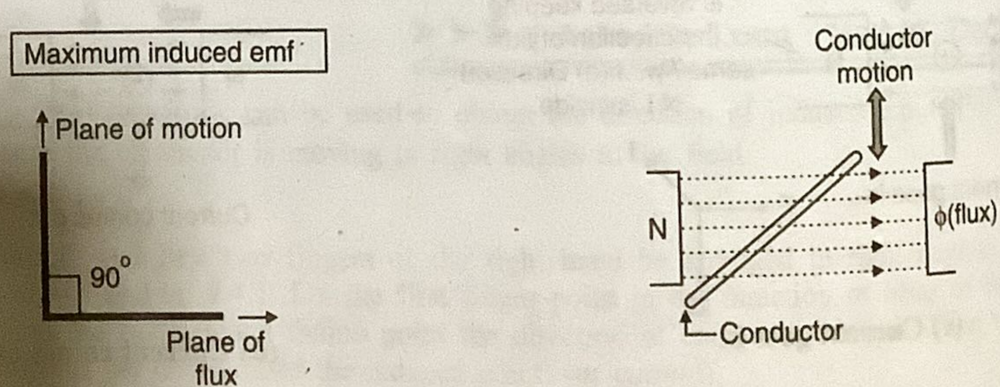


Fig. 7.4.3(b)

7. As shown in Fig. 7.4.3(b), the conductor moves in a plane which is perpendicular to the plane of flux. So $\theta = 90^\circ$ and the induced emf is maximum.

$$\text{i.e.} \quad e_{max} = Blv \text{ volts} \quad ...(7.4.1)$$

8. As shown in Fig. 7.4.3(c), the plane of conductor movement is making an angle of θ degrees with the plane of flux. Hence the induced emf is in between 0 and maximum.

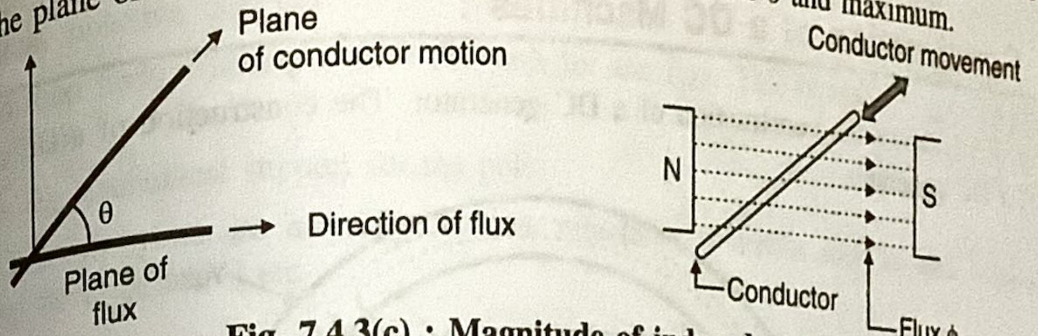


Fig. 7.4.3(c) : Magnitude of induced emf

7.4.3 Shape of the Induced EMF :

- The induced emf in the conductor is given by,

$$e = Blv \sin\theta$$

Hence if B, l and v are constant then

$$e = k \sin\theta$$

- Hence "e" is directly proportional to $\sin\theta$. Therefore the shape of induced emf will be a sinewave as shown in Fig. 7.4.4.
- The induced voltage is maximum at $\theta = 90^\circ$ and 270° and minimum at $\theta = 0^\circ$, 180° and 360°. One rotation of the armature conductor corresponds to one cycle of induced emf.

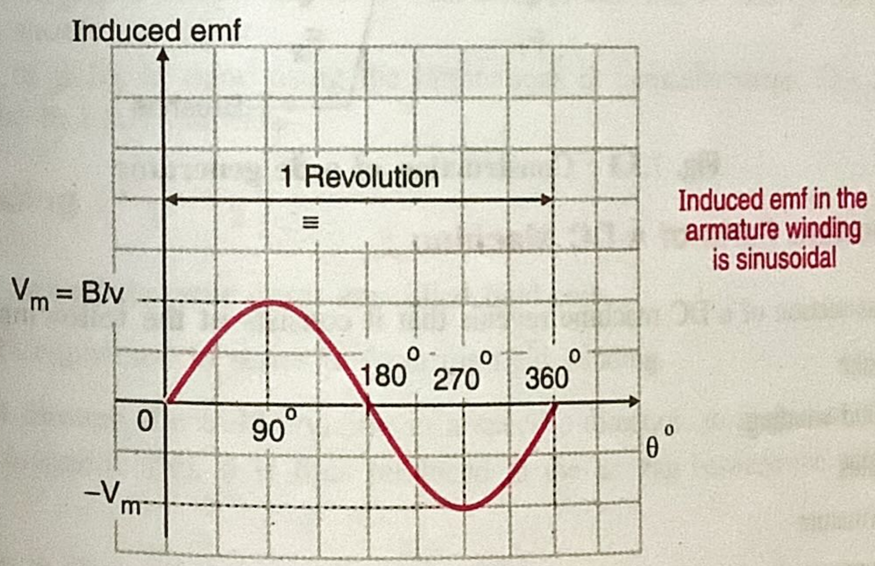


Fig. 7.4.4

- Thus it is interesting to note that, the induced voltage in the armature winding of a DC generator is not DC but it is alternating.

- To convert it into a unidirectional (DC) signal, we have to use a rectifying device called **commutator. Thus it is a device used in the DC generators to convert the alternating induced voltage to a DC voltage.**
- The machine which produces an ac voltage is called as an alternator. As the basic nature of emf produced by a DC generator is sinusoidal.

7.5 Construction of a DC Machines :

Fig. 7.5.1 shows the construction of a DC generator. The construction of a DC motor is same as that of a DC generator.

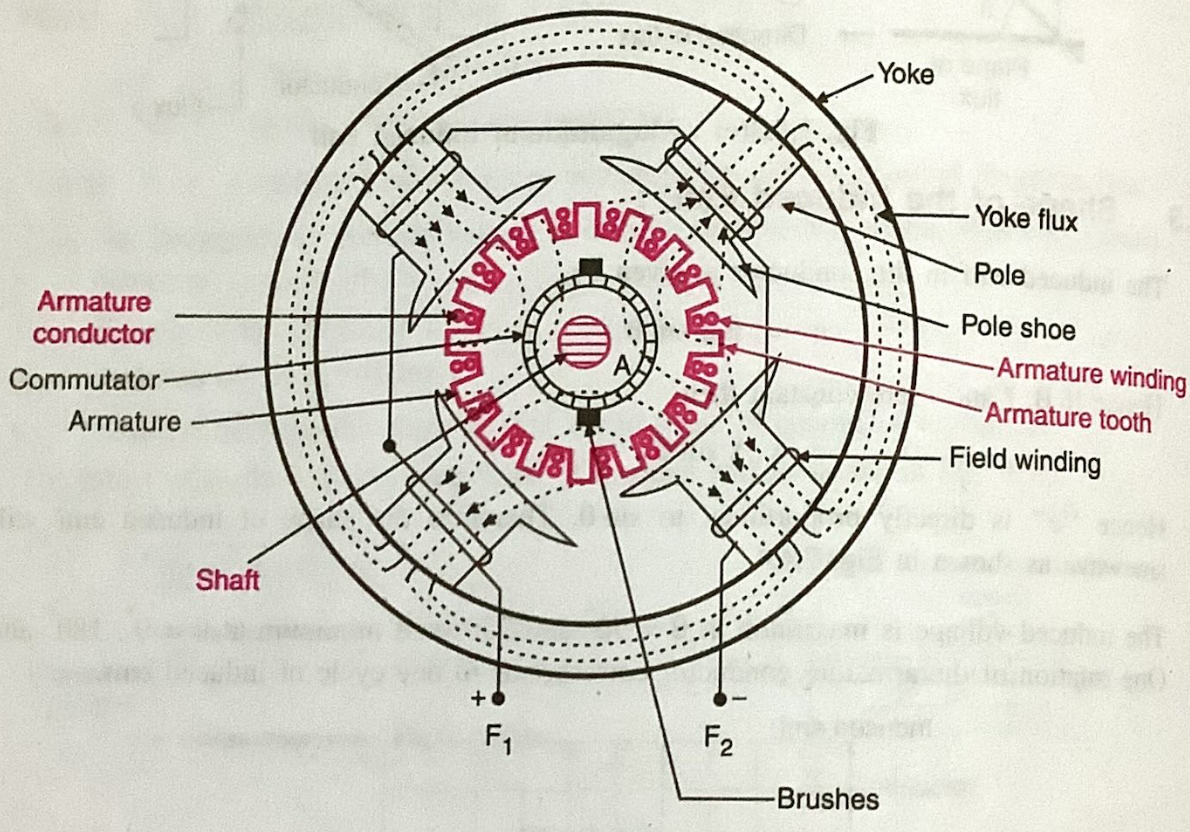


Fig. 7.5.1 : Construction of a dc generator

7.5.1 Important Parts of a DC Machine :

The cross-section of a DC machine reveals that it consists of the following important parts :

- Yoke
- Field winding
- Poles
- Armature
- Commutator, brushes and gear
- Bearings.

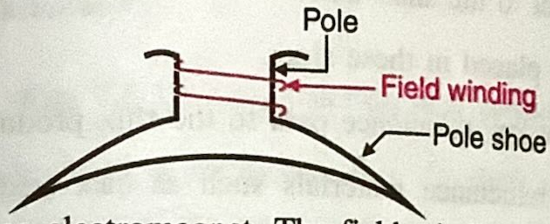
7.5.2 Yoke :

The important information about the yoke which acts as the outer cover of a DC machine are given below :

- Yoke is also called as frame. It provides protection to the rotating and other parts of the machine from moisture, dust etc.
- Yoke is an iron body which provides the path for the flux. This is essential to complete the magnetic circuit.
- It provides the mechanical support for the poles.
- Materials used for yoke are basically the low reluctance materials such as cast iron, silicon steel, rolled steel, cast steel etc.

7.5.3 Poles, Pole Shoe and Pole Core :

The important points about the poles are as follows :



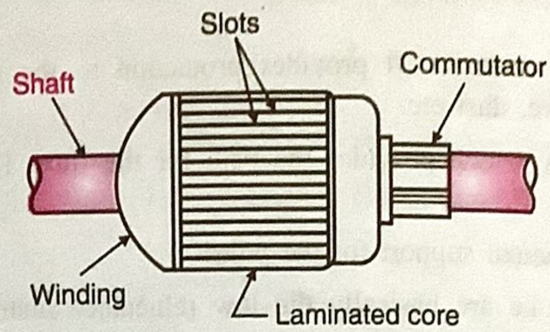
- A pole of a generator is an electromagnet. The field winding is wound over the poles.
- Poles produce the magnetic flux when the field winding is excited.
- Pole shoe is an extended part of a pole. Due to its typical shape, it enlarges the area of the pole.
- Due to this enlarged area, more flux can pass through the air gap to armature.
- A low reluctance magnetic material such as cast steel or cast iron is used for the construction of a pole or pole shoe.
- The construction of poles is done using the laminations of particular shape. This is to reduce the power loss due to Eddy currents.

7.5.4 Field Winding ($F_1 - F_2$) :

- The coils wound around the pole cores are called field coils.
- The field coils are connected in series to form the field winding.
- Current is passed through the field winding in a specific direction, to magnetize the poles and pole shoes. The magnetic flux ϕ is thus produced in the air gap between the pole shoes and armature.
- The field winding is also called as exciting winding.
- The material used for the field conductor is copper.
- Due to the current flowing through the field winding alternate N and S poles are produced. Which pole is produced at a particular core is decided by the right hand thumb rule for a current carrying circular conductor.

7.5.5 Armature Core :

The important information about armature core is as follows :



- Armature core is a cylindrical drum mounted on the shaft.
- It is provided with a large number of slots all over its periphery.
- All these slots are parallel to the shaft axis.
- Armature conductors are placed in these slots.
- Armature core provides a low reluctance path to the flux produced by the field winding.
- High permeability, low reluctance materials such as cast steel or cast iron are used for the armature core.
- The air holes are provided for the air circulation which helps in cooling the armature core.
- The laminated construction is used to produce the armature core to minimize the Eddy current losses.

7.5.6 Armature Winding :

- The armature conductors made of copper are placed in the armature slots present on the periphery of armature core.
- Armature conductors are interconnected to form the armature winding.
- When the armature winding is rotated using a prime mover, it cuts the magnetic flux lines and voltage gets induced in it.
- Armature winding is connected to the external circuit (load) through the commutator and brushes.

Material used :

The armature winding is supposed to carry the entire load current. Hence it should be made up of a conducting material such as copper.

7.5.7 Commutator :

The construction of a commutator is as shown in Fig. 7.5.2.

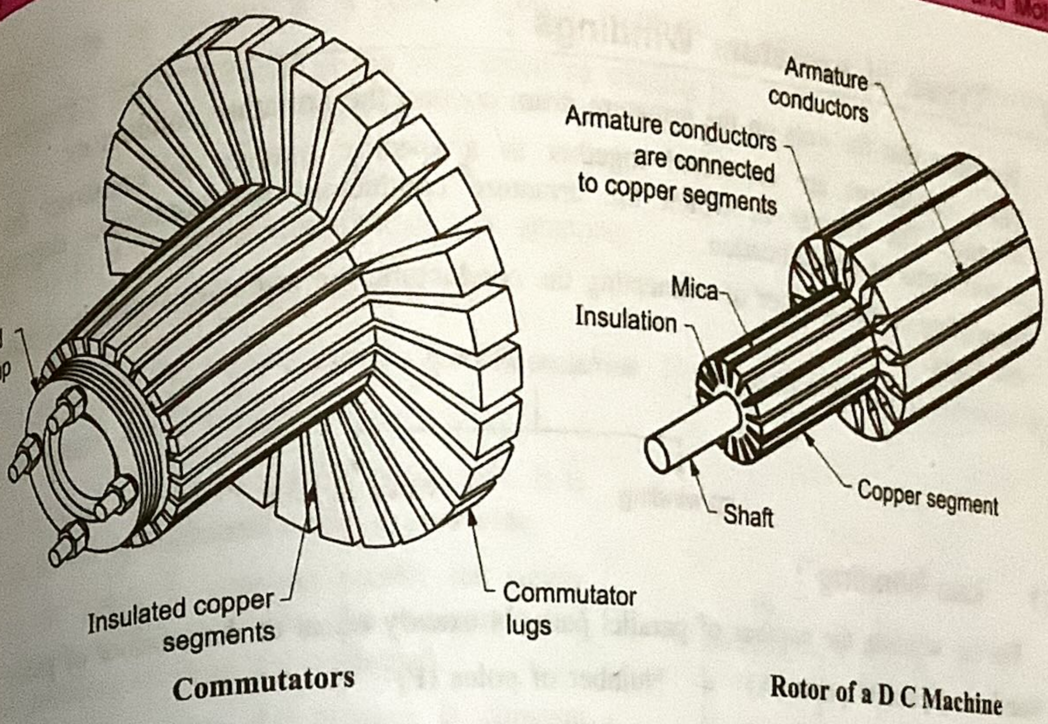


Fig. 7.5.2 : Construction of a commutator

- A commutator is a cylindrical drum mounted on the shaft alongwith the armature core.
- It is made of a large number of wedge-shaped segments of hard-drawn copper.
- The segments are insulated from each other by thin layers of mica.
- The armature winding is tapped at various points and these tappings are successively connected to various segments of the commutator.

Functions of a commutator :

1. It convert the alternating emf generated internally in a d.c. voltage. So it basically works like a rectifier.
2. It collects the current from the armature conductors and passes it to the external load via-brushes.
3. When used in dc motors, it helps to produce a unidirectional torque.

Material used :

The commutator segments are made of copper and the insulating material between the segments is mica.

7.5.8 Brushes :

- Current is conducted from the armature to the external load by the carbon brushes which are held against the surface of commutator by springs.
- Brushes wear with time. Hence they should be inspected regularly and replaced occasionally.

Function of brushes :

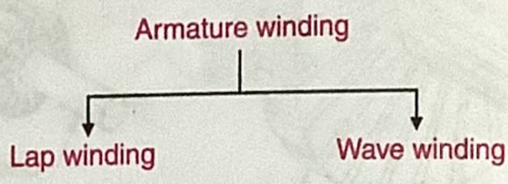
To collect current from the commutator and apply it to the external load.

Material used :

Brushes are made of carbon. They are rectangular in shape.

7.6 Types of Armature Windings :

- We know that the slots on the armature drum contain the armature conductors.
- These conductors are connected together in a specific manner to construct the armature winding. The manner in which the armature conductors are connected depends on the requirements of an application.
- Depending on the manner of connecting the conductors, the armature winding is classified into two types.



7.6.1 Lap Winding :

For lap winding the number of parallel paths is exactly equal to the number of poles P.

Number of paraliel paths (A) = Number of poles (P)

The lap winding is useful for low voltage high current machines :

Due to the existence of a large number of parallel paths, the lap wound armature winding is capable of supplying larger load currents.

7.7 E.M.F. Equation of a DC Generator :

[Asked in Exam : May 04, May 07 !!!]

- As noted above, a dc generator takes mechanical energy as input and delivers electrical energy as output.
- When a mechanical device, such as a diesel engine drives the armature drum, armature winding cuts the magnetic flux produced by the pole. An equation for e.m.f. induced can be obtained as under.

Let P = Number of poles of the generator.

ϕ = Flux produced by each pole, Wb.

N = Speed in r.p.m. at which the generator is driven.

Z = Number of conductors of armature winding.

A = Number of parallel paths of armature winding.

- Then according to Faraday's law of induction, magnitude of e.m.f. induced in a conductor is,

$$E = \frac{d\phi}{dt} \quad \text{... (7.7.1)}$$

- For one complete revolution of a conductor, the flux cut by the conductor is ($P\phi$) Wb and time required to complete one revolution is (60/N) seconds. Therefore, Equation (7.7.1) may be written as,

$$E = \frac{P\phi}{(60/N)} = \frac{P\phi N}{60} \quad \text{... (7.7.2)}$$

As Z conductors are divided in A parallel groups, there are $\frac{Z}{A}$ conductors in series in each group. Therefore e.m.f. induced in the total armature winding is,

$$E = \frac{P\phi N}{(60)} \cdot \frac{Z}{A} \quad \dots (7.7.3)$$

Equation (7.7.3) is the e.m.f. equation of a dc generator.

7.7.1 Circuit Model of a DC Machine :

- Fig. 7.7.1(a) shows the circuit model of a DC machine. Note that the armature resistance R_a being very small, is not shown.
- The field coil axis is at 90° to the brush axis. It is as per the actual arrangement in the dc machine.
- Since we are going to consider mostly the steady state behavior of the machine, the inductances of field and armature winding are neglected.
- The voltage drop across the brushes is constant (1 – 2 Volts).

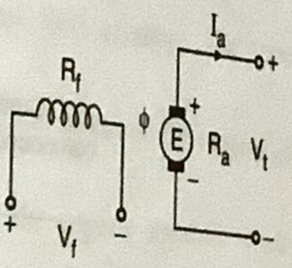


Fig. 7.7.1(a) : Circuit model of dc machine

Circuit model of DC generator :

The circuit model for a dc generator is shown in Fig. 7.7.1(b). The armature current I_a is in the same direction as that of E (induced emf).

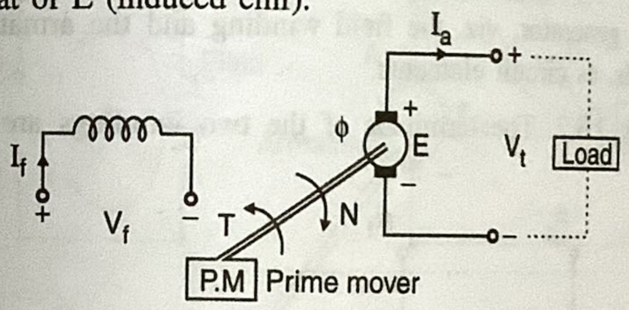


Fig. 7.7.1(b) : Circuit model of dc generator

7.8 Types of DC Generators (Classification) :

- A dc generator consists of two winding namely the field winding which produces the magnetic flux and the rotating armature winding.
- The current can be supplied to the field winding of a generator in two different ways. The way in which the field current of a generator is supplied will decide the type of dc generator.
- The two different ways of supplying the field current are as follows :
  1. To connect the field winding to an external source such as battery.
  2. To use the emf induced in the armature winding of the generator to supply its own field current.
- In the first case, the generator is called as the **separately excited generator** and in the second case it is called as the **self excited generator.**

- The armature and field windings of the self excited generators and connected to each other in many different ways, and according to these interconnections, the self excited generators are classified further.
- Fig. 7.8.1 shows the classification of generators.

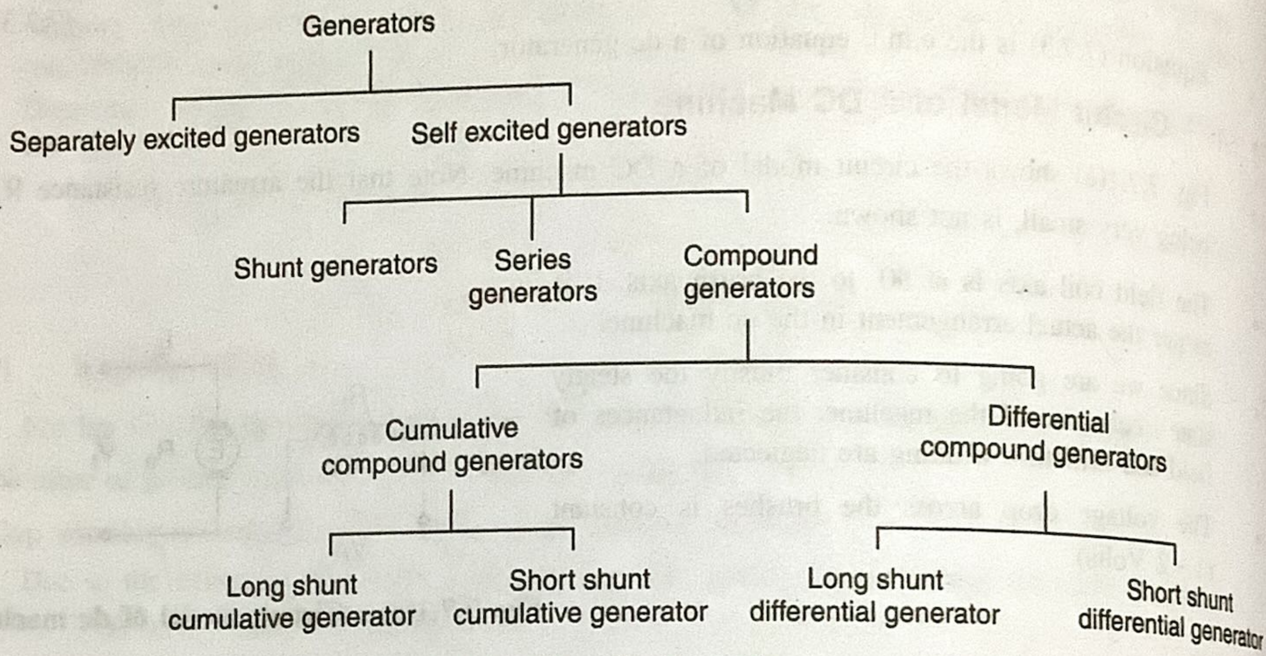


Fig. 7.8.1 : Classification of generators

7.8.1 Symbolic Representation of a Generator :

- The two windings of a generator, viz. the field winding and the armature winding are shown by two different symbols, as circuit elements.
- They are shown in Fig. 7.8.2. The terminals of the two windings are marked as F_1, F_2 and A_1, A_2 respectively.

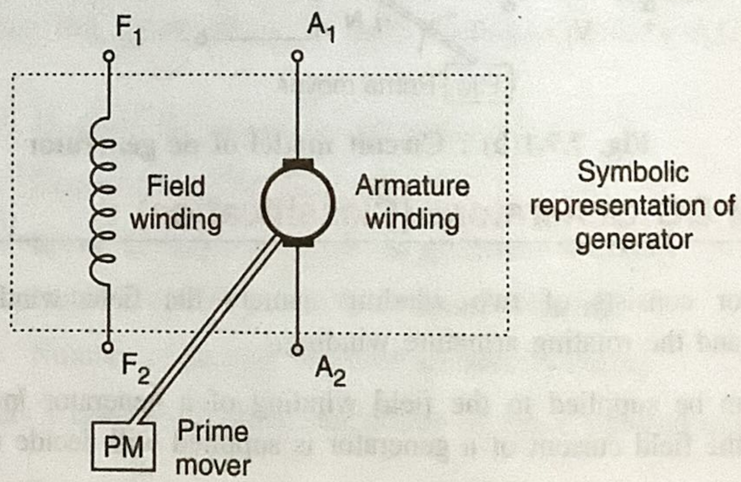


Fig. 7.8.2 : Symbolic representation of a generator

- In Fig. 7.8.2, the field winding is shown like a coil whereas the armature winding is shown like a drum as this winding is placed on the armature drum.
- Two small projections are shown at the armature winding terminals. They indicate the brushes.

- As noted earlier, the armature winding is connected to the external circuit through the brushes.
- By using these symbols, characteristics of different types of generators, are discussed below.
- The prime mover is coupled mechanically to the shaft of the DC generator. The prime mover is used to rotate the armature winding mechanically in the clockwise or anticlockwise direction.
- The external load such as lamps, is connected between the armature windings (A_1 and A_2), whereas the field winding is connected to an external d.c. supply.

7.8.2 Separately Excited Generator :

- The separately excited generator is as shown in Fig. 7.8.3.
- The field winding F_1 F_2 is connected to the external DC source.
- There is no physical connection between the armature and field windings. The armature is driven mechanically by a prime mover.
- The prime mover is a machine such as diesel engine, which is mechanically coupled (shaft to shaft) to the armature winding to rotate it mechanically.
- The field current produces magnetic flux which is cut by the rotating armature winding and emf E is induced into it.
- Thus mechanical energy gets converted into electrical energy. This energy is then supplied to the load.

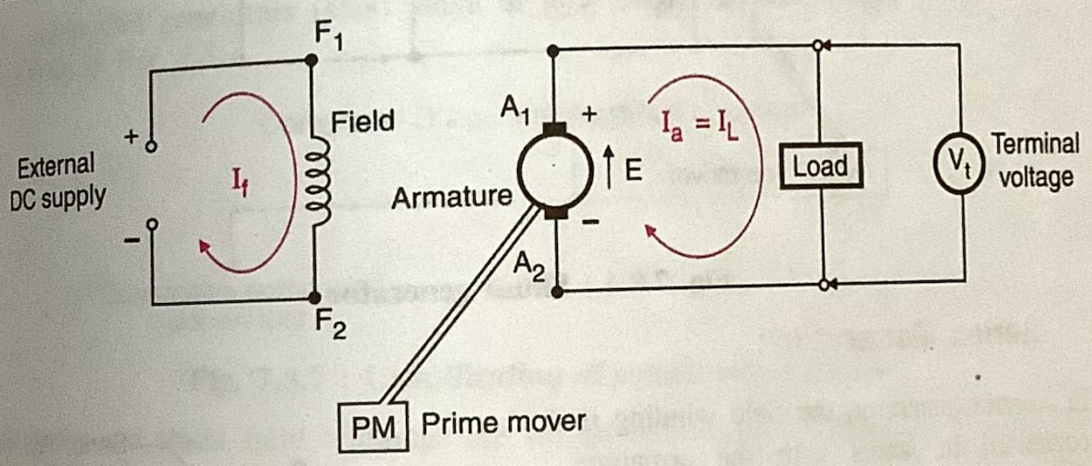


Fig. 7.8.3 : Separately excited generator

7.8.3 Self Excited Generators :

- In the self excited generators, the field winding is not excited from any external energy source, but the induced voltage in the armature itself.
- But then the question arises that if the field winding is not excited then how can the voltage be induced in the armature winding. And if the armature does not produce any voltage then how can there be any field current ?
- The answer to all these questions is the **residual magnetism**, which is possessed by the field poles under normal operating condition.

- The residual magnetism will induce a small voltage into the armature winding, which supplies a small field current.
- This will build flux and more voltage will be induced into the armature. Due to this cumulative process, the rated field current will be supplied and the generator generates the rated armature voltage.

Types of self excited generators :

The self excited generators are classified into three types as :

1. Shunt type generator.
2. Series type generator.
3. Compound generators.

7.8.4 Shunt Generator :

- The shunt generator is a self excited generator where the field winding is fed by the armature itself, the two windings being connected in parallel.
- The term shunt indicates the parallel connection. The connections between the armature and field windings are as shown in Fig. 7.8.4.

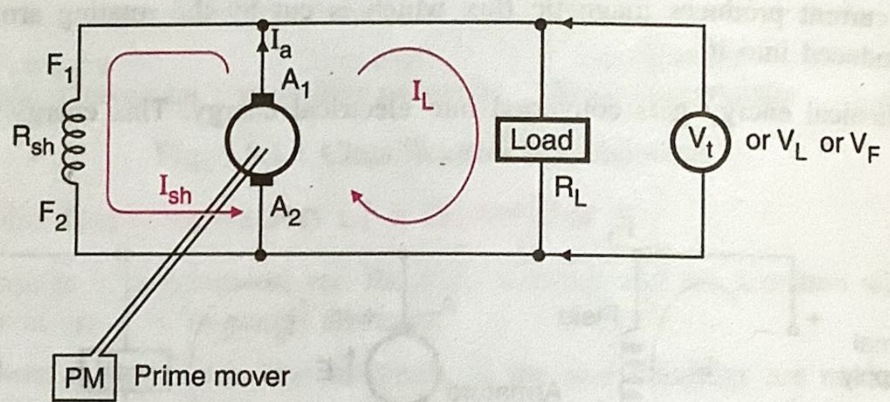


Fig. 7.8.4 : Shunt generator

7.8.5 Series Generator :

- In a series generator, the field winding is connected in series with the armature winding as shown in Fig. 7.8.5.
- The series combination then supplies the load current. Note that in Fig. 7.8.5, the field winding terminals are marked as S_1 and S_2 instead of F_1 and F_2, just to indicate that the field winding is in series with the armature winding.

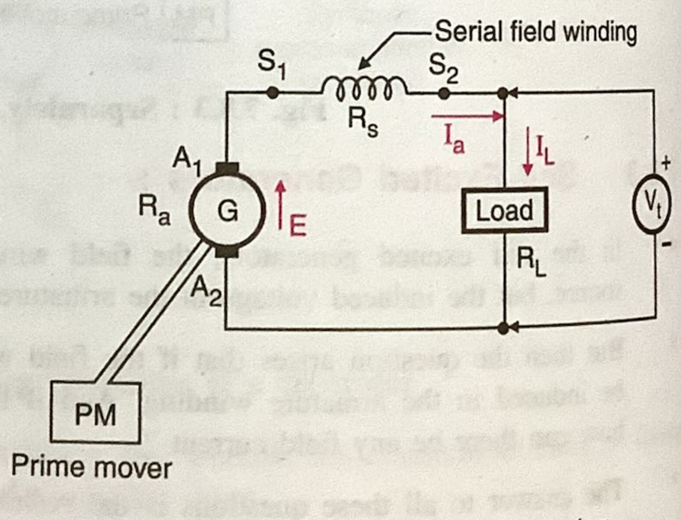
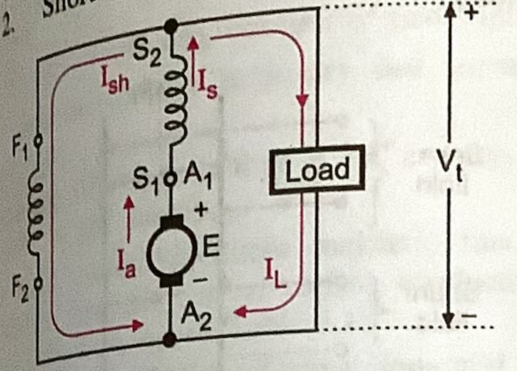


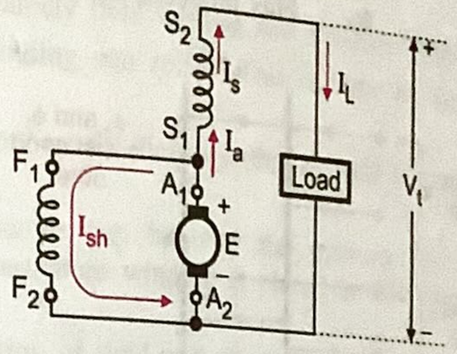
Fig. 7.8.5 : A series generator

7.8.6 Compound DC Generators :

- In the preceding sections we have discussed the series and shunt dc generators in which the field winding is connected in either series or parallel with the armature winding.
- But in the compound generators, there are two independent field windings. One of them is connected in series with the armature whereas the other one is connected in parallel with the armature winding. This is as shown in Figs. 7.8.6(a) and (b).
- The two types of compound dc generators shown in Fig. 7.8.6 are :
  1. Long shunt compound dc generator
  2. Short shunt compound dc generator



(a) Long shunt compound dc generator



(b) Short shunt compound dc generator

Fig. 7.8.6

7.8.7 Cumulative and Differential Compound Generators :

- The compound generators (short shunt or long shunt) can be further classified into two types as shown in Fig. 7.8.7.

Compound DC generators (Short or Long shunt)
- Cumulative compound generators
- Differential compound generators

Fig. 7.8.7 : Classification of compound generators

- The series and shunt field windings are wound independently on each pole core as shown in Fig. 7.8.8(a).

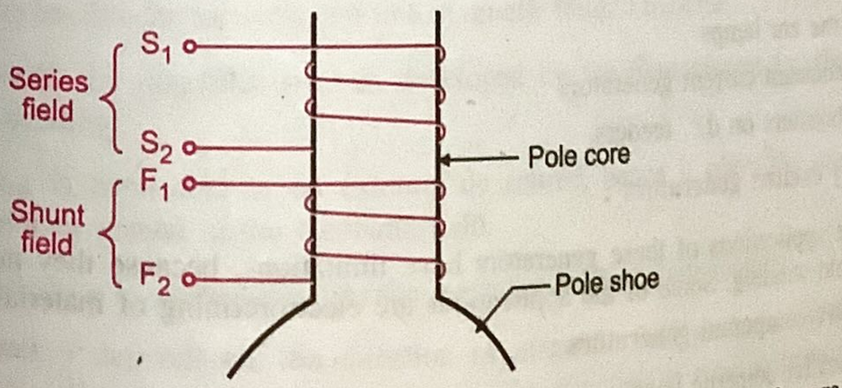


Fig. 7.8.8(a) : Series and shunt field windings are wound on the same pole core

- The magnetic flux produced by these windings can either assist each other (Fig. 7.8.8(b)) or oppose each other (Fig. 7.8.8(c)).
- This depends on the directions of currents flowing through the two windings.

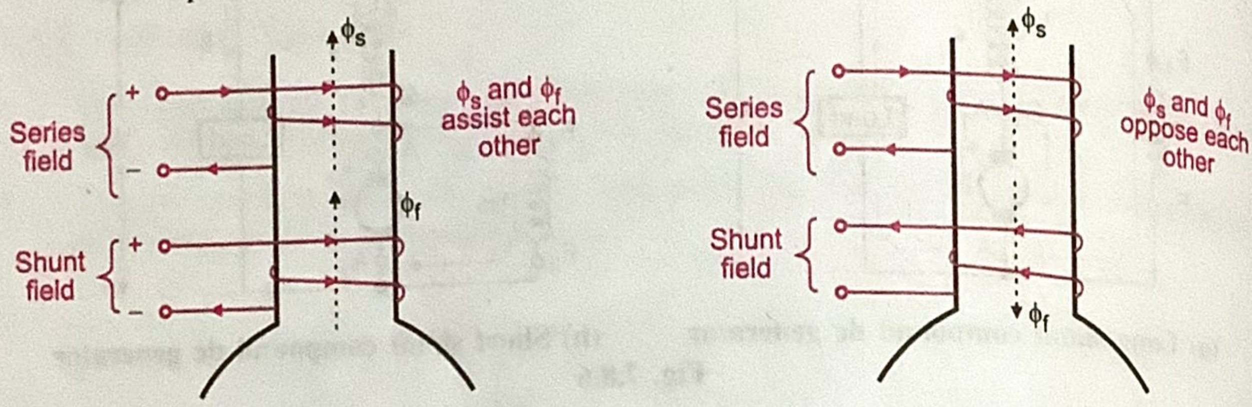
Cumulative compound generator :

If the fluxes produced by the series and shunt field windings assist each other (Fig. 7.8.8(b)), then the type of generator is called as cumulative compound generator.

$$\therefore \quad \text{Total flux } \phi_T = \phi_s + \phi_f \qquad \text{...(7.8.1)}$$

where ϕ_s = Flux produced by the series winding

ϕ_f = Flux produced by the shunt winding.



(b) Cumulative compound generator (c) Differential compound generator

Fig. 7.8.8

Differential compound generator :

If the fluxes produced by the series and shunt field windings oppose each other as shown in Fig. 7.8.8(c), then the type of generator is called as differential compound generator.

$$\therefore \quad \text{Total flux, } \phi_T = \phi_f - \phi_s \qquad \text{...(7.8.2)}$$

7.9 Applications of Different Types of Generators :

The summary of applications of various types of generators is as follows :

Shunt generator :

- Lighting loads
- Battery charging.

Series generator :

- For the arc lamps
- As constant current generators
- As boosters on d.c. feeders.

Separately excited generators :

The applications of these generators have limitations, because they need a separate excitation for the field winding. Some of the applications are electrorefining of materials or electro-plating.

Cumulative compound generators :

- Used for domestic lighting
- For energy transmission over a long distance.