7

DC Machines

TOPICS DISCUSSED

- Working of a dc machine as a generator and as a motor
- Basic principle of dc machines
- Constructional details
- Need of brush and commutator
- Types of windings
- EMF equation
- Types of dc machines and their characteristics
- Starting of a dc motor
- Speed control
- Losses and efficiency

7.1 INTRODUCTION AND PRINCIPLE OF WORKING

DC machines work either as a dc generator or as a dc motor. In a dc generator, a set of conductors or coils placed on a rotating body, called armature, are rotated continuously inside a magnetic field with the help of a prime mover (prime mover is another machine, armature winding. The ac generated gets converted into dc when the voltage is collected from the rotating armature through the brush and commutator arrangement. The brush and commutator arrangement, therefore, works like a full-wave rectifier which converts generated ac into dc for the output circuit. A dc generator, therefore, converts mechanical energy supplied through the prime mover to electrical energy to be supplied from the generator armature to an electrical load. We, of course, will need to create a magnetic field by a field system as shown in Fig. 7.1. It can be noticed from the figure that the magnetic poles are electromagnets fixed on a hollow cylindrical frame. Depending on the direction of the winding and the direction of current flow through the field windings, alternate North and South poles are formed, creating a magnetic field inside which the cylindrical rotor called armature is placed and is rotated.

The brush and commutator arrangement has not been shown in the figure. The armature conductors have been shown rotated in the magnetic field by a prime mover at N rpm (revolutions per minute).

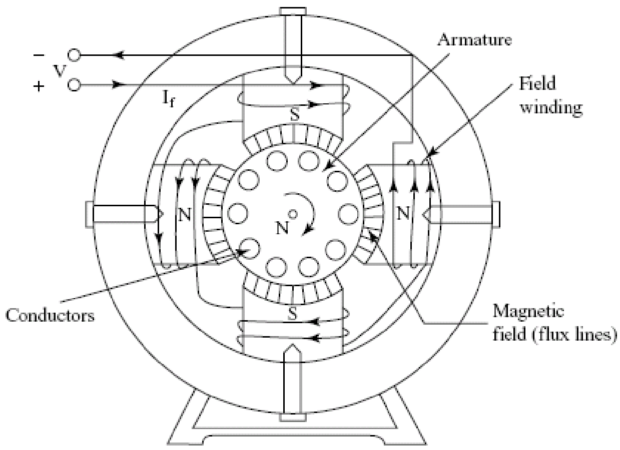


Figure 7.1 Cross-sectional view of a four-pole dc machine

All the field–pole windings have been shown connected in series. The direction of current flow in the pole windings are such that alternate North and South poles have been formed. The field system have been energized by passing current, I_f through their windings from a separate dc source. To understand the working of a dc generator we will consider, for simplicity, a two-pole construction having only one coil on the armature. The two terminals of the armature coil are to be brought out for connection to the load circuit. For this, two arrangements are possible, i.e., (i) through brush and slip-ring arrangement, and (ii) through brush and commutator arrangement. We will consider these two arrangements side by side and see the nature of output voltage and load current.

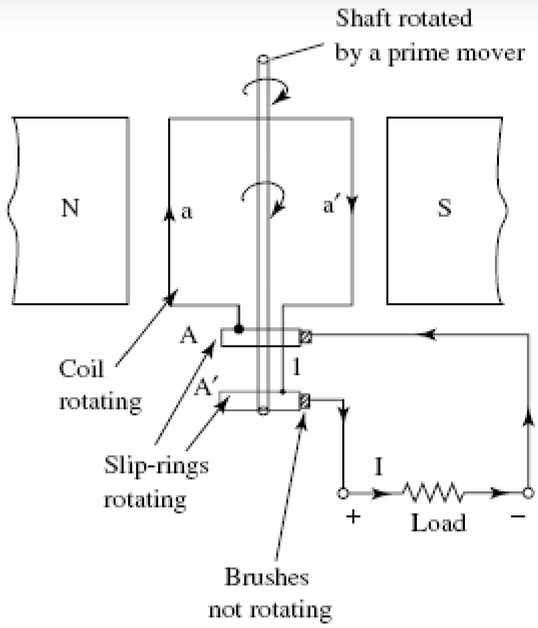
7.1.1 Nature of Load Current When Output is Taken Out Through

shaft is rotated by a prime mover, the coil rotates. The slip rings are nothing but extensions of the coil-end connections. The slip rings also rotate as the coil rotates. The brushes sit on the slip rings and make sliping contact with the coil and are able to connect the EMF generated to the load for supply of current.

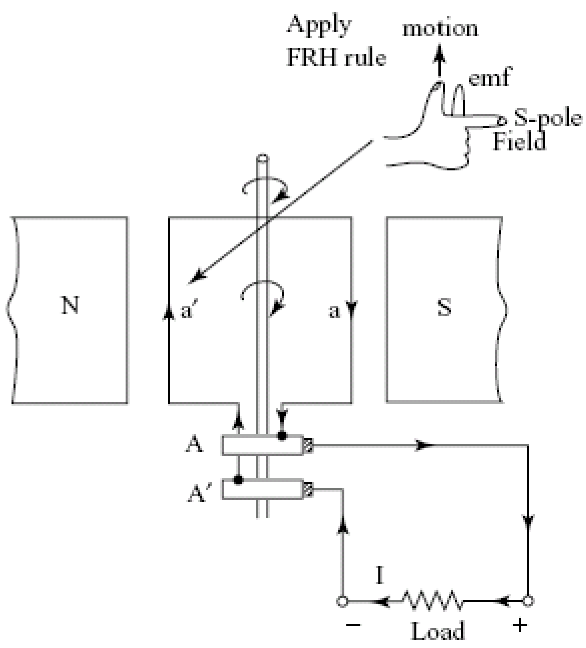
In Fig. 7.2 (a), the coilside a of coil a–a′ is under North pole and the coilside a′ is under South pole. After half revolution the positions of the coilsides change as shown in Fig. 7.2 (b). The direction of EMF induced in the coilsides have been shown. The EMF induced will cause current to flow through the load resistance as shown. It is noted that the direction of current through the load resistance has changed after half revolution of the coil.

In Fig. 7.2 (a), current flows from a to a′ and after half revolution of the coil, current in the coil flows from a′ to a. After every half revolution, current in the coil will get reversed.

When the armature is rotated continuously by the prime mover, the EMF induced in the coil is alternating in nature as can be seen from Fig. 7.2 (a) and (b). The direction of EMF induced in the coil sides a and a′ has been determined by applying Fleming's Right-Hand rule. We can conclude that when a coil is rotating in a magnetic field, an alternating EMF is induced in it which will cause an alternating current to flow through the load resistance if connection is made through the brush and slip-ring arrangement.



(a) Coil rotating in a magnetic field



(b) After half revolution of the coil

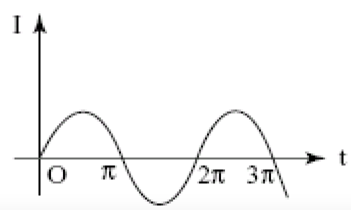


Figure 7.2 AC generated in the coil causes ac to flow through the load when connection is through brush and slip-ring arrangement

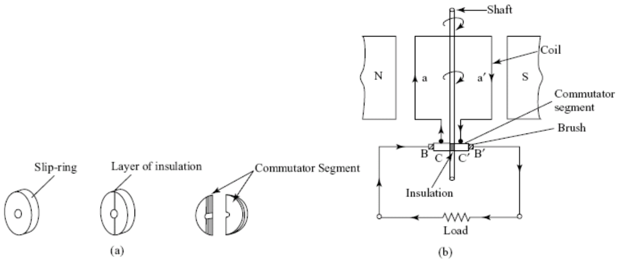


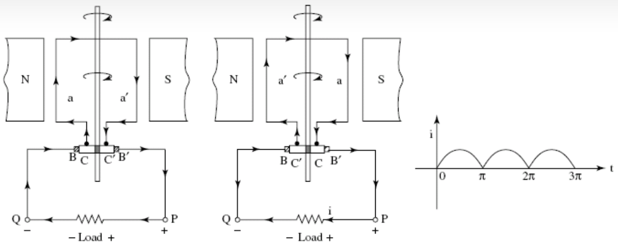
Figure 7.3 (a) a slip ring cut into two pieces with a layer of insulation between the pieces; (b) a coil rotating in magnetic field has been connected to the load through brush and commutator arrangement

7.1.2 Nature of Load Current When Output Is Taken Through Brush and Commutator Arrangement

Now we will consider a brush and commutator arrangement of connecting the rotating coil to the load. When a slip ring is cut into two pieces and joined together by putting insulation in the joints, a simple commutator assembly with two commutator segments are produced. The coil ends are connected permanently to the two commutator segments. The commutator is fixed on the shaft and rotates along with the coil when the shaft is driven by the prime mover as has been shown in Fig. 7.3.

The direction of the induced EMF in the coil sides is determined by applying Fleming's Right-Hand rule. When the coil is connected to the load, current will flow through the load as has been shown. Current from coil side a′ flows to the load through commutator segment C′ and brush B′. From the load, the current returns to the coil through brush B, commutator segment C and then to the coil side a. No current can flow from commutator segment C to C′ or from C′ to C as there exits a layer of insulation between them. With such an arrangement when the coil rotates in the magnetic field, a unidirectional current will flow through the load as has been shown in Fig. 7.4 (a) and (b). In Fig. 7.4 (a), current in the coil flows from coil side a to coil side a′. After half revolution the direction of current is changed from a′ to a. In every half revolution of the coil, this change in direction of current will take place. The current through the load resistance, however, will be unidirectional because the connections from the armature coil to the load have been taken through brush and commutator.

It is observed from the output current wave shape that we are getting a fluctuating dc and not a constant dc. In actual practice, in a dc generator, instead of using a single coil a large number of coils are placed on the armature slots so as to generate a considerable amount of voltage. Consequently, a large number of thin commutator segments are used to make the commutator assembly. The sum of the EMFs induced in the armature coils when connected to the load through the brush and commutator arrangement will be a



(a) A coil is shown rotated in a magnetic field by a prime mover. The direction of current flowing through the load is from P to Q

(b) After half revolution the position of coil sides along with commutator segments change. The position of brushes are fixed.Load current flows from P to Q

(c) Output wave shape of the load current

Figure 7.4 (a) A coil is shown rotated in a magnetic field; (b) after half revolution the position of the coil side along with commutator segments change, the position of brushes remain unchanged; (c) output dc wave shape of the load current

The function of brush and commutator in a dc machine working as a generator is to convert ac generated in the armature coils into dc at the output.

7.1.3 Function of Brush and Commutators in Motoring Action

We shall now examine the operation of an elementary dc motor by considering a single coil (for simplicity) on its armature. In a dc machine, operating as a motor, electrical energy is converted into mechanical energy. Fig. 7.5 shows the armature coil fed from a source of dc supply. The armature having the coil on it is placed in a magnetic field created by the field system as shown in Fig. 7.5 (a).

In Fig. 7.5 (b) is shown how current will flow from the positive polarity of the supply source through brush B′ and commutator segment C′ to coil side a′ and then to coil side a, returning through commutator segment C and brush B to the negative terminal of the supply source. By applying Fleming's Left Hand rule to coil-side a′ in Fig. 7.5 (b) we find that the conductor will experience an upward force whereas the coil side a will experience a downward force. These two forces would create a torque to rotate the armature in the anticlockwise direction.

After every half revolution, i.e., for every rotation of 180° mechanical, coil side a′ along with the connected commutator segment C′ will change positions with the coil side a and the connected commutator segment C. After half revolution it is seen that the direction of current in the coil has reversed. Earlier as in Fig. 7.5 (b), current was flowing from a′ to a and after half revolution current is flowing from a to a′ as shown in Fig. 7.5 (c).

Supply polarities remaining fixed, it is seen that current in the armature coil is alternating its direction. However, the direction of the rotation of the coil, as obtained, is unidirectional, i.e., in this case in the anti clockwise direction. The students are advised to check the nature of torque developed in the armature if the supply is given from a dc source but through the brush and slip-ring arrangement. It will be seen that the torque developed will be alternating in every

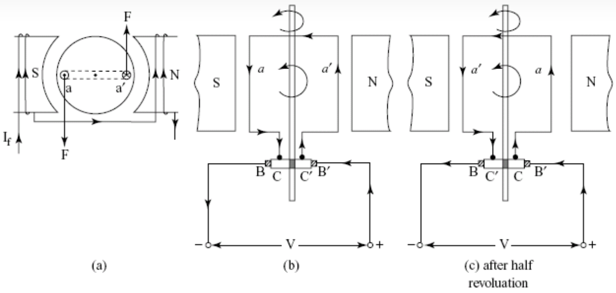


Figure 7.5 Illustrates motoring operation. Supply is through brush and commutator arrangement for achieving continuous rotation

Thus, it can be concluded that the function of brush and commutator in a dc motor is to produce unidirectional torque, i.e., to cause rotation of the armature of the motor in a particular direction.

We shall now study the constructional details of a dc machine.

7.2 CONSTRUCTIONAL DETAILS

A dc machine consists of a field system which produces the magnetic field, the armature which carries the armature conductors placed in slots, the brush and commutator arrangement, the shaft, and the bearings.

These are explained in brief in the following sections.

7.2.1 The Field System

The purpose of the field system is to produce a magnetic field inside which a set of conductors will be rotating. The field system consist of a set of electromagnets fixed on the inside periphery of a hollow cylindrical structure called the yoke as shown in Fig. 7.6. The field poles have field windings wound on a laminated iron core. The number of poles of a dc machine may be two or multiples of two. A dc current supplied from a dc source magnetizes the field system. Alternate North and South poles are formed on the basis of the direction of the current flowing through the field windings. Small poles, called interpoles are often fixed between two main poles, particularly in case of large dc machines.

The field windings are made of thin insulated copper wire of a large number of turns. The resistance of field winding is fairly high of the order of 100 Ω or so. The side view of such a field system has been shown in Fig. 7.6 (a).

7.2.2 The Armature

The armature of a dc machine is built by using circular laminated sheet steel to form a cylindrical structure with a shaft passing through its centre.

A simplified cross-sectional view of a dc machine with the armature placed inside the field system has been shown in Fig. 7.7.

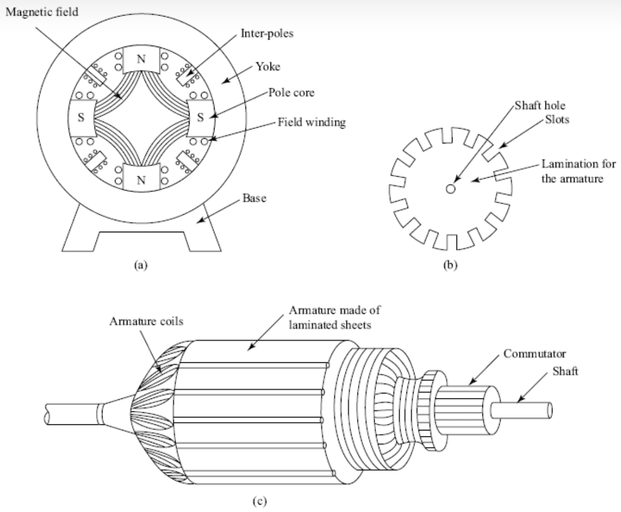


Figure 7.6 Parts of a dc machine: (a) the field system creating a magnetic field when current will flow through the field windings; (b) laminated sheets used to make the cylindrical armature; (c) the armature made of laminated sheets and the commutator assembly

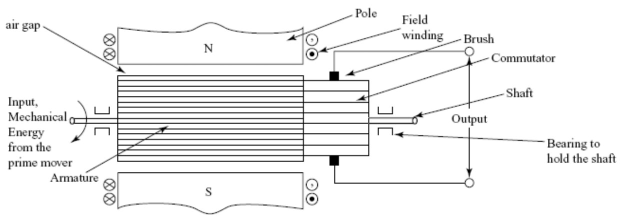


Figure 7.7 Simplified diagram of a dc machine working as a generator

In a dc machine the field system is stationary while the armature along with the commutator is the rotating part. The armature winding is made using a large number of coils connected in series and parallel to get the desired voltage and current. The coils are made of insulated copper wires and are placed in a large number of armature slots. The coil ends are connected to large number of commutator segments of the commutator. The commutator segments are insulated from each other using some good quality thin insulating sheets like mica sheets. Carbon brushes are placed on the commutator surface and terminals are brought out from the brushes.

The air-gap between the field poles and the armature is kept small, of the order of few mm. The commutator, like the armature, is cylindrical in shape and is made up of a large number of wedge-shaped segments of hard drawn copper. The fixed carbon brushes sitting on the commutator surface make slipping contacts with the armature are placed in brush holders which are fixed with the stationary part of the machine. When the armature rotates, the brushes and the commutator surface make constant smooth rubbing, which over a period of time reduces the length of the brushes (due to wear and tear). There is no deterioration of the surface of the commutator due to this rubbing action. When required, the set of brushes can be replaced by new ones.

Armature and the commutator together is made into one unit. A shaft made of mild steel runs through the armature and comes out from both sides. Two sets of bearings are used to support the whole of the revolving system. The shaft extension on one end is used to connect the prime mover while at the commutator end the shaft is extended for use of the bearing. The shaft is held in position inside the stator with the help of end shields.

7.2.3 Armature Winding

When the armature coils rotate in the magnetic field, EMF is induced in each coil. If all the coils are connected in series, the total EMF available will be the sum of all the EMFs in all the coils. But the current that this winding would be able to deliver to the load will be governed by the current-carrying capacity of each of the armature coils. If higher current to desired, the coils have to be connected in series and parallel. Thus, the armature winding will have a set of coils connected in series in each of its parallel paths as shown in Fig. 7.8 (a) and (b). The arrangement is exactly similar to series–parallel connection of cells used to make a battery of certain voltage and ampere rating.

Let the armature winding be made of 16 coils. When the armature is rotated in the magnetic field at a certain speed, let EMF induced in each coil be 2 V. Let the current-carrying capacity of each coil be 3 A. If all the coils are connected in series to form the total armature winding, we will get 32 V across the armature terminals and a maximum current of 3 A can be delivered to the load. If the current increases beyond 3A, the winding will get heated up excessively, which is not desirable. If four coils are connected in series, there will be four series circuits which will induce an EMF of 8 V in each circuit. If the four series circuits are connected in parallel to supply current to the load, a maximum of 12 A can be supplied to the load although the rated current of 3A will flow through each coil as shown in Fig. 7.8 (a) and (b). Here the parallel paths of the armature winding is four. However, depending on the voltage and current requirements, the number of parallel paths could be different, say 2, 4, 6, etc.

7.2.4 Types of Armature Winding

All the coils placed in armature slots are connected together in a particular manner to form the armature winding. Two basic types of winding connections are made. They are (i) lap winding and (ii) wave winding. In all cases, the coil ends are connected to commutator segments. The commutator segments are, in fact, extension of coil end connections. Brushes placed on commutator touching the commutator segments make sliping contact with the coils. The two types of armature windings are explained below.

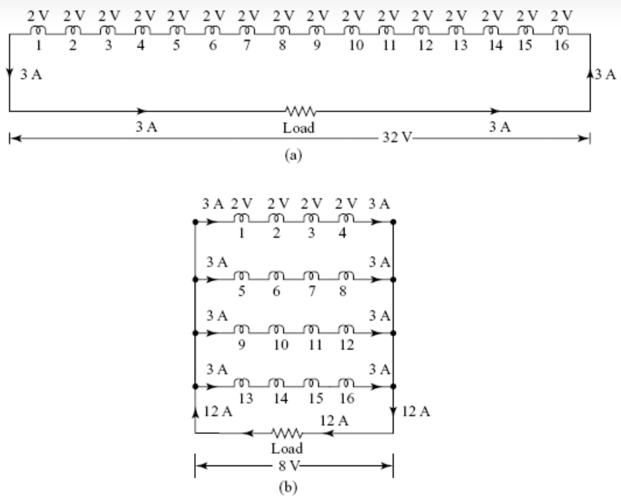


Figure 7.8 Series–parallel connection of armature coils to form the armature winding: (a) series connection of all the armature coils; (b) series–parallel connection of the coils

(a) Lap winding

Here, the end of one coil is connected to the beginning of the next coil. If connections are made this way the coils look as if they are super imposed on each other and then given a push in one direction as shown in Fig. 7.9 (a). Fig. 7.9 (b) shows a wave winding.

1 – 1′, 2 – 2′, 3 – 3′, etc. are the armature coils. In lap winding coil side 1′ is connected with coil side 2, coil side 2′ is connected to coil side 3 and this way the whole winding is completed. In lap winding the number of parallel paths formed in the armature winding is equal to the number of poles of the machine.

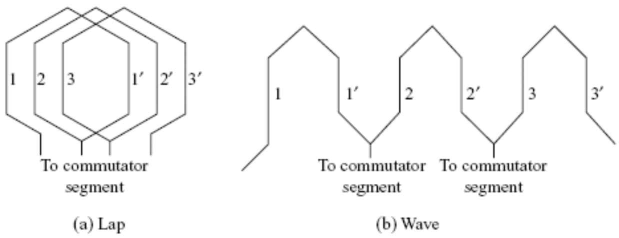


Figure 7.9 Lap and wave windings illustrated

(b) Wave winding

Here the winding connections are made as show in Fig. 7.9 (b). The end of one coil is connected to the next coil side under the next similar poles. The winding so formed looks like a wave, and hence the name. The number of parallel paths formed is always equal to 2. Note that the coils are connected to commutator segments in both types of windings.

netic field, the total number of conductors connected in series, and the total magnetic field flux being cut by the conductors. The exact equation in now being developed as under.

Fig. 7.10 shows a single conductor rotated by a prime mover in a magnetic field.

Let us assume the following:

No. of poles = P.

Flux per pole = ϕ Wb.

Speed of the driving prime mover = N rpm.

Actual number of armature conductors = Z.

Number of parallel paths of the armature winding = A.

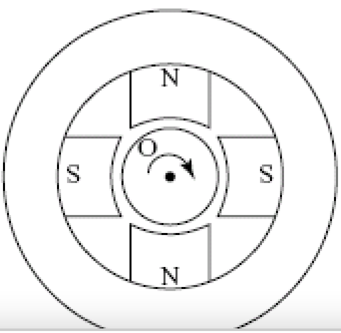
Induced EMF in the conductors will be due to relative velocity between the conductor and the flux produced by the field poles.

When the conductor in Fig. 7.10 makes 1 revolution, the flux cut by the conductor = Pϕ Wbs.

(The students will appreciate that if there were two poles and flux per pole was ϕ Wbs, the conductor would cut 2ϕ flux, for a four-pole system, the flux cut per revolution would be 4 ϕ Wbs, and so on). Thus, if f is the flux per pole, and P is the number of poles, flux cut by a conductor in 1 revolution will be Pϕ Wbs.

The conductor is rotating at a speed of N rpm or $\frac{N}{60}$ (revolutions per second)

Time taken by the conductor to make 1 revolution = $\frac{60}{N}$ seconds.



Therefore, induced EMF in 1 conductor

$$= \frac{\text{Flux cut in 1 revolution in Wbs}}{\text{Time taken in making 1 revolution in secs}}$$

$$= \frac{P\phi}{60/N} = \frac{P\phi N}{60}\,\text{V}$$

Z is the total number of armature conductors and they are connected in A number of parallel paths. The total number of conductors per parallel path would be equal to $\frac{Z}{A}$.

The induced EMF available across the output terminals will be equal to the induced EMF per parallel path.

Thus the total induced EMF, E is

$$E = \frac{P\phi N}{60}\left(\frac{Z}{A}\right)\text{V}$$

or,

$$E = \frac{\phi ZNP}{60A}\,\text{V} \qquad (7.1)$$

When the dc machine is also working as a motor, the current-carrying conductors placed in the magnetic field will develop torque and rotate in a particular direction. When they would rotate, EMF will also be induced in them.

The equation for induced EMF will be the same both in generating and motoring mode of operation of the machine. The induced EMF in the armature of a dc motor is often called back EMF as it opposes the applied voltage.

7.4 TYPES OF DC MACHINES

In the dc generator shown in Fig. 7.11, the armature has to be rotated by some prime mover and the field windings have to be excited by giving a dc supply to them. We, therefore, would need a separate dc source of supply for the field winding. Such a generator where the field winding is supplied from a separate dc source for its excitation is called a *separately excited dc generator*.

EMF E will be induced in the armature when it is rotated by a prime mover and the field windings are excited from a separate dc source.

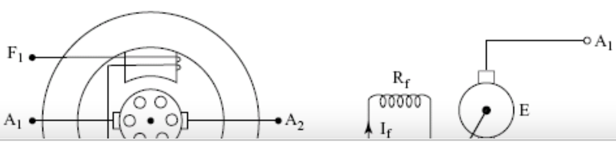


Figure 7.11 (a) A dc generator with field and armature winding terminals brought out; (b) the field windings of the generator are excited from a dc supply source

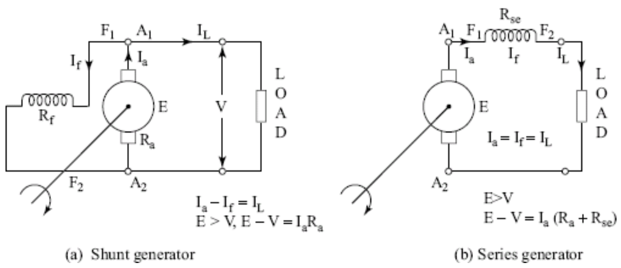


Figure 7.12 (a) Shunt generator; (b) series generator

Now, let as consider what would happen when the armature is rotated by a prime mover without exciting the field windings, i.e., when field winding current, $I_f = 0$.

Even when the field windings are not excited, there is some residual magnetizm in the field poles due to their earlier excitation.

A feeble magnetic field will, therefore, exist due to which a very small amount of voltage will be induced in the armature winding when rotated. Let us assume that this induced EMF is 5 V. If the field winding having a resistance of say 100 Ω is connected across the armature, a small amount of current, 5 V/100 Ω = .05 A will flow through the field windings, which will produce some more flux, and as a consequence more EMF will be induced in the armature. This way voltage will be built up across the armature terminals when the field windings are connected in parallel with the armature as shown in Fig. 7.12 (a). Such a generator is called a shunt generator or a *self-excited generator*.

Fig. 7.12 (b) shows the connection diagram of field and armature windings for a series generator. The field current I_f is equal to I_a, i.e., a very high current will now flow through the field windings. For a series generator, therefore, field windings are made of thick wires of a few turns to provide the required ampere turns needed for production of magnetic field of a particular strength.

A compound generator will have both shunt field winding and series field winding. Both the field windings are wound around the pole core. Shunt field winding is connected in parallel with the armature while the series field winding is connected in series with the armature. The resultant field produced will be equal to the sum of the field produced by the two field ampere turns. Such a generator is called a *cumulative compound generator.*

When the flux produced by the series field opposes the flux produced by the shunt field, the generator is called a *differential com-*

The characteristic of dc shunt, series, and compound generators will be different because of the way the field and armature windings are connected.

Let us examine the no-load and load characteristics of dc generators.

7.5.1 No-load Characteristics

Fig. 7.13 (a) shows a separately excited dc generator. The generator armature is rotated at a constant speed by a prime mover. When no field current is there, a small amount of EMF will be induced due to residual magnetism. By increasing the field current, I_f gradually, we will get the no-load or open-circuit characteristic as shown in Fig. 7.13 (a).

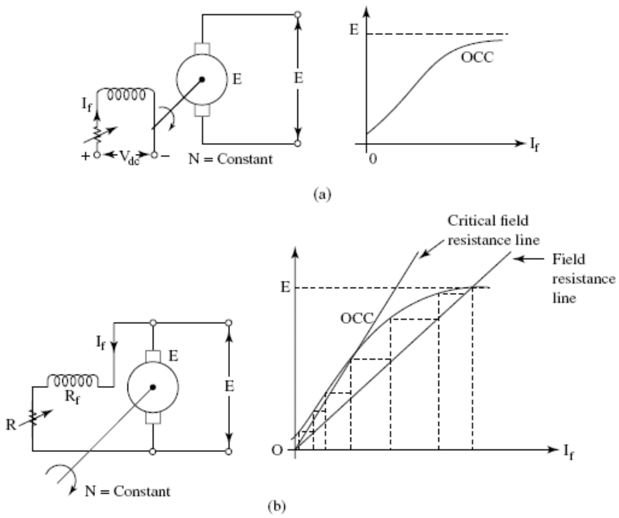


Figure 7.13 No-load or open-circuit characteristic (OCC) of dc generators: (a) separately excited generator; (b) shunt generator

In the case of a shunt generator, the voltage gets built up due to residual magnetism as has been shown in Fig. 7.13 (b). The induced voltage will be the value at which the OCC and field resistance line cross each other. By adjusting the value of the field-circuit resistance, i.e., by adding an extra resistance in the field circuit, the value of E can be adjusted. The speed of the prime mover is assumed constant. A self-excited dc shunt generator will fail to build up its voltage if there is no residual magnetism in the field poles and if the value of the field resistance in higher than the critical field resistance. The value of the critical field resistance can be determined by drawing a line tangent to the OCC and finding its slope. The students should notice that the OCC is initially linear, but later becomes somewhat horizontal. This shows that with increase of field current, I_f the induced EMF increases linearly but later the core saturates. Further increase of I_f does not give rise to much increase in induced EMF.

the load current I_L. The equation relating E, V, and I_a for a dc generator is given as

$$V = E - I_a R_a \tag{7.2}$$

Where R_a is the armature winding resistance and I_a is the current flowing through the armature winding.

Thus, as the generator is loaded, the voltage available across the load will be somewhat reduced due to I_a R_a drop. It may be noted that R_a is very small and is of the order of less than 1 Ω. Therefore, I_a R_a drop although small will reduce the terminal voltage with increase of load current or armature current. In addition, some more amount of voltage drop will be due to the reduction of the magnetic field strength when current flows through the armature winding which is called armature current reaction or simply armature reaction. This is explained as follows.

Effect of armature reaction

When the generator is loaded the armature current will produce a certain amount of flux that would come into existance in the air gap. This would create a demagnetization and cross-magnetization effect. The demagnetization component of the armature flux will work in opposition to the main field flux, thereby reducing the EMF induced, E and as a consequence reducing V. This effect of armature flux on the main field flux is called *armature reaction*. It may be noted that armature reaction occurs only when current flows through the armature winding i.e., only when the generator is loaded. Because of reduction of E due to *armature reaction, the terminal voltage E will further get reduced a little in case of shunt* generators. To *reduce the effect of armature reaction, compensating windings and inter poles are used,* which produces the same amount of flux as produced by the armature current but in opposite direction so as to eliminate the effect of armature flux on the main field flux. The load characteristics of dc generators have been shown in Fig. 7.14. The voltage drop from E to V is very small as compared to E. The shunt generators can be considered as constant voltage output generators for practical purposes.

In case of series generators, the field current is the same as the load current. Initially there is some induced EMF due to residual magnetizm of the field poles. As the generator is loaded, current through the field increases and E and V increase and later saturation effect takes place. Further loading increases the armature reaction effect and voltage starts falling.

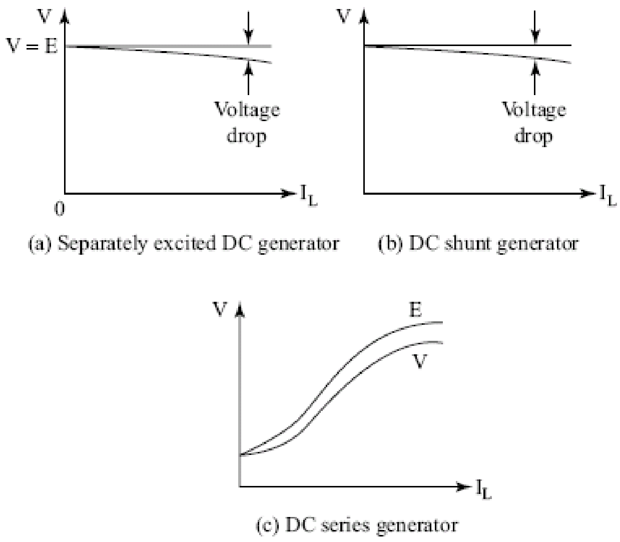


Figure 7.14 Load characteristics of dc generators: (a) separately excited dc generator; (b) dc shunt generator; (c) dc series generator

7.6 APPLICATIONS OF DC GENERATORS

Shunt generators are used in applications, such as for battery charging, dc excitation in ac generators, lighting applications etc. A series generator's load characteristic is a rising one. That is, as the load increases, voltage increases due to increase in field current. Such generators cannot be used for lighting applications as voltage variation will effect illumination level.

However, dc series generators can be used to boost up voltage of an existing system to compensate for the voltage drop in the system. Series generators are also used as welding generators and in arc lamps. The characteristics of dc compound generators can be modified by the use of series winding either in circumlative or in differential mode. That is, either the series field flux will be aiding the main field flux or opposing it. The operation of a dc machine as a dc motor will now be dealt with.

7.7 OPERATION OF A DC MACHINE AS A MOTOR

Like dc generators, dc motors are also constructed to work as dc shunt, series, and compound motors. In all such motors, electrical power input, i.e., $V \times I$ gets converted into mechanical output. The mechanical output is in the form of torque developed which enables the motor shaft to carry some mechanical load on it. For example, a dc motor will rotate the wheels of an electric train or a trolley bus. The constructional details of a dc motor is similar to that of a dc generator except for certain minor changes in the cooling system.

7.7.1 Working Principle of a DC Motor

A dc motor works on the basic principle that when a current-carrying conductor is placed in a magnetic field it experiences a force. In a dc motor, the armature carries a number of conductors placed in slots and the armature is placed inside the magnetic field created by a dc supply source of V Volts as shown. The direction of current flowing through the winding have been shown by cross and dot A cross indicates current flowing in the direction perpendicular to the plane of the paper downwards and a dot indicates that current is coming towords the observer looking into the paper.

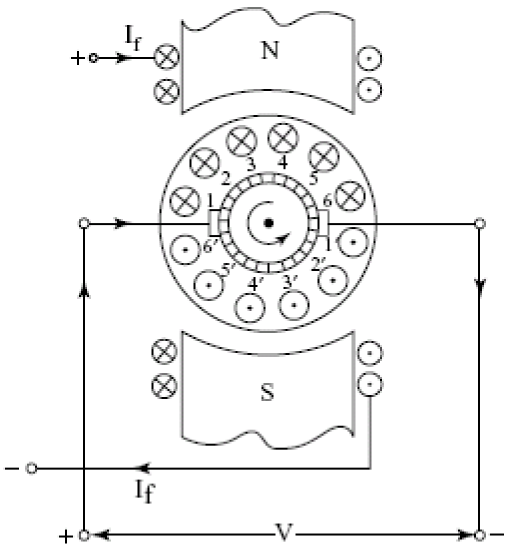


Figure 7.15 Working principle of a dc motor illustrated

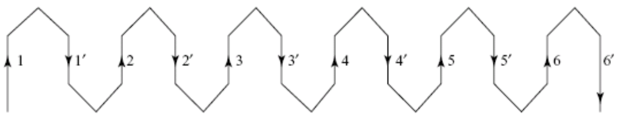


Figure 7.16 Coils 1–1′, 2–2′, 3–3′, 4–4′, 5–5′, and 6–6′ of the armature are shown connected in series

There are six coils 1–1′, 2–2′, 3–3′, 4–4′, 5–5′, and 6–6′ placed in armature slots. Current in coil sides 1, 2, 3, etc. are shown by cross and current at the other coil sides, i.e., 1′, 2′, 3′, etc. are shown by dots. The flow of current through the coils has been shown diagrammatically as in Fig. 7.16. By applying Fleming's Left-Hand rule, it is seen that force developed on the upper half of the armature conductors in Fig. 7.15 is from right to left and for the lower half of the armature conductors it is from left to right. These forces lead to development of torque which causes rotation of the armature in the anticlockwise direction as shown in Fig. 7.15. It may be noted carefully from the figure that as the armature rotates in the anticlockwise direction, current in the conductors of a coil passing under the brushes would change. This will ensure that at any point of time any

7.7.2 Changing the Direction of Rotation

The direction of rotation of the armature will change if the polarities of supply to either the armature or to the field windings are changed. If the polarities of supply to both the field and armature are changed, the direction of rotation will remain unchanged. This has been shown diagramatically as in Fig. 7.17.

Thus, to change the direction of rotation, we have either to change the polarities of supply to the armature or to the field.

7.7.3 Energy Conversion Equation

When the armature of the dc motor starts rotating because of the interaction between the field flux and the current-carrying armature conductors, EMF will be induced in the armature as the conductors are cutting the field flux. This EMF and the EMF induced in the armature when the machine is working as a generator is the same. However, now this EMF will oppose the supply voltage, V. Since the EMF induced opposes the supply voltage, it is also known as back EMF, E_b such that

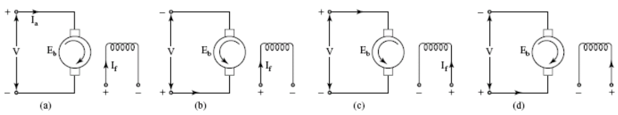


Figure 7.17 Method of changing the direction of rotation of a dc motor: (a) polarities of both armature and field positive, leading to clockwise rotation; (b) polarities of armature changed, leading to anticlockwise rotation; (c) polarities of supply to field changed, leading to anticlockwise rotation; (d) polarities of both armature and field reversed, no change in direction of rotation

From equation (iii) we can write for a dc motor,

Electrical Input power = Electrical equivalent of mechanical power developed + Armature copper loss

Electrical equivalent of mechanical power developed – Rotationed losses = Mechanical power output

7.8 TORQUE EQUATION

Torque developed T, angular velocity ω, and mechanical power, P are related as

$$P = T\omega$$

$$E_b I_a = T\omega = T\frac{2\pi N}{60}$$

or, $$T = \frac{60}{2\pi N} E_b I_a$$

$$= \frac{60}{2\pi N}\frac{\phi ZNP}{60A} I_a = \left(\frac{ZP}{2\pi A}\right)\phi I_a$$

Torque, $$T = K\phi I_a \tag{7.4}$$

where $$K = \frac{ZP}{2\pi A}$$

Thus, we can say that torque developed is proportional to the magnetic field strength or the magnetic flux ϕ and the magnitude of current I_a flowing through the conductors placed in the magnetic field.

7.9 STARTING A DC MOTOR

For a dc motor we can express armature current as (see eq. 7.3)

$$I_a = \frac{V - E_b}{R_a} \quad \text{and} \quad E_b = E = \frac{\phi ZNP}{60\,A}$$

where R_a is the armature winding resistance and E_b is the back EMF or induced EMF in the armature.

At the moment of start, the speed N of the motor is zero. If N = 0, E_b = 0.

Thus, $$I_a = \frac{V}{R_a}$$

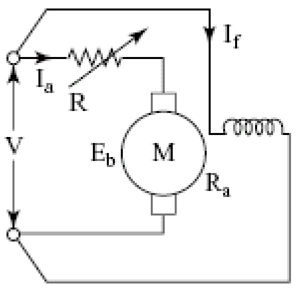


Figure 7.18 Starting of a dc motor with a variable resistance connected in the armature circuit

The value of armature resistance for a dc motor is very small. Let us assume that V = 220 V and R_a = 0.5 Ω. Then at start,

$$I_a = \frac{220}{0.5} = 440\ \text{A}$$

This is a huge current to be allowed to flow through the armature in a small dc motor. To restrict this high amount of current to flow through the armature, a variable resistance can be connected in series with the armature so that eq. (7.3) gets modified as

$$I_a = \frac{V - E_b}{R_a + R} \tag{7.5}$$

Once the motor starts rotating, back EMF E_b starts increasing and the numerator of the expression for I_a as in eq. (7.5) gets reduced. As the numerator goes on reducing, the denominator of expression (7.5) can be gradually reduced by reducing the value of variable resistance, R. This resistance is completely cut out of the circuit, once the motor picks up sufficient speed.

This variable resistance connected in the armature circuit is called a starter. *Thus, a starter is a variable resistance connected in series with the armature circuit to limit the initial current drawn by the motor*. Once the motor picks up speed, back EMF E_b comes into full existence, and automatically the armature current gets reduced even when the extra resistance is cut out. Removing the extra variable resistance from the circuit when it is not required is essential to avoid unnecessary wastage of energy as I^2R loss.

7.10 SPEED CONTROL OF DC MOTORS

The basic equations for a dc motor are

$$E_b = \frac{\phi ZNP}{60A} = K\phi N \tag{7.6}$$

from (7.6) and (7.7),

$$N = \frac{E_b}{K\phi} = \frac{V - I_a R_a}{K\phi} \tag{7.8}$$

From this expression for speed, we can say that the speed N of the motor can be changed by any or a combination of the following

By changing the supply voltage V, the speed can be changed. As supply voltage can only be reduced, speed N can also be reduced from its rated value by this method.

7.10.2 Field Control Method

By varying the flux ϕ, speed can be changed. The field current produces the flux ϕ, and hence this method is called the field control method. By putting a variable resistance in the field circuit, field current can be reduced, and hence flux produced can be reduced. When flux is reduced, speed is increased. Thus, by the field control method the speed of the motor can only be increased. See eq. (7.8).

By a combination of voltage control and field control methods, the speed of the motor can be increased and also decreased above and below its normal speed.

7.10.3 Armature Control Method

By putting an extra variable resistance in the armature circuit the speed can be reduced as

$$N = \frac{V - I_a(R_a + R^{\nearrow})}{K\phi} \text{ where } R^{\nearrow} \text{ is a variable resistance}$$

It can be seen here that the speed can only be reduced because the numerator will get reduced.

7.11 STARTER FOR A DC MOTOR

We have mentioned earlier that a starter is a variable resistance connected in series with the armature circuit during starting to reduce the starting current. This resistance is gradually cut out as the motor starts running. Two types of starters, namely a three-point starter and a four-point starter are described below.

7.11.1 Three-point Starter

A three-point starter circuit is described as follows. To start the motor, the starter arm, as shown in Fig. 7.19 (a) is moved in the clockwise direction. The arm will touch the point 1 of the starting resistance R. The whole of the resistance will appear in the armature circuit. The field winding will also get full supply through the coil of the NVR. The motor will develop torque and start rotating with full starting resistance in the armature circuit. The resistance will be cut in succession by moving the starter arm in the clockwise direction and will be brought to RUN position. In the RUN position, the soft iron piece fixed on the starter arm will face the NVR magnet piece and remain attracted. The starter arm, therefore, will stay in the RUN position against the spring tension, and the operator can remove his hand from the arm. In case of supply failure, the NVR electromagnet will get de-energized, and the starter arm will automatically return to OFF position due to the spring pressure. In case the motor is over loaded, the armature will draw excessive current which is not desirable. The coil of the OLR will remain energized electromagnet. The starter arm will eventually return to OFF position stopping the motor.

Protecting devices like no-volt-release (NVR) and over-load-release (OLR) mechanisms have been added while designing a dc motor starter. The starter shown in Fig. 7.19 (a) is called a three-point starter. The three points or connection points are designated as L, A, and F. The connection of the starter terminals to the motor armature and field terminals and the supply terminals are as follows. Connect one supply line to L. Connect one armature terminal A to point A and connect starter terminal F to field terminal F as has been shown in Fig. 7.19 (a). The other ends of armature and field, i.e., AA and FF are joined together and are connected to the supply line L_2.

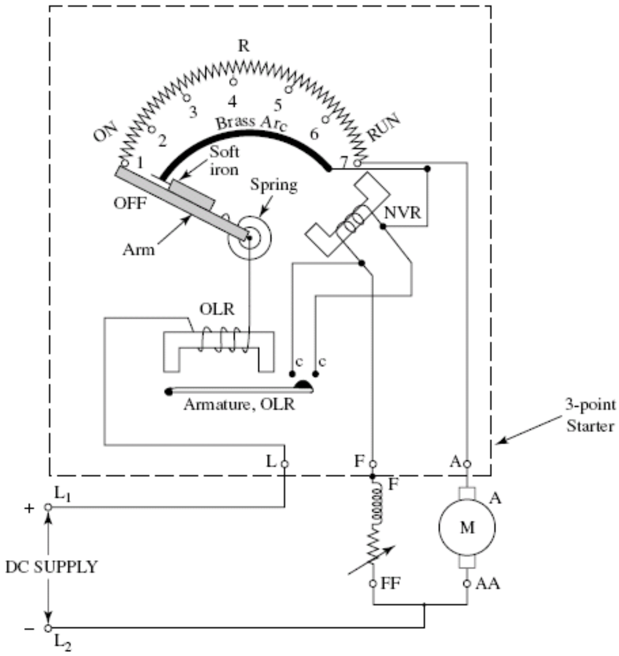


Figure 7.19 (a) Three-point starter connections for starting a dc motor

Figure 7.19 (b) A four-point starter for a dc motor

7.11.2 Four-point Starter

The disadvantage of a three-point starter is that when a large value resistance is connected in the field circuit to increase the speed of a motor, the field current gets reduced. Since the field winding and may release the arm of the starter during normal running of the motor when current flowing through its coil becomes too small. The effect of this will be that the motor will stop, which may not be desirable.

In a four-point starter the NVR coil is connected independently across the supply voltage instead of connecting it in series with the motor field winding.

Thus, in a four-point starter there will be three parallel circuits connected across the supply voltage as has been shown in Fig. 7.19 (b). When the starter arm is brought to the ON position, current will flow through the armature circuit through the starter resistance. Current will flow from the supply via the starting arm and the starter resistance. This will limit the starting current to a large extent. Simultaneously, the field circuit will also get full supply through the brass arc. The variable resistance, R_1 can be used to control the field current to control the speed of the motor. Current will also flow through the NVR coil as supply will come through the starter arm, the brass arc, and following the path abcde as has been shown. Thus, change in field current, I_f will not have any effect on the current flowing through the NVR coil circuit. When the starter arm is brought to the RUN position, the armature will attain full speed and remain connected to the supply via the starter arm. The field circuit and the NVR circuit will get full voltage independently. The NVR will keep the starter arm in the RUN position even after the hand is released. The spring tension cannot bring back the arm to OFF position because of the attractive force of the NVR. In case of overload, the NVR terminals will be short circuited due to the attractive force of the OLR and the starter arm will get released

7.12 TYPES AND CHARACTERISTICS OF DC MOTORS

DC machines are available as shunt, series, and compound machines. In motoring mode of operation, they are called dc shunt motors, dc series motors, and dc compound motors. The relationship between three variables, namely torque, speed, and load (load current) are studied to find the suitability of each type of motor for different applications. For example, if a mechanical load has to be rotated at a constant speed, we would need a motor as a drive whose speed will remain constant at all loads, i.e., there should not be any variation of its speed from no-load condition upto full-load condition. Again, if a set of dc motors are to drive an electric train, the starting torque developed by the motors should be very high. The motors have to develop sufficient torque so as to start the train from rest condition with a large number of passengers and other loads inside the train.

The characteristics of all types of motors are drawn as follows.

7.12.1 Characteristics of DC Shunt Motors

The basic equations of a dc motor are

$$E_b = K\phi N$$

$$E_b = V - I_a R_a$$

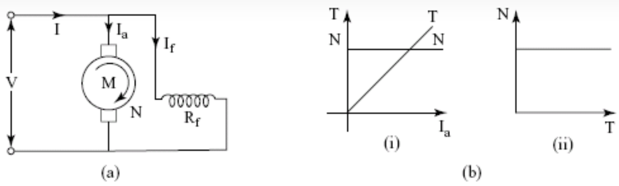


Figure 7.20 (a) DC shunt motor; (b) characteristics of a dc shunt motor

$$T = K\phi I_a$$

$$N = \frac{V - I_a R_a}{K\phi}$$

For a shunt motor flux produced by the field current is directly proportional to the field current.

Hence,

$$\phi \propto I_f$$

From Fig. 7.20 (a),
$$I_f = \frac{V}{R_f}$$

As can be seen from Fig. 7.20 (a), when V and R_f are constant, I_f will be constant.

Since I_f is constant, ϕ is constant. Then

$$T = K\phi I_a = K_1 I_a \quad \text{where } K\phi = K_1$$

$$\therefore \quad T \propto I_a$$

Torque T versus current I_a characteristic has been shown in Fig. 7.20 (bi).

$$N = \frac{V - I_a R_a}{K_2 I_f} \quad \text{where } \phi = \frac{K_1}{K} = K_2$$

Thus, N will remain constant as I_a, which is proportional to load, increases as has been shown in Fig. 7.20 (bi).

By knowing the variation of T and N against the load current, I_a, the relationship of T versus N can be drawn as shown in Fig. 7.20 (bii).

It can be seen that dc shunt motors are approximately constant speed motors and can be used in applications like lathe machines, drilling machines, milling machines, in printing press, paper mills, etc.

7.12.2 Characteristics of DC Series Motors

In a dc series motor the field winding is connected in series with the armature so that same current flows through the field and armature windings. The flux produced, ϕ is proportional to the field current which is equal to I_a. The relevant equations are written as

$$N = \frac{V - I_a R_a}{K\phi}$$

$$\phi \propto I_f \quad \text{and} \quad I_f \propto I_a$$

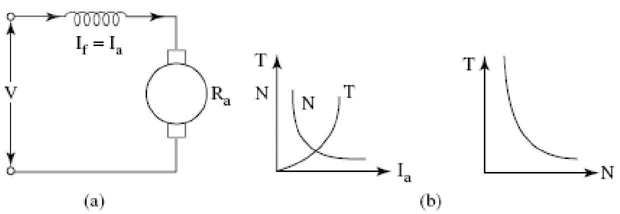


Figure 7.21 (a) Circuit diagram of a series motor; (b) characteristics of a dc series motor

Therefore,

$$\phi \propto I_a$$

$$T \propto \phi I_a$$

$$T \propto I_a^2$$

Since $I_a R_a$ is very small as compared to V, $V - I_aR_a$ ϕ V constant, and $f \propto I_a$

Therefore, from $N = \dfrac{V - I_a R_a}{K\phi}$

we can write $N \propto \dfrac{1}{I_a}$

i.e., $N \times I_a = \text{constant}$

Thus, the relations of N versus I_a and T versus I_a are drawn as shown in Fig. 7.21 (b). The relation between N and T is also drawn. From N versus T characteristics it is seen that at nee, i.e., at starting T is very high. That is, a series motor develops a very high torque at starting.

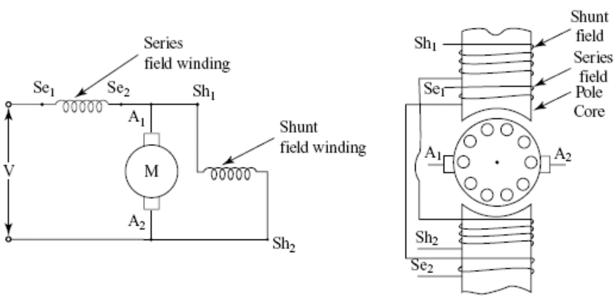
Therefore, a series motor is suitable for application as a drive motor in electric trains, cranes, hoists, trolley bus, etc., where the drive motor should develop very high starting torque.

From N versus I_a characteristic, it is observed that the motor will attain dangerously high speed when I_a is zero. That is, at no load the speed of the motor will be very high which may be dangerous. That is why a series motor is never allowed to run on no load. A load is always connected to its shaft before starting.

7.12.3 Characteristics of DC Compound Motors

In a compound motor two separate field windings are wound around each pole. One is shunt field winding and the other is series field winding. The shunt field winding is connected in parallel with the armature while the series field winding is connected in series with the armature as shown in Fig. 7.22. The flux produced due to the shunt field current remains constant but the flux produced by the series field current increases with the load current. The characteristic curves of a compound motor will be in between those of shunt and series motors.

The series field winding produces flux which is proportional to the armature current, i.e., the load on the motor. The flux produced by the series field either aids the shunt field or opposes the shunt field. (cummulative effect or differential effect). The characteristics relating T, N, I_a get modified from the shunt field characteristics as shown in Fig. 7.23.



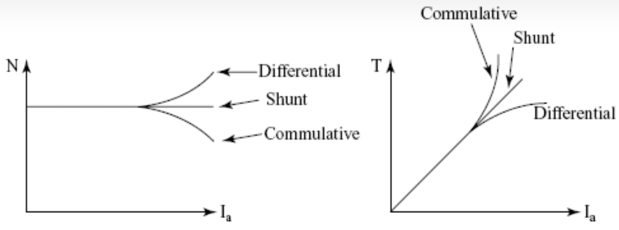


Figure 7.23 Characteristics of dc compound motors

In cummulative compound motors there is some drop in speed from no load to full load. For suddenly applied loads the motor speed gets reduced which may be advantageous in application like punching and shearing machines, rolling mills, lifts, mine hoists, etc. In differential compound motors, the resultant flux gets reduced as load increases, and hence the speed increases. This is seen from the expression for speed, N which is

$$N = \frac{V - I_a(R_a + R_{se})}{K\phi}$$

From the above expression it can be seen that if flux ϕ is reduced, speed N will increase.

7.13 LOSSES AND EFFICIENCY

The efficiency of a dc machine, like any other machine is the ratio of output power to the input power. The efficiency can never be 100 per cent because output is never equal to input. Some energy is lost in the machine during conversion of energy from mechanical to electrical or vice-versa. To achieve higher efficiency, the designer of the machine tries to keep the losses as low as possible.

7.13.1 Losses in a DC Machine

In a dc machine, like any other machines, the whole of input energy does not get converted into output energy. A portion of the input energy gets lost in the machine as shown in Fig. 7.24.

The various losses that take place in a dc machine are described as follows.

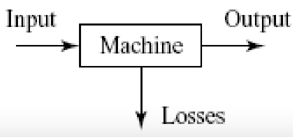


Figure 7.24 Shows the relationship between input, output, and losses

(a) I^2 R loss in the armature winding

Due to current flow in the armature winding a good amount of power gets lost as $I_a^2R_a$, where I_a is the armature current and R_a is the resistance of the armature circuit. As load on the machine changes, I_a also changes. Hence, $I_a^2R_a$ is called the variable loss as this loss varies with the variation of load on the motor.

(b) Core loss or iron loss in the armature

Iron loss or core loss consists of hysteresis loss and eddy current loss. The core is made up of magnetic material and is subjected to variations in magnetic flux. When the armature rotates it comes under North and South poles alternately. *Hysteresis loss* occurs due to the alternate magnetization of the magnetic material. *Hysteresis loss depends upon the flux density, the frequency of variation of flux, and the volume of the core material.*

Eddy current loss is due to the presence of circulating current in the core material. When the armature rotates in the magnetic field EMF is induced in the armature core also. This EMF causes a circulating current i_c in the core which is wasted as $i_c^2\ r_c$ and produces heat. To reduce eddy current loss in the core, the core is made up of varnished, laminated steel sheets instead of a solid core. This causes increase of resistance, r_c through which the eddy current flows. *Eddy current loss depends upon flux density, frequency of alternation of flux, thickness of laminations used, and the volume of the core material.*

(c) Loss in the field windings

Losses take place in the field windings due to flow of current. This loss is equal to (VI_f) W where V is the applied voltage and I_f is the field current.

(d) Friction and windage losses

Due to rotation of the armature, air-friction loss which is also called windage loss, takes place. Frictional loss occurs due to brush and commutator rubbing and loss due to bearing friction.

7.13.2 Efficiency of DC Machine

The efficiency of a dc machine is expressed as

$$\eta = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{Losses}}$$

$$= \frac{VI_a}{VI_a + I_a^2 R_a + V I_f + C}$$

Where C is the sum of iron, friction, and windage losses.

$$\frac{d}{dI_a}\left[\frac{V}{V+I_aR_a+\dfrac{(VI_f+C)}{I_a}}\right]=0$$

From which,

$$I_a^2\ R_a=(VI_f+C)$$

that is, *variable loss* = *constant loss*.

Thus, the efficiency of a dc machine will be maximum at a load at which the variable loss becomes equal to the constant loss of the machine.

Testing of DC machines: Determination of efficiency

Efficiency of a dc machine can be determined by directly loading the machine. The output is measured and input is recorded. The ratio of output power to input power will give the value of efficiency. This method of determining efficiency is called direct loading method. The output and input are to be expressed in the same unit.

Efficiency of large machines are calculated by indirect method, i.e., by measuring the losses. Indirect method is preferred because for large machines, loading of the machine may be difficult in the laboratory. Further energy will be wasted during experimentation. A popular method, known as *Swinberne's method* of determining efficiency is described as follows.

Swinberne's method

In this method the dc machine is run as a motor. The applied voltage and the speed is adjusted to their rated values as shown in Fig. 7.25. There is no load connected to the motor shaft.

When the motor is running on no load, the input power is wasted as losses. The losses at no load are (i) iron loss; (ii) friction and windage loss, and (iii) $I_{ao}^2\ R_a$ loss.

The armature current, I_{ao} at no load is small, and hence $I_{ao}^2\ R_a$ will be very small. However, this value can be calculated. Iron loss, and friction and windage loss depend upon supply voltage and motor speed, respectively. The supply voltage is kept constant and speed of the motor is approximately constant at all loads. These losses are called constant losses as they remain constant at all loads. Thus, we can calculate the constant losses by subtracting $I_{ao}^2\ R_a$ from the no-load input to the motor. By knowing the constant losses, efficiency of

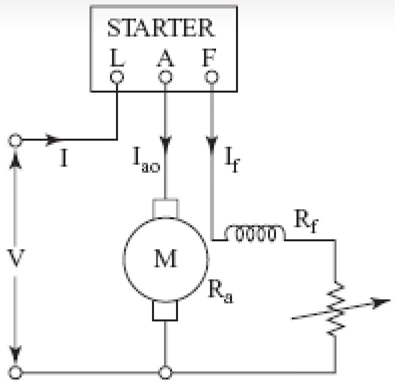


Figure 7.25 Swineberne's test for determining efficiency

Example 7.1 A 220 V, 50 kW dc shunt generator was run as a motor on no load at rated speed. The current drawn from the line was 8 A and the shunt field current was 2 A. The armature resistance of the machine is 0.1 Ω. Calculate the efficiency of the generator at full load.

Solution:

Input power at no load = VI

= 220 × 8

= 1760 W

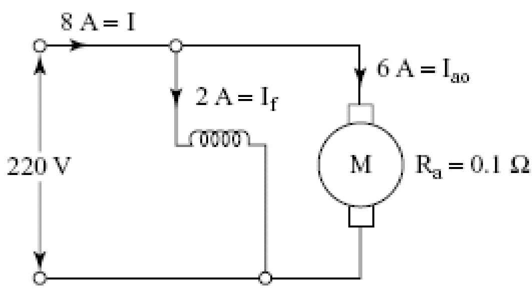


Figure 7.26

Iron, friction and windage, and field copper losses = No-load input – $I_{ao}^2 R_a$

= 1760 – 6^2 × 0.1

= 1760 – 3.6

= 1756.4 W

The generator output current at full load.

$$= \frac{50 \times 1000}{220} = 227.2 \text{ A}$$

$$\text{Full-load armature Copper loss} = I_a^2 R_a$$

$$= (229.2)^2 \times 0.1$$

$$= 5253 \text{ W}$$

This is the variable loss.

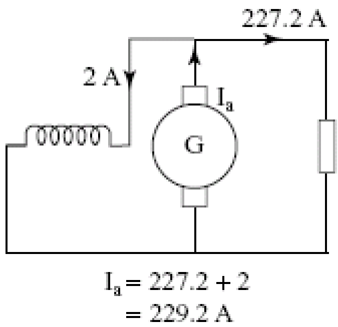


Figure 7.27

Efficiency of the generator in percentage = Output/(Output + Constant losses + Variable loss)

$$= \frac{50 \times 1000 \times 100}{50 \times 1000 + 1756.4 + 5253}$$

$$= 89 \text{ per cent}$$

7.14 APPLICATIONS OF DC MACHINES

7.14.1 DC Generators

In earlier days dc generators were used to generate electricity and the power was supplied to consumers through dc distribution networks. At present, use of dc generators for generation and distribution of electricity is rare. All commercial generators are ac generators which are also called alternators. Generation and transmission of alternating current has a number of advantages. The use of dc generators is confined to supplying excitation current to ac generators and to convert ac to dc for industrial applications.

7.14.2 DC Motors

where variable load has to be driven but at constant speed, such as driving a lathe, the speed change can be obtained using a shunt field regulator.

7.14.3 DC Series Motors

In applications where high starting torque is required, such as in driving hoists, cranes, electric trains, etc. series motors are used. Series motors are also used where the motor can be permanently coupled to the load, such as fans, where the torque requirement increases with speed.

Series motors attain very high speed at light load. That is why series motors should never be run on no load.

7.14.4 DC Compound Motors

DC compound motors are used in applications where large starting torque is required but there is a chance for the load to fall to a very low value. In such applications dc series motors cannot be used.

7.15 SOLVED NUMERICAL PROBLEMS

Example 7.2 A four-pole dc generator having wave-wound armature winding has 51 slots, each slot containing 20 conductors. Calculate the voltage generated in the armature when driven at 1500 rpm. Assume flux per pole to be 0.5 mWb.

Solution:

P = 4, A = 2 (because the armature winding is wave wound)

N = 1500 rpm

Total number of armature conductors, Z = 20 × 51

= 1020

Equation for induced EMF, $$E = \frac{\phi ZNP}{60A} V$$

Substituting values

$$E = \frac{0 \cdot 5 \times 10^{-3} \times 1020 \times 1500 \times 4}{60 \times 2}$$

= 255 V

Example 7.3 A six-pole, lap-connected dc generator has a total of 650 conductors. The flux per pole is 0·05 Wb. Calculate the speed at which the armature is to be driven to generate an EMF of 220 V.

Solution:

P = 6, A = P = 6 (because the armature winding is lap connected)

$$\phi = 0.05 \text{ Wb}; E = 220 \text{ V}$$
$$Z = 650, N = ?$$
$$E = \frac{\phi ZNP}{60A}$$

Substituting values

$$220 = \frac{0.05 \times 650 \times N \times 6}{60 \times 6}$$

or,

$$N = \frac{220 \times 60}{650 \times 0.05} = 406 \text{ rpm}$$

Example 7.4 A four-pole 220 V dc shunt generator supplies a load of 3 kW at 220 V. The resistance of the armature winding is 0.1 Ω and that of the field winding is 110 Ω. Calculate the total armature current, the current flowing through armature conductors, and the EMF induced. Assume that the armature winding is wave wound.

Solution:

Output power = 3 kW = 3000 W

Power = output voltage, V × Output current, I_L

$$I_L = \frac{3000}{220} = 13.6 \text{ A}$$

From the figure it can be seen that

Figure 7.28

The armature winding is wave wound. The number of parallel paths is 2. That is, all the armature conductors are connected in such a way that half the armature current flows through each path. Thus, current flowing though each armature conductor will be $I_a/2$ i.e., = 7.8 Amps. E is the EMF induced in the armature. A voltage drop of I_aR_a takes place in the armature winding when it is supplying current.

The remaining voltage, V is available across the load terminals.

Thus,

$$E - I_aR_a = V$$

Example 7.5 A four-pole, 12 kW, 240 V dc generator has its armature coils wave connected. If the same machine is lap connected, all other things remaining constant, calculate the voltage, current, and power rating of the generator.

Solution:

In a wave winding all the armature coils are arranged in two parallel paths. The current-carrying capacity of each conductor, therefore, will be half of the total armature current.

I × V = P

$$I = \frac{12 \times 1000}{240} = 50\ \text{A}$$

Current per path $= \frac{50}{2} = 25\ \text{A}$

Figure 7.29

When there will be lap connection of windings, armature coils will be connected in P number of parallel paths. That is, in this case there will be four parallel paths. If each conductor or coil carries 25 A, the total output current will be 100 A. The number of coils in each path will be reduced to half, and hence the induced EMF per parallel path will be = 120 V. The output power = 120 × 100 W = $\frac{120 \times 100}{1000}\ \text{kW}$ = 12 kW.

Thus, we observe that output power remains the same but the voltage and current ratings change.

Example 7.6 A dc shunt generator delivers 12 kW at 240 V while running at 1500 rpm. Calculate the speed of the machine when running as a shunt motor and taking 12 kW at 240 V. The armature resistance is 0.1 Ω and field resistance is 80 Ω.

Solution:

As a generator,

$$I_f = \frac{V}{R_f} = \frac{240}{80} = 3\text{ A}$$

$$I_L = \frac{12 \times 1000}{240} = 50\text{ A}$$

$$I_a = I_L + I_f = 50 + 3 = 53\text{ A}$$

$$E_g = V + I_a R_a = 240 + 53 \times 0.1$$
$$= 245.3\text{ V}$$

As a motor,

Let the speed of the machine as generator be N_1 and as motor be N_2

$$E_g = \frac{\phi Z N_1 P}{60\text{ A}} \text{ and } E_m = \frac{\phi Z N_2 P}{60\text{ A}}$$

or, $$\frac{Eg}{Em} = \frac{N1}{N2}$$

or, $$N_2 = N_1 \frac{Em}{Eg} = 1500 \times \frac{235.3}{245.3} = 1439\text{ rpm}$$

Figure 7.30

Example 7.7 A four-pole 220 V dc series motor has 240 slots in the armature and each slot has six conductors. The armature winding is wave connected. The flux per pole is 1.75×10^{-2} Wb when the motor takes 80 A. The field resistance is 0.05 Ω and the armature resistance is 0.1 Ω. The iron and friction losses 440 W. Calculate the speed of the motor. Also calculate the output horse power.

Solution:

In a series motor the armature winding and the field winding are connected in series across the supply voltage. Thus, the line current, field current, and the armature current are the same,

i.e., $I_a = I_f = I_L = 80$ A

The total member of armature conductors, $Z = 240 \times 6$

Figure 7.31

Power developed by the armature = E × I_a

$$= \frac{248 \times 80}{1000} = 19.84 \text{ kW}$$

Power output = Power developed – Iron and Frictional losses

= 19.84 − 0.44
= 19.4 kW

If we want to convert in horse power, we use the relation 1 kW = 0.735 hp.

Thus, power output = 19.4 × 0.735 = 14.26 hp.

Example 7.8 A 220 V dc shunt motor takes 5 A at no load. The armature resistance is 0.2 Ω and field resistance is 110 Ω. Calculate the efficiency of the motor when it takes 40 A on full load.

Solution:

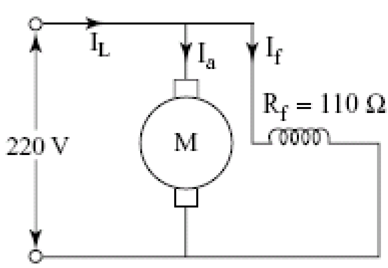


Figure 7.32

At no-load, I_L = 5 A

The whole of input is lost as $I_a^2 R_a$ loss + $I_f^2 R_f$ loss + Iron loss + Friction and Windage loss.

$I_a^2 R_a = 5^2 \times 0.2 = 5$ W
$I_f^2 R_f = 2^2 \times 110 = 440$ W

Iron, friction, and windage losses = 1100 − 5 − 440 = 655 W

These losses are constant losses and are same at any load. This means, on full load these losses will remain at 655 W.

At full-load, $I_L = 40$ A

Iron, friction, and windages losses = 655 W

Total losses = 289 + 440 + 655 = 1384 W

Efficiency
$$= \frac{\text{Output}}{\text{Input}} = \frac{\text{Input} - \text{losses}}{\text{Input}}$$
$$= \frac{(220 \times 40 - 1384) \times 100}{220 \times 40} = 84.3 \text{ per cent}$$

Example 7.9 A four-pole dc generator has 1000 conductors. The flux per pole is 25 mWb. Calculate the EMF induced when the armature is lap connected and run at 1500 rpm. At what speed the generator must be driven to produce the same EMF with the armature winding wave connected?

Solution:

Case I

$P = 4$, $Z = 1000$, $\phi = 25 \times 10^{-3}$ Wb
$A = 4$, $N = 1500$ rpm

Example 7.10 Calculate the output power of a 12-pole separately excited having 1200 lap-connected conductors each carrying a current if 15 A. The armature is being driven at 300 rpm. The flux per pole is 60 mWb. Resistance if armature circuit is 0.1 Ω.

Solution:

Current flowing in each parallel path is the same as current flowing through each conductor in the path. Since there are 12 parallel paths

Example 7.11 A four-pole, 500 V, wave-wound dc shunt motor has 900 conductors on its armature. Calculate the speed of the motor if its armature current is 80 A, the flux per pole is 21 mWb and armature resistance is 0.1 Ω.

Solution:

The back EMF induced in the armature of the motor is E_b.

For motor

$V - E_b = I_a R_a$

or,
$$\begin{aligned} E_b &= V - I_a R_a \\ &= 500 - 80 \times 0.1 \\ &= 492 \text{ V} \qquad \text{(ii)} \end{aligned}$$

Equating (i) and (ii)

Example 7.12 A dc machine induces an EMF of 240 V at 1500 rpm. Find the developed torque for an armature current of 25 A.

Solution:

Power developed, $P = E \times I_a$

$= 240 \times 25$
$= 6000$ W

Again, $P = T \times \omega$ where ω is the angular velocity in radians per second.

Example 7.13 A dc shunt machine connected to 220 V supply has armature resistance of 0.1 Ω and field resistance of 110 Ω. Find the ratio of the speed of the machine working as a generator to the speed of the machine when working as a motor when the line current is 100 A in both the cases.

Solution:

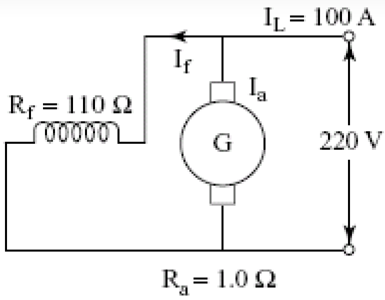


Figure 7.33

$$I_{sh} = \frac{V}{R_f} = \frac{220}{100} = 2\,A$$

As a generator, the machine will supply 100 A to the supply mains.

$I_a = I_f + I_L = 2 + 100 = 102$ A

Output voltage = 220 V.

$E_g = V + I_a R_a = 220 + 102 \times 0.1 = 230.2$ V

As a motor, the machine will draw 100 A from the supply out of which 2 A will go to the field circuit.

7.16 REVIEW QUESTIONS

A. Short Answer Type Questions

1. Draw a next sketch of a dc machine and name the component parts.
2. What is the function of the following parts of a dc machine: (i) field poles; (ii) armature; (iii) brush and commutator; (iv) shaft?
3. Explain the function of brush and commutator in a dc machine for generating action.
4. With a simple example show how lap winding and wave windings are made.
5. Deduce the EMF equation for a dc machine.
6. Describe various methods of speed control of dc motors.
7. Explain why dc motors should require starters.
8. Draw the connection diagram of a dc motor starter.
9. Draw characteristics of dc series motors and mention applications.

13. Draw the connection diagrams for dc shunt, series, and compound motors.
14. Explain the working principle of a dc generator.
15. How can you determine the efficiency of a dc machine without actually loading the machine?
16. Why do we use laminated sheets for the armature and the field cores?
17. How can you change the direction of rotation of a dc motor?
18. Why is it advisable not to start a dc series motor without having any load on it?
19. Why do we connect the coils of the armature in series parallel?
20. What are the various losses in a dc machine. Which losses are called constant losses and why?
21. How can you determine the efficiency of a dc machine without actually loading the machine?

B. Numerical Problems

22. The wave-connected armature of a two-pole 200 V generator has 400 conductors and runs at 300 rpm. Calculate the useful flux per pole.

[Ans ϕ = 10 mWb]

23. The induced EMF in a dc machine while running at 500 rpm is 180 V. Calculate the induced EMF when the machine is running at 600 rpm. Assume constant flux.

[Ans E = 216 V]

24. A 250 V shunt motor draws 5 A while running on no load at 1000 rpm. Calculate the speed of the motor when it is loaded and draws a current of 50 A. The armature circuit resistance is 0.2 Ω and field circuit resistance in 250 Ω.

[Ans N = 964 rpm]

25. A dc shunt machine has armature resistance of 0.5 Ω and field resistance of 750 Ω. When seen as a motor on no load at 500 V, the line current drawn is 3 A. Calculate the efficiency of the machine when it operates as a generator with an output of 2 kW at 500 V.

[Ans η = 89.6 per cent]

26. A four-pole wave-connected dc armature has 50 slots with 10 conductors per slot. The armature is rotated at 1000 rpm of the useful flux per pole is 30 mwb, calculate the amount of EMF induced.

27. A six-pole armature has 410 wave-connected conductors. The flux per pole is 0.02 wb. Calculate the speed at which the armature must be rotated so as to generate 400 V.

[Ans 975 rpm]

28. A 200 V dc shunt motor having an armature resistance of 0.2 Ω and field resistance of 100 Ω draws a line current of 50 A at full-load at a speed of 1500 rpm. What will be its speed at half load?

[Ans 1539 rpm]

29. A 500 V shunt motor takes a current of 5 A on no-load. Calculate the efficiency of the motor when it takes 100 A. Take R_a = 0.5 Ω and R_f = 250 Ω.

[Ans 85.4 per cent]

30. A shunt motor takes 125 A at 400 V at 1000 rpm at a particular load. If the total torque remains unchanged, Calculate the speed and armature current when the magnetic field is reduced 80 per cent of its original value. Take R_a = 0.25 Ω.

[Ans 1224 rpm, 156.25 A]

31. A dc shunt generator has a field resistance of 60 Ω and armature resistance of 0.03 Ω. As a generator, the machine delivers 40 kW at 240 V when driven at a speed of 450 rpm. Calculate the speed of the machine when running as a motor taking 40 kW of power input at 240 V.

[Ans N=424 rpm]

C. Multiple Choice Questions

1. The expression for EMF induced in a dc machine is
    1.
    2.
    3.
    4.
2. Which of the following statements is not true for a dc machine?
    1. EMF induced is directly proportional to air-gap flux
    2. EMF induced is directly proportional to number of armature conductors
    3. EMF induced in inversely proportional to number of parallel paths of the armature conductors
    4. EMF induced is inversely proportional to the number of poles.
3. The poles and armature of a dc machine is made of laminated steel sheets to

4. The EMF induced in the armature of a dc generator is alternating in nature but in the output circuit dc is made available by
    1. Brush and slip-ring arrangement
    2. Brush and commutator arrangement
    3. diode rectifiers
    4. converter circuit.
5. The windings of a dc machine are either
    1. lap or wave connected
    2. lap or spirally connected
    3. wave or spirally connected
    4. made of concentric coils or of short-pitched coils.
6. Critical field resistance of a dc generator is that value of the resistance at which
    1. the field resistance line always lies below the OCC
    2. the field resistance line is tangent to the OCC
    3. the field resistance line crosses the OCC atleast at two points
    4. the field resistance line does not touch the OCC at all.
7. The EMF induced in a four-pole dc generator having 1000 conductors, lap-connected windings, flux per pole of 10 mwb and rotated at 600 rpm is
    1. 1000 V
    2. 500 V
    3. 250 V
    4. 100 V.
8. The brush and commutator arrangement in a dc motor is used to achieve
    1. unidirectional current in the armature
    2. unidirectional torque to achieve continuous rotation of the armature
    3. change in the direction of rotation of the armature
    4. high starting torque.
9. The number of parallel paths of the armature winding of an eight-pole, 250 V, wave wound dc machine having 1500 armature conductors is
    1. 4
    2. 2
    3. 6
    4. 8.
10. Which of the following statements is not true for the EMF induced in a dc machine?
    1. EMF induced is directly proportional to speed of the armature
    2. EMF induced is inversely proportional to flux per pole
    3. EMF induced is directly proportional to number of armature conductors
    4. EMF is directly proportional to the flux per pole.
11. The direction of rotation of a dc motor can be changed
    1. by reversing the polarities of the supply
    2. by reversing either the polarities of the supply to armature or to the poles
    3. by reversing only the polarities of the supply to the armature
    4. by reversing only the polarities of the supply to the field poles.
12. The speed of a dc motor is

    4. inversely proportional to both back EMF and flux.
13. The nature of EMF induced in the armature coils in a dc machine is
    1. dc
    2. ac
    3. pulsating dc
    4. variable dc.
14. A dc machine is connected to 220 V supply mains. Its armature resistance is 0.2 Ω. What should the magnitude of EMF generated so that it may feed 100 A to the supply?
    1. 200 V
    2. 220 V
    3. 240 V
    4. 260 V.
15. Residual magnetizm of the field poles is necessary for the voltage built up in
    1. dc shunt motor
    2. dc shunt generator
    3. dc series motor
    4. dc separately excited generator.
16. A dc motor when connected directly to the supply would draw a very heavy current because
    1. the back EMF at starting is zero
    2. the back EMF at starting is maximum
    3. the back EMF is opposing the supply voltage
    4. torque required at starting is high.
17. The speed of a dc shunt motor can be reduced by
    1. decreasing the field current
    2. increasing the supply voltage to the motor
    3. decreasing the supply voltage to the motor
    4. by decreasing the supply voltage to the motor and simultaneously decreasing the field current.
18. The relationship between torque, T and armature current, Ia for a dc series motor is
    1. $T \propto I_a$
    2. $T \propto \frac{1}{I_a}$
    3.
    4. $T \propto \frac{1}{I_a^2}$.
19. The relationship between torque, T and armature current, Ia for a dc shunt motor is
    1. $T \propto I_a$
    2.
    3. $T \propto I_a^2$
    4. .
20. Efficiency of a dc machine is less than that of an equivalent transformer because
    1. there is friction and windage losses in dc machines
    2. core losses are more in dc machines than in transformers
    3. copper losses are more in dc machines than in transformers
    4. for all the reasons mentioned in (a), (b) and (c).

3. (b)
4. (b)
5. (a)
6. (b)
7. (d)
8. (b)
9. (b)
10. (b)
11. (b)
12. (a)
13. (b)
14. (c)
15. (b)
16. (a)
17. (c)
18. (c)
19. (a)
20. (a)