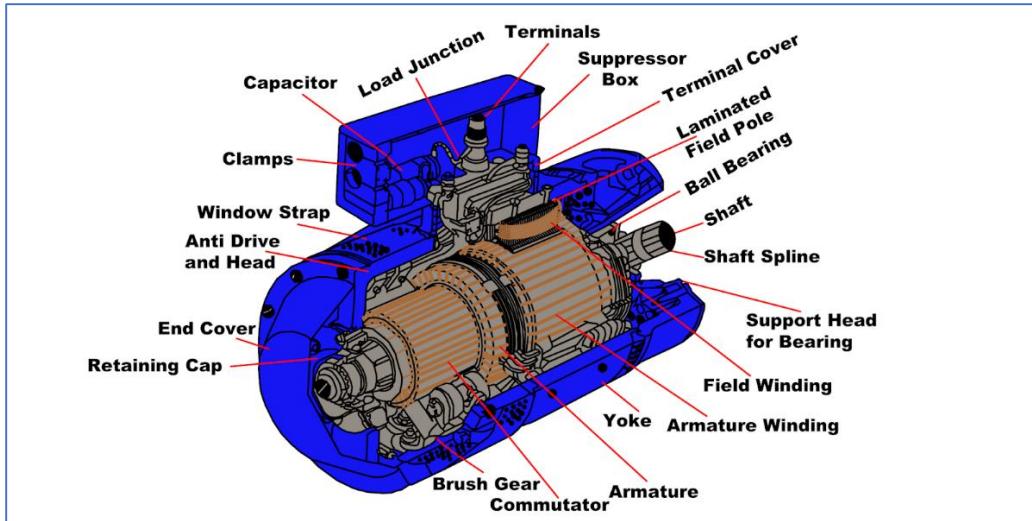


Ministry of Higher Education and Scientific Research
Al-Mustaqlal University
College of Engineering Technology
Medical Instrumentation Techniques Engineering Department
Electrical Machines
Second Class



Lectures 9 and 10

D.C machines: General structure, Equivalent circuit, Methods of excitation



By Prof.Dr. Bayan M Sabbar

1. DC machines

A DC Machine is an **electro-mechanical energy conversion device**. There are two types of DC machines; one is the **DC generator**, and another one is known as **DC motor**.

A DC generator converts mechanical power (ωT) into DC electrical power (E_I), whereas, a DC motor converts DC electrical power into mechanical power. The AC motor is invariably applied in the industry for conversion of electrical power into mechanical power, but at the places where the wide range of speeds and good speed regulation is required, like in electric traction system, a DC motor is used. The construction of the dc motor and generator is nearly the same. The generator is employed in a much protected way. Hence there is an open construction type. But the motor is used in the location where they are exposed to dust and moisture, and hence it requires enclosures for example dirt proof, fireproof, etc. according to requirement. Although the battery is an important source of DC electric power, it can only supply limited power to any

machines. There are some applications where large quantities of DC power are required, such as electroplating, electrolysis, etc. Hence, at such places, DC generators are used to deliver power.

The rotating electrical or DC machine has mainly two parts; one is **Stator**, and another one is **Rotor**. The stator and rotor are separated from each other by an **air gap**. The stator is the outer frame of the machine and is **immovable**. The rotor is free to move and is the inner part of the machine. Both the stator and the rotor are made of **ferromagnetic materials**. Slots are cut on the inner periphery of the stator and the outer periphery of the rotor. Conductors are placed in the slots of the stator or rotor. They are interconnected to form windings. The winding in which voltage is induced is called the **Armature windings**. The winding through which a current is passed to produce the main flux is called the **Field windings**. To provide main flux in some of the machine permanent magnets is also used.

2. Working principle

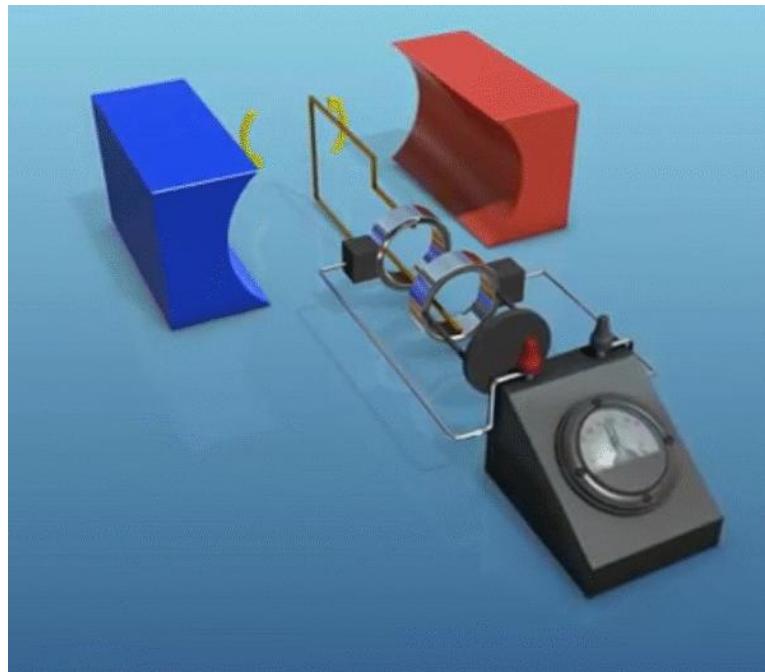


Fig 1 Work principle of DC generator (basic assumption).

Imagine the coil to be rotating in clock-wise direction (shown in Fig.1). As the coil assumes successive positions in the field, the flux linked with it changes. Hence, an e.m.f. is induced in it which is Cut-away view of dc generator proportional to the rate of change of flux linkages ($e = Nd\Phi/dt$). When the plane of the coil is at right angles to lines of flux *i.e.* when it is in position, 1, then flux linked with the coil is maximum but *rate of change of flux linkages is minimum*.

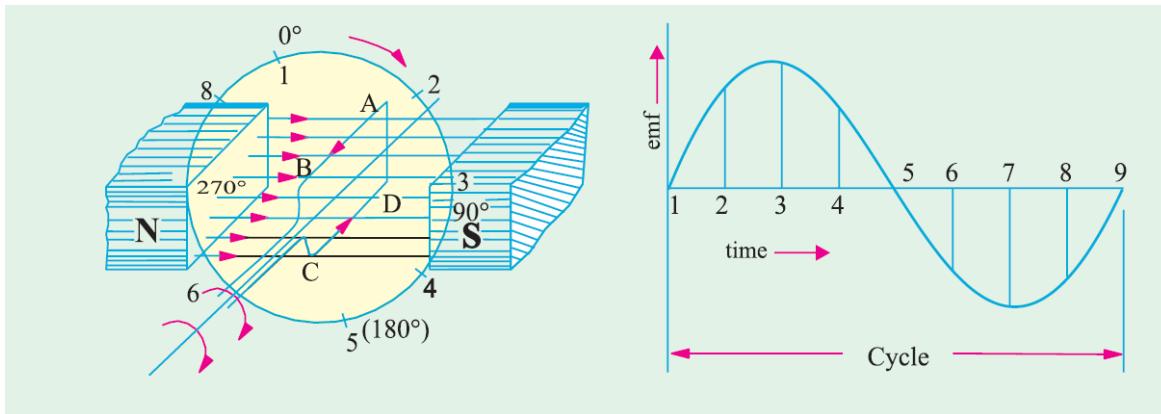


Fig 2 Generated voltage in slip ring generator.

It is so because in this position, the coil sides *AB* and *CD* do not cut or shear the flux; rather they slide along them *i.e.* they move parallel to them. Hence, there is no induced e.m.f. in the coil. Let us take this no-e.m.f. or vertical position of the coil as the starting position. The angle of rotation or time will be measured from this position.

As the coil continues rotating further, the rate of change of flux linkages (and hence induced e.m.f. in it) increases, till position 3 is reached where $\theta = 90^\circ$. Here, the coil plane is horizontal *i.e.* parallel to the lines of flux. As seen, the flux linked with the coil is minimum but *rate of change of flux linkages is maximum*. Hence, maximum e.m.f. is induced in the coil when in this position.

In the next quarter revolution *i.e.* from 90° to 180° , the flux linked with the coil gradually **increases** but the rate of change of flux linkages **decreases**. Hence, the induced e.m.f. decreases gradually till in position 5 of the coil, it is reduced to zero value.

So, we find that in the first half revolution of the coil, no (or minimum) e.m.f. is induced in it when in position 1, maximum when in position 3 and no e.m.f. when in position 5. The direction of this induced e.m.f. can be found by applying Fleming's Right-hand rule which gives its direction from *A* to *B* and *C* to *D*. Hence, the direction of current flow is ***ABMLCD***. The current through the load resistance *R* flows from *M* to *L* during the first half revolution of the coil.

In the next half revolution *i.e.* from 180° to 360° , the variations in the magnitude of e.m.f. are similar to those in the first half revolution. Its value is maximum when coil is in position 7 and minimum when in position 1. But it will be found that the direction of the induced current is from *D* to *C* and *B* to *A* as shown in. Hence, the path of current flow is along ***DCLMBA*** which is just the reverse of the previous direction of flow. Therefore, we find that the current which we obtain from such a simple generator reverses its direction after every half revolution. Such a current undergoing periodic reversals is known as alternating current. It is, obviously, different from a direct current which continuously flows in one and the same direction. It should be noted that alternating current not only reverses its direction, it does not even keep its magnitude constant while flowing in any one direction. The two half-cycles may be called positive and negative half-cycles respectively.

For making the flow of current unidirectional in the ***external*** circuit, the slip-rings are replaced by split-rings. The split-rings are made out of a conducting cylinder which is cut into two halves or segments insulated from each other by a thin sheet of mica or some other insulating material. As before, the coil ends are joined to these segments on which rest the carbon or copper brushes.

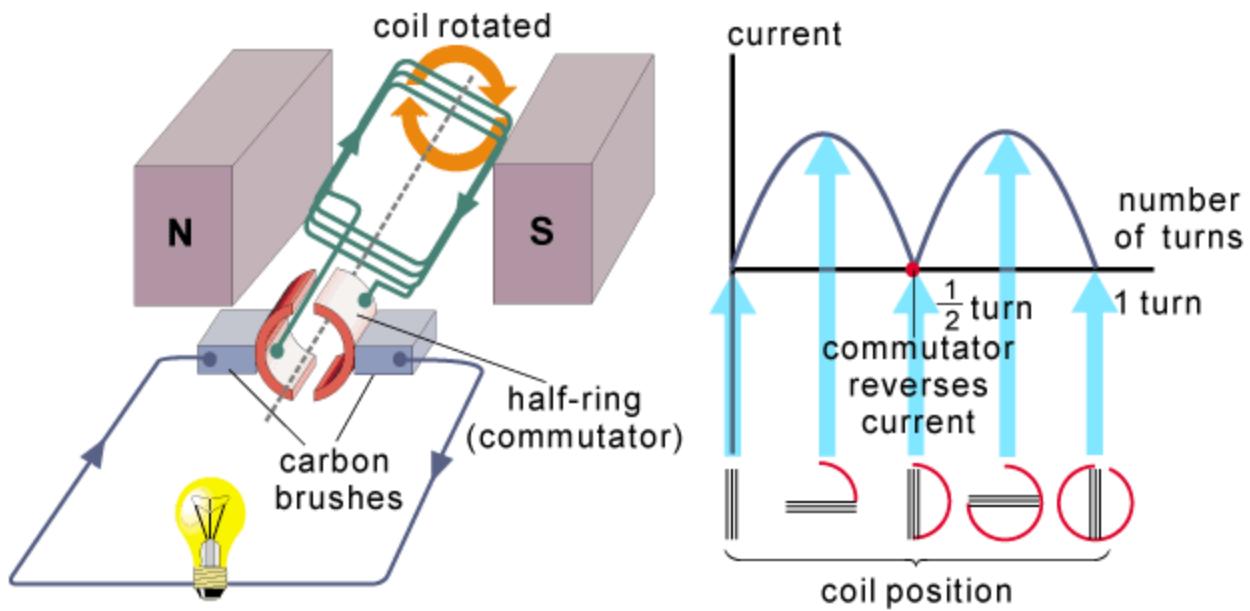


Fig 3. Half ring commutator.

It is seen that in the first half revolution current flows along **(ABMNLCD)** i.e. the brush No. 1 in contact with segment 'a' acts as the positive end of the supply and 'b' as the negative end. In the next half revolution, the direction of the induced current in the coil has reversed. But at the same time, the positions of segments 'a' and 'b' have also reversed with the result that brush No. 1 comes in touch with the segment which is positive i.e. segment 'b' in this case. Hence, current in the load resistance again flows from **M** to **L**. The waveform of the current through the external circuit is as shown in. ***This current is unidirectional but not continuous like pure direct current.***

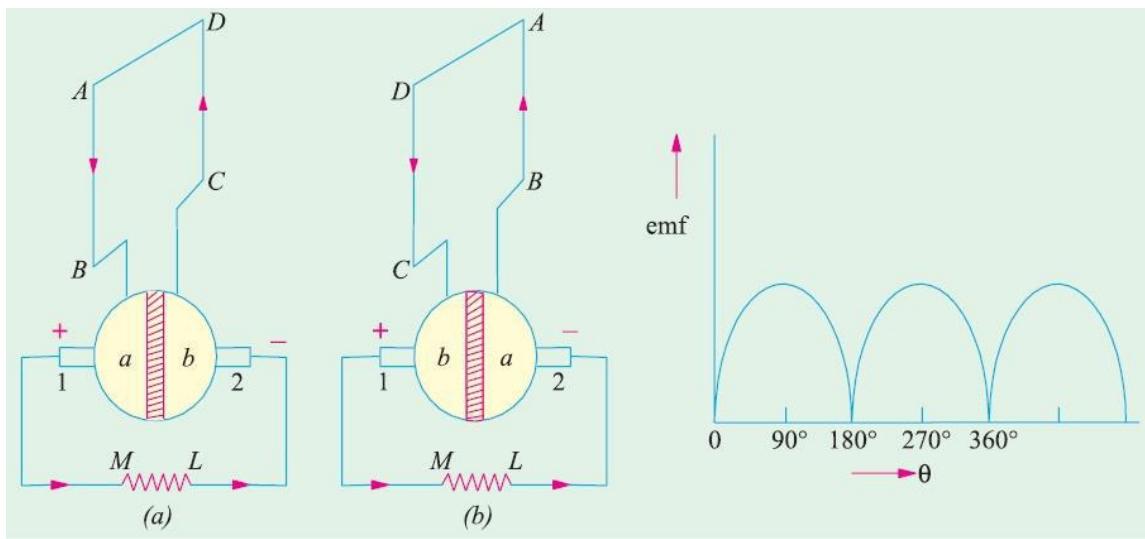


Fig. 4 E.M.F in DC generator with half ring.

It should be noted that the position of brushes is so arranged that the changeover of segments 'a' and 'b' from one brush to the other takes place when the plane of the rotating coil is at right angles to the plane of the lines of flux. It is so because in that position, the induced e.m.f. in the coil is zero.

Another important point worth remembering is that even now the current induced in the coil sides is alternating as before. It is only due to the rectifying action of the split-rings (also called commutator) that it becomes unidirectional in the external circuit. Hence, it should be clearly understood that even in the armature of a d.c. generator, the induced voltage is alternating.

3. Construction of a DC Generator

The simple loop generator has been considered in detail merely to bring out the basic principle underlying construction and working of an actual generator illustrated in Fig. 26.8 which consists of the following essential parts:

1. Magnetic Frame or Yoke
2. Pole-Cores and Pole-Shoes

3. Pole Coils or Field Coils

4. Armature Core

5. Armature Windings or Conductors

6. Commutator

7. Brushes and Bearings

Of these, the yoke, the pole cores, the armature core and air gaps between the poles and the armature core or the magnetic circuit whereas the rest form the electrical circuit.

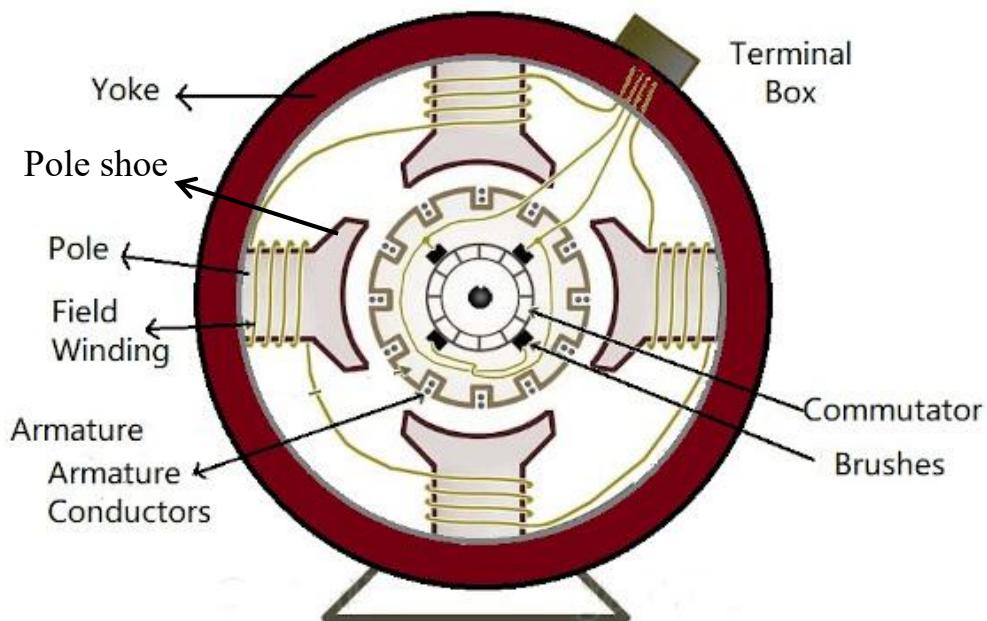


Fig 5. Design of DC machine.

3.1 Yoke

The outer frame or yoke serves double purpose:

- (i)** It provides mechanical support for the poles and acts as a protecting cover for the whole machine.
- (ii)** It carries the magnetic flux produced by the poles.

In small generators where cheapness rather than weight is the main consideration, yokes are made of cast iron. But for large machines usually cast steel or rolled steel is employed. The modern process of forming the yoke consists of rolling a steel slab round a cylindrical mandrel and then welding it at the bottom. The feet and the terminal box etc. are welded to the frame afterwards. Such yokes possess sufficient mechanical strength and have high permeability.

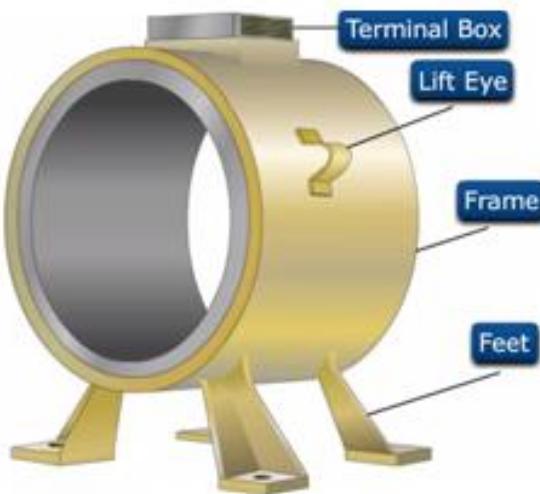


Fig 6. Yoke.

3.2 Pole Cores and Pole Shoes

The field magnets consist of pole cores and pole shoes. The pole shoes serve two purposes

(i) They spread out the flux in the air gap and also, being of larger cross-section, reduce the reluctance of the magnetic path

(ii) They support the exciting coils (or field coils).

There are two main types of pole construction:-

(a) The pole core itself may be a solid piece made out of either cast iron or cast steel but the pole shoe is laminated and is fastened to the pole face by means of counter sunk screws.

(b) In modern design, the complete pole cores and pole shoes are built of thin laminations of annealed steel which are riveted together under hydraulic pressure. The thickness of

laminations varies from 1 mm to 0.25 mm. The laminated poles may be secured to the yoke in any of the following two ways:

- Either the pole is secured to the yoke by means of screws bolted through the yoke and into the pole body.
- The holding screws are bolted into a steel bar which passes through the pole across the plane of laminations.

3.3 Pole Coils

The field coils or pole coils, which consist of copper wire or strip, are former wound for the correct dimension. Then, the former is removed and wound coil is put into place over the core.

When current is passed through these coils, they electromagnetic the poles which produce the necessary flux that is cut by revolving armature conductors.

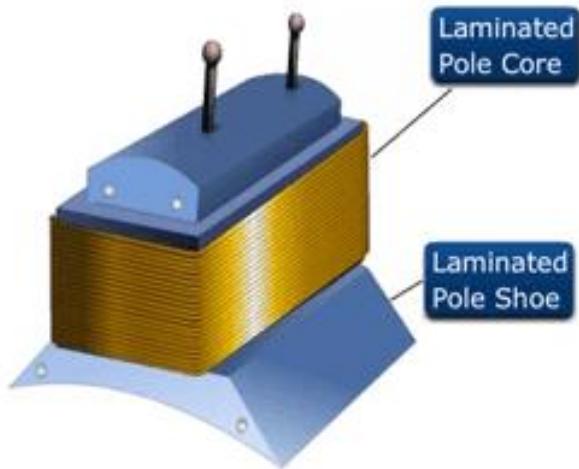


Fig 7. Pole Coil.

3.4 Armature Core

It houses the armature conductors or coils and causes them to rotate and hence cut the magnetic flux of the field magnets. In addition to this, its most important function is to provide a path of very low reluctance to the flux through the armature from a *N*-pole to a *S*-pole.

It is cylindrical or drum-shaped and is built up of usually circular sheet steel discs or laminations approximately 0.5 mm thick. It is keyed to the shaft.

The slots are either die-cut or punched on the outer periphery of the disc and the keyway is located on the inner diameter as shown. In small machines, the armature stampings are keyed directly to the shaft. Usually, these laminations are perforated for air ducts which permit axial flow of air through the armature for cooling purposes. Such ventilating channels are clearly visible in the laminations.

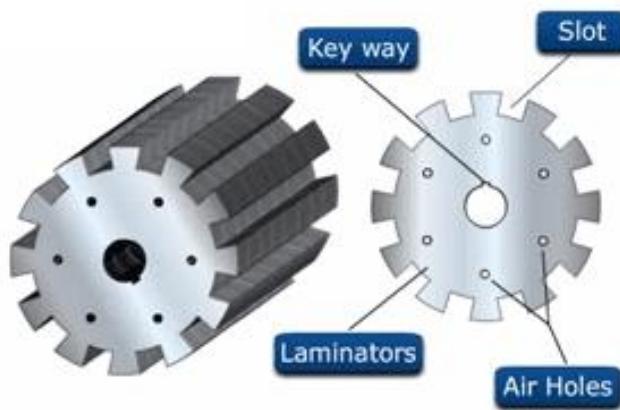


Fig 8. Armature core.

Up to armature diameters of about one meter, the circular stampings are cut out in one piece as shown in Fig above. But above this size, these circles, especially of such thin sections, are difficult to handle because they tend to distort and become wavy when assembled together. Hence, the circular laminations, instead of being cut out in one piece, are cut in a number of suitable sections or segments which form part of a complete ring.

A complete circular lamination is made up of four or six or even eight segmental laminations. Usually, two keyways are notched in each segment and are dovetailed or wedge-shaped to make the laminations self-locking in position.

The purpose of using laminations is to reduce the loss due to eddy currents. Thinner the laminations, greater is the resistance offered to the induced e.m.f., smaller the current and hence lesser the $I^2 R$ loss in the core.

3.5 Armature Windings

The armature windings are usually former-wound. These are first wound in the form of flat rectangular coils and are then pulled into their proper shape in a coil puller. Various conductors of the coils are insulated from each other. The conductors are placed in the armature slots which are lined with tough insulating material. This slot insulation is folded over above the armature conductors placed in the slot and is secured in place by special hard wooden or fiber wedges.

The winding of the machine is classified into two types. They are closed type winding and Open type winding. The classification of winding is shown in the figure below.

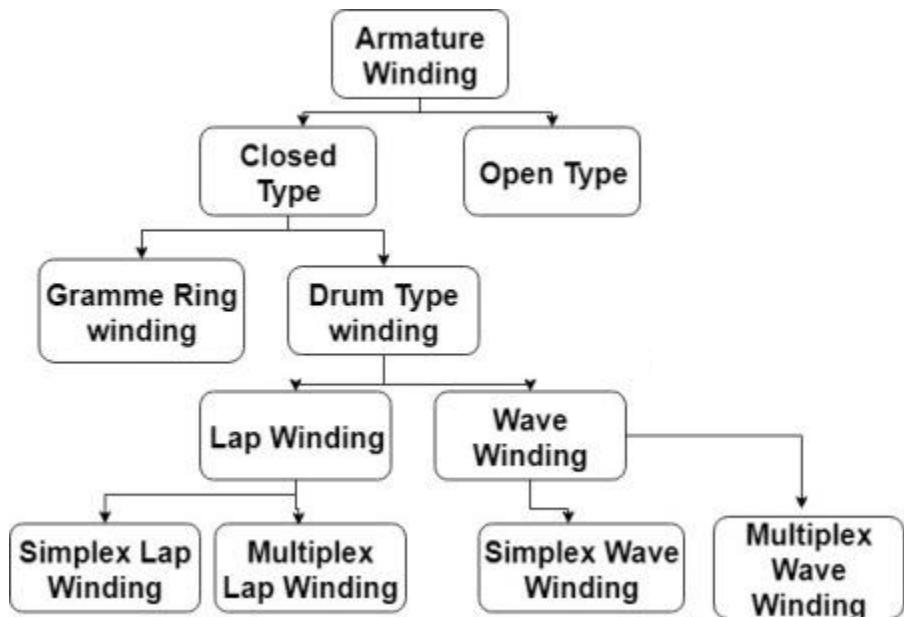


Fig 8. Classification of armature windings.

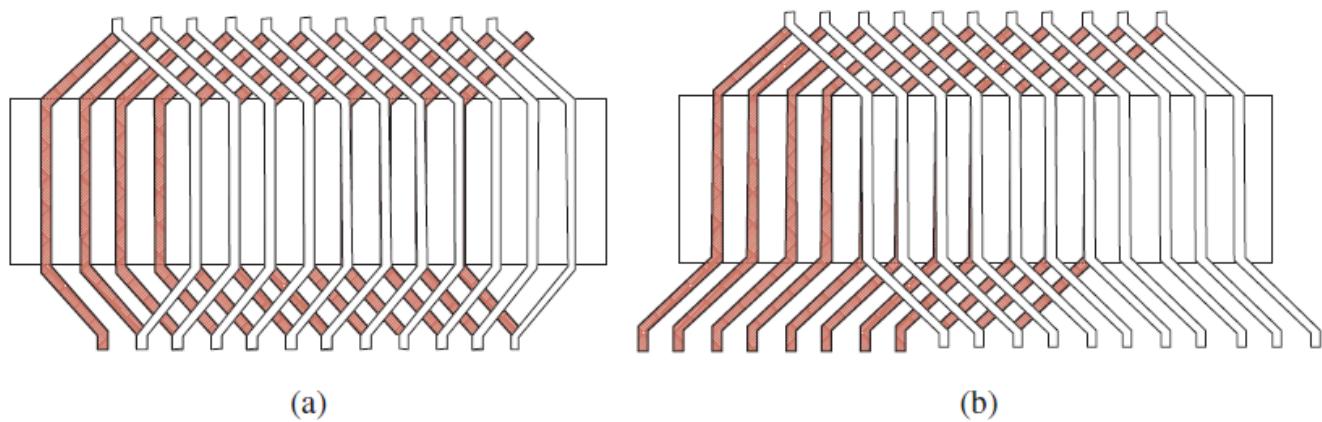
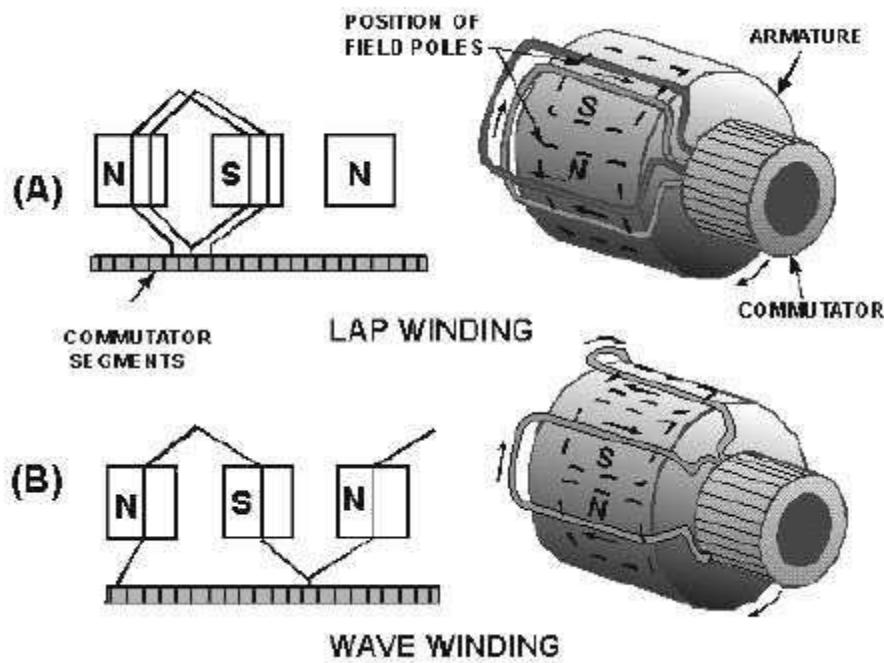


Fig 9. Lap vs Wave type.

3.6 Commutator

The function of the commutator is to facilitate collection of current from the armature conductors. As shown in fig 9, it rectified *i.e.* converts the alternating current induced in the armature conductors into unidirectional current in the external load circuit. It is of cylindrical structure and is built up of wedge-shaped segments of high-conductivity hard-drawn or drop forged copper. These segments are insulated from each other by thin layers of mica. The number

of segments is equal to the number of armature coils. Each commutator segment is connected to the armature conductor by means of a copper lug or strip (or riser). To prevent them from flying out under the action of centrifugal forces, the segments have *V*-grooves, these grooves being insulated by conical mica rings.

3.7 Carbon Brushes

These brushes are connected with the commutators and get current from the commutator and provides to the load. • These are constructed with the carbon and their main function is to reduce the sparking at load and machine connection points.

4. Types of DC Machines

There are 2 main types of DC machines first one is a generator and the second one is a dc motor, dc motor uses dc current and provides mechanical power and dc generator generates dc voltage. As we discuss when current-carrying conductor when placed in field emf induced forces apply on it. There are two main categories by which the dc machine gets excited first one is self-excited and the second one is separately excited.

In self-excited machines field current produced by the machines itself while in separately excited machines the field current is provided by the separated source. Due to these two excitations methods, the dc machines are further divided into different types that are described here.

- Compound DC machine.
- Shunt DC machine.
- Separately excited DC machine.
- Series DC machine.

Types of DC Generators

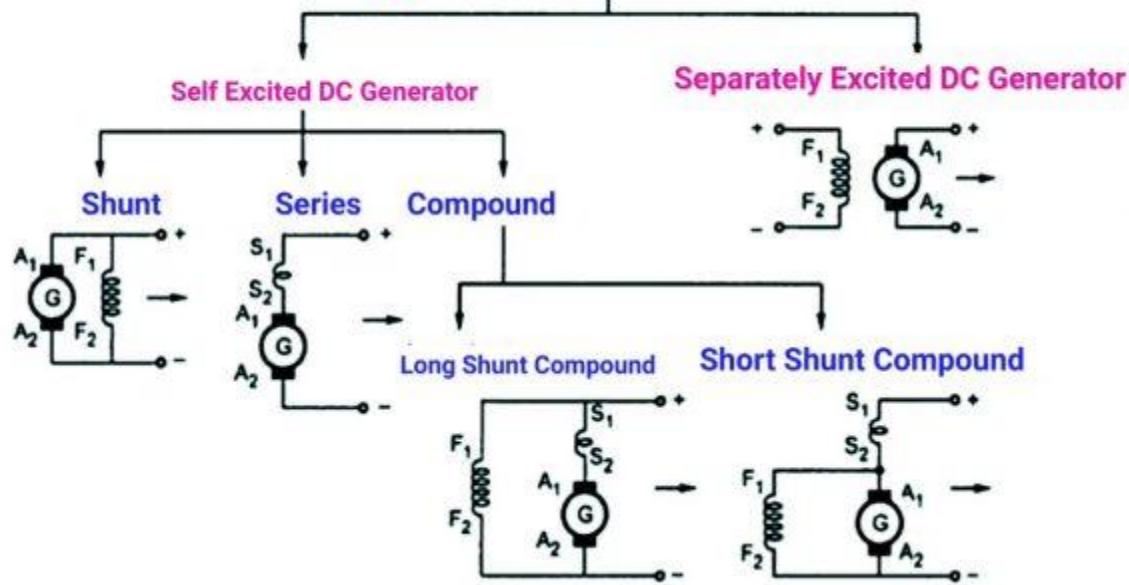


Fig 10. Classification of DC machine.

4.1 Separately Excited DC Machine

If there is no internal voltage induced at the field windings and there is no field current so external power source is connected at the field winding to produce current and voltage these winding is known as separate windings.

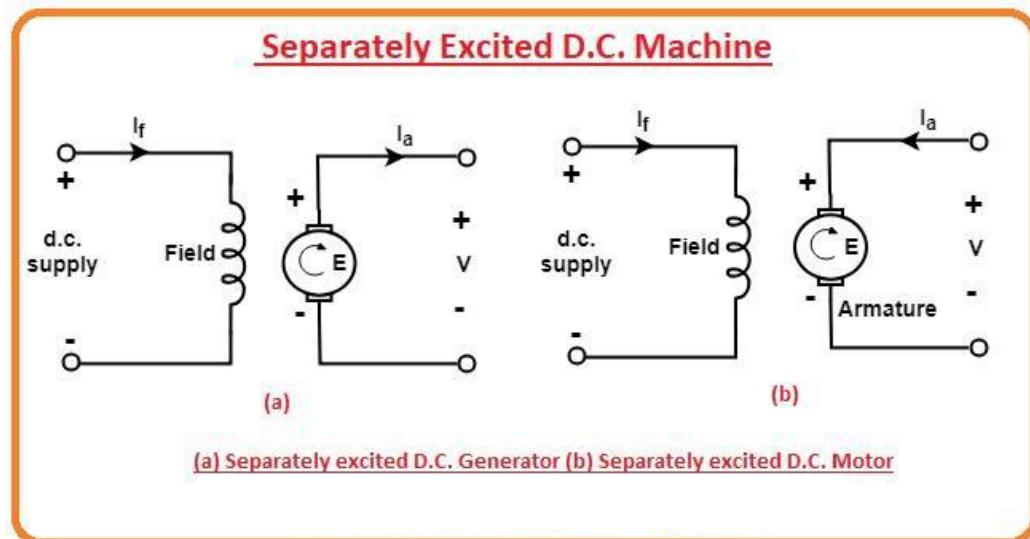


Fig 11. Separately Excited DC Machine.

4.2 Self-Excited DC Machines

4.2.1 Shunt DC Machine

- In this type of dc machine the field winding (it is located at the stator of a machine) linked with the armature winding (wound rotor) in parallel.
- Due to a parallel connection, the voltage across the field windings is equaled to the supply voltage in the case of a motor and equals generated voltage in the case of a generator.
- So these windings have large no of turns.

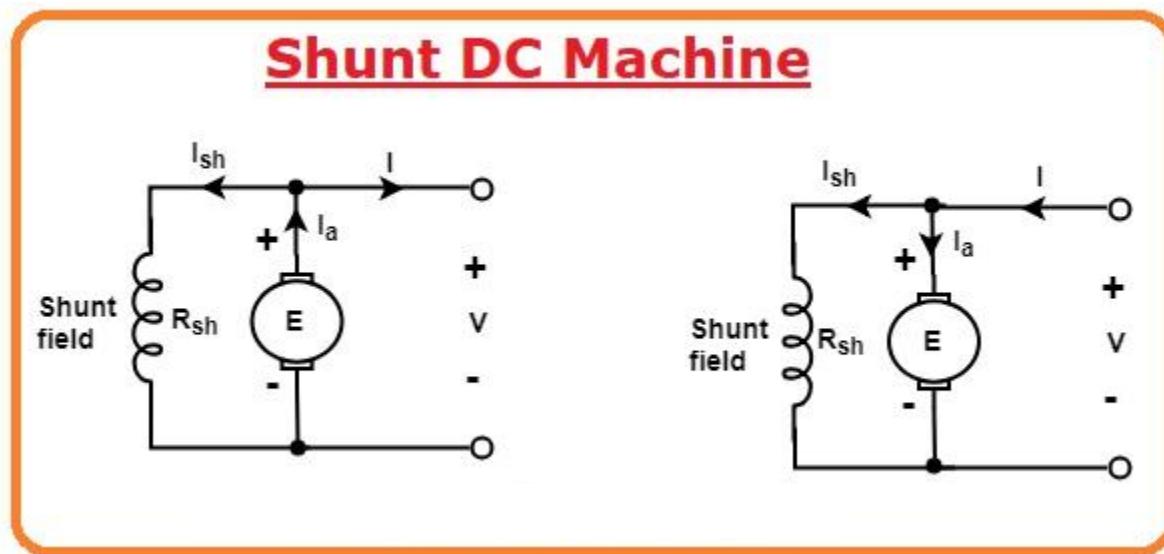
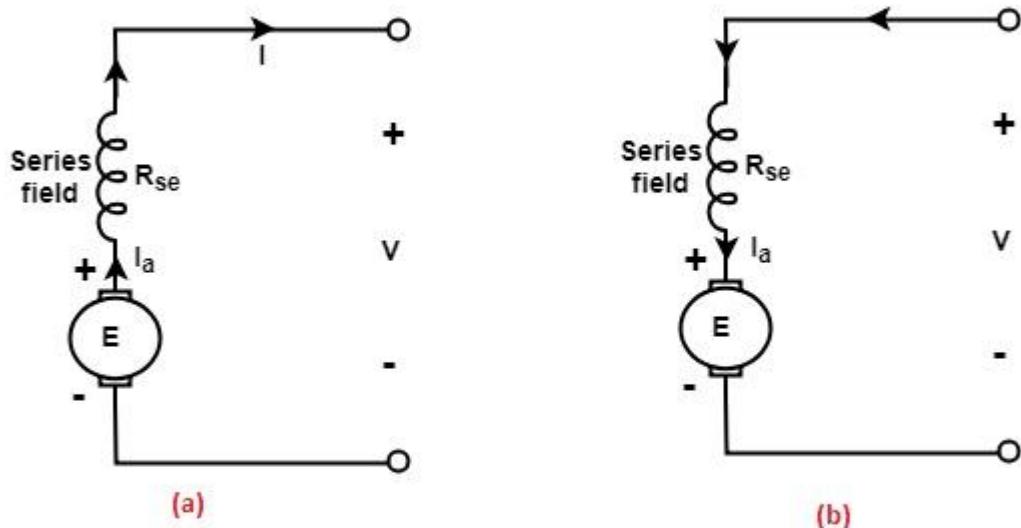


Fig 12. Shunt DC Machine.

4.2.2 Series Wound DC Machine

- In these dc machines, the field windings are connected with the armature windings in series connection schemes.
- As this winding is in series so the armature current also passes through it that has high value for less power losses the turns of the field windings are less in this machine.

Series Wound DC Machine

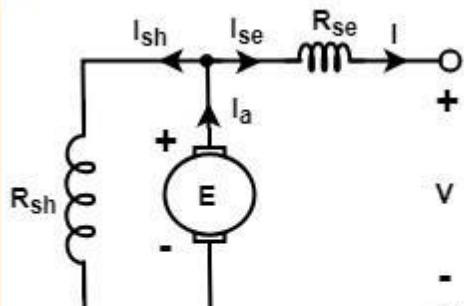


(a) D.C. series generator (b) D.C. series motor

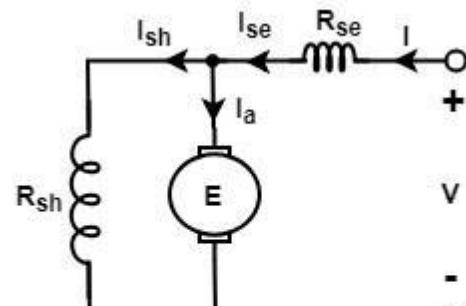
Fig 13. Series DC Machine.

4.2.3 Compound DC Machine

- This motor consists of series and shunts windings in its circuitry. 2 windings are placed at every pole of the machine.
- The number of turns in the series is less due to the large value of armature current flowing through it and shunt windings have large no of turns.
- There are 2 methods by which these two windings are connected in these machines if the field windings are in parallel with the armature windings then the machines are known as the short shunt compound. In the given figure, you can see these arrangements.



(a)

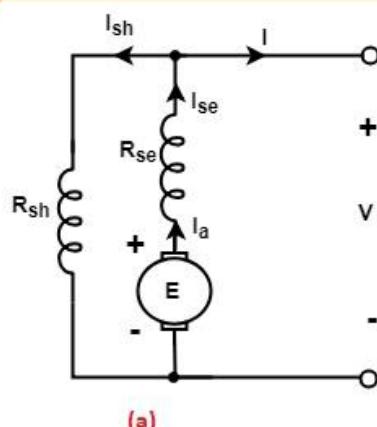


(b)

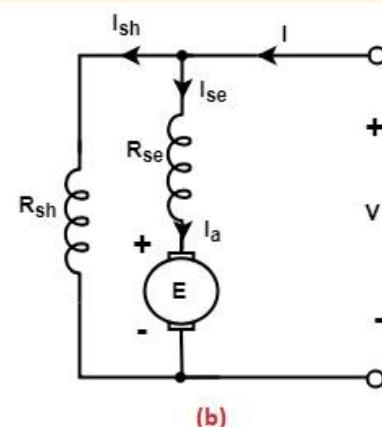
(a) Short-shunt compound D.C. generator (b) Short-shunt compound D.C. motor

Fig 14. Short-Shunt DC Machine.

If the field windings are in parallel with the armature and series windings the machines are known as the long shunt compound machines. In the given figure, you can see resultant circuitry. That is a complete post on the dc machines if you have any questions about this post asks in comments.



(a)



(b)

(a) Long-shunt D.C. Generator (b) Long-shunt D.C. Motor

Fig 15. Long-Shunt DC Machine.

Example 1: A shunt generator delivers 450 A at 230 V and the resistance of the shunt field and armature are 50 Ω and 0.03 Ω respectively. Calculate the generated e.m.f.

Solution

Generator circuit is shown in Fig

Current through shunt field winding is

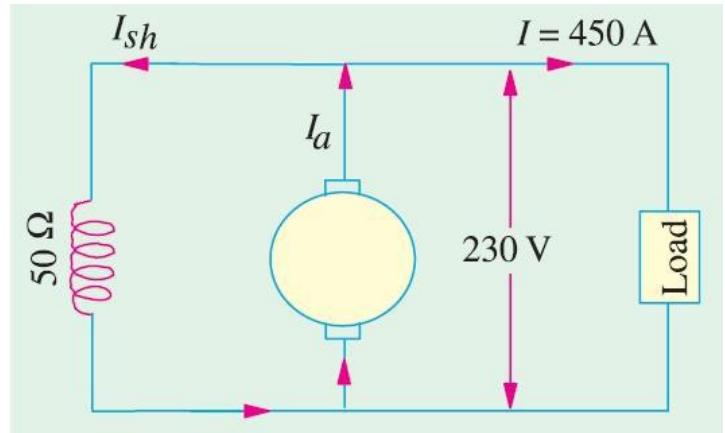
$$I_{sh} = 230/50 = 4.6 \text{ A}$$

Load current $I = 450 \text{ A}$

$$\therefore \text{Armature current } I_a = I + I_{sh}$$

$$= 450 + 4.6 = 454.6 \text{ A}$$

$$\text{Armature voltage drop } I_a R_a = 454.6 \times 0.03 = \mathbf{13.6 \text{ V}}$$



Example 2: A long-shunt compound generator delivers a load current of 50 A at 500 V and has armature, series field and shunt field resistances of 0.05 Ω , 0.03 Ω and 250 Ω respectively.

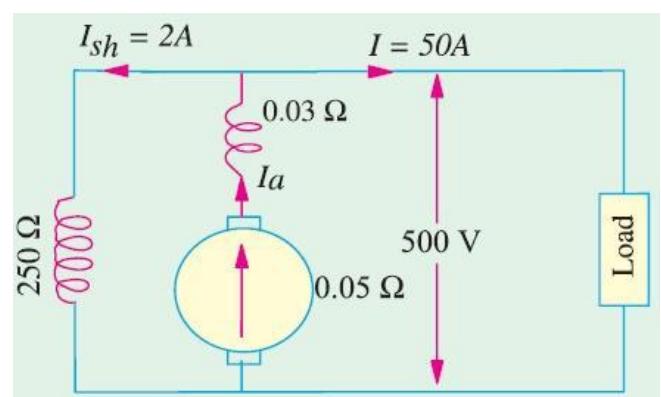
Calculate the generated voltage and the armature current. Allow 1 V per brush for contact drop.

Solution

Generator circuit is shown in Fig

$$I_{sh} = 500/250 = 2 \text{ A}$$

Current through armature and series winding is $I_a = 50 + 2 = 52 \text{ A}$



$$\text{Voltage drop on series field winding} = 52 \times 0.03 = 1.56 \text{ V}$$

Armature voltage drop

$$I_a R_a = 52 \times 0.05 = 2.6 \text{ V}$$

Drop at brushes = $2 \times 1 = 2 \text{ V}$

$$\text{Now, } E_g = V + I_a R_a + \text{series drop} + \text{brush drop} = 500 + 2.6 + 1.56 + 2 = \mathbf{506.16 \text{ V}}$$

Example 3: A short-shunt compound generator delivers a load current of 30 A at 220 V, and has armature, series-field and shunt-field resistances of 0.05Ω , 0.30Ω and 200Ω respectively. Calculate the induced e.m.f. and the armature current. Allow 1.0 V per brush for contact drop.

Solution

Generator circuit diagram is shown in Fig.

$$\text{Voltage drop in series winding} = 30 \times 0.3 = 9 \text{ V}$$

$$\text{Voltage across shunt winding} = 220 + 9 = 229 \text{ V}$$

$$I_{sh} = 229/200 = 1.145 \text{ A}$$

$$I_a = 30 + 1.145 = 31.145 \text{ A}$$

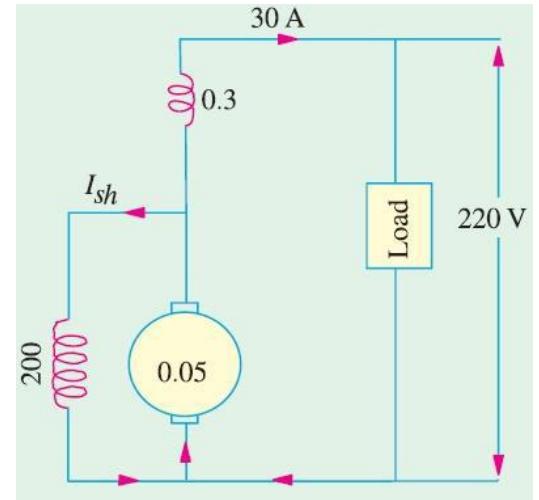
$$I_a R_a = 31.145 \times 0.05 = 1.56 \text{ V}$$

$$\text{Brush drop} = 2 \times 1 = 2 \text{ V}$$

$$E_g = V + \text{series drop} + \text{brush drop} + I_a R_a = 220 + 9 + 2 + 1.56 = 232.56 \text{ V}$$

Example 4: In a long-shunt compound generator, the terminal voltage is 230 V when generator delivers 150 A. Determine

- (i) induced e.m.f.
- (ii) total power generated
- (iii) distribution of this power.



Given that shunt field, series field, divertor and armature resistance are $92\ \Omega$, $0.015\ \Omega$, $0.03\ \Omega$ and $0.032\ \Omega$ respectively.

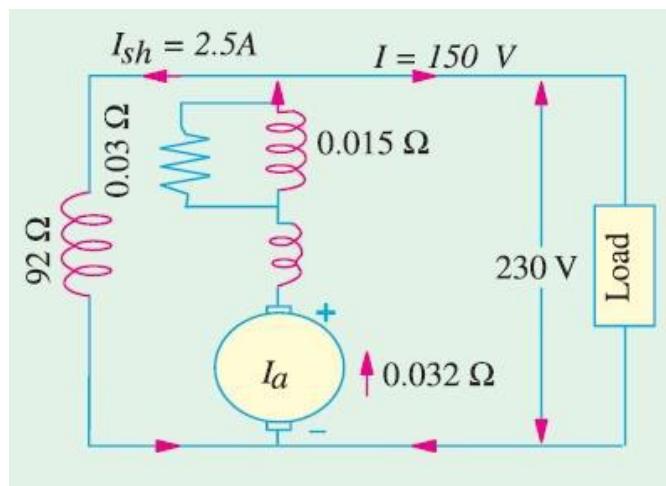
Solution.

$$I_{sh} = 230/92 = 2.5\ A$$

$$I_a = 150 + 2.5 = 152.5\ A$$

Since series field resistance and diverter resistances are in parallel Fig their combined resistance is $= 0.03 \times 0.015 / 0.045 = 0.01\ \Omega$

Total armature circuit resistance is $= 0.032 + 0.01 = 0.042\ \Omega$



$$\text{Voltage drop} = 152.5 \times 0.042 = 6.4\ V$$

(i) Voltage generated by armature

$$E_g = 230 + 6.4 = \mathbf{236.4\ V}$$

(ii) Total power generated in armature

$$E_g I_a = 236.4 \times 152.5 = \mathbf{36,051\ W}$$

(iii) Power lost in armature

$$I_a^2 R_a = 152.5^2 \times 0.032 = 744\ W$$

$$\text{Power lost in series field and divertor} = 152.5^2 \times 0.01 = 232\ W$$

$$\text{Power dissipated in shunt winding} = VI_{sh} = 230 \times 0.01 = 575\ W$$

$$\text{Power delivered to load} = 230 \times 150 = 34500\ W$$

$$\text{Total} = 36,051\ W.$$