Basics of Electrical & Electronics

Unit-III

INTRODUCTION

A DC machine is an electromechanical energy conversion device. It can convert mechanical power (ωT) into DC electrical power (EI) and is known as a DC generator. On the other hand, when it converts DC electrical power into mechanical power, it is known as a DC motor.

Although battery is an important source of DC electric power, it can supply a limited power. There are some applications where large quantity of DC power is required (e.g., electroplating electrolysis) and, at such places, DC generators are used to deliver power.

It has been seen that AC motors are invariably applied in the industry for the conversion of electrical power into mechanical power; however, at the places where wide range of speeds and good speed regulation are required (such as electric traction), DC motors have to be applied.

In short, we can say that DC machines have their own role in the field of engineering. In this chapter, we shall study the common topics of DC machines.

ELECTROMECHANICAL ENERGY CONVERSION DEVICES (MOTORS AND GENERATORS)

A device (machine) that makes possible the conversion of energy from electrical to mechanical form or from mechanical to electrical form is called an electro-mechanical energy conversion device or electro-mechanical transducer, as shown in Figure 11.1.

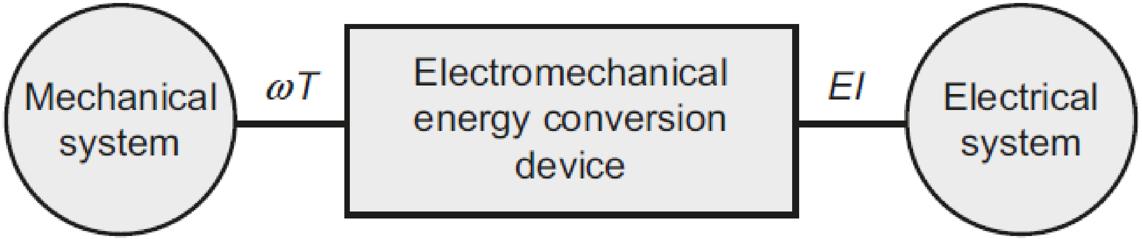


Fig. 11.1 Electro-mechanical energy conversion

Depending upon the conversion of energy from one to the other, the electromechanical device can be named as generator or motor.

ELECTRIC GENERATOR AND MOTOR

Depending upon the energy conversion, a DC machine may work as a generator or motor.

Generator

An electromechanical device (electrical machine) that converts mechanical energy or power (ωT) into electrical energy or power (EI) is called generator.

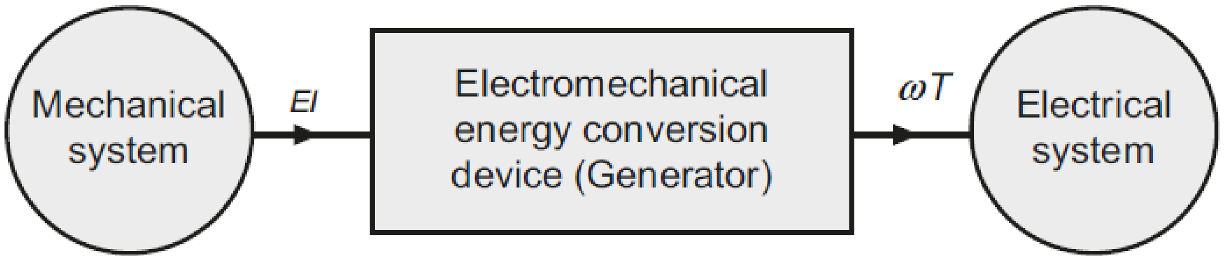


Fig. 11.2 Generator

Generators are used in hydroelectric power plants, steam power plants, diesel power plants, nuclear power plants, and automobiles. In these power plants, various natural sources of energy are first converted into mechanical energy, and then, it is converted into electrical energy with the help of generators. The block diagram of energy conversion, when the electromechanical device works as a generator, is shown in Figure 11.2.

Motor

An electromechanical device (electrical machine) that converts electrical energy or power (EI) into mechanical energy or power (ωT) is called a motor.

Electric motors are used for driving industrial machines, for example, hammer presses, drilling machines, lathes, shapers, blowers for furnaces, etc., and domestic appliances, for example, refrigerators, fans, water pumps, toys, mixers, etc. The block diagram of energy conversion, when the electromechanical device works as a motor, is shown in Figure 11.3.

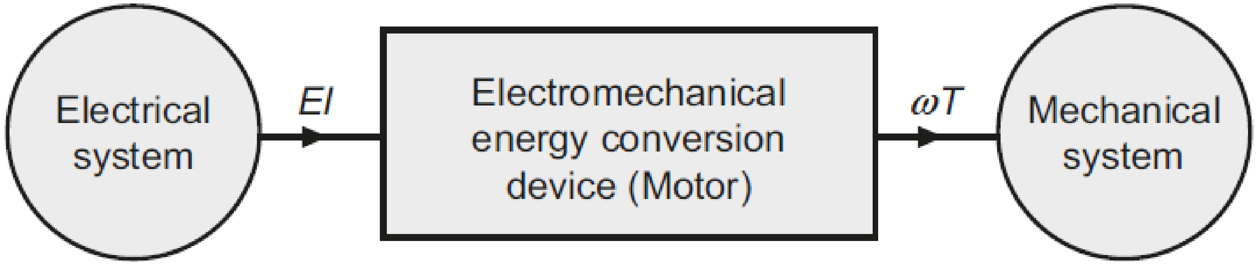


Fig. 11.3 Motor

Note: The same electromechanical device is capable of operating either as a motor or generator depending upon whether the input power is electrical or mechanical. Thus, the motor and generator actions are reversible.

The conversion of energy either from electrical to mechanical or from mechanical to electrical takes place through magnetic field. During the conversion, whole of the energy in one form is not converted in the other useful form. In fact, the input power is divided into the following three parts:

1. Most of the input power is converted into useful output power.
2. Some of the input power is converted into heat losses (I^2R) that are due to the flow of current.

MAIN CONSTRUCTIONAL FEATURES

The complete assembly of various parts in a scattered form of a DC machine is shown in Figure 11.4. The essential parts of a DC machine are described as follows:

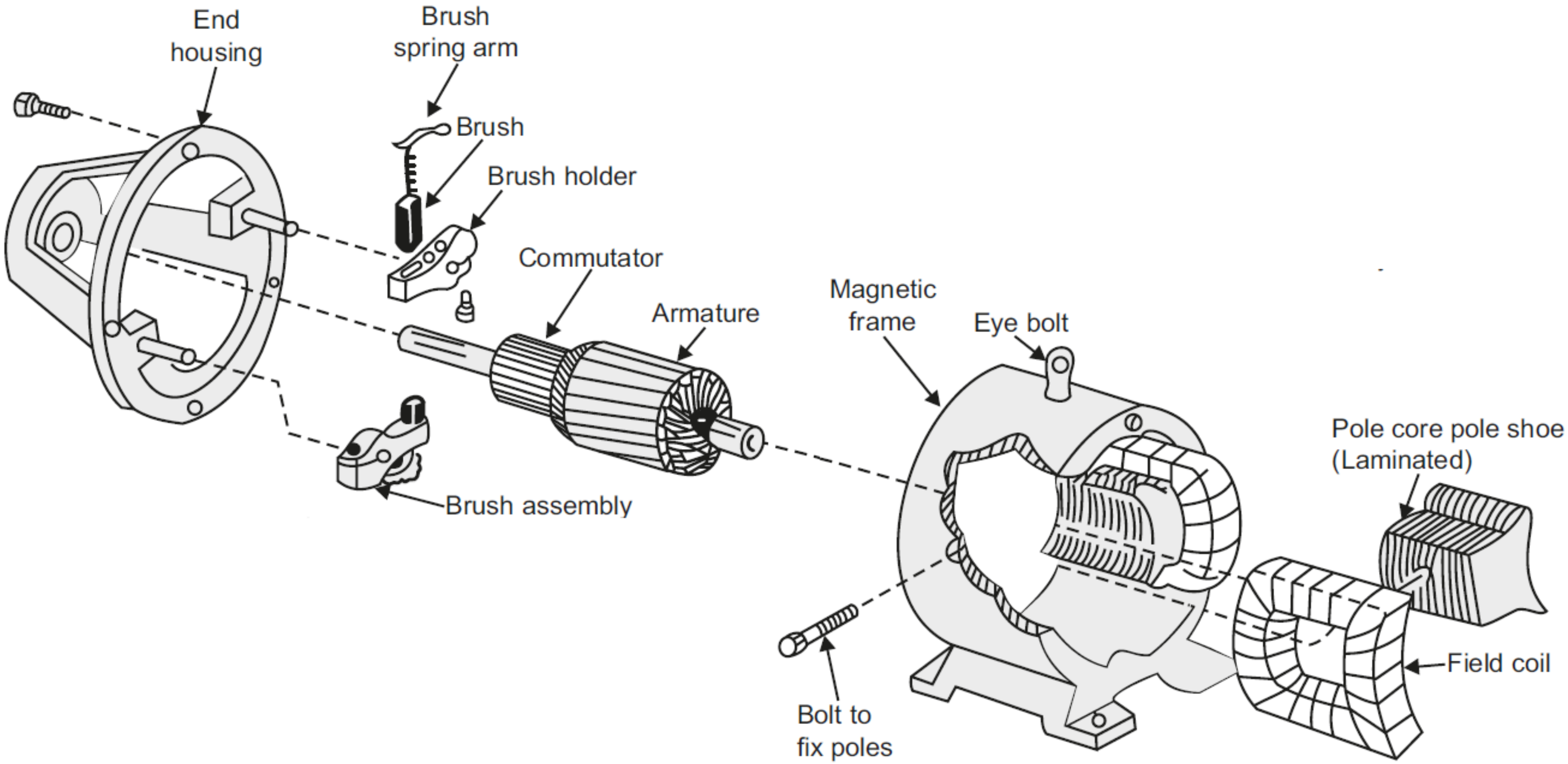
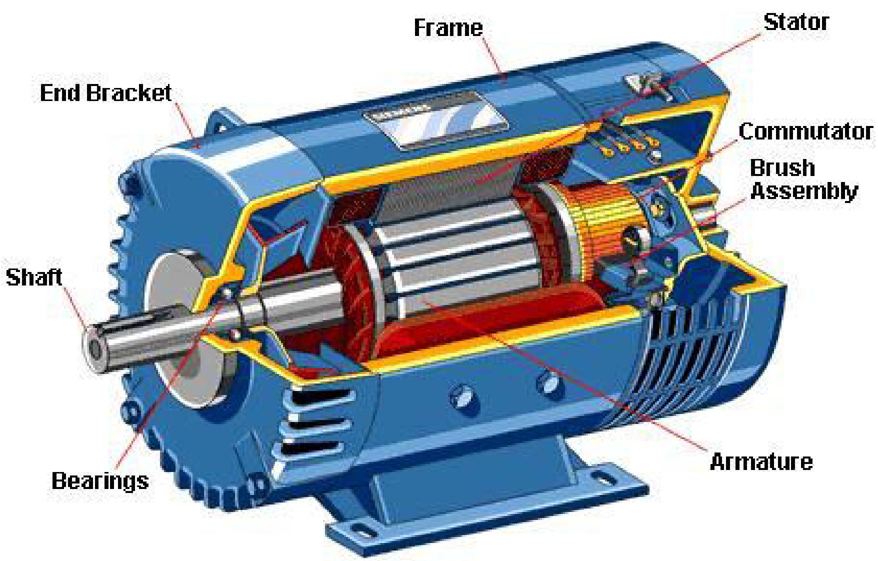
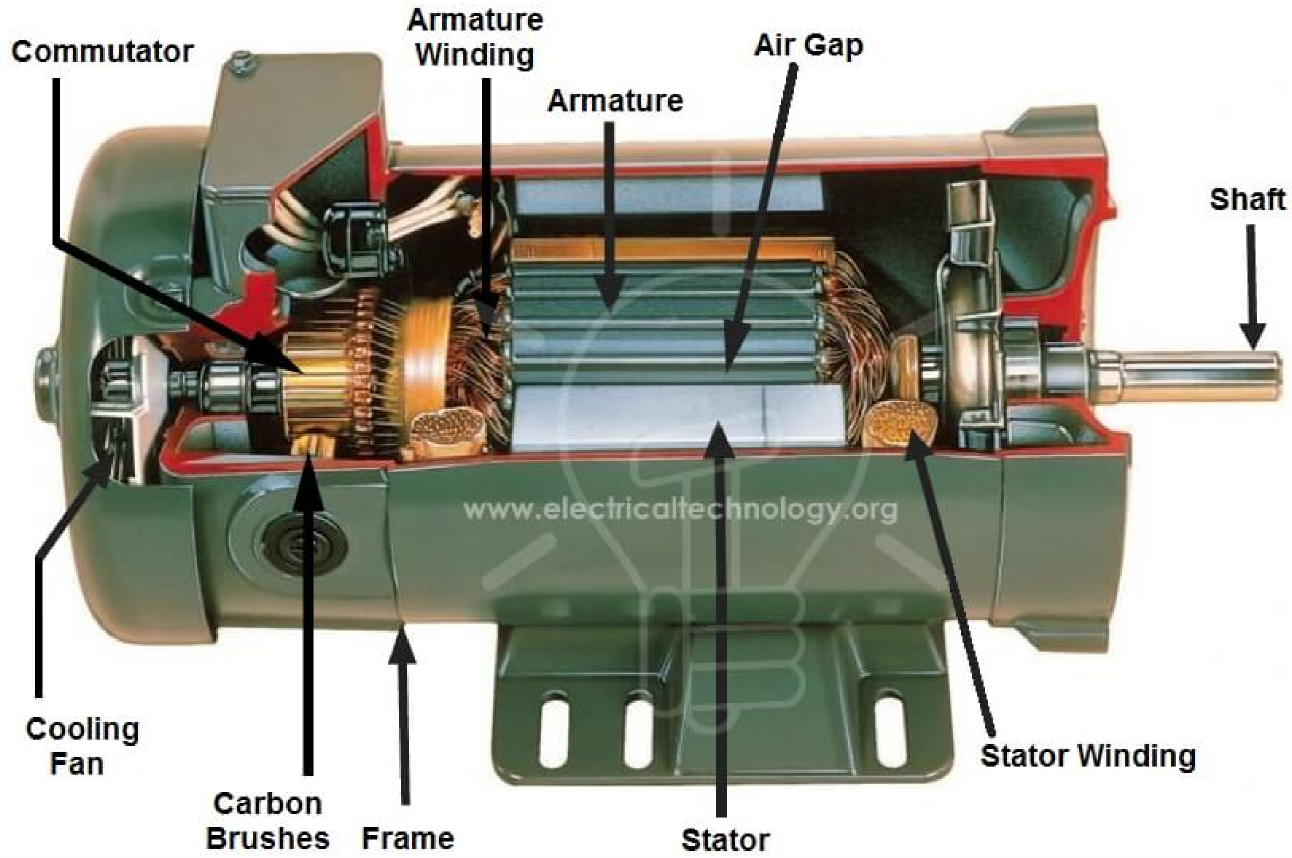


Fig. 11.4 Main parts of DC machine

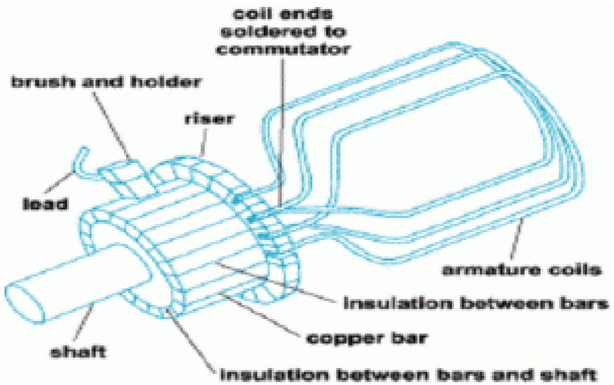
MAIN CONSTRUCTIONAL FEATURES

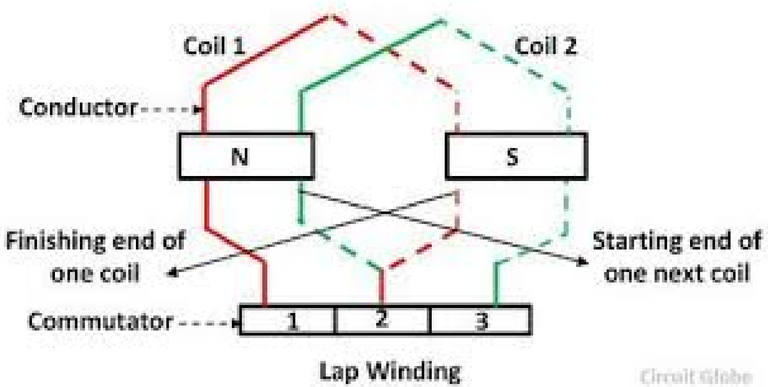


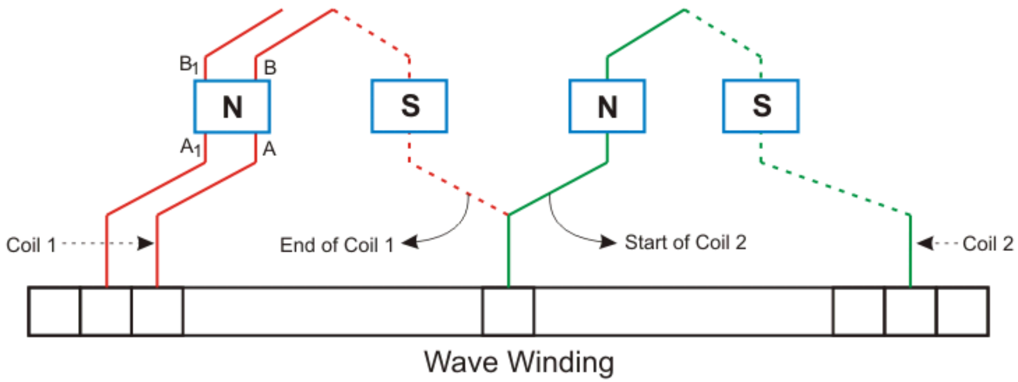


Construction of DC Machine

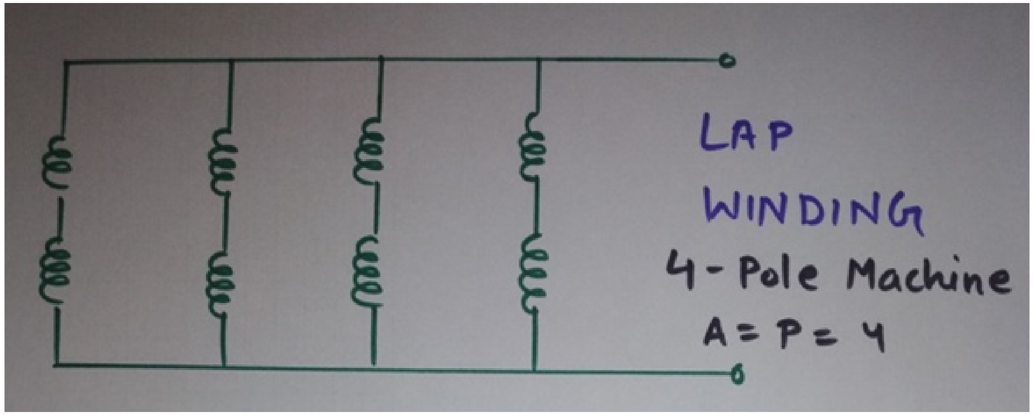
MAIN CONSTRUCTIONAL FEATURES

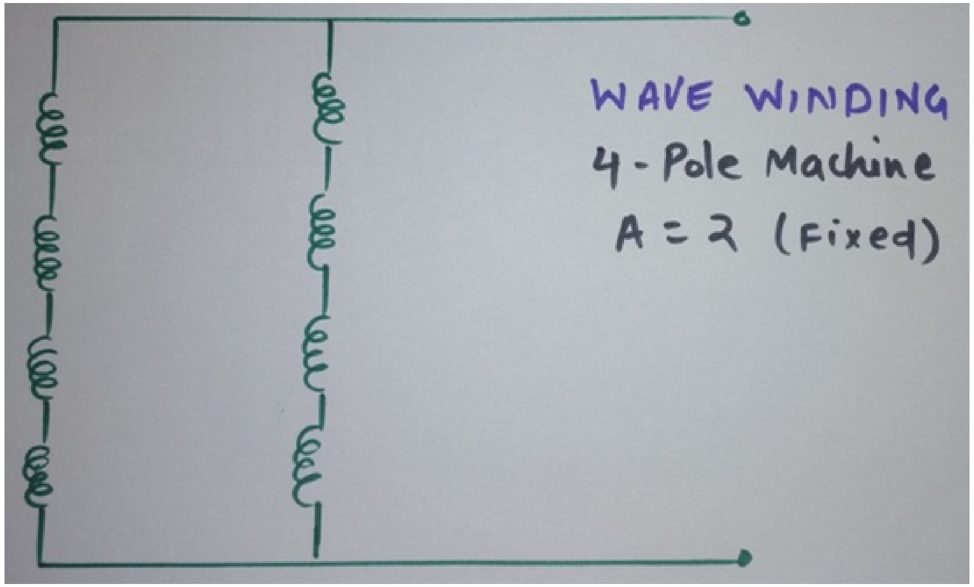






MAIN CONSTRUCTIONAL FEATURES





Sr. No	Lap winding	Wave winding
1.	Number of parallel paths (A) = poles (P)	Number of parallel paths (A) = 2 (always)
2.	Number of brush sets required is equal to number of poles.	Number of brush sets required is always equal to two.
3.	Preferable for high current, low voltage capacity generators.	Preferable for high voltage, low current capacity generators.
4.	Normally used for generators of capacity more than 500 A.	Preferred for generators of capacity less than 500 A.

1. **Magnetic frame or yoke:** The outer cylindrical frame to which main poles and inter-poles are fixed and by means of which the machine is fixed to the foundation is called the yoke. It serves the following two purposes:
   (a) It provides mechanical protection to the inner parts of the machine.
   (b) It provides a low reluctance path for the magnetic flux.

   The yoke is made of cast iron for smaller machines, and for larger machines, it is made of cast steel or fabricated rolled steel since these materials have better magnetic properties as compared to cast iron.
2. **Pole core and pole shoes:** The pole core and pole shoes are fixed to the magnetic frame or yoke by bolts. They serve the following purposes:
   (a) They support the field or exciting coils.
   (b) They spread out the magnetic flux over the armature periphery more uniformly.
   (c) Since pole shoes have large X-section, the reluctance of magnetic path is reduced. Usually, the pole core and pole shoes are made of thin cast steel or wrought iron laminations that are riveted together under hydraulic pressure as shown in Figure 11.5.

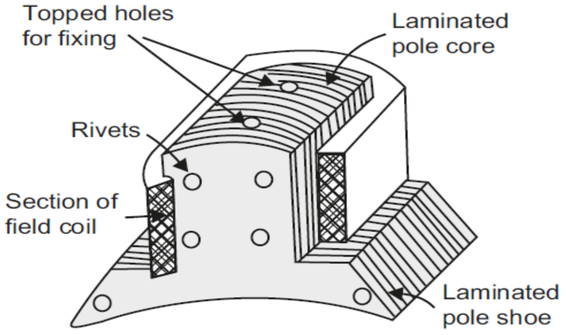


Fig. 11.5 Pole core and pole shoe

3. **Field or exciting coils:** Enamelled copper wire is used for the construction of field or exciting coils. The coils are wound on the former (see Fig. 11.6) and then placed around the pole core as shown in Figure 11.5. When DC is passed through the field winding, it magnetises the poles that produce the required flux. The field coils of all the poles are connected in series in such a way that when current flows through them, the adjacent poles attain opposite polarity as shown in Figure 11.7.

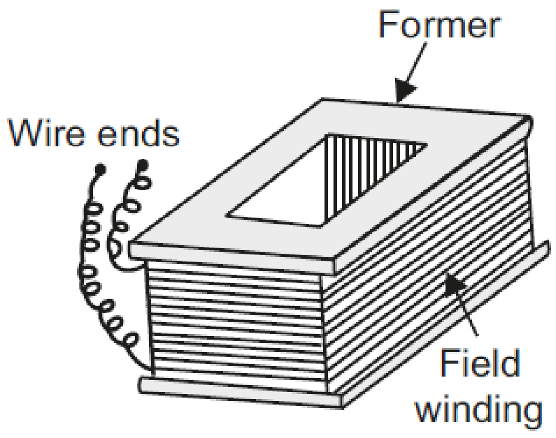


Fig. 11.6 Field winding

4. **Armature core:** It is cylindrical in shape and keyed to the rotating shaft. At the outer periphery, slots are cut, as shown in Figure 11.8, and they accommodate the armature winding. The armature core shown in Figure 11.8 serves the following purposes:
   (a) It houses the conductors in the slots.
   (b) It provides an easy path for magnetic flux.

Since armature is a rotating part of the machine, reversal of flux takes place in the core. Hence, hysteresis losses are produced. To minimise these losses, silicon steel material is used

5. **Armature winding:** The insulated conductors housed in the armature slots are suitably connected. This is known as armature winding. The armature winding is the heart of a DC machine. It is a place where conversion of power takes place, that is, in the case of generator, mechanical power is converted into electrical power; while in the case of motor, electrical power is converted into mechanical power. On the basis of connections, there are two types of armature windings, namely lap winding and wave winding.

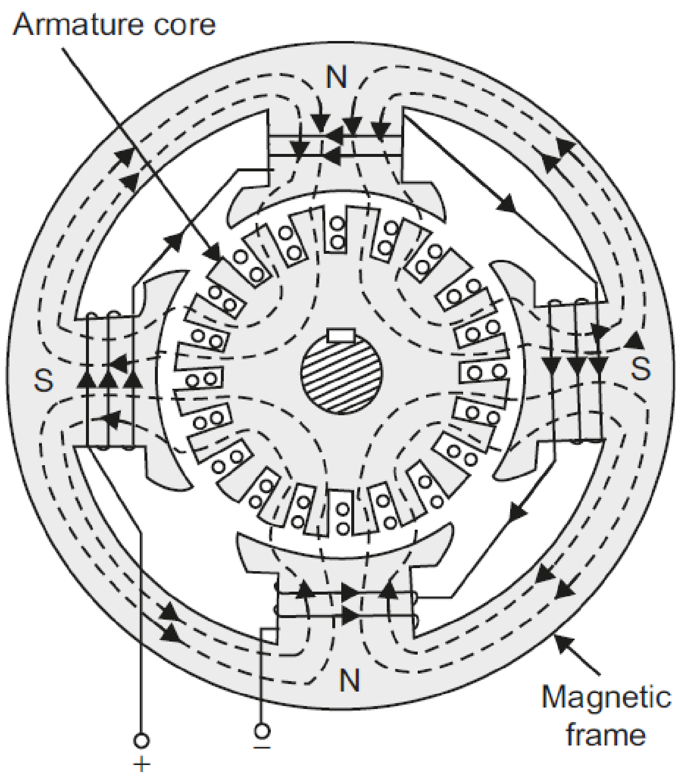


Fig. 11.7 Connections of field winding

(a) **Lap winding:** In lap winding, the conductors are connected in such a way that the number of parallel paths are equal to the number of poles. Thus, if machine has P poles and Z armature conductors, then there will be P parallel paths and each path will have Z/P conductors in series. In this case, the number of brushes is equal to the number of parallel paths. Out of which, half the brushes are positive and the remaining (half) are negative.

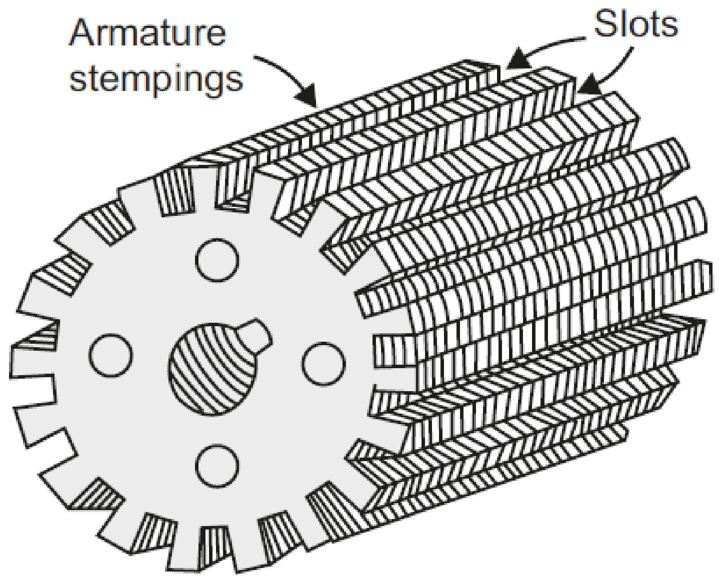


Fig. 11.8 Armature core

(b) **Wave winding:** In wave winding, the conductors are so connected that they are divided into two parallel paths, irrespective of the number of poles of the machine. Thus, if machine has Z armature conductors, there will be only two parallel paths each having $Z/2$ conductors in series. In this case, the number of brushes is equal to two, that is, number of parallel paths.

6. **Commutator:** It is the most important part of a DC machine and serves the following purposes:
   (a) It connects the rotating armature conductors to the stationary external circuit through brushes.
   (b) It converts the AC induced in the armature conductors into unidirectional current in the external load circuit during the generator action, whereas it converts the alternating torque into unidirectional (continuous) torque produced in the armature during the motor action.

The commutator is of cylindrical shape and is made up of wedge-shaped hard-drawn copper segments. The segments are insulated from each other by a thin sheet of mica. The segments are held together by means of two V-shaped rings that fit into the V-grooves cut into the segments. Each armature coil is connected to the commutator segment through riser. The sectional view of the commutator assembly is shown in Figure 11.9.

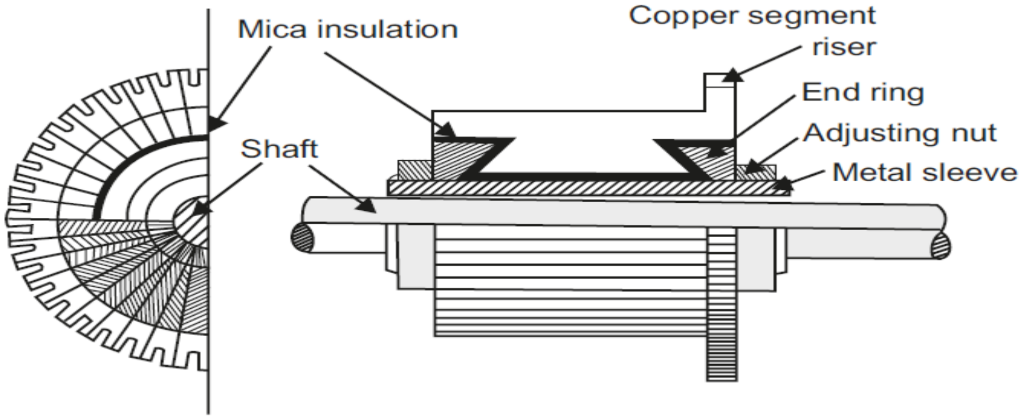


Fig. 11.9 Commutator

7. **Brushes:** The brushes are pressed upon the commutator and form the connecting link between the armature winding and the external circuit. They are usually made of high grade carbon because carbon is a conducting material, and at the same time, in powdered form, it provides imbricating effect on the commutator surface. The brushes are held in particular position around the commutator by brush holders and rocker.
8. **Brush rocker:** It holds the spindles of the brush holders. It is fitted on to the stationary frame of the machine with nut and bolts. By adjusting its position, the position of the brushes over the commutator can be adjusted to minimise the sparking at the brushes.
9. **End housings:** End housings are attached to the ends of the main frame and support bearings. The front housing supports the bearing and the brush assemblies, whereas the rear housing usually supports the bearing only.
10. **Bearings:** The ball or roller bearings are fitted in the end housings. The function of the bearings is to reduce friction between the rotating and the stationary parts of the machine. Mostly, high carbon steel is used for the construction of bearings as it is very hard material.
11. **Shaft:** The shaft is made of mild steel with a maximum breaking strength. The shaft is used to transfer mechanical power from or to the machine. The rotating parts such as armature core, commutator, and cooling fan are keyed to the shaft.

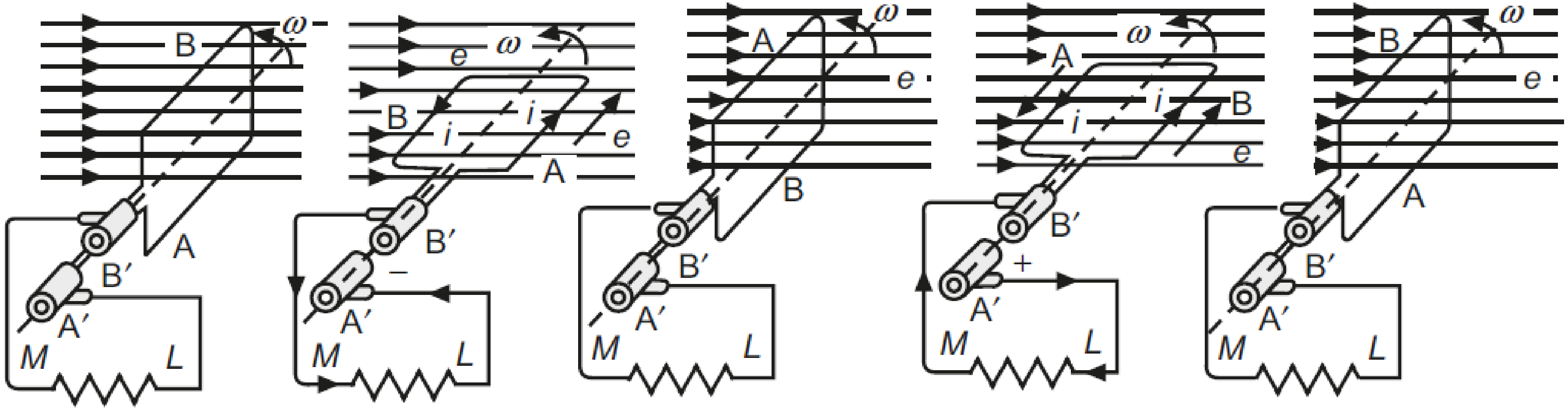
ARMATURE RESISTANCE

The resistance between the armature terminals is called armature resistance. It is generally represented by R_a. The value of armature resistance is usually quite small (less than 1 Ω). Armature resistance depends upon the following factors:

1. Length, area of cross-section, and material of armature winding.
2. Type of armature winding, that is, lap or wave winding. This will show the manner in which the conductors (i.e., their series–parallel combination) are connected.

SIMPLE LOOP GENERATOR AND FUNCTION OF COMMUTATOR

For simplicity, consider only one coil AB placed in the strong magnetic field. The two ends of the coil are joined to slip rings A′ and B′, respectively. Two brushes rest on these slip rings, as shown in Figure 11.10.



$\theta = 0$ (i) $\theta = 90°$ (ii) $\theta = 180°$ (iii) $\theta = 270°$ (iv) $\theta = 360°$ (v)

Fig. 11.10 **Direction of induced emf/current in internal and external circuit of rotating coil at different instants using two slip-rings**

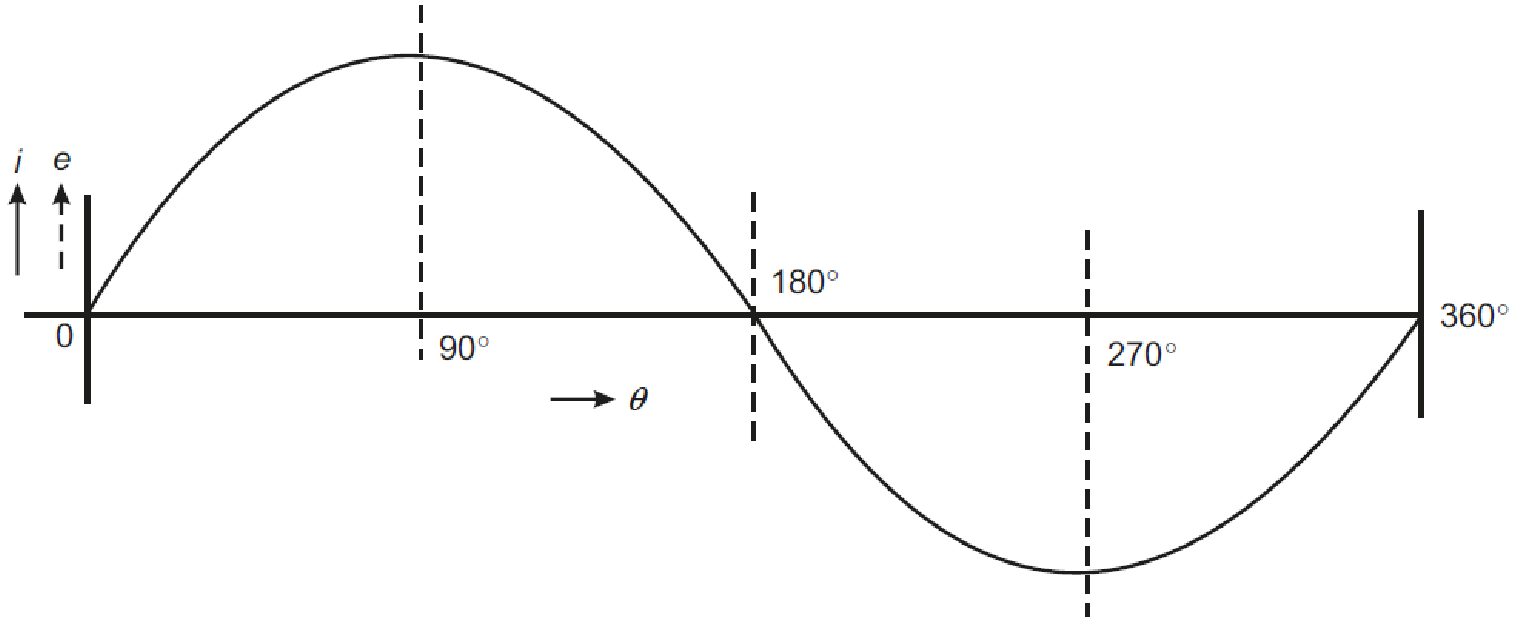


Fig. 11.11 Graphical representation of current in external circuit at various instants

When this coil is rotated in counter clockwise direction at an angular velocity of ω radians/s, the magnetic flux is cut by the coil and an emf is induced in it. The position of the coil at various instants is shown in Figure 11.10 and the corresponding value of the induced emf and its direction is shown in Figure 11.11. The induced emf is alternating and the current flowing through the external resistance is also alternating, that is, at the second instant, current flows in external resistance from M to L; while at the fourth instant, it flows from L to M as shown in Figure 11.11.

Commutator Action

Now, consider that the two ends of the coil are connected to only one slip ring split into two parts (segment), that is, A″ and B″. Each part is insulated from the other by a mica layer. Two brushes rest on these parts of the ring as shown in Figure 11.12.

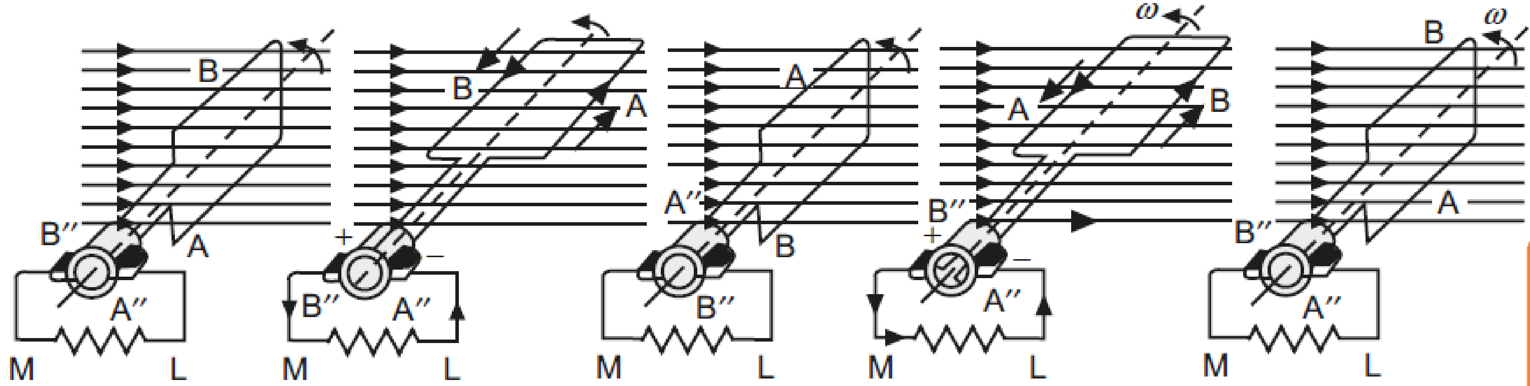
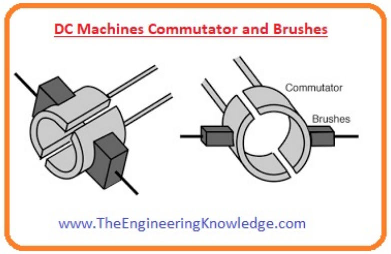


Fig. 11.12 **Direction of induced emf/current in internal and external circuit of a rotating coil at different instants using split-ring**



In this case, when the coil is rotated in counter clockwise direction at an angular velocity of ω radians/s, the magnetic flux is cut by the coil and an emf is induced in it. The magnitude of emf induced in the coil at various instants will remain the same as shown in Figure 11.13.

However, the flow of current in the external resistor or circuit will become unidirectional, that is, at the second instant, the flow of current in the external resistor is from M to L as well as the flow of current in the external resistor is from M to L in the fourth instant, as shown in Figure 11.12. Its wave shape is shown in Figure 11.13.

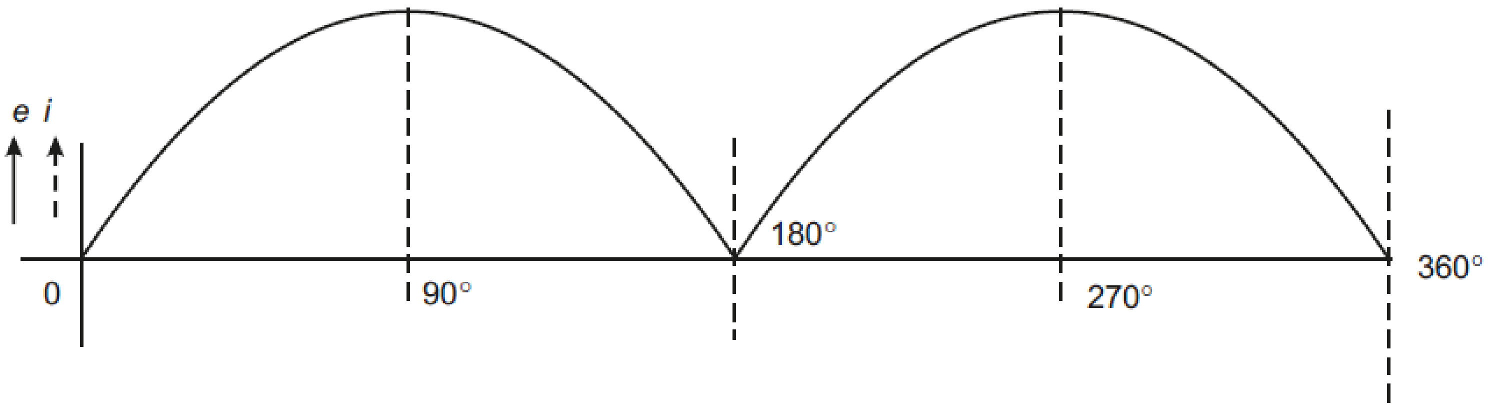
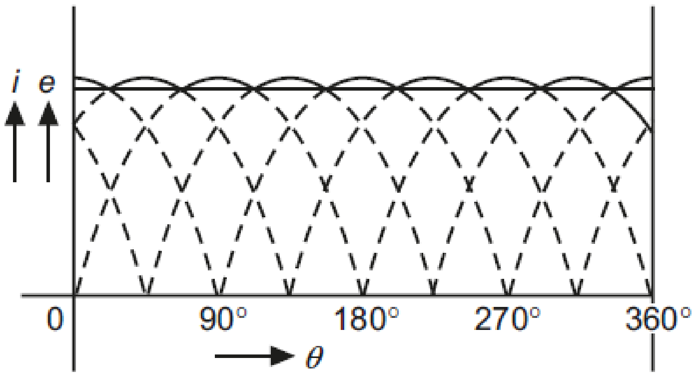


Fig. 11.13 **Graphical representation of current in external circuit at various instants**

Hence, an AC is converted into unidirectional current in the external circuit with the help of a split ring (i.e., commutator).

In an actual machine, there are number of coils connected to the number of segments of the ring called commutator. The emf or current delivered by these coils to the external load is shown in Figure 11.14(a). The actual flow of current flowing in the external load is shown by the firm line that fluctuates slightly. The number of coils placed on the armature are even much more than this and a pure DC is obtained at the output as shown in Figure 11.14(b).

Thus, in actual machine working as a generator, the function of commutator is to convert the AC produced in the armature into DC in the external circuit.



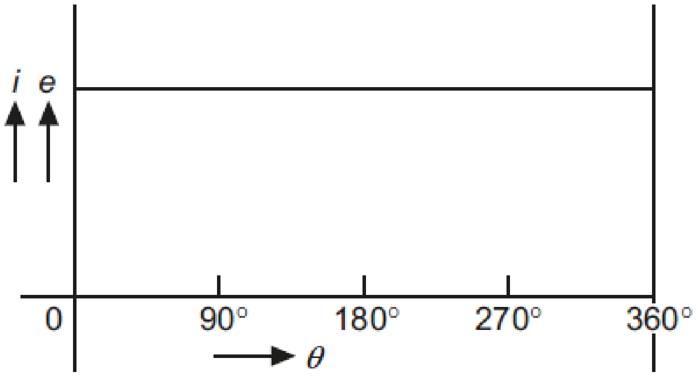


Fig. 11.14 (a) Pulsating current in external circuit using number of coils (b) Graphical representation of actual current in external circuit of a DC generator

EMF EQUATION

Let P = number of poles of the machine

ϕ = flux per pole in Wb

Z = total number of armature conductors

N = speed of armature in rpm

A = number of parallel paths in the armature winding

In one revolution of the armature, flux cut by one conductor = $P\phi$Wb

Time taken to complete one revolution, $t = 60/N$ s

Therefore, average induced emf in one conductor is

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

The number of conductors connected in series in each parallel path = Z/A

Therefore, average induced emf across each parallel path or across the armature terminals

$$E = \frac{P\phi N}{60} \times \frac{Z}{A} = \frac{PZ\phi N}{60A} \text{ V}$$

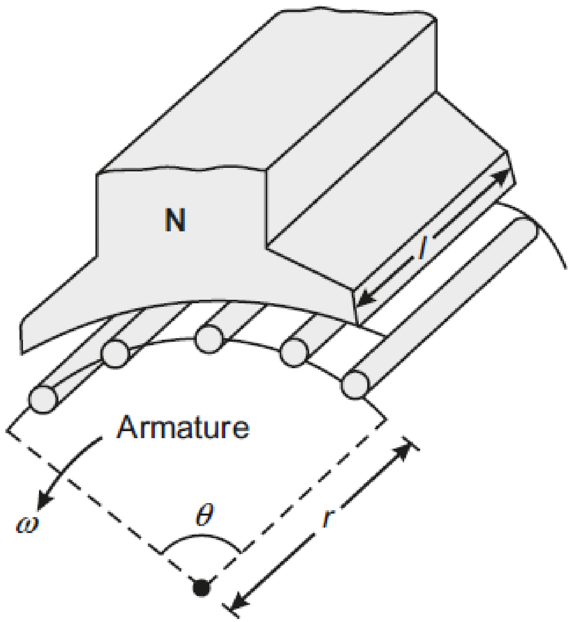


Fig. 11.15 No. of conductors under the influence of one pole

or $$E = \frac{PZ\phi n}{A} \text{ where } n \text{ is the speed in r.p.s, that is, } n = \frac{N}{60}$$

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

$$E = K\phi n, \text{ where } K = \frac{PZ}{A} \text{ is a constant or } E \propto \phi n$$

or $$E = K_1\phi N, \text{ where } K_1 = \frac{PZ}{60A} \text{ is another constant or } E \propto \phi N$$

or $$E \propto \phi\omega, \text{ where } \omega = \frac{2\pi N}{60} \text{ is the angular velocity in radian/s}$$

Thus, we conclude that the induced emf is directly proportional to flux per pole and speed. Moreover, the polarity of the induced emf depends upon the direction of magnetic field and the direction of rotation. If either of the two is reversed, the polarity of induced emf, that is, brushes is reversed; however, when both are reversed, the polarity does not change.

This induced emf is fundamental phenomenon to all DC machines whether they are working as a generator or motor. However, when the machine is working as a generator, this induced emf is called generated emf and is represented as E_g, i.e., $E_g = \frac{PZ\phi N}{60A}$ V.

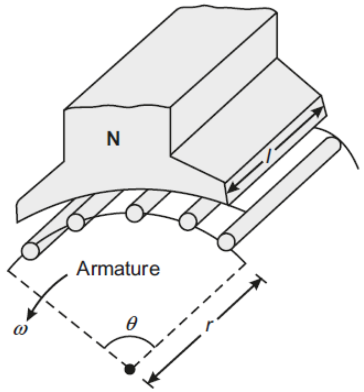


Fig. 11.15 No. of conductors under the influence of one pole

Example

An 8-pole lap-wound DC generator has 960 conductors, a flux of 40 mWb per pole and is driven at 400 rpm. Find OC emf.

Solution:

Open-circuit emf, $E_g = \dfrac{\phi ZNP}{60A}$

where $\phi = 40\ \text{mWb} = 40 \times 10^{-3}\ \text{Wb}$; $Z = 960$; $N = 400\ \text{rpm}$; $P = 8$

$A = P = 8$ (lap winding)

$$E_g = \frac{40 \times 10^{-3} \times 960 \times 400 \times 8}{60 \times 8} = 256\ \text{V}$$

Example

Calculate the voltage induced in the armature winding of a 4-pole, wave wound DC machine having 500 conductors and running at 1,000 rpm. The flux per pole is 30 mWb.

Solution:

Here, $P = 4$; $A = 2$ (wave wound); $Z = 728$; $N = 1{,}800$ rpm

$$\phi = 35 \text{ mWb} = 35 \times 10^{-3} \text{ Wb}$$

Generated voltage, $$E_g = \frac{\phi ZNP}{60A} = \frac{35 \times 10^{-3} \times 728 \times 1{,}800 \times 4}{60 \times 2} = 1{,}528.8 \text{ V}$$

Example

A 4-pole, lap-wound armature has 144 slots with two coil sides per slot, where each coil has two turns. If the flux per pole is 20 mWb and the armature rotates at 720 rpm, what is the induced emf (i) across the armature and (ii) across each parallel path?

Solution:

Here, $P = 4$; $A = P = 4$ (lap wound); $\phi = 20$ mWb $= 20 \times 10^{-13}$ Wb; $N = 720$ rpm

Number of slots = 144 with two coil sides per slot and each coil has two turns

Therefore, $Z = 144 \times 2 \times 2 = 576$

Induced emf across armature, $E_g = \dfrac{\phi ZNP}{60A} = \dfrac{20 \times 10^{-3} \times 576 \times 720 \times 4}{60 \times 4} = 138.24$ V

Voltage across each parallel path $= E_g = 138.24$ V

Example

A wave-wound armature of an 8-pole generator has 51 slots. Each slot contains 16 conductors. The voltage required to be generated is 300 V. What would be the speed of coupled prime mover if flux per pole is 0.05 Wb?

If the armature is rewound as lap-wound machine and run by same prime mover, what will be the generated voltage?

Solution:

Here, $P = 8$; $\phi = 0.05$ Wb; number of slots = 51; conductors per slot = 16

Therefore, $Z = 51 \times 16 = 816$

When the machine is wave wound, $A = 2$ and $E_g = 300$ V

Now, $$E_g = \frac{\phi ZNP}{60A} \quad \text{or} \quad 300 = \frac{0.05 \times 816 \times N \times 8}{60 \times 2}$$

Therefore, speed $$N = \frac{300 \times 60 \times 2}{0.05 \times 816 \times 8} = 110.3 \text{ rpm}$$

When the machine is rewound as lap winding, $A = P = 8$ and $N = 110.3$ rpm

$$E_g = \frac{0.05 \times 816 \times 110.3 \times 8}{60 \times 8} = 75 \text{ V}$$

Example

The emf generated by a 4-pole DC generator is 400 V, when the armature is driven at 1,200 rpm. Calculate the flux per pole if the wave-wound generator has 39 slots having 16 conductors per slot.

Solution:

Induced emf, $$E_g = \frac{\phi ZNP}{60A}$$

where $P = 4$; $E_g = 400$ V; $N = 1{,}200$ rpm; $Z = 39 \times 16 = 624$; $A = 2$ (wave winding)

Therefore, flux per pole, $$\phi = \frac{E_g \times 60A}{ZNP} = \frac{400 \times 60 \times 2}{624 \times 1{,}200 \times 4} = 0.016 \text{ Wb} = 16 \text{ mWb}$$

Example

A 4-pole generator with wave-wound armature has 51 slots, each having 24 conductors. The flux per pole is 0.01 Wb. At what speed must the armature rotate to give an induced emf of 220 V? What will be the emf developed if the winding is lap connected and the armature rotates at the same speed?

Solution:

$$\text{Induced emf, } E_g = \frac{\phi ZNP}{60A}$$

where $\phi = 0.01$ Wb; $Z = 51 \times 24 = 1{,}224$; $E = 220$ V; $P = 4$; $A = 2$ (wave winding).

$$220 = \frac{0.01 \times 1{,}224 \times N \times 4}{60 \times 2} \quad \text{or} \quad N = \frac{220 \times 60 \times 2}{0.01 \times 1{,}224 \times 4} = 539.21 \text{ rpm}$$

For lap winding, $A = P = 4$

$$E_g = \frac{0.01 \times 1224 \times 539.21 \times 4}{60 \times 4} = 110 \text{ V}$$

WORKING PRINCIPLE OF DC MOTORS

The operation of a DC motor is based on the principle that when a current carrying conductor is placed in a magnetic field, a mechanical force is experienced by it. The direction of this force is determined by Fleming's left-hand rule and its magnitude is given by the relation:

$$F = Bil \text{ Newton}$$

For simplicity, consider only one coil of the armature placed in the magnetic field produced by a bipolar machine (see Fig. 11.33(a)). When DC supply is connected to the coil, current flows through it that sets up its own field, as shown in Figure 11.33(b). By the interaction of the two fields (i.e., field produced by the main poles and the coil), a resultant field is set up, as shown in Figure 11.33(c). The tendency of this is to come to its original position, that is, in straight line due to which force is exerted on the two coil sides and torque is produced; this torque rotates the coil.

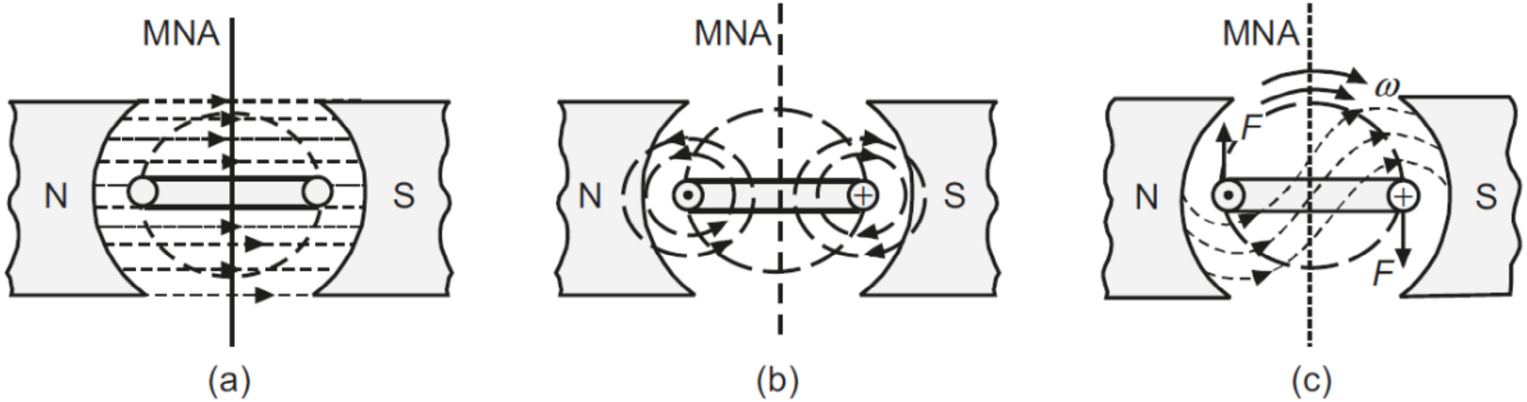


Fig. 11.33 (a) Field produced by main poles (b) Field produced by current carrying coil (c) Resultant field and direction of force exerted on conductors

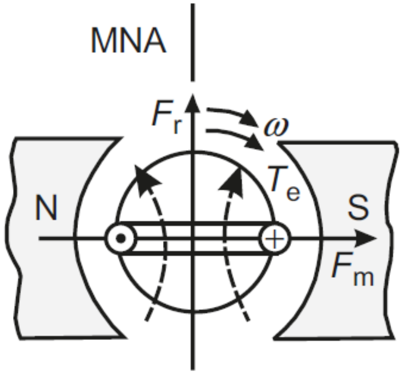


Fig. 11.34 **Position of main field and rotor field, torque development by the alignment of two fields**

Alternately, it can be said that the main poles produce a field F_m. Its direction is marked in Figure 11.34. When current is supplied to the coil (armature conductors), it produces its own field marked as F_r. This field tries to come in line with the main field and an electromagnetic torque is developed in the clockwise direction, as shown in Figure 11.35.

In actual machine, a large number of conductors are placed on the armature. All the conductors placed under the influence of one pole (say North pole) carry the current in one direction (outward). While the other conductors placed under the influence of other pole, that is South pole, carry the current in opposite direction, as shown in Figure 11.35. A resultant rotor field is produced. Its direction is marked by the arrow arrowhead F_r. This rotor field F_r tries to come in line with the main field F_m and torque (T_e) is developed. Thus, rotor rotates. It can be seen that to obtain a continuous torque, the direction of flow of current in each conductor or coil side must be reversed when it passes through the magnetic neutral axis (MNA). This is achieved with the help of a commutator.

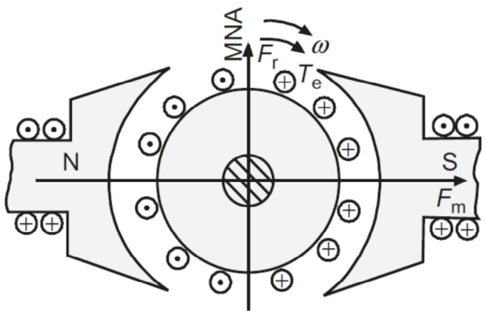


Fig. 11.35 **Torque development in actual motor**

Function of a Commutator

The function of a commutator in DC motors is to reverse the direction of flow of current in each armature conductor when it passes through the MNA to obtain continuous torque.

BACK EMF

It has been seen that when current is supplied to the armature conductors, as shown in Figure 11.36(a), placed in the main magnetic field, torque is developed; thus, the armature rotates. Simultaneously, the armature conductors cut across the magnetic field and an emf is induced in these conductors. The direction of this induced emf in the armature conductors is determined by Fleming's right-hand rule and is marked in Figure 11.36(b).

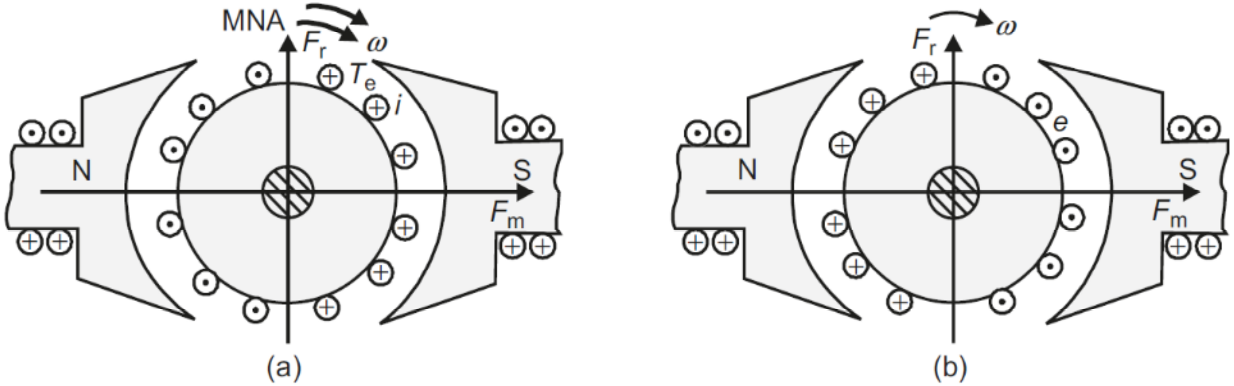


Fig. 11.36 (a) Flow of rotor current due to applied voltage (b) Direction of induced emf in rotor conductors

It can be seen that the direction of this induced emf is opposite to the applied voltage. That is why this induced emf is called back emf (E_b). The magnitude of this induced emf is given by the relation:

$$E_b = \frac{PZ\phi N}{60\,A} \quad \text{or} \quad E_b = \frac{ZP}{60\,A}\phi N \quad \text{or} \quad E_b \propto \phi N \quad \left(\text{since } \frac{ZP}{60\,A} \text{ are constant}\right)$$

Further, $N \propto \dfrac{E_b}{\phi}$ shows that speed of motor is inversely proportional to magnetic field or flux.

A simple conventional circuit diagram of the machine working as motor is shown in Figure 11.37. In this case, the supply voltage is always greater than the induced or back emf (i.e., $V > E_b$). Therefore, current is always supplied to the motor from the mains and the relation among the various quantities will be $E_b = V - I_a R_a$.

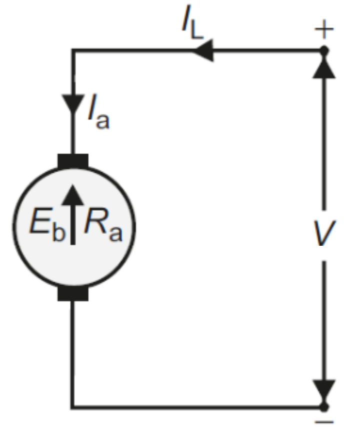


Fig. 11.37 Conventional circuit diagram of a DC motor

Significance of Back EMF

The current flowing through the armature is given by the relation: $I_a = \dfrac{V - E_b}{R_a}$. When mechanical load applied on the motor increases, its speed decreases that reduces the value of E_b. As a result, the value $(V - E_b)$ increases that consequently increases I_a. Hence, motor draws extra current from the mains. Thus, the back emf regulates the input power as per the extra load.

TORQUE EQUATION

We know that when a current carrying conductor is placed in the magnetic field, a force is exerted on it that exerts turning moment or torque $(F \times r)$ (see Fig. 11.38). This torque is produced due to electromagnetic effect, and hence it is called electromagnetic torque.

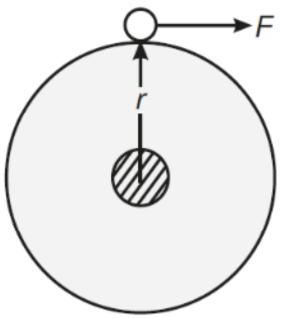


Fig. 11.38 **Force exerted on a single conductor**

Let P = number of poles

ϕ = flux per pole in Wb

r = average radius of armature in metre

l = effective length of each conductor in metre

Z = total armature conductors

I_a = total armature current

A = number of parallel paths

$$T = \frac{PZ\phi I_a}{2\pi A} \text{ Nm}$$

$$T = \frac{PZ\phi N}{2\pi A} \text{ Nm}$$

$$T \propto \phi I_a$$

SHAFT TORQUE

In DC motors, whole of the electromagnetic torque (T_e) developed in the armature is not available at the shaft. A part of it is lost to overcome the iron and mechanical (friction and windage) losses. Therefore, shaft torque (T_{sh}) is somewhat less than the torque developed in the armature. Thus, in the case of DC motors, the actual torque available at the shaft for doing useful mechanical work is known as shaft torque.

Brake Horse Power

In the case of motors, the mechanical power (H.P.) available at the shaft is known as brake horse power (BHP). If T_{sh} is the shaft torque in Nm and N is speed in rpm, then

$$\text{useful output power} = \omega T_{sh} = 2\pi N T_{sh}/60 \text{ W}$$

$$\text{Output in BHP} = \frac{2\pi N T_{sh}}{60 \times 735.5}$$

power developed in the armature

$$EI_a = \omega T$$

Example

A 50 H.P., 400 V, 4-pole, 1,000 rpm, DC motor has flux per pole equal to 0.027 Wb. The armature having 1,600 conductors is wave connected. Calculate the gross torque when the motor takes 70 A.

Solution:

Torque developed, $T = \dfrac{P\phi Z I_a}{2\pi A}$

where $P = 4$; $\phi = 0.027$ Wb; $Z = 1{,}600$; $I_a = 70$ A; $A = 2$ (wave connected)

$$T = \frac{4 \times 0.027 \times 1{,}600 \times 70}{2 \times \pi \times 2} = 963 \text{ Nm}$$

Example

The induced emf in a DC machine is 200 V at a speed of 1,200 rpm. Calculate the electromagnetic torque developed at an armature current of 15 A.

Solution:

Here, $E_b = 200$ V; $N = 1{,}200$ rpm; $I_a = 15$ A

Now, power developed in the armature,

$$\omega T_e = E_b I_a$$

$$\text{or} \quad T_e = \frac{E_b I_a}{\omega} = \frac{E_b I_a}{2\pi N} \times 60$$

$$= \frac{200 \times 15}{2\pi \times 1{,}200} \times 60$$

$$= 23.87 \text{ Nm}$$

Example

A 6-pole, lap-wound DC motor takes 340 A when the speed is 400 rpm. The flux per pole is 0.05 Wb and the armature has 864 turns. Neglecting mechanical losses, calculate the BHP of the motor.

Solution:

Here, $P = 6$; $A = P = 6$ (lap wound); $I_L = 340$ A; $N = 400$ rpm,

$\phi = 0.05$ Wb; number of turns = 864

$Z = 864 \times 2 = 1{,}728$

$$\text{Back emf, } E_b = \frac{\phi ZNP}{60A} = \frac{0.05 \times 1,728 \times 400 \times 6}{60 \times 6} = 576 \text{ V}$$

Armature current, $I_a = I_L = 340$ A

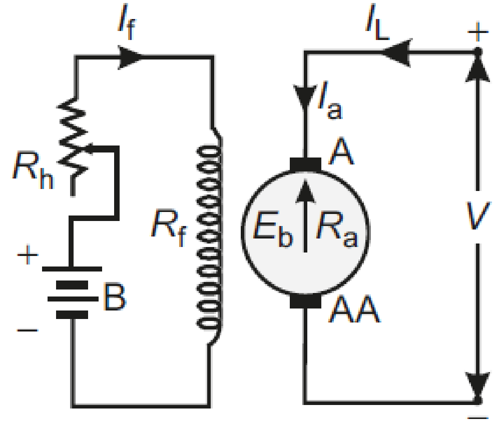
Power developed $= E_b \times I_a = 576 \times 340 = 195{,}840$ W

$$\text{Neglecting losses, BHP} = \frac{E_b I_b}{735.5} = \frac{195,840}{735.5} = 266.27$$

TYPES OF DC MOTORS

On the basis of the connections of armature and their field winding, DC motors can be classified as follows.

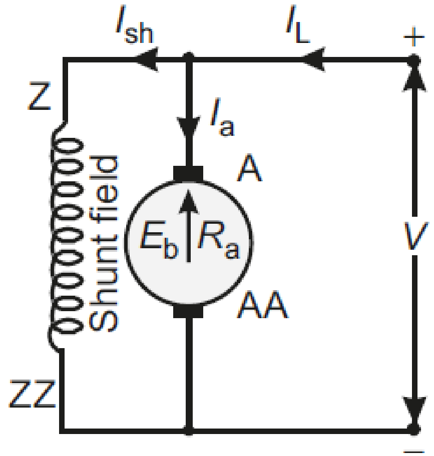
1 Separately Excited DC Motors



The conventional diagram of a separately excited DC motor is shown Figure 11.40. Its voltage equation will be

$$E_b = V - I_a R_a - 2v_b \text{ (where } v_b \text{ is voltage drop per brush)}$$

2 Self-excited DC Motors

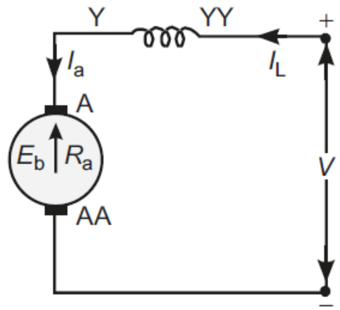


These motors can be further classified as follows:

1. **Shunt motors:** Their conventional diagram is shown in Figure 11.41.
   Important relations: $I_{sh} = V/R_{sh}$; $I_a = I_L - I_{sh}$
   $E_b = V - I_a R_a - 2v_b$ (where v_b is voltage drop per brush)

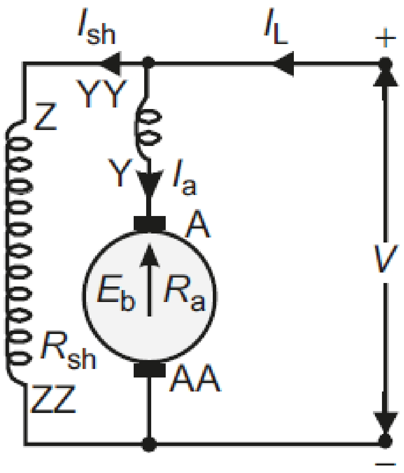
2. **Series motor:** Its conventional diagram is shown in Figure 11.42.

Important relations: $I_L = I_a = I_{se}$; $E_b = V - I_a(R_a + R_{se}) - 2v_b$



3. **Compound motor:** Its conventional diagram (for long shunt) is shown in Figure 11.43.

$$I_{sh} = \frac{V}{R_{sh}}; I_a = I_L - I_{sh}; E_b = V - I_a(R_a + R_{se}) - 2v_b$$



In all the above mentioned voltage equations, the brush voltage drop v_b is sometimes neglected since its value is very small.

The compound motor can be further subdivided as follows:

(a) **Cumulative compound motors**: In these motors, the flux produced by both the windings is in the same direction, that is,

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

(b) **Differential compound motors**: In these motors, the flux produced by the series field winding is opposite to the flux produced by the shunt field winding, that is,

$$\phi_r = \phi_{sh} - \phi_{se}$$

APPLICATIONS AND SELECTION OF DC MOTORS

As per the characteristics of DC motors, different types of DC motors are applied for different jobs as follows:

1. **Separately excited motors:** Very accurate speeds can be obtained by these motors. Moreover, these motors are best suited where speed variation is required from very low value to high value. These motors are used in steel rolling mills, paper mills, diesel-electric propulsion of ships, etc.
2. **Shunt motors:** From the characteristics of a shunt motor, we have seen that it is almost constant speed motor. Therefore, it is used under the following conditions:
   (a) Where the speed between no-load to full-load has to be maintained almost constant.
   (b) Where it is required to drive the load at various speeds (various speeds are obtained by speed control methods) and any one of the speed is required to be maintained almost constant for a relatively long period.

   As such, the shunt motors are most suitable for industrial drives such as lathes, drills, grinders, shapers, spinning and weaving machines, and line shafts in the group drive.

3. **Series motors:** The characteristics of a series motor reveal that it is variable speed motor, that is, the speed is low at high torques and vice versa. Moreover, at light loads or at no-load, the motor attains dangerously high speed. Therefore, it is employed under the following conditions:
   (a) Where high torque is required at the time of starting to accelerate heavy loads quickly.
   (b) Where the load is subjected to heavy fluctuations and speed is required to be adjusted automatically.

   As such the series motors are most suitable for electric traction, cranes, elevators, vacuum cleaners, hair driers, sewing machines, fans and air compressors, etc.
4. **Compound motors:** The important characteristic of this motor is that the speed falls appreciably on heavy loads as in a series motor; however, at light loads, the maximum speed is limited to safe value. Therefore, it is used under the following conditions:
   (a) Where high torque is required at the time of starting and where the load may be thrown off suddenly.
   (b) Where the load is subjected to heavy fluctuations.

   As such the cumulative compound motors are best suited for punching and shearing machines, rolling mills, lifts and mine hoists, etc.

Example

A 6-pole, 440 V DC motor has 936 wave-wound armature conductors. The useful flux per pole is 25 mWb. The torque developed is 45.5 kgm. If armature resistance is 0.5 Ω, then calculate (i) armature current and (ii) speed.

Solution: Number of poles, $P = 6$

Number of armature conductors, $Z = 936$

Flux per pole, $\phi = 25$ mWb $= 25 \times 10^{-3}$ Wb

Number of parallel path, $A = 2$ (wave-wound armature)

Terminal voltage, $V = 440$ V

Armature resistance, $R_a = 0.5\ \Omega$

Torque developed, $T = 45.5$ kgm $= 45.5 \times 9.81 = 446.35$ Nm

(i) Using the relation, $T = \dfrac{PZ\phi I_a}{2\pi A}$

$$\text{Armature current,}\quad I_a = \frac{2\pi A \times T}{PZ\phi} = \frac{2\pi \times 2 \times 446.35}{6 \times 936 \times 25 \times 10^{-3}} = 39.95 \text{ A}$$

(ii) Induced emf, $E = V - I_a R_a$ (motor action)

$$= 440 - 39.95 \times 0.5 = 420 \text{ V}$$

Using the relation, $\omega T = EI_a$ or $\dfrac{2\pi N}{60} \times T = EI_a$

$$\text{Speed}\quad N = \frac{60 \times EI_a}{\pi T}$$

$$= \frac{60 \times 420 \times 39.95}{2\pi \times 446.35}$$

$$= 359 \text{ rpm}$$

3 – Phase Induction motor

INTRODUCTION

Induction machines are also called asynchronous machines, that is, the machines that never run at a synchronous speed. Whenever we say induction machine we mean to say induction motor. Induction motors may be either single phase or three phase. The single-phase induction motors are usually built in small sizes (up to 3 H.P.). Three-phase induction motors are the most commonly used AC motors in the industry, because they have simple and rugged construction, low cost, high efficiency, reasonably good power factor, self-starting torque, and low maintenance. Nearly, more than 90 per cent of the mechanical power used in industry is provided by three-phase induction motors.

CONSTRUCTIONAL FEATURES OF A THREE-PHASE INDUCTION MOTOR

A three-phase induction motor consists of two main parts, namely stator and rotor.

1. **Stator:** It is the stationary part of the motor. It has three main parts, namely outer frame, stator core, and stator winding.
   - (a) **Outer frame:** It is the outer body of the motor. Its function is to support the stator core and to protect the inner parts of the machine. For small machines, the fame is casted, but for large machines, it is fabricated.

     To place the motor on the foundation, feet are provided in the outer frame as shown in Figure 12.1.

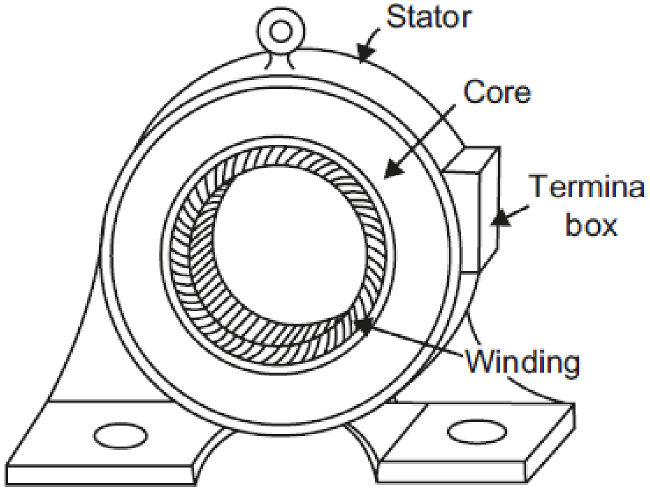


Fig. 12.1 Stator of 3-phase induction motor

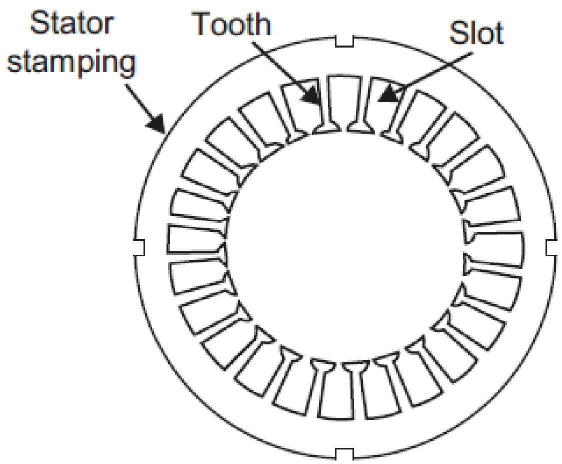


Fig. 12.2 Stator stamping

(b) **Stator core:** The stator core is to carry the alternating magnetic field which produces hysteresis and eddy current losses; therefore, core is built up of high grade silicon steel stamping. The stampings are assembled under hydraulic pressure and are keyed to the frame. Each stamping is insulated from the other with a thin varnish layer. The thickness to the stamping usually varies from 0.3 to 0.5 mm. Slots are punched on the inner periphery of the stampings, as shown in Figure 12.2, to accommodate stator winding.

(c) **Stator winding:** The stator core carries a three-phase winding which is usually supplied from a three-phase supply system. The six terminals of the winding (two of each phase) are connected in the terminal box of the machine. The stator of the motor is wound for definite number of poles, the exact number being determined by the requirement of speed. It will be observed that greater the number of poles, the lower is the speed and vice-versa, since $N_s \propto \frac{1}{P}\left(Q\, N_s = \frac{120f}{P}\right)$. The three-phase winding may be connected in star or delta externally through a starter.

2. **Rotor:** It is the rotating part of the motor. There are two types of rotors, which are employed in three-phase induction motors, namely squirrel-cage rotor and phase-wound rotor.

   (a) **Squirrel-cage rotor:** The motors employing this type of rotor are known as 'squirrel-cage induction motors'. Most of the induction motors are of this type because of simple and rugged construction of rotor. A squirrel-cage rotor consists of a laminated cylindrical core having semi-closed circular slots at the outer periphery. Copper or aluminium bar conductors are placed in these slots and short circuited at each end by copper or aluminium rings, called short-circuiting rings, as

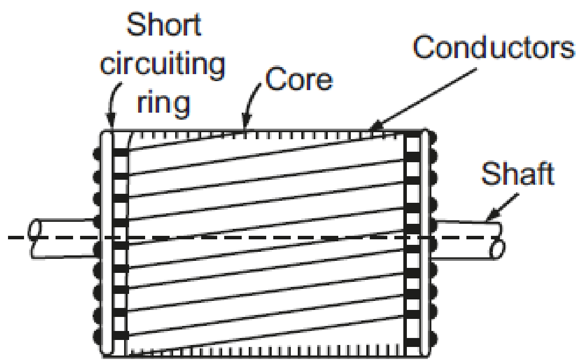


Fig. 12.3 **Squirrel cage rotor**

shown in Figure 12.3. Thus, the rotor winding is permanently short circuited, and it is not possible to add any external resistance in the rotor circuit.

The rotor slots are usually not parallel to the shaft but are skewed. Skewing of rotor has the following advantages:

(i) It reduces humming, thus ensuring quiet running of a motor.

(ii) It results in a smoother torque curves for different positions of the rotor.

(iii) It reduces the magnetic locking of the stator and rotor.

(iv) It increases the rotor resistance due to the increased length of the rotor bar conductors.

(b) **Phase-wound rotor:** Phase-wound rotor is also called slip-ring rotor and the motors employing this type of rotor are known as 'phase-wound or slip-ring induction motors'. Slip-ring rotor consists of a laminated cylindrical core having semi-closed slots at the outer periphery and carries a three-phase insulated winding. The rotor is wound for the same number of poles as that of stator. The three finish terminals are connected together forming star point, and the three start terminals are connected to three copper slip-rings fixed on the shaft (Figure 12.4).

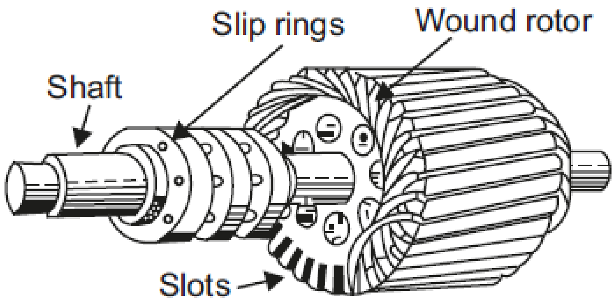
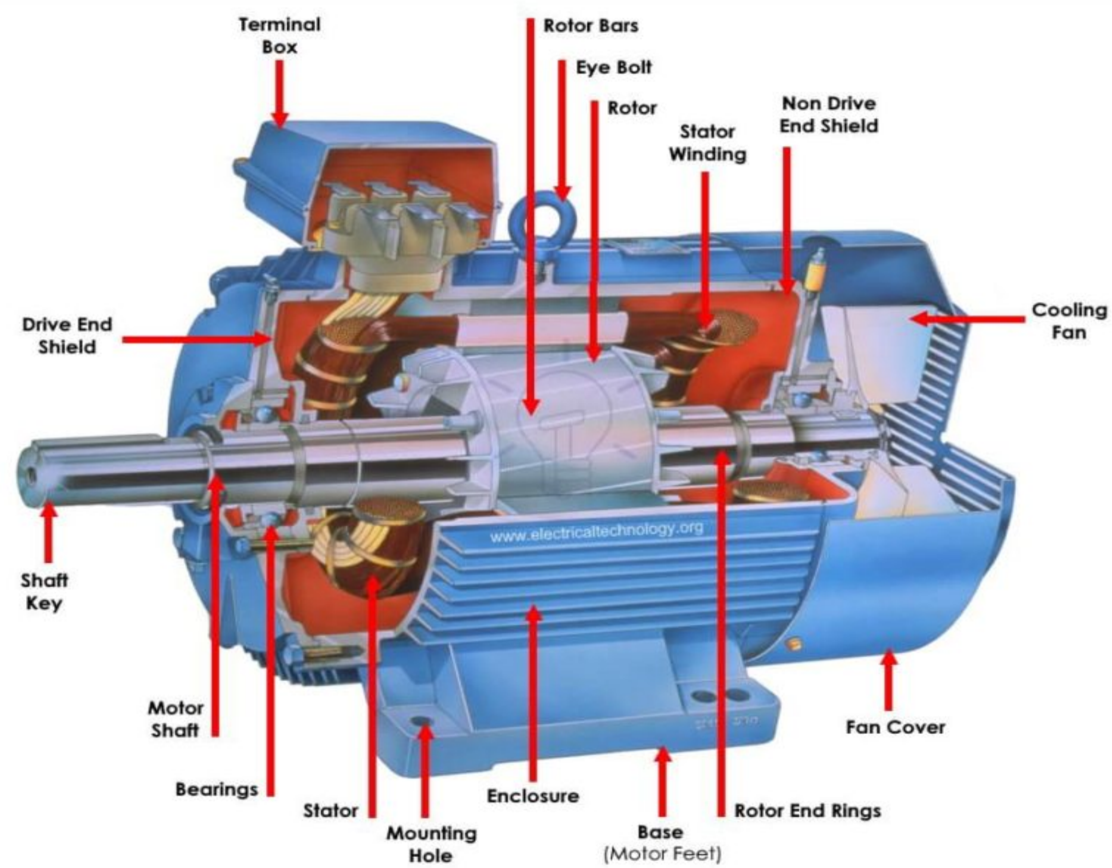
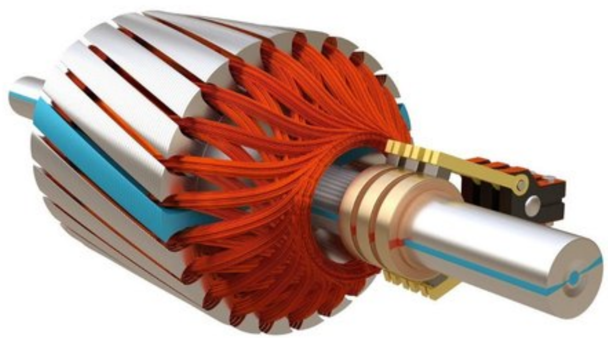


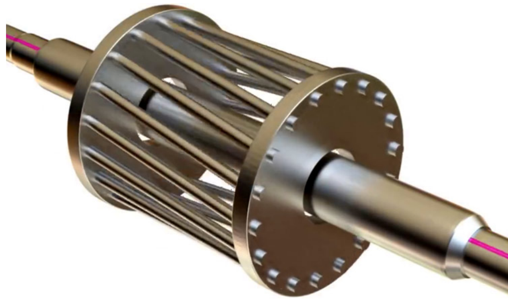
Fig. 12.4 Phase-wound rotor

In this case, depending upon the requirement, any external resistance can be added in the rotor circuit. In this case also, the rotor is skewed.

A mild steel shaft is passed through the centre of the rotor and is fixed to it with key. The purpose of shaft is to transfer mechanical power.







PRODUCTION OF REVOLVING FIELD

Consider a stator on which three different windings represented by three concentric coils a_1a_2, b_1b_2, and c_1c_2, respectively, are placed 120° electrically apart.

Let a three-phase supply, as shown in Figure 12.5, is applied to the stator. Three-phase currents will flow through the three coils and produce their own magnetic fields. The positive half cycle of the alternating current (AC) is considered as inward flow of current in the start terminals and negative half cycle is considered as outward flow of current in the start terminals. The direction of flow of current is opposite in the finish terminals of the same coil.

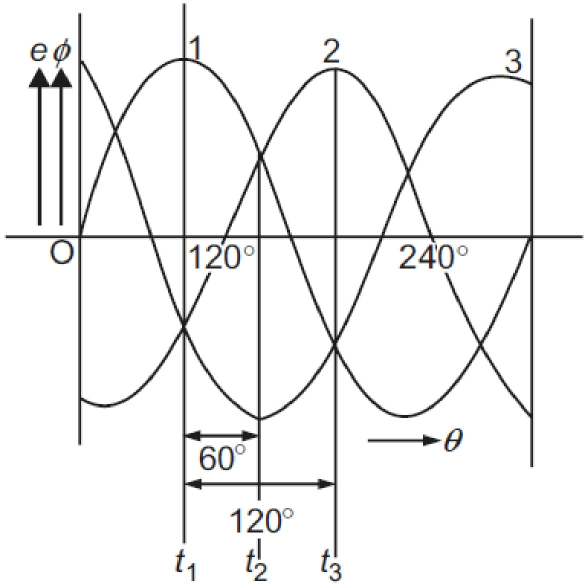


Fig. 12.5 **Wave diagram of 3-phase AC supply with instants t_1, t_2 and t_3**

Let at any instant t_1, current in coil side a_1 be inward and in b_1 and c_1 outward, whereas the current in the other sides of the same coils is opposite, that is, in coil side a_2 is outward and b_2 and c_2 is inward. The resultant field and its direction (F_m) are marked in Figure 12.6.

At instant t_2, when θ is 60°, current in coil sides a_1 and b_1 is inward and in c_1 is outward, whereas the current in the opposite sides is opposite. The resultant field and its direction is shown in Figure 12.7, which is rotated through an angle $\theta = 60°$ from its previous position.

At instant t_3 when θ is 120°, current in coil side b_1 is inward and in c_1 and a_1 is outward. The resultant field and its direction is shown in Figure 12.8, which is rotated through an angle $\theta = 120°$ electrical from its first position.

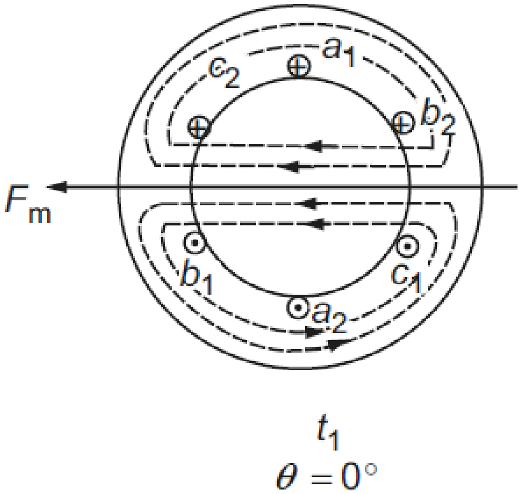


Fig. 12.6 **Position of resultant field at instant t_1**

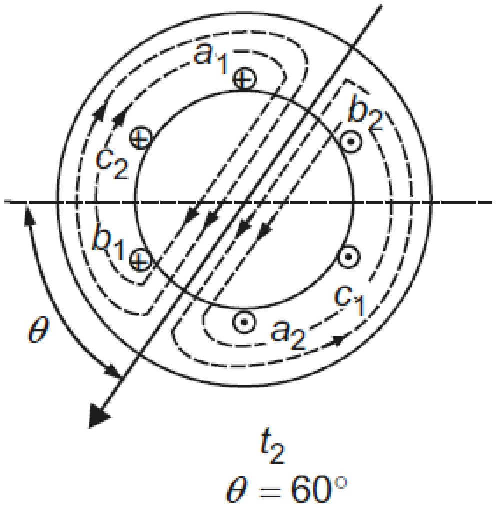


Fig. 12.7 **Position of resultant field at instant t_2**

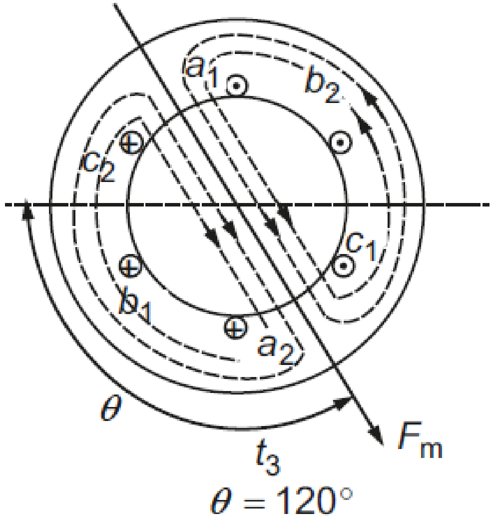


Fig. 12.8 **Position of resultant field at instant t_3**

Thus, in one cycle, the resultant field completes one revolution. Hence, we conclude that when three-phase supply is given to a three-phase wound stator, a resultant field is produced which revolves at a constant speed, called synchronous speed $(N_s = 120° f/P)$.

In this case, we have observed that when supply from phase 1, 2, and 3 is given to coil a_1a_2, b_1b_2, and c_1c_2, respectively, an anticlockwise rotating field is produced. If the supply to coil a_1a_2, b_1b_2, and c_1c_2 is given from phase 1, 3, and 2, respectively, the direction of rotating field is reversed. Therefore, to reverse the direction of rotation of rotating field, the connections of any two supply terminals are inter changed.

PRINCIPLE OF OPERATION

When three-phase supply is given to the stator of a three-phase wound induction motor, a revolving field is set up in the stator. At any instant, the magnetic field set-up by the stator is shown in Figure 12.9. The direction of resultant field is marked by an arrow head F_m. Let this field is rotating in an anticlockwise direction at an angular speed of ω_s radians per second, that is, synchronous speed.

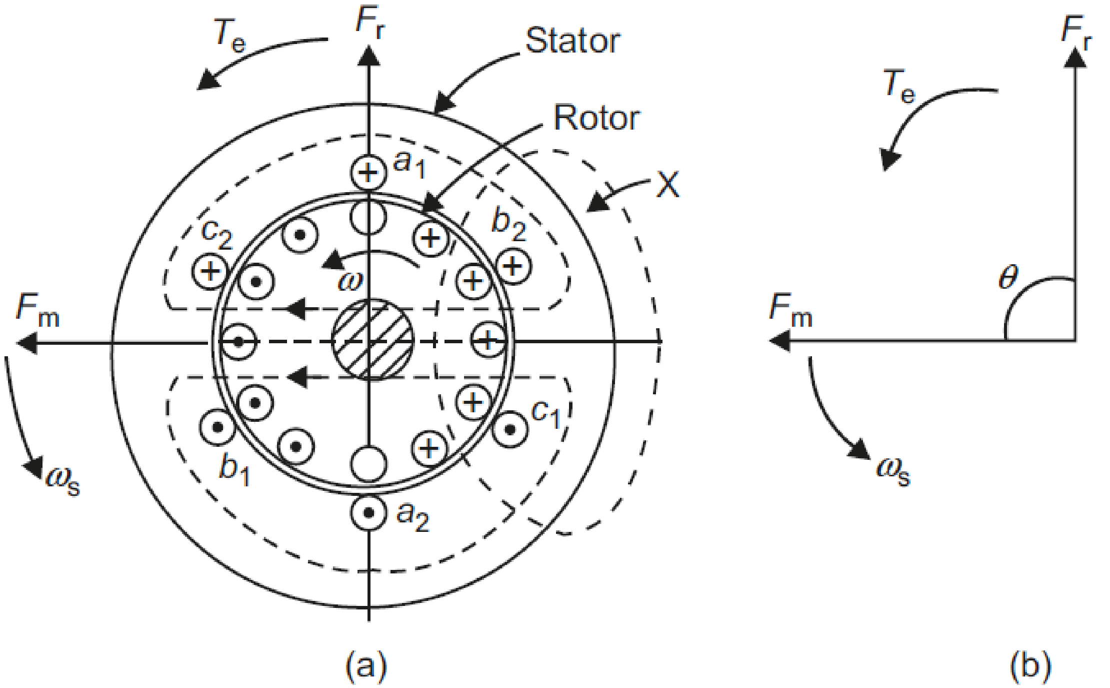


Fig. 12.9 **(a) Induced emf/current in rotor conductors at an instant**
(b) Phasor representation of stator and rotor field at an instant

The stationary rotor conductors cut the revolving field and due to electromagnetic induction an emf is induced in the rotor conductors. As the rotor conductors are short circuited, current flows through them in the direction as marked in the figure. Rotor current carrying conductors set up a resultant field F_r. This field tries to come in line with the stator main field F_m. Due to this, an electromagnetic torque T_e is developed in the anticlockwise direction. Therefore, rotor starts rotating in same direction in which stator field is revolving.

REVERSAL OF DIRECTION OF ROTATION OF THREE-PHASE INDUCTION MOTORS

In Figure 12.2, it has been observed that a revolving field is set up in the stator of a three-phase induction motor, when three-phase supply is given to its winding and the direction of rotation depends upon the supply sequence.

In Figure 12.3, it has been observed that rotor of a three-phase induction motor rotates in the same direction as that of the revolving field.

The direction of rotation of the revolving field or that of the rotor can be reversed if the sequence of supply is reversed. The supply sequence can be reversed by interchanging the connections of any two supply leads at the stator terminals.

Hence, the direction of rotation of a three-phase induction motor can be reversed by interchanging the connections of any two supply leads at the stator terminals.

SLIP

The rotor of an induction motor always rotates at a speed less than synchronous speed. The difference between the flux speed (Ns) and the rotor speed (N) is called slip. It is usually expressed as a percentage of synchronous speed (Ns) and is represented by symbol S.

Mathematically,

% slip, $$\% S = \frac{N_s - N}{N_s} \times 100$$

or fractional slip, $$S = \frac{N_s - N}{N_s}$$

Rotor speed, $$N = N_s(l - S)$$

The difference between synchronous speed and rotor speed is called slip speed, that is,

$$\text{Slip speed} = N_s - N$$

The value of slip at full-load varies from about 6 per cent small motors to about 2 per cent for large motors.

Importance of Slip

Slip plays an important role in the operation of an induction motor. We have already seen that the difference between the rotor speed and synchronous speed of flux determine the rate at which the flux is cut by rotor conductors and hence the magnitude of induced emf, that is, $e_2 \propto N_s - N$

Rotor current, $i_2 \propto e_2$ and torque, $T \propto i_2$

$$T = K(N_s - N)$$

or

$$T = KN_s\left(\frac{N_s - N}{N_s}\right)$$

or

$$T = K_1 S$$

Hence

$$T \propto S$$

Thus, greater the slip greater will be the induced emf or rotor current, and hence, larger will be the torque developed.

At no-load, induction motor requires small torque to meet with the mechanical, iron, and other losses, and therefore, slip is small. When the motor is loaded, greater torque is required to drive the load, and therefore, the slip increases and rotor speed decreases slightly.

Therefore, it is observed that slip in an induction motor adjusts itself to such a value to meet the required driving torque under normal operation.

FREQUENCY OF ROTOR CURRENTS

The frequency of rotor currents depends upon the relative speed between rotor and stator field. When the rotor is stationary, the frequency of rotor currents is the same as that of the supply frequency. But once the rotor starts to rotate, the frequency of rotor currents depends upon slip speed ($N_s - N$). Let at any speed N, the frequency of rotor currents be f_r.

Then, $$f_r = \frac{(N_S - N) \times P}{120} = \frac{(N_S - N)}{N_S} \times \frac{N_S \times P}{120} = S \times f$$

Example

In a three-phase slip-ring, four-pole induction motor, the rotor frequency is found to be 2.0 Hz, while connected to a 400 V, three-phase, 50 Hz supply. Determine motor speed in rpm.

Solution:

Synchronous speed, $$N_S = \frac{120 \times f}{P} = \frac{120 \times 50}{4} = 1500 \text{ rpm}$$

Slip, $$S = \frac{\text{Frequency of rotor emf}}{\text{Supply frequency}} = \frac{f_r}{f} = \frac{2}{50} = 0.04$$

Speed of motor on load, $N = N_S\,(1 - S) = 1500\,(1 - 0.04) = 1440$ rpm

Example

A three-phase, four-pole induction motor operates from a supply whose frequency is 50 Hz. Calculate its synchronous speed, speed of rotor when slip is 0.04 and frequency of rotor currents at standstill.

Solution:

Synchronous speed, $N_S = \dfrac{120 \times f}{p} = \dfrac{120 \times 50}{4} = 1500 \text{ rpm}$

Speed of rotor when the slip is 0.04

$N = (1 - S) \times N_s = (1 - 0.04) \times 1500 = 1440$ rpm

Frequency of rotor currents at standstill

At standstill $= S = 1$ and $N = 0$

$\therefore$ Frequency of rotor current $f_r = S \times f = 1 \times 50 = 50$ Hz

Example

A 12-pole, three-phase alternator driven at a speed of 500 rpm supplies power to an eight-pole, three-phase induction motor. If the slip of the motor is 0.03 pu, then calculate the speed.

Solution:

No. of poles of the alternator, $P_a = 12$

Speed of alternator, $N_a = 500$ rpm

No. of poles of the induction motor, $P_m = 8$; slip $S = 0.03$ pu

Supply frequency delivered by the alternator, $f = \frac{P_a \times N_a}{120} = \frac{12 \times 500}{120} = 50\,\text{Hz}$

Synchronous speed of three-phase induction motor, $N_S = \frac{120 \times f}{P_m} = \frac{120 \times 50}{8} = 750\,\text{rpm}$

Speed of three-phase induction motor, $N = N_S \times (1 - S) = 750 \times (1 - 0.03) = 727.5$ rpm

Servomotors

The motors which respond to the error signal abruptly and accelerate the load quickly are called **servomotors.** Servomotors are usually employed with control system.

Servomotors may be either DC (shunt or series) motors or AC (2-phase) induction motors. DC motors are preferred because of their high torque to inertia ratio and high starting torque. On the other hand AC motors are known for their reliability and freedom from commutation problems such as noise and wearing of brushes etc. Servomotors vary in size from 0.05 HP to 1000 HP.

The fundamental characteristics to be sought in any servomotor (DC or AC) are

(i) The motor output torque should be proportional to its applied control voltage (developed by the amplifier in response to an error signal).

(ii) The direction of the toque is determined by the (instantaneous) polarity of the control voltage.

DC Servomotors

The DC motors which are employed in the control system are called **DC servomotors.**

There are four types of DC servomotors which are used in the control system. These are (1) the field-controlled shunt motor, (2) the armature controlled shunt motor, (3) the series split-field motor, and (4) the permanent-magnet (fixed field excitation) shunt motor.

1 Field-controlled DC Servomotors

In this motor armature current is always kept constant and the field is excited by the DC error amplifier, as shown in Fig. 12.2. The torque produced by the motor is zero when no field excitation is supplied by the DC error amplifier. Torque produced by the motor varies directly as the field flux and also as the field current up to saturation ($T = k\,\phi\,I_a$). The direction of the motor (i.e., rotation) is reversed if polarity of the field is reversed.

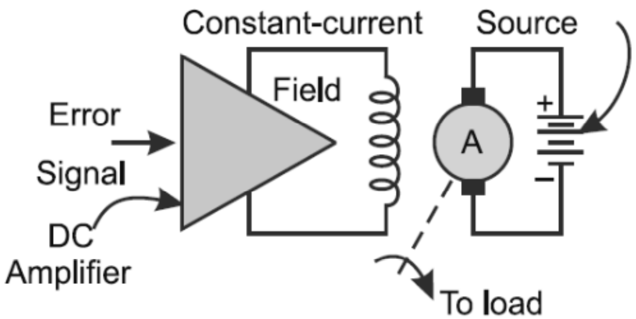


Fig. 12.2 Field control DC servomotor

The control of field current by this method is used only in small servomotors because

(i) it is undesirable to supply a large and fixed armature current as would be required for large DC servomotors and

(ii) its dynamic response is slower than the armature-controlled motor because of the longer time constant of the highly inductive field circuit.

2 Armature-controlled DC Servomotors

This servomotor employs a fixed DC field excitation furnished by a constant-current source, as shown in Fig. 12.3. As sated, this type of control possesses certain dynamic advantages not possessed by the field-control method. A sudden large or small change in armature voltage produced by an error signal will cause an almost immediate response in torque because the armature circuit is essentially resistive as compared to the highly inductive field circuit.

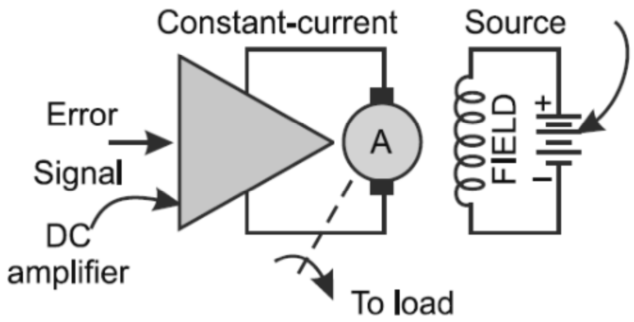


Fig. 12.3 Armature control DC servomotor

The field of this motor is normally operated well beyond the knee of the saturation curve to keep the torque less sensitive to slight changes in voltage from the constant-current source. In addition, a high field flux increases the torque sensitivity to the motor ($T = k\phi I_a$) for the same small change in armature current. DC motors up to 1000 hp are driven by armature voltage control in this manner. If the error signal polarity is reversed, the motor reverses its direction.

3 Series Split-field DC Servomotors

4 Permanent-magnet Armature-controlled DC Servomotor

AC Servomotors

The AC motors which are employed in the control system are called **AC servomotors.**

Along with smaller DC stepping motors, most of the smaller AC servomotors are of the AC two-phase or the shaded-pole induction motor-type.

Two-phase AC Servomotors

Figure 12.6 shows the schematic diagram of a two-phase servomotor. This motor is a true two-phase motor, having two stator windings displaced 90° in space on the stator. The reference windings in constantly and usually excited through a capacitor by the fixed AC supply. With no error signal, the squirrel-cage rotor is at standstill. A small error signal of some particular instantaneous polarity with respect to the reference winding is amplified by the AC amplifier and fed to the control winding. Torque i.e., rotation is produced in such a direction so as to reduce the error signal, and the motor ceases to rotate when a null (zero error signal) is produced at the control winding.

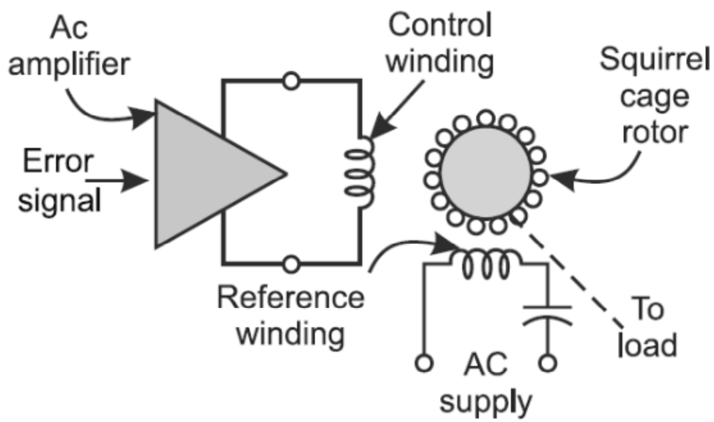


Fig. 12.6 Two-phase AC servomotor

Shaded-pole AC Servomotor

Stepper Motors

A motor in which the rotor turns in discrete movements is called a ***stepper motor****.*

A stepper motor, as its name implies, turns in discrete movements called steps. After the rotor makes a step, it stops turning until it receives the next command (or signal).

Principle of Operation

Stepper motor operation can be easily visualised by considering a series of electromagnets or solenoids arranged in a circle as shown in Fig. 12.16. When these solenoids are energised in sequence, their fields interact with the rotor, causing it to turn either clock wise or counter clockwise, depending upon the input commands (or signals). The stepping angle (α) is determined by the design of the motor, but it should not be greater than 180° in any case.

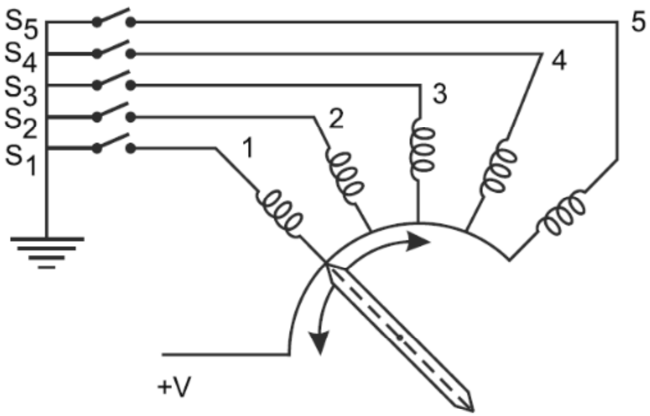


Fig. 12.16 Rotor movement

Types of Stepper Motors

There are two basic types of magnetic stepper motors

(i) Permanent-magnet (*PM*) stepper motor

(ii) Variable-reluctance (*VR*) stepper motor.

1 Permanent-magnet (PM) Stepper Motor

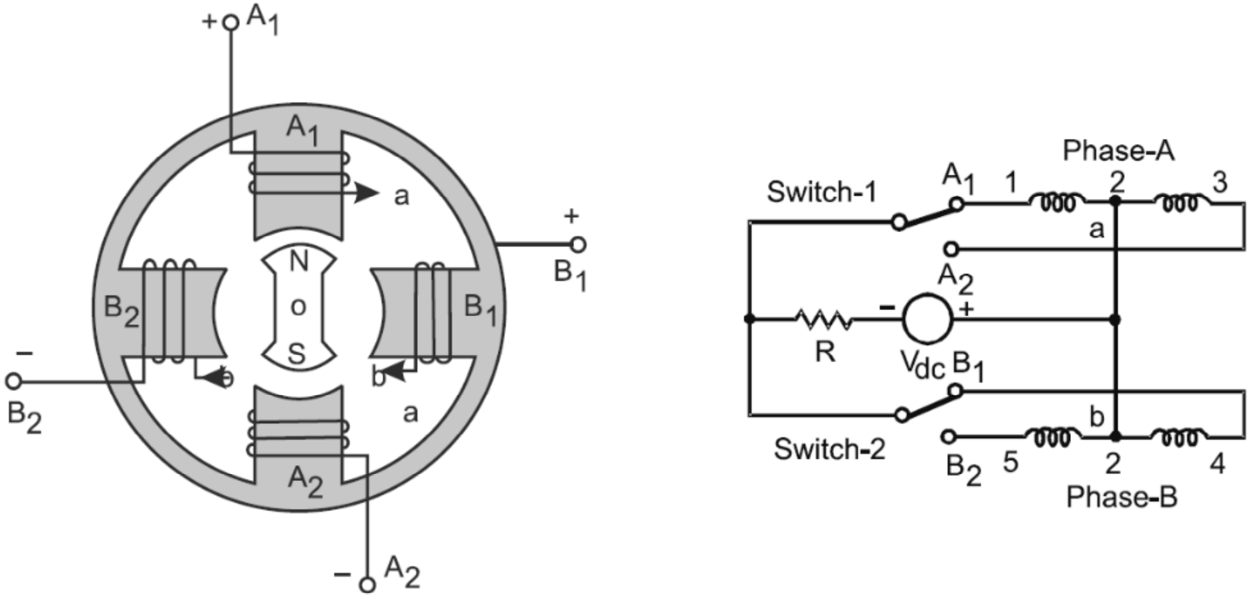
A stepper motor in which rotor is made of permanent magnet having even number of poles is called **a permanent-magnet (PM) stepper motor.**

Construction

The stator of a permanent-magnet stepper motor carries the similar winding as that of a conventional two-phase, three-phase or higher poly-phase induction or synchronous motor. The end terminals of all the windings are brought out to the terminal box for DC excitations. The rotor of this motor has even number of poles made of high retentivity steel alloy (Alnico) producing a multipole permanent magnet. Both rotor and stator may employ salient or non-salient pole construction. Usually, the stepper motors having small stepping angles are of non-salient pole type construction.

Working

Figure 12.17 (a) shows a typical *PM* stepper motor. With stator winding $A_1 - A_2$ energised only, for the polarity shown in Fig. 12.17(b) the *PM* rotor is "locked" in the position shown. If stator coil



(a) Winding position

(b) Switching circuit

Fig. 12.17 Permanent magnet stepper motor with switching circuit

$A_1 - A_2$ is de-energized and $B_1 - B_2$ is energised, the polarity of south (S) is produced at B_1 and north (N) at B_2, causing the *PM* rotor to rotate 90° in response to the *excitation torque* produced by the winding $B_1 - B_2$. The excitation torque is maximum when the angle between the *PM* rotor and stator winding is 90°.

Reversing the current in windings *A* and *B*, consecutively, in turn, results in continuous clock wise rotation of the *PM* rotor. Instead of reversing the supply voltages feeding each phase, a simplified switching arrangement using two solid-state (transistors or thyristors) switches accomplishes the current reversals in each phase of the two-phase windings, as shown in Fig. 12.17 (b).

The adjoining table shows the switching sequence for the four-step stepper motor. Note that for a two-pole, two-phase stepper, the pole-phase product is 4. If 360° is divided by this product, we obtain the *stepping length, or stepping angle,* for any *PM* or *VR* stepper motor.

i.e.,
$$\alpha = \frac{360°}{nP} \; degrees$$

where n = the number of phases or stacks

P = the number of rotor poles (or teeth)

Switching step	*Switch 1*	*Switch 2*	*Angle of rotation*
1	1	4	90°
2	3	4	180°
3	3	5	270°
4	1	5	360° (0°)
1	1	4	90°

Since the number of teeth (or poles) on a rotor of given diameter is limited, it might appear that the solution to smaller stepping lengths is to increase the number of phases. But, as shown in Fig. 12.17 (b), increasing the number of phases (or stacks) results in a corresponding increase in the number of solid-state driven circuits. Since increasing the number of phases produces no particular performance advantages, steppers are rarely found having more than three phases or stacks.

Finally, if reversal of the stepping motor is desired, the switching steps shown in the table (reading from top the bottom) may be reversed by performing the sequences steps 4-3-2-1 (reading from bottom to top).

Example

Determine the stepping angle for a 3-phase, 24 pole PM stepper motor.

Solution:

Stepping angle, $\alpha = \dfrac{360^\circ}{nP}$ Where $n = 3$ *and* $P = 24$

$\therefore \quad \alpha = \dfrac{360^\circ}{3 \times 24} =$ **5°/step** (*Ans.*)

Example

To obtain a stepping angle of 7.5° for a 3-phase PM stepper motor, how many poles should the rotor have?

Solution:

Stepper angle, $\alpha = \dfrac{360^\circ}{nP}$ where, $n = 3$ and $\alpha = 7{\cdot}5°/step$

$\therefore \quad 7{\cdot}5^\circ = \dfrac{360^\circ}{3 \times P}$ or $P = \dfrac{360^\circ}{3 \times 7{\cdot}5^\circ} =$ **16** (*Ans.*)

Variable-reluctance (VR) Stepper Motor