

DC Generator

Chapter Objectives

After the completion of this unit, students/readers will be able to understand:

- ✓ What is a DC generator and how does it convert mechanical energy into electrical energy?
- ✓ What are the main constructional features of a DC machine, material used for different parts and their function?
- ✓ How armature winding is designed and placed in the armature slots? Give details of lap and wave winding design.
- ✓ What are the factors on which emf induced in the armature depends?
- ✓ What are the factors on which torque developed in the armature depends?
- ✓ What is armature reaction and how does it affect the performance of machine?
- ✓ What is commutation? What is meaning of bad and good commutation?
- ✓ What are causes of sparking at the brushes and how can it be reduced or removed?
- ✓ What are inter-poles and compensating winding and how are these helpful in improving commutation?
- ✓ What are different types of DC generators on the basis of field excitation?
- ✓ How is voltage built-up in DC shunt generator and what is critical resistance?
- ✓ What are the performance characteristics of DC generators and their field of applications?
- ✓ What are the losses in a DC generator?
- ✓ What is efficiency of a DC generator and under what conditions does it become maximum?

Introduction

A DC machine is an electro-mechanical energy conversion device. When it converts mechanical power (ωT) into DC electrical power (EI), it 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, but it can supply limited power. There are some applications where large quantity of DC power is required (such as in chemical and metal extraction plants, for electroplating and electrolysis processes etc.), at such places DC generators are used to deliver power.

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

4.1 DC Generator

An electro-mechanical energy conversion device (or electrical machine) that converts mechanical energy or power (ωT) into DC electrical energy or power (EI) is called **DC generator**.

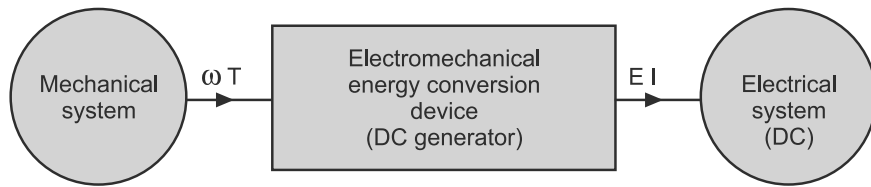
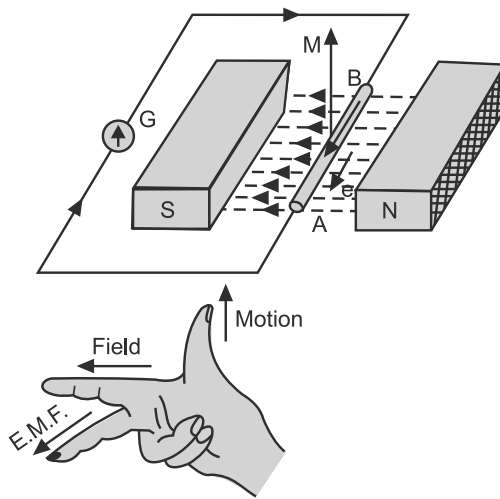


Fig. 4.1 Block diagram of electro-magnetic energy conversion (Generator action)

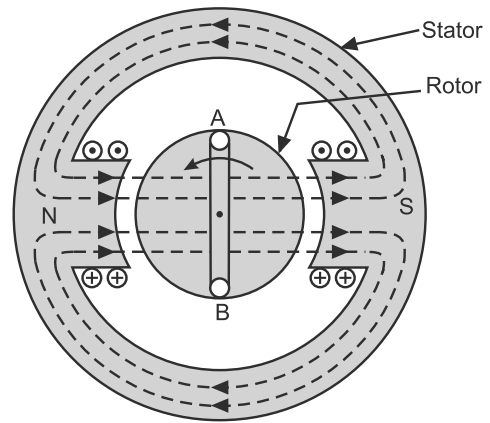
Working Principle

The basic principle of a DC generator is *electro-magnetic induction* i.e.,

“When a conductor cuts across the magnetic field, an **emf** is induced in it.”



(a) Linear motion of conductor in a uniform magnetic field



(b) Coil rotating in a uniform magnetic field

Fig. 4.2 Generation of emf

Consider Fig. 4.2(a), here, when a conductor is moved vertically upward or downward, the deflection in the galvanometer clearly shows that an *emf* is induced in the conductor since flux is cut by the conductor. But, when it is moved horizontally (left or right), there is no deflection in the galvanometer which shows that no *emf* is induced in the conductor since flux cut is zero and conductor moves just parallel to the magnetic lines of force.

In fact, in a generator, a coil is rotated at a constant speed of ω radians per second in a strong magnetic field of constant magnitude as shown in Fig. 4.2(b). An *emf* is induced in the coil by the phenomenon of *dynamically induced emf* ($e =$

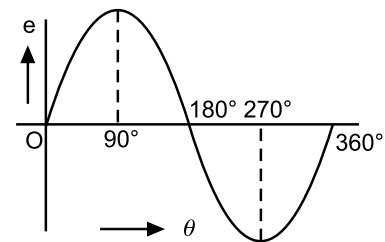


Fig. 4.2(c) Wave shape of induced emf

$Blv \sin \theta$, $e \propto \sin \theta$). The magnitude and direction of induced emf changes periodically depending upon sine of angle θ . The wave shape of the induced emf is shown in Fig. 4.2(c), which is AC for internal as well as external load.

This AC is converted into DC with the help of commutator, as explained in the Articles to follow. Thus, the working principle of a DC generator is **electro-magnetic induction**.

4.2 Main Constructional Features

The complete assembly of various parts in a scattered form of a DC machine is shown in Fig. 4.3. The essential parts of a DC machine are described below:

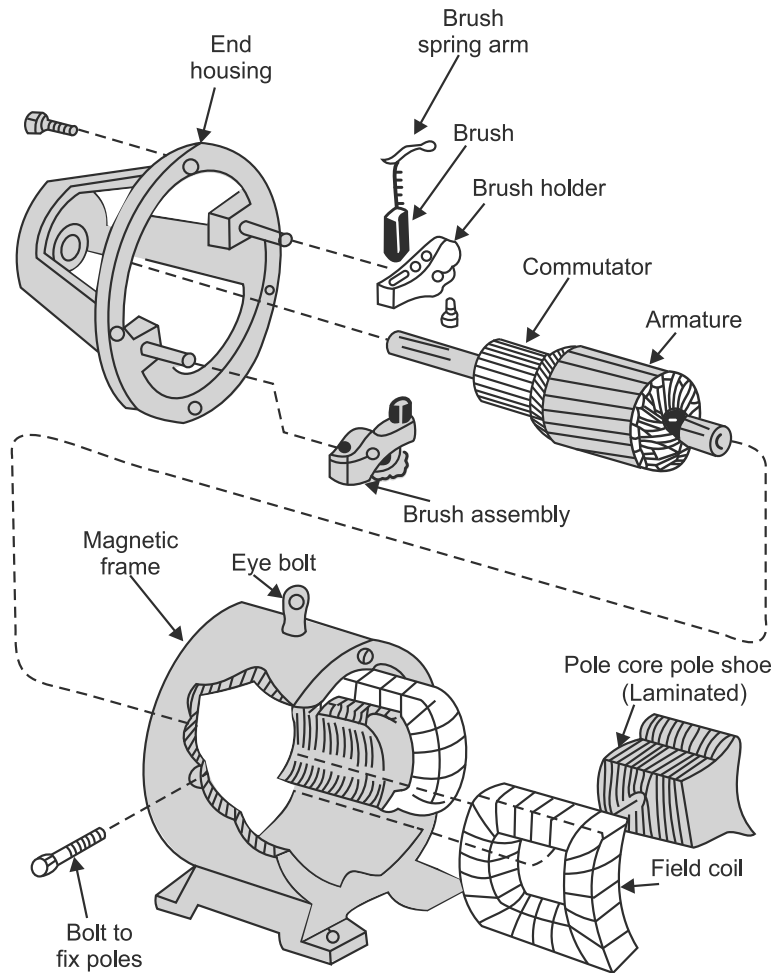


Fig. 4.3 Disassembled parts of a DC machine

1. Magnetic Frame or Yoke

The outer cylindrical frame to which main poles and inter poles are fixed is called yoke. It also helps to fix the machine on the foundation. It serves two purposes:

- (i) It provides mechanical protection to the inner parts of the machine.
- (ii) 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:

- (i) They support the field or exciting coils.
- (ii) They spread out the magnetic flux over the armature periphery more uniformly.
- (iii) Since pole shoes have larger X-section, the reluctance of magnetic path is reduced.

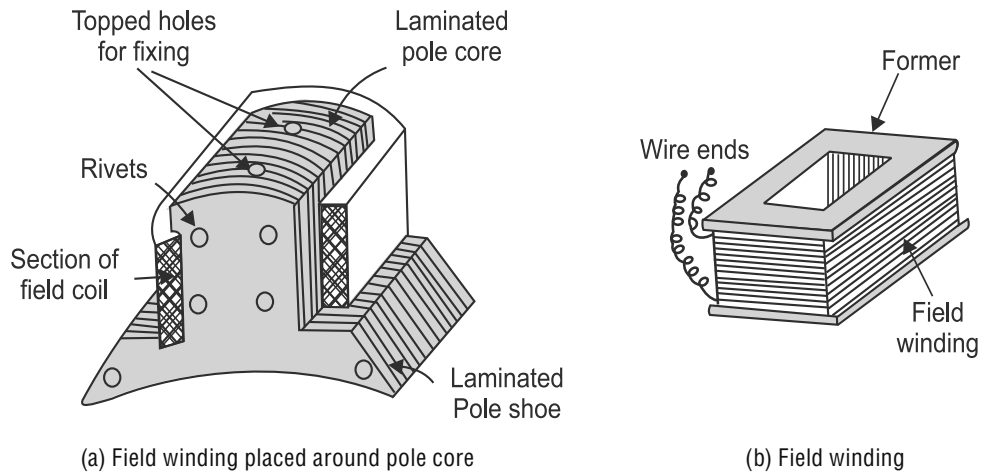


Fig. 4.4 Pole core, pole shoe and field winding

Usually, the pole core and pole shoes are made of thin cast steel or wrought iron laminations which are riveted together under hydraulic pressure as shown in Fig. 4.4(a).

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. 4(b)] and then placed around the pole core as shown in Fig. 4(a). When direct current is passed through the field winding, it magnetises the poles which 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 Fig. 4.5.

4. Armature Core

It is cylindrical in shape and keyed to the rotating shaft. At the outer periphery slots are cut, as shown in Fig. 4.6, which accommodate the armature winding. The armature core shown in Fig. 4.6, serves the following purposes:

- (i) It houses the conductors in the slots.
- (ii) 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 for its construction. When it rotates, it cuts the magnetic field and an emf is induced in it. This emf circulates eddy currents which results in eddy current loss in it. To reduce these losses, armature core is laminated, in other words we can say that about 0.3 to 0.5 mm thick stampings are used for its construction. Each lamination or stamping is insulated from the other by varnish layer (see Fig. 4.6).

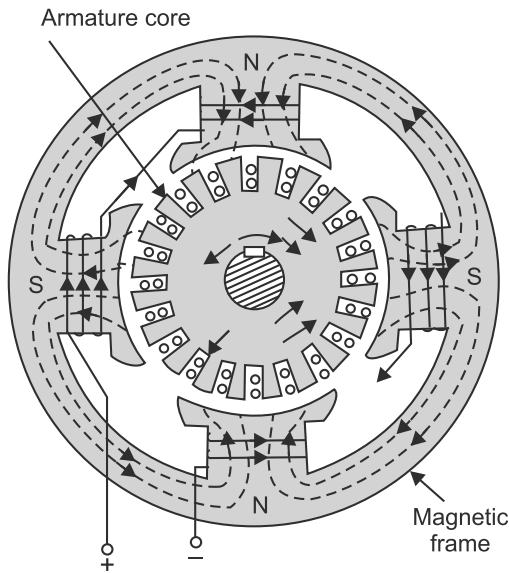


Fig. 4.5 Magnetic circuit of DC machine

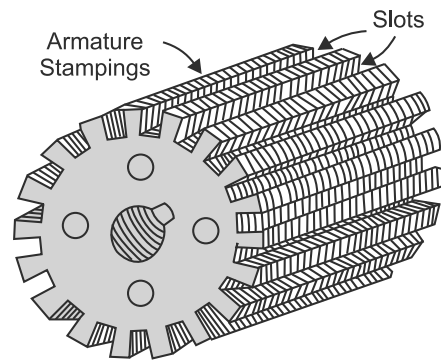


Fig. 4.6 Armature core

5. Armature Winding

The insulated conductors housed in the armature slots are suitably connected. This is known as armature winding. The armature winding acts as the heart of a DC machine. It is a place where one form of power is converted to the other form i.e., in case of generator, mechanical power is converted into electrical power and in case of motor, electrical power is converted into mechanical power. On the basis of connections, there are two types of armature windings named (i) Lap winding and (ii) Wave winding (detailed discussions in the coming articles).

- (i) *Lap winding*: In this winding, the connections are such that the number of parallel paths is equal to number of poles. Thus, if machine has P poles and Z armature conductors, then there will be P parallel, paths, each path will have Z/P conductors in series. In this case, the number of brushes is equal to the number parallel paths. Out of which half the brushes are positive and the remaining (half) are negative.
- (ii) *Wave winding*: In this winding, the connections are such that the numbers of parallel paths are only two irrespective of the number of poles. 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 i.e., number of parallel paths.

6. Commutator

It is an important part of a DC machine and serves the following purposes:

- (i) It connects the rotating armature conductors to the stationary external circuit through brushes.
- (ii) It converts the alternating current induced in the armature conductors into unidirectional current in the external load circuit in generator action, whereas, it converts the alternating torque into unidirectional (continuous) torque produced in the armature in 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 Fig. 4.7.

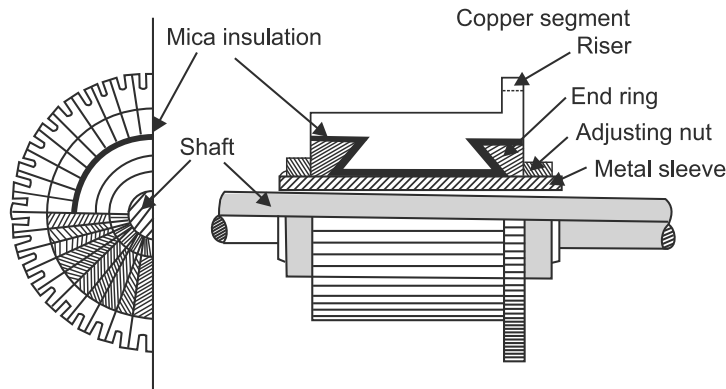


Fig. 4.7 Commutator

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 conducting material and at the same time in powdered form provides lubricating 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 bearings may be ball or roller bearings these are fitted in the end housings. Their function is to reduce friction between the rotating and 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 like armature core, commutator, cooling fan etc. are keyed to the shaft.

4.3 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 Fig. 4.8.

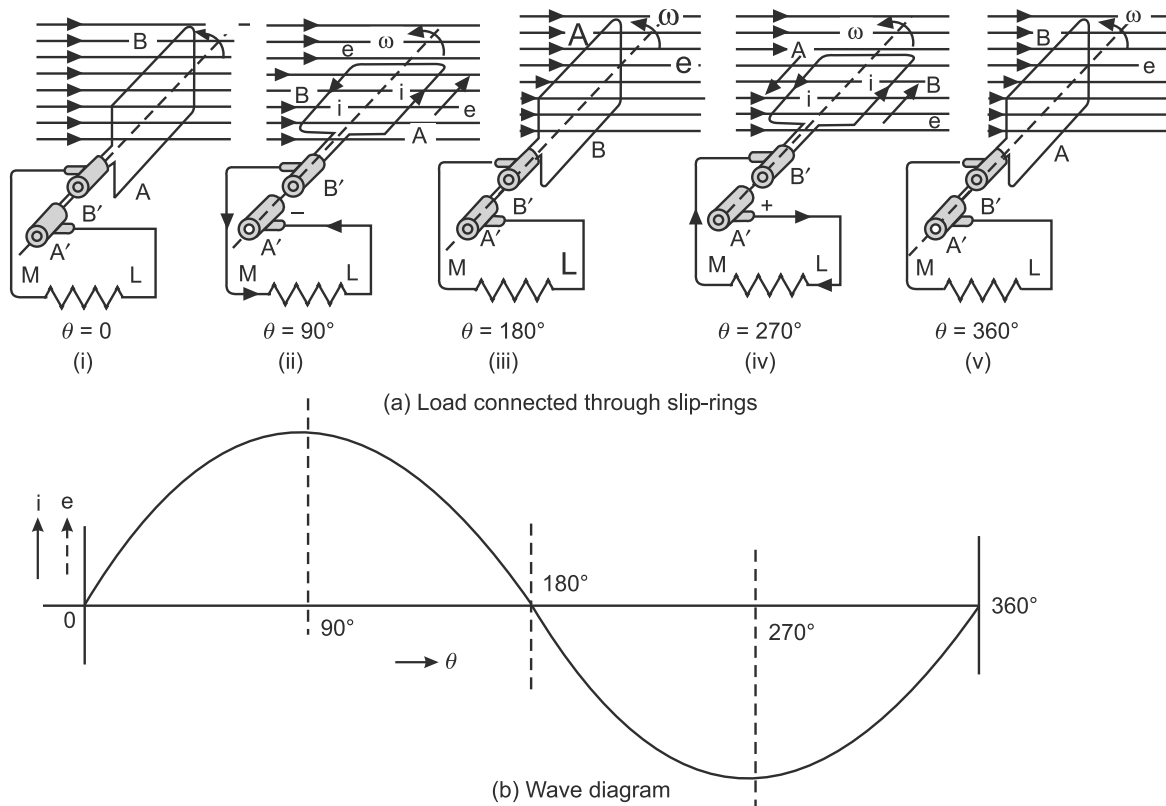


Fig. 4.8 Generated emf for external circuit connected through slip rings

When this coil is rotated in counter clockwise direction at an angular velocity of ω radius per second, 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 Fig. 4.8(a) and the corresponding value of the induced emf and its

direction is shown in Fig. 4.8(b). The induced emf is alternating and the current flowing through the external resistance is also alternating i.e., at second instant current flows in external resistance from M to L , whereas, at fourth instant it flows from L to M as shown in Fig. 4.8(b).

Commutator Action

Now, consider that the two ends of the coil are connected to only one slip ring split into two parts (segment) i.e., 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 Fig. 4.9(a).

In this case when the coil is rotated in counter clockwise direction at an angular velocity of ω radians per second, 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 Fig. 4.8(b).

However, the flow of current in the external resistor or circuit will become unidirectional i.e., at 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 Fig. 4.9(a). Its wave shape is shown in Fig. 4.9(b).

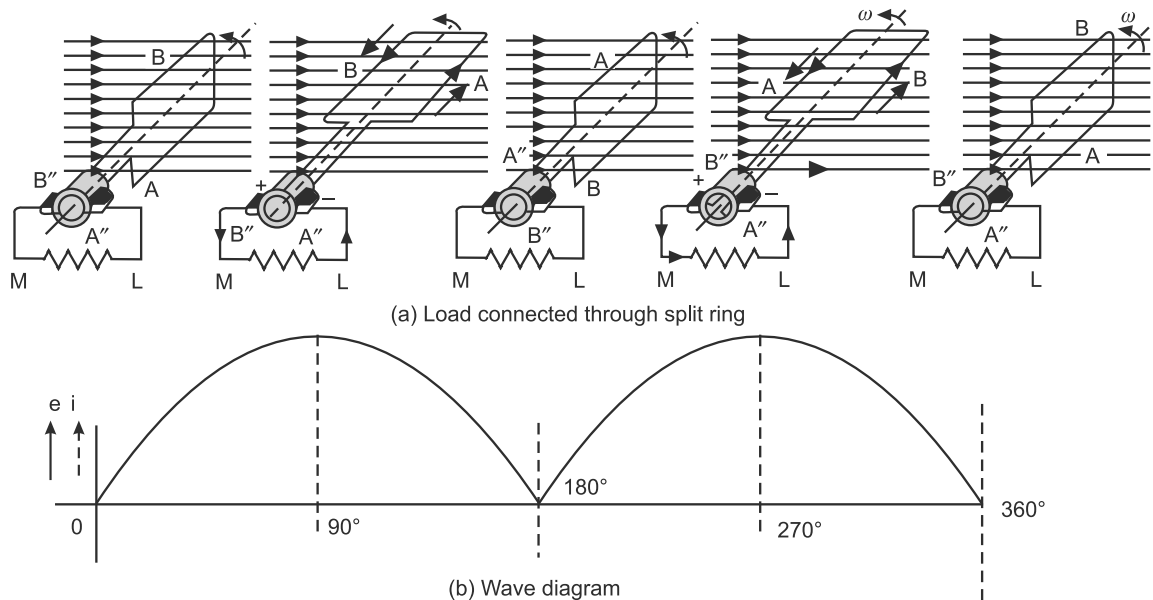
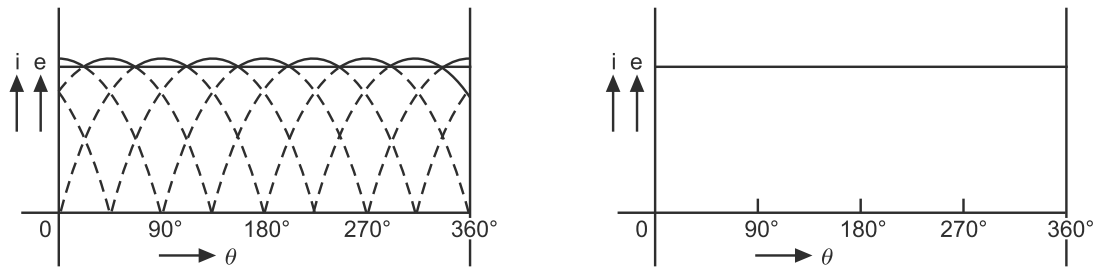


Fig. 4.9 Generated emf for external circuit connected through split ring

Hence, an alternating current 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 Fig. 4.10(a). The actual flow of current flowing in the external load is shown by the firm line which fluctuates slightly. The number of coils placed on the armature is even much more than this and a pure direct current is obtained at the output as shown in Fig. 4.10(b).

Thus, in actual machine working as a generator, the function of commutator is to convert the **alternating current** produced in the armature into **direct current** in the external circuit.



(a) Wave shape of output delivered by number of coils (b) True wave shape of output delivered by a dc generator

Fig. 4.10 Wave shape of output delivered by a DC generator

4.4 Connections of Armature Coils with Commutator Segments and Location of Brushes

Consider an armature which has four coils 1, 2, 3 and 4 equally spaced in the armature slots as shown in Fig. 4.11. The number of commutator segments is equal to number of coils. When the armature is rotated clockwise, the direction of induced emf and hence the current in coil sides 3', 1, 4', 2 is downward and in coil sides 1', 3, 2', 4 is upward. The coils should be connected in such a way that the emf induced in the two sides of the same coil be added up as shown in Fig. 4.12, The coil sides 1–4', 1'–2, 2'–3 and 3'–4 are connected to the commutator segments namely 1, 2, 3 and 4 as shown in Fig. 4.13.

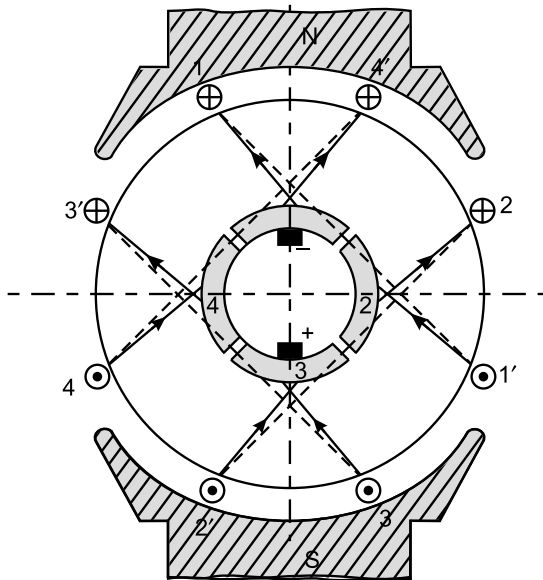


Fig. 4.11 Coils and commutator segments

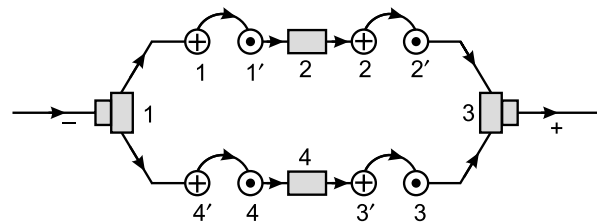


Fig. 4.12 Electrical connections

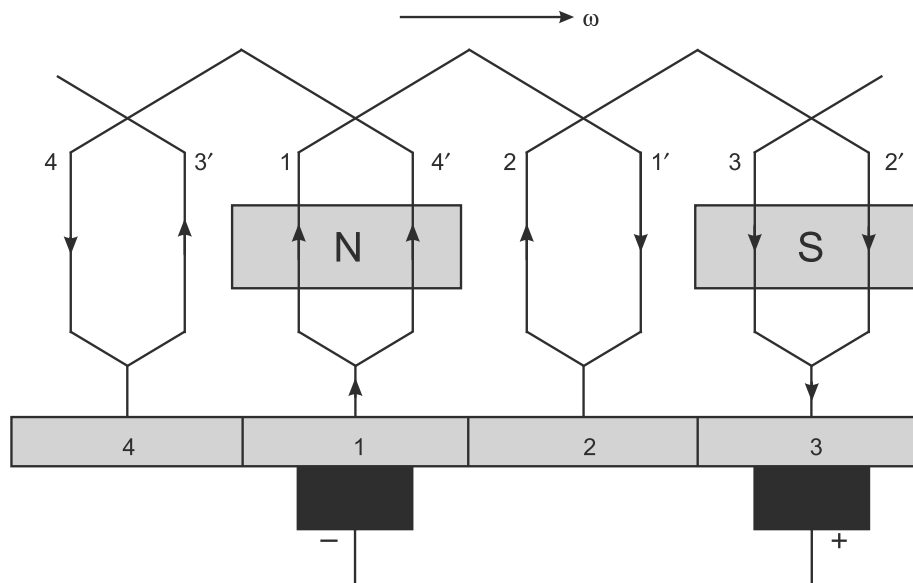


Fig. 4.13 Developed windings diagram for 2-pole, 4-coil, 4-segment DC machine.

The next point of discussion is to determine how many brush sets are required and where these are to be placed with respect to the poles. The brushes are to collect or deliver the current and are placed at such a position that sparking is minimum at the brushes. The rules to be followed for determining the position of brushes are given below:

- (i) Place the brush at each meeting point or each separating point of two emf's. The brushes at the meeting point are of positive polarity and those at the separating point are of negative polarity. At segment 1, current is separated towards conductor 1 and 4', hence it is a separating point. Whereas, current is coming towards segment 3 from conductor 2' and 3, hence it is a meeting point. So, the commutator segment 1 is the position of negative brush and commutator segment 3 of the positive brush.
- (ii) Brushes are generally equally spaced and placed directly opposite to the pole centres. This brings out a very important point, namely, that in certain positions of the commutator the brushes will be actually short circuiting the coils connected to the segments with which they are in contact (Fig. 4.14). In this case only two coils are short circuited, which is taking place continuously and as such the width of brushes must be greater than the thickness of the mica insulation between segments. However, for representation, the general convention is to place the brushes at geometrical neutral plane (G.N.P.). All conductors above the brush axis carry current in one direction and all conductors below the brush axis carry current in the opposite direction. This convention represents that the brushes are placed at the coil or coils in which the voltage induced is zero.

The actual position of the brushes is shown in Figs. 4.14, 4.15 and 4.16. These figures also show the position of coil sides and the direction of currents after the coils 2 and 4 undergo commutation. The negative brush short circuits the segments 1 and 4 whereas positive brush short circuit the segments 2 and 3. The coils 4 and 2 are short circuited by the brushes and hence no emf should induce in these coils. The armature winding forms a closed circuit and consists of two parallel paths. When a coil

under goes commutation no emf is induced in it since it passes through magnetic neutral axis (*MNA*), and the coil is short-circuited by the brushes, hence no sparking will take place.

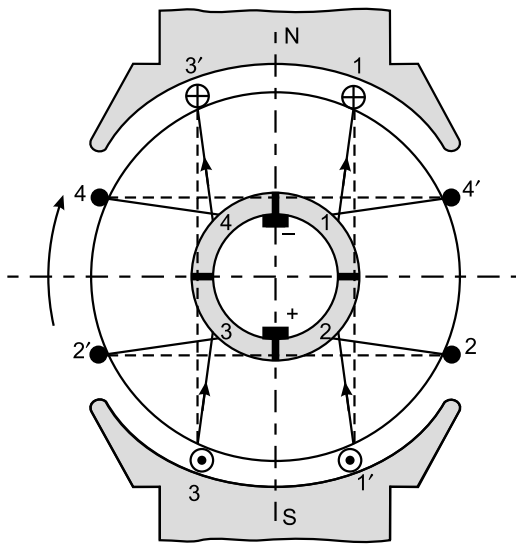


Fig. 4.14 Brush position

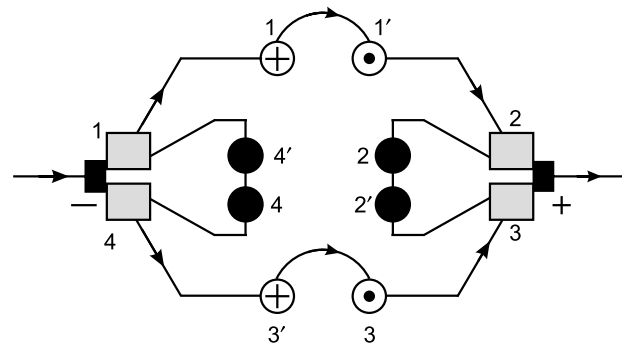


Fig. 4.15 Brush position and electrical connections

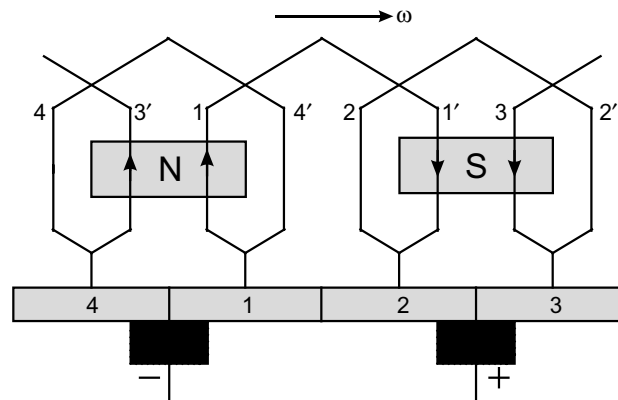


Fig. 4.16 Brush position at an instant

4.5 Armature Winding

At the outer periphery of an armature core, slots are cut. In these slots number of conductors are placed which are connected with each other in proper arrangement forming series-parallel paths depending upon the requirement. This arrangement of connections is known as *armature winding*. To understand the armature winding schemes, it is desirable to have an idea about the following terms.

- 1. Conductor:** The length of wire embedded in armature core and lying within the magnetic field is called the conductor (see Fig. 4.17(a), where *AB* is a conductor). It may be having one or more parallel strands. Total number of conductors in the armature winding are represented by the symbol *Z*.

- 2. Turn:** Two conductors lying in a magnetic field connected in series at the back, as shown in Fig. 4.17(a), so that emf induced in them is additive is known as a turn.

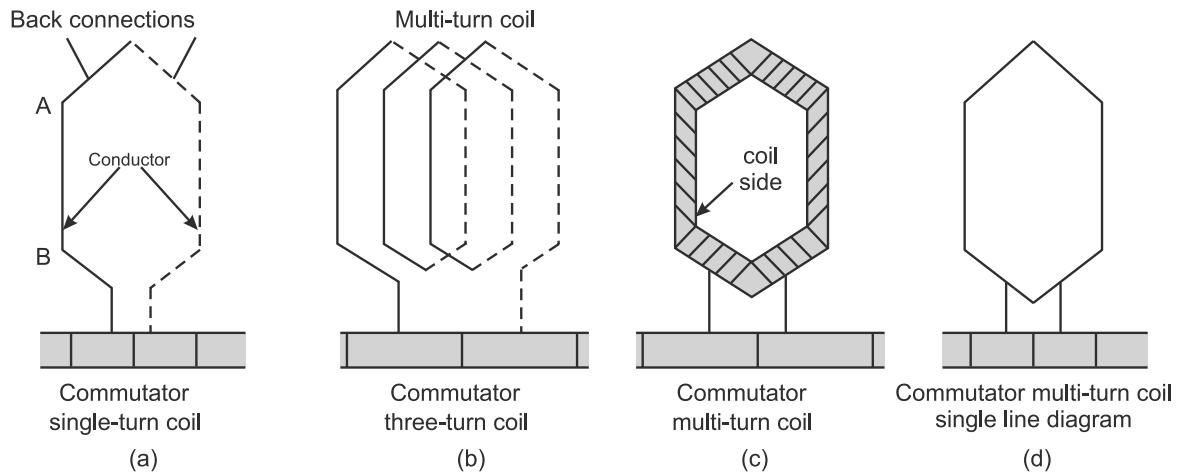


Fig. 4.17 Representation of a coil.

- 3. Coil.** A coil may be a single turn coil having only two conductors, as shown in Fig. 4.17(a), or it may be a multi-turn coil having more than two conductors as shown in Fig. 4.17(b). In Fig. 4.17(b), a three-turn coil is shown. The bunch of three conductors may be wrapped by the cotton tape, as shown in Fig. 4.17(c), before placing in the slot of armature. A multi-turn coil can be represented by single line diagram as shown in Fig. 4.17(d). Multi-turn coils are used to develop higher voltages. When the armature conductors are more, it is not feasible to use single turn coils because it will require large number of commutator segments and if used it will not give spark-less commutation. Moreover, it will not be economical due to use of more copper in the end connections. The total number of coils in the armature winding are represented by symbol 'C'.
- 4. Coil side.** Each coil (single turn or multi-turn) has two sides called *coil sides*. Both the coil sides are embedded in two different slots as per the winding design (nearly a pole pitch apart).
- 5. Coil group.** A group of coils may have one or more coils.
- 6. Winding.** When number of coil groups are arranged on the armature in a particular fashion as per the design, it is called an armature winding.
- 7. Inductance effect.** All the coils have some inductance effect as current is changing in them. Due to inductance effect the flow of current is opposed causing reduction in resultant output voltage. Over-hanging end connections have some adverse effect due to inductance.

Terms Related to Winding Design

- 8. Front-end and Back-end connectors.** A wire that is used to connect end of a coil at the front to the commutator segment is called a front-end connector.

Whereas, a wire that is used to connect one coil side to the other coil side at the back is called back-end connector.

- 9. Pole pitch.** In general, it is defined as number of armature slots per pole. It may also be defined as the number of armature conductors per pole. If there are 36 conductors for 4 poles then pole pitch will be equal to $36/4$ i.e., 9 conductors per pole.
- 10. Back pitch.** The distance in terms of number of armature conductors between first and last conductor of the same coil i.e., the distance between two coil sides of the same coil is called *back pitch*. It is also called the *coil span* or *coil spread* and is denoted by Y_b , as shown in Figs. 4.18(a), (b) and (c)

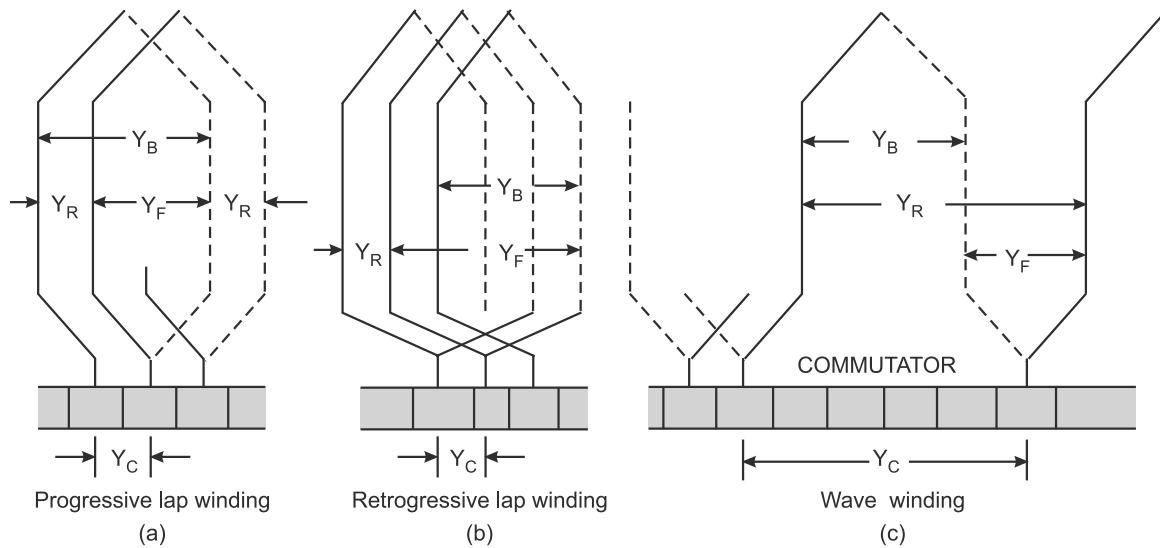


Fig. 4.18 Terms used in coils

- 11. Front pitch.** The distance in terms of number of armature conductors or number of slots between second conductor of one coil and the first conductor of the next coil which are connected to the same commutator segment on the front is called *front pitch*. It is denoted by Y_F , as shown in Figs. 4.18 (a), (b) and (c).
- 12. Resultant pitch.** The distance in terms of number of armature conductors or number of slots between the start of one coil and the start of the next coil to which it is connected is called *resultant pitch*. It is denoted by Y_R as shown in Figs. 4.18(a), (b) and (c).
- 13. Commutator pitch.** The distance measured in terms of commutator segments between the segments to which the two ends of a coil are connected is called *commutator pitch*. It is denoted by Y_C as shown in Figs. 4.18(a), (b) and (c).
- 14. Coil span or coil pitch.** The distance in terms of number of armature conductors or number of slots between two sides of the same coil is called *coil span* or *coil pitch*.

The coil span may be equal to, less than or more than pole pitch. Accordingly, the coils are known as full pitched, short pitched or over pitched coils respectively.

For instance, consider Fig. 4.19. where pole pitch is say 4. One side of coil-A is placed in slot No. 1 and the other side is placed in slot No. 5, then the coil span is $5-1 = 4$ which is equal to pole pitch hence coil-A is called a full-pitched coil. Whereas, in case of coil-B, the coil span is $6-3 = 3$ which is less than pole pitch, this coil is called a short pitched coil.

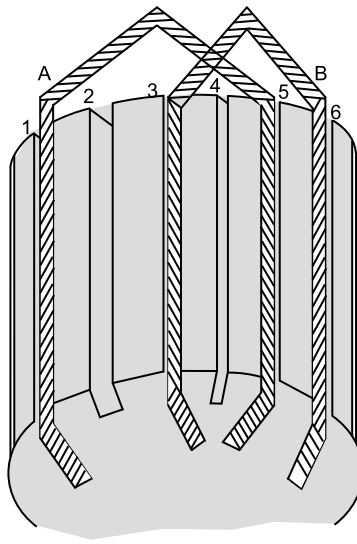


Fig. 4.19: Full-pitch and short-pitch winding

When the coils are full pitched, the induced emf in a coil is the arithmetic sum of the emfs induced in two sides of the same coil since the coil sides are displaced by 180° electric al. In this case, the two sides of the same coil are placed at similar position of two adjacent poles (North and South).

In case of short pitched and over pitched coils, the resultant induced emf is reduced because the two sides would fall under the influence of the same pole at some instant. At this instance the induced emf in the two sides will oppose each other causing reduction in resultant emf (phasor difference).

The advantage of short pitched winding is that in this case the copper used for end connections is reduced substantially which reduces the cost of machine. It also improves the commutation (reduction of sparking at brushes) because inductance of overhang connections is reduced. Moreover, it reduces the copper losses and improves the efficiency to some extent. Hence, many a times short pitched winding is used.

- 15. Degree of Re-entrant of an armature winding.** There can be single re-entrant or multi re-entrant armature winding. While tracing through a winding once, if all armature conductors are included on returning to the starting point, the winding is called single re-entrant winding. It will be double re-entrant if only half of the conductors are included in tracing through the winding once.

4.6 Types of Armature Winding

The continuous or closed armature windings are of two types:

1. Gramme-ring winding 2. Drum Winding

The gramme-ring type of armature winding is an early form of armature winding. This winding is replaced by more efficient drum type winding. The gramme-ring type of armature winding was having following disadvantages.

Disadvantages

- (i) Only half the coil was available to link with the pole flux. The other half of the portion of winding was lying inside the core which was used only as connectors and so there was wastage of copper.
- (ii) As each turn was to pass through the centre of the core, therefore, it was difficult to wind and require more labour, hence was costlier.
- (iii) The maintenance and repairs were more costly.
- (iv) Insulation of winding was also difficult.
- (v) For the same pole flux and armature velocity the emf induced in ring winding was half of that induced in the drum winding having same number of coils.
- (vi) Construction was having a large air gap, so stronger field excitation was required to produce the required flux.

4.7 Drum Winding

In this type of winding, the conductors are housed in slots cut over the armature surface and connected to one another at the front and back through connectors. It has the following two main advantages.

1. Whole of the copper used is active except end connectors, i.e., it cuts flux and, therefore, is active in generating emf.
2. The coils can be pre-formed and insulated before placing on the armature, which reduces the construction cost.

The drum winding may be either single layer or double layer winding. In single layer winding, only one conductor or one coil side is placed in each armature slot. It is rarely used because of its more cost.

In two-layer winding, as shown in Fig. 4.20, there are two conductors or coil sides per slot arranged in two layers. Mostly it is employed because of economy reasons. These coils are usually are wound on machine driven formers which give them proper shape. The turns may be bound together with cotton tape. The ends are left bare to solder them to the commutator segments. The coils are then dipped into some insulating compound such as asphalt and are then dried. If the machine is to be operated at high temperatures, other materials, such as mica and paper tape, fibre glass tape, and silicon impregnated insulation may be used.

Before placing the coils in the slots, liners of leatheroid are placed to ensure mechanical protection is provided to the coils. After dropping the coils into the slots, wedges of wood or hard fibre are driven to hold them in place, as shown in Figs. 4.20(a) and (b).

To obtain maximum voltage a full pitched winding is used. However, the span may be reduced to as much as eight-tenth of the pole pitch without any serious reduction in the induced emf. When this is done, the winding is called short pitch (or fractional pitch) winding.

Usually, one side of every coil lies in the top of one slot and the other side lies in the bottom of some other slot at a distance of approximately one pole pitch along the armature. Thus, at least two coil sides occupy each slot. Such windings, in which two coil sides occupy each slot are most commonly used for all medium sized machines. In case of large machines, more coil-sides can be placed in a single slot as shown in Figs. 4.20(b) and 4.20(d). Placing of several elements in a single slot gives fewer slots than segments which have got following advantages.

- (i) By providing more conductors in one slot, the number of slots decreases. As the number of slots is reduced the armature core teeth become mechanically stronger to bear the stresses.
- (ii) In this arrangement, the number of commutator segments is increased, the voltage between segments adjacent to each other decreases and the number of turns of wire in the coil or coils connected to adjacent segments also decreases. The result is that there is less sparking at the commutator because of the improved commutation.
- (iii) The overall cost of construction is reduced.

In general there are two types of drum type armature windings: (i) lap winding (ii) wave windings.

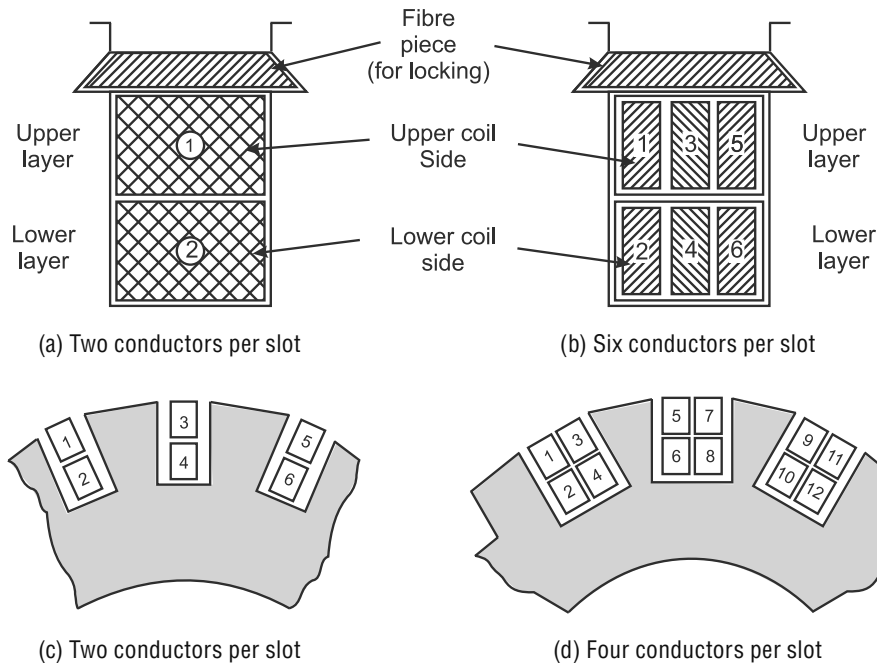


Fig. 4.20 Double-layer winding

4.8 Lap Winding

Single turn lap winding is shown in Figs. 4.21(a) and (b). In lap winding a coil side under one pole is connected directly to the coil side of another coil which occupies nearly the corresponding position under the next pole and the finish end of other coil is connected to a commutator segment and to the start end of the adjacent coil situated under the same pole and all coils are connected similarly forming a closed loop. Since the sides of successive coils overlap each other, it is called a lap winding. Lap winding may be further classified as a simplex (single) or multiplex (double or triple) windings.

Simplex lap winding: In this winding, there are as many parallel paths as there are field poles on the machine.

Double or duplex lap winding: In this case, two similar simplex windings are placed in alternate slots on the armature and connected to alternate commutator segments. Thus, each winding carries half of the armature current.

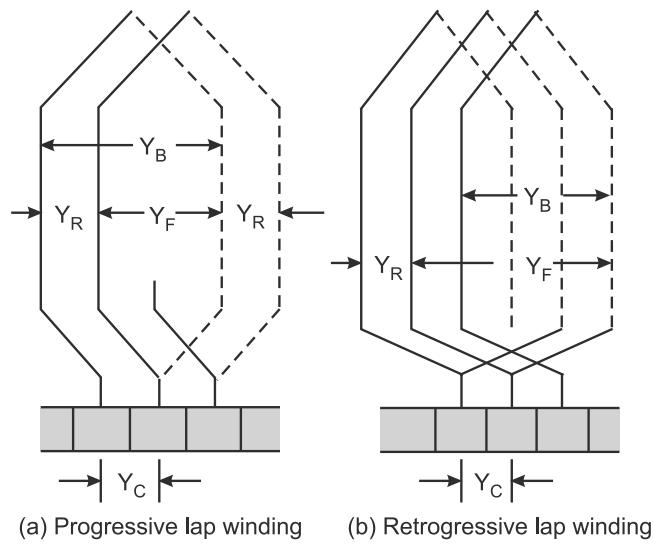


Fig. 4.21 Lap winding connections

Triple or triplex lap winding: In this case, three similar simplex windings are placed to occupy every third slot and connected to every third commutator segment. Thus, each winding carries one third of the armature current. Similarly, there can be multiplex lap winding having even more than three simplex winding as per the requirement.

The above explanation clearly shows that the sole purpose of employing multiplex lap winding is to increase the number of parallel* paths enabling the armature to carry a large total current, at the same time reducing the conductor current to improve commutation conditions.

Following points regarding lap winding should be carefully noted:

1. The back and front pitches must be odd. But they cannot be equal. They differ by 2 or some multiple thereof.
2. The coil or back pitch Y_B must be nearly equal to a pole pitch $\left(\frac{Z}{P}\right)$.
3. The average pitch $Y_A = \frac{Y_B + Y_F}{2}$. It is equal to pole pitch $= \frac{Z}{P}$.
4. Commutator pitch $Y_C = \pm 1$ for simplex winding (in general, $Y_C = \pm m$ where m is the multiplicity of winding)
5. Resultant pitch Y_R is always even, being the arithmetical difference of two odd numbers, i.e., $Y_R = Y_B - Y_F$. It is equal to $2m$ where m is multiplicity of winding.
6. For a two-layer winding, the number of slots and number of commutator segments are equal to the number of coils (i.e., half the number of coil sides).
7. The number of parallel paths in the armature $= mP$ where m is the multiplicity of winding and P the number of poles.

Taking the first condition, we have $Y_B = Y_F \pm 2$.

* In duplex lap winding the number of parallel circuits is twice the number of poles and in triplex lap winding, the number of parallel circuits is three times the number of poles.

- (a) If $Y_B > Y_F$ i.e., $Y_B = Y_F + 2$, then we get a progressive or right-handed winding i.e., a winding which progresses in the clockwise direction when we look towards the commutator end. Obviously, $Y_C = +1$, in this case.
- (b) In case $Y_B < Y_F$ i.e., $Y_B = Y_F - 2$, we get a retrogressive or left-handed winding i.e., a winding which advances in the anti-clockwise direction just opposite to the previous case. In this case, $Y_C = -1$.

(c) Hence,
$$\left. \begin{aligned} Y_F &= \frac{Z}{P} - 1 \\ Y_B &= \frac{Z}{P} + 1 \end{aligned} \right\} \dots(4.1) \text{ for progressive winding and } \left. \begin{aligned} Y_F &= \frac{Z}{P} + 1 \\ Y_B &= \frac{Z}{P} - 1 \end{aligned} \right\} \dots(4.2) \text{ for retrogressive}$$

winding

Obviously, Z/P must be even to make the winding possible.

4.9 Numbering of Coils and Commutator Segments in Developed Winding Diagram

The developed winding diagram can be obtained by removing the armature periphery, cutting it along the slot and laying it out flat so that the slots and conductors can be viewed to trace out the armature winding. While drawing developed winding diagrams, we will designate only the coil sides with number (not individual turns). The upper side of the coil will be represented by a firm continuous line, whereas the lower side will be represented by a dotted line. The consecutive number i.e., 1, 2, 3,..... etc. will be assigned to the coil sides such that odd numbers are assigned to the top conductors and even numbers to the lower sides for a two-layer winding. The commutator segments will also be numbered consecutively, the number of the segments will be equal to the number of coils and the upper side will be connected to it.

The readers will be able to understand how to develop armature winding diagram by going through the following examples:

Example 4.1

Draw the developed winding diagram of a progressive lap winding for 4 pole, 16 slot single layer showing therein position of poles, direction of motion, direction of induced emf and position of brushes.

Solution:

Here, Number of poles, $P = 4$

Number of coil sides, $Z = 16$

$$\text{Pole pitch, } Y_P = \frac{Z}{P} = \frac{16}{4} = 4$$

For progressive winding, $Y_B = Y_P + 1 = 4 + 1 = 5$

$$Y_F = Y_B - 2m = 5 - 2 \times 1 = 3 \text{ (here } m = 1)$$

The connections are to be made as per the following table:

Back End Connections

1 to $(1 + 5) = 6$
 3 to $(3 + 5) = 8$
 5 to $(5 + 5) = 10$
 7 to $(7 + 5) = 12$
 9 to $(9 + 5) = 14$
 11 to $(11 + 5) = 16$
 13 to $(13 + 5) = 18(18-16=2)$
 15 to $(15 + 5) = 20(20-16=4)$

Front End Connections

6 to $(6 - 3) = 3$
 8 to $(8 - 3) = 5$
 10 to $(10 - 3) = 7$
 12 to $(12 - 3) = 9$
 14 to $(14 - 3) = 11$
 16 to $(16 - 3) = 13$
 18 to $(18 - 3) = 15$
 4 to $(4 - 3) = 1$

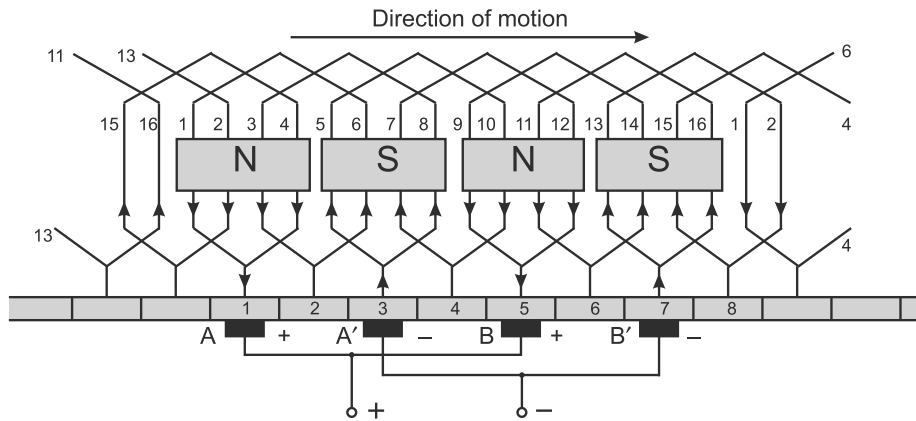


Fig. 4.22 Developed winding diagram

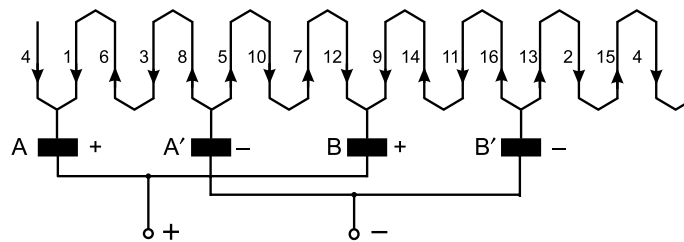


Fig. 4.23 Spiral winding diagram

Steps to draw developed winding diagram

1. Draw 16 coil-sides and number them.
2. Since it is a single layer winding draw all the 16 coil-sides by firm continuous lines.
3. Draw four poles *N*, *S*, *N* and *S* alternately, each pole covers the space of $16/4 = 4$ coil sides. Consider that the poles are below the coil sides.
4. Mark the direction of motion (or rotation) of the conductors, say it is from left to right as marked.
5. Connect conductor 1 to 6 at the back and 6 to 3 at the front and so on as per the table.

6. Mark the direction of flow of current in the coil-sides i.e., downward in the coil sides which are in the influence of north-pole and upward for south-pole.
7. Connect each front end of the coil to each commutator segment as marked in Fig. 4.22.
8. Place four brushes at four commutator segments where either current is meeting (segment No. 1 and 5) or separating (segment No. 3 and 7).
9. The brushes where current is meeting are joined together and a positive terminal is obtained. The other two brushes where current is separating are joined together and a negative terminal is obtained.
10. The series, spiral winding connections are shown in Fig. 4.23, the brushes are placed as explained above.

Example 4.2

Draw a developed winding diagram of a simple two-layer lap-winding for a four-pole generator with 16 coils. Also draw the equivalent ring diagram with position of brushes and diagram representing parallel circuits thus formed.

Solution:

Here, Number of poles, $P = 4$

Number of coils, $C = 16$

Number of coil sides, $Z = 16 \times 2 = 32$

It is a two-layer winding,

$\therefore$ Number of coil sides in each slot = 2

$$\text{Pole pitch, } Y_P = \frac{Z}{P} = \frac{32}{4} = 8$$

For progressive winding, $Y_B = Y_P + 1 = 8 + 1 = 9$

and $Y_F = Y_B - 2m = 9 - 2 \times 1 = 7$ (here $m = 1$)

The connections are to be made as per the following table:

Back End Connections

1 to $(1 + 9) = 10$
 3 to $(3 + 9) = 12$
 5 to $(5 + 9) = 14$
 7 to $(7 + 9) = 16$
 9 to $(9 + 9) = 18$
 11 to $(11 + 9) = 20$
 13 to $(13 + 9) = 22$
 15 to $(15 + 9) = 24$
 17 to $(17 + 9) = 26$
 19 to $(19 + 9) = 28$

Front End Connections

10 to $(10 - 7) = 3$
 12 to $(12 - 7) = 5$
 14 to $(14 - 7) = 7$
 16 to $(16 - 7) = 9$
 18 to $(18 - 7) = 11$
 20 to $(20 - 7) = 13$
 22 to $(22 - 7) = 15$
 24 to $(24 - 7) = 17$
 26 to $(26 - 7) = 19$
 28 to $(28 - 7) = 21$

$21 \text{ to } (21 + 9) = 30$
 $23 \text{ to } (23 + 9) = 32$
 $25 \text{ to } (25 + 9) = 34(34-32=2)$
 $27 \text{ to } (27 + 9) = 36(36-32=4)$
 $29 \text{ to } (29 + 9) = 38(38-32=6)$
 $31 \text{ to } (31 + 9) = 40(40-32=8)$

$30 \text{ to } (30 - 7) = 23$
 $32 \text{ to } (32 - 7) = 25$
 $34 \text{ to } (34 - 7) = 27$
 $36 \text{ to } (36 - 7) = 29$
 $38 \text{ to } (38 - 7) = 31$
 $8 \text{ to } (8 - 7) = 1$

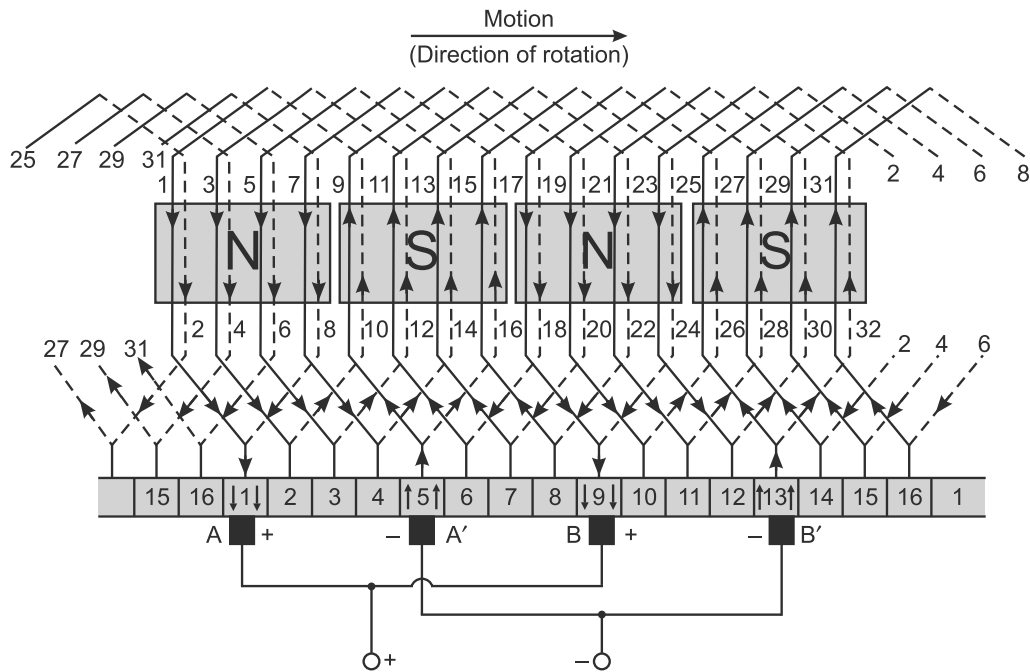


Fig. 4.24 Developed winding diagram

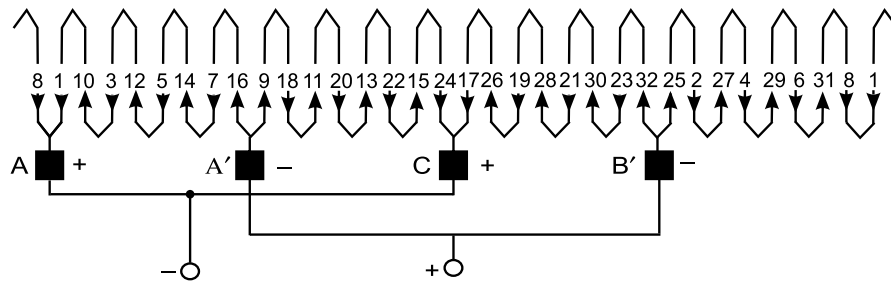


Fig. 4.25 Spiral winding diagram

Steps to draw developed winding diagram

1. Draw $16 \times 2 = 32$ coil-sides and number them.
2. Since it is a two-layer winding draw all the upper (odd numbered) coil-sides by firm continuous lines and all the lower (even numbered) coil sides by dotted lines.

3. Draw four poles N , S , N and S alternately, each pole covers the space of $32/4 = 8$ coil sides. Consider that the poles are below the coil sides.
4. Mark the direction of motion (or rotation) of the conductors, say it is from left to right as marked.
5. Connect conductor 1 to 10 at the back and 10 to 3 at the front and so on as per the table.
6. Mark the direction of flow of current in the coil-sides i.e., downward in the coil sides which are in the influence of N -pole and upward for the S -pole.
7. Connect each front end of the coil to each commutator segment as marked in Fig. 4.24.
8. Place four brushes at four commutator segments where either current is meeting (segment No. 1 and 9) or separating (segment No. 5 and 13).
9. The brushes where current is meeting are joined together and a positive terminal is obtained. The other two brushes where current is separating are joined together and a negative terminal is obtained.
10. The series, spiral winding connections are shown in Fig. 4.25, the brushes are placed as explained above.

The equivalent ring diagram of the armature winding is shown in Fig. 4.26.

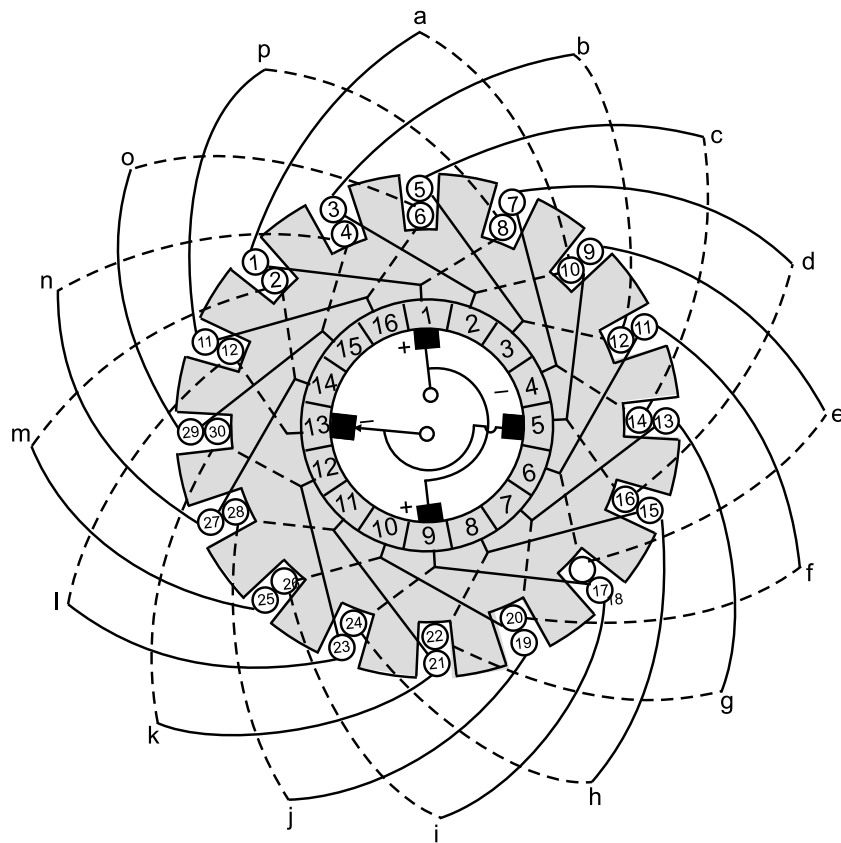


Fig. 4.26 Ring winding diagram

When brushes of same polarity are connected together, then all the armature conductors are divided into four parallel paths as shown in Fig. 4.27.

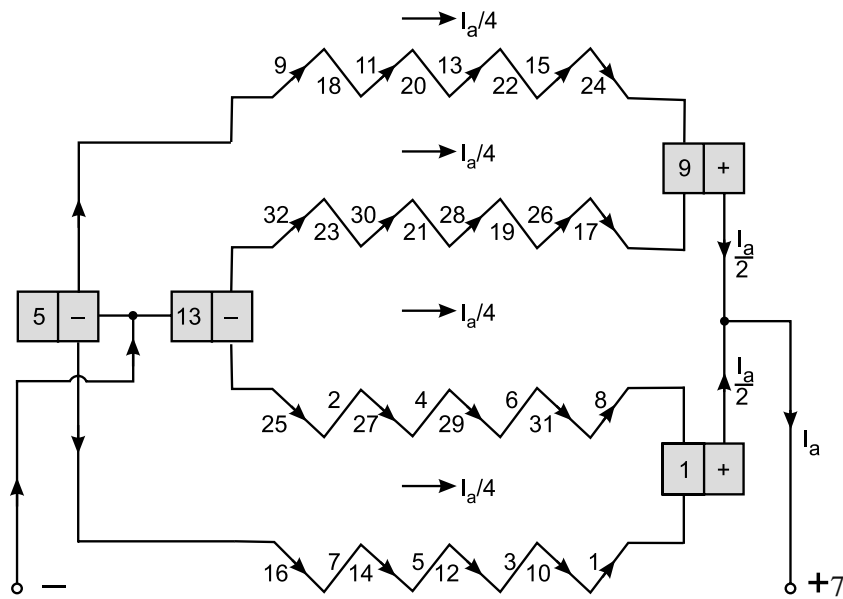


Fig. 4.27 Brush position and parallel paths

4.10 Characteristics of a Simplex Lap Winding

From the above examples it is concluded that

1. A simplex lap winding is a singly re-entrant closed winding because winding may start from any coil side (here it starts from coil side No. 1) returns back to the same coil side after connecting all the coil sides of the armature once and only once.
2. Both back pitch (Y_B) and front pitch (Y_F) of all the coils remain the same and odd number.
3. Total number of brushes is equal to the number of poles. These brushes are connected to the coil sides which lie in between the poles and have no emf induced in them at that particular instant.
4. There are as many parallel paths in the armature as the number of poles (see Fig. 4.27). That is why such a winding is also known as '*Multiple Circuit*' or '*parallel*' winding.

In general, number of parallel paths in armature, $A = mP$ where m is the multiplicity of the lap winding. For simplex lap winding $m = 1$ ($\therefore A = P$), for duplex lap winding $m = 2$ and so on.

5. The emf developed across the positive (+ve) and negative (-ve) brushes is equal to the emf generated in any one of the parallel paths.

Generated emf, E_g = emf generated per parallel path

$$= \text{Average emf/coil side} \times \frac{Z}{P}$$

where $\frac{Z}{P}$ is the number of coil sides connected in series per parallel path.

6. If l is the length of each armature conductor (or coil side), including overhang, a is the area of cross-section and ρ is the resistivity of conductor material, then

Resistance of each conductor (or coil side) = $\rho \frac{l}{a}$

Since $\frac{Z}{P}$ conductors are connected in series in each parallel path.

Resistance of each parallel path = $\rho \frac{l}{a} \times \frac{Z}{P}$

Say the number of parallel paths = A

Then armature resistance, $R_a = \frac{\rho \frac{l}{a} \times \frac{Z}{P}}{A} = \rho \frac{l}{a} \cdot \frac{Z}{P \times A}$

In simplex lap winding, $A = P$

$$\therefore \text{Armature resistance, } R_a = \frac{\rho l Z}{a P^2} = \frac{\rho l Z}{a A^2} \quad \dots (4.3)$$

7. If I_a is the total armature current, then current carried by each parallel path or conductor is I_a/P (in general I_a/A).

Example 4.3

Design and draw a 2 layer progressive duplex lap winding for a 6 pole DC generator with 24 slots, each slot having 2 coil sides. Indicate the direction of motion, position of poles, position of brushes with their polarities and parallel paths formed there-of.

Solution:

Here, Number of poles, $P = 6$

Number of slots = 24

Number of coil sides, $Z = 24 \times 2 = 48$ (2 layer winding)

For duplex winding, $m = 2$

$$\text{Pole pitch, } Y_p = \frac{Z}{P} = \frac{48}{6} = 8$$

For progressive winding, $Y_B = Y_p + 1 = 8 + 1 = 9$

$$\text{and } Y_F = Y_B \pm 2m = 9 - 2 \times 2 = 5 \text{ (since } m = 2)$$

The connections are to be made as per the following table.

Steps to draw developed winding diagram

1. Draw $24 \times 2 = 48$ coil-sides and number them.
2. Since it is a two-layer winding draw all the upper (odd numbered) coil-sides by firm continuous lines and all the lower (even numbered) coil sides by dotted lines.
3. Draw six poles N, S, N, S, N and S alternately, each pole covers the space of $48/6 = 8$ coil sides. Consider that the poles are below the coil sides.
4. Mark the direction of motion (or rotation) of the conductors, say it is from left to right as marked.

Winding-I		Winding-II	
Back-end Connections	Front-end Connections	Back-end Connections	Front-end Connections
1 to $(1 + 9) = 10$	10 to $(10 - 5) = 5$	3 to $(3 + 9) = 12$	12 to $(12 - 5) = 7$
5 to $(5 + 9) = 14$	14 to $(14 - 5) = 9$	7 to $(7 + 9) = 16$	16 to $(16 - 5) = 11$
9 to $(9 + 9) = 18$	18 to $(18 - 5) = 13$	11 to $(11 + 9) = 20$	20 to $(20 - 5) = 15$
13 to $(13 + 9) = 22$	22 to $(22 - 5) = 17$	15 to $(15 + 9) = 24$	24 to $(24 - 5) = 19$
17 to $(17 + 9) = 26$	26 to $(26 - 5) = 21$	19 to $(19 + 9) = 28$	28 to $(28 - 5) = 23$
21 to $(21 + 9) = 30$	30 to $(30 - 5) = 25$	23 to $(23 + 9) = 32$	32 to $(32 - 5) = 27$
25 to $(25 + 9) = 34$	34 to $(34 - 5) = 29$	27 to $(27 + 9) = 36$	36 to $(36 - 5) = 31$
29 to $(29 + 9) = 38$	38 to $(38 - 5) = 33$	31 to $(31 + 9) = 40$	40 to $(40 - 5) = 35$
33 to $(33 + 9) = 42$	42 to $(42 - 5) = 37$	35 to $(35 + 9) = 44$	44 to $(44 - 5) = 39$
37 to $(37 + 9) = 46$	46 to $(46 - 5) = 41$	39 to $(39 + 9) = 48$	48 to $(48 - 5) = 43$
41 to $(41 + 9) = 50 = 2$	50 to $(50 - 5) = 45$	43 to $(43 + 9) = 52 = 4$	52 to $(52 - 5) = 47$
45 to $(45 + 9) = 54 = 6$	6 to $(6 - 5) = 1$	47 to $(47 + 9) = 56 = 8$	8 to $(8 - 5) = 3$

5. It is a duplex winding having two entrants, start the connections of one winding from conductor (or coil side) number 1. Connect 1 to 10 at the back and 10 to 5 at the front and so on as per the table.

For second winding start from coil side No. 3. Connect 3 to 12 at the back and 12 to 7 at the front and so on as per the table.

6. Mark the direction of flow of current in the coil-sides i.e., downwards in the coil sides which are under the influence of North-pole and upward for South pole.
7. Connect each front end of the coil to each commutator segment as marked in Fig. 4.28.

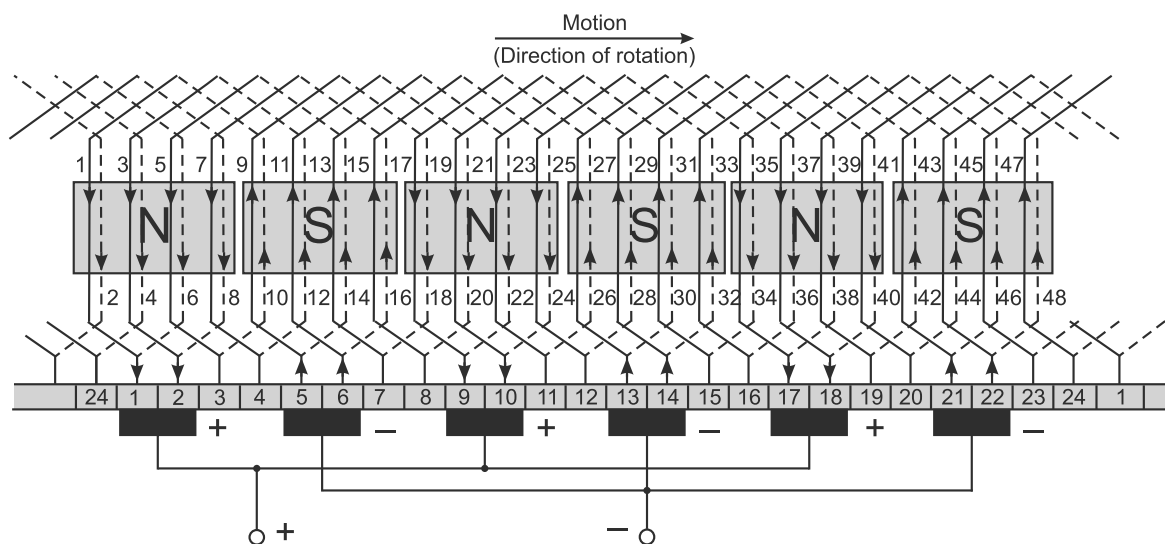


Fig. 4.28 Developed winding diagram

8. Place six brushes at six places, each brush is to cover two commutator segments, as shown in Fig. 4.28. Brushes are placed where either current is meeting (segment No. 1–2; 9–10 and 17–18) or separating (segment No. 5–6; 13–14; 21–22).
9. The three brushes where current is meeting are joined together and a positive terminal is obtained. The other three brushes where current is separating are joined together and a negative terminal is obtained.
10. The series, spiral winding connections of the two windings with separate entrant are shown in Fig. 4.29, the brushes are placed as explained above.

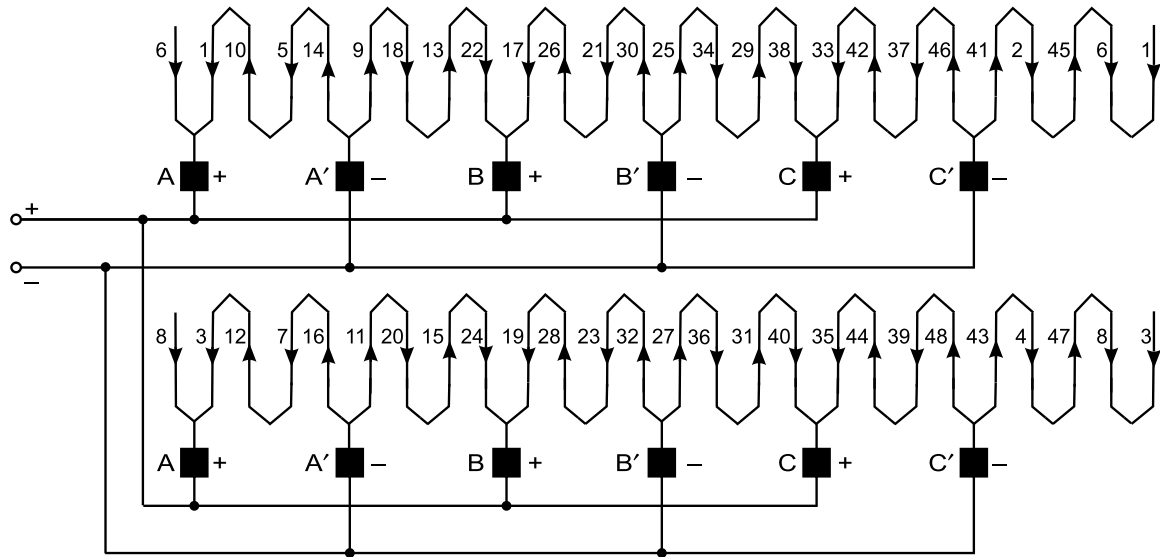


Fig. 4.29 Spiral winding diagram

11. The parallel paths formed by each winding are drawn in Figs. 4.30 and 4.31. Here, each winding is having six parallel paths. In all there are 12 (i.e., $A = mP$ when $m = 2$ and $P = 6$ in this case) parallel paths.

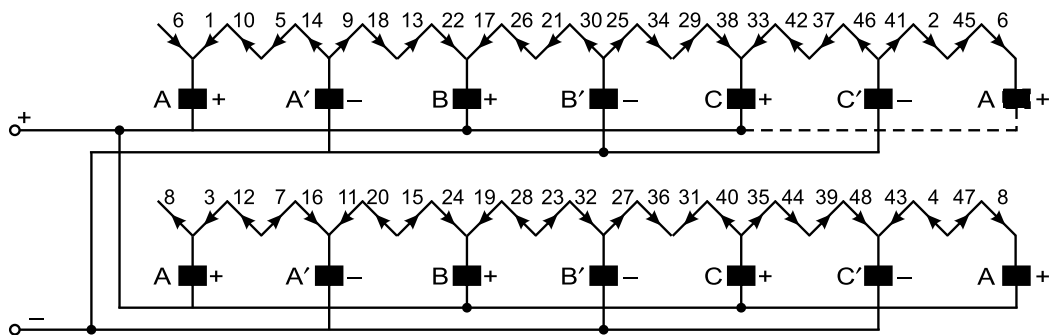


Fig. 4.30 Position of brushes

4.11 Characteristics of a Multiplex Lap Winding

From the winding diagram for duplex lap winding, the following conclusions have been drawn:

1. There are two independent winding, each closed on itself. Accordingly, the winding is said to be a *doubly re-entrant duplex winding*.

It is important to note that that in duplex winding, if the coils are not multiple of 2, there will not be two independent windings and in such cases, the winding will close only once, then it is known as singly re-entrant duplex winding.

Similarly, for triplex winding, the number of coils must be a multiple of 3 and so on.

2. Total number of brushes is equal to the number of poles but each brush must have a span of two commutator segments to collect current provided by two windings, as shown in Fig. 4.28. Similarly, for triplex winding each brush must have a span of three segments and so on.
3. The number of parallel paths for each winding is equal to the number of poles (i.e., 6 in this case). Therefore, total number of parallel paths for the armature is mP where m is the multiplicity, in this case $m = 2$, therefore the number of parallel paths = $2 \times 6 = 12$, as shown in Fig. 4.31.
4. The number of conductors in each parallel path are Z/mP (here $m = 2$)
In this case, No. of conductors connected in series in each parallel path, say,

$$Z_s = \frac{Z}{mP} = \frac{48}{2 \times 6} = 4$$

5. It is obvious that multiplex lap winding is used in the machines where we require high current to be delivered at small voltages.

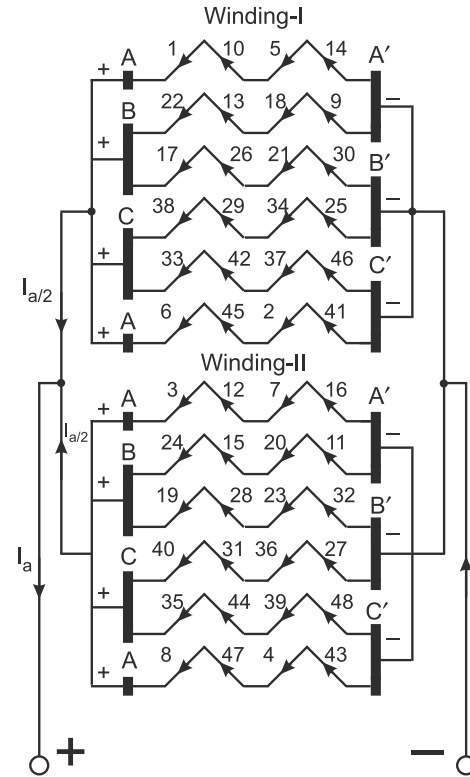


Fig. 4.31 Parallel paths

4.12 Equalising Connections and their Necessity

In simplex lap winding, the number of parallel paths are equal to the number of poles and all the conductors of any one parallel path lie under one pair of poles. If the flux produced by all the poles is exactly the same, the emf induced in each parallel path and hence the current carried by each one of them will be equal. But in spite of best efforts, this condition cannot be obtained due to different properties of steel used for construction of poles and variation of air-gap between the poles and armature. Hence, there is always a slight difference in the induced emf in various parallel paths which results in large circulating currents in the armature winding. This circulating current flows

from one parallel path to the other from one commutator segment to the other through brushes. This circulating current has the following ill-effects:*

1. Armature circulating current heats-up the armature winding.
2. It causes heavy sparking at the brushes which not only heats-up the machine but also causes undue burning and wear of commutator and brushes. If it is carried too far, it may result in flash over from positive to negative brushes.

To overcome this detrimental effect, usually, equalising connections are provided in all lap-wound armatures. These connections are made with the help of very low resistance (almost zero) wires called equalisers.

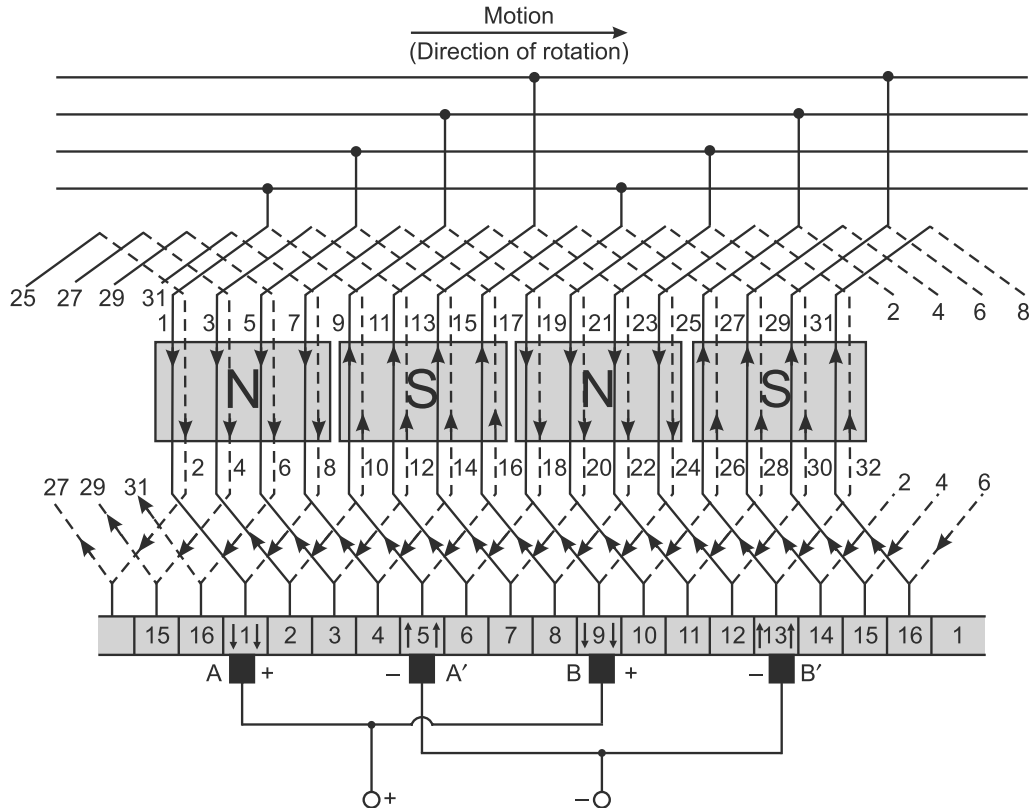


Fig. 4.32 Developed winding diagram

An equaliser is a copper wire having very low resistance and is used to connect the points of different parallel paths of armature winding which should have same potential under ideal conditions. These equaliser rings carry the circulating current and relieve the brushes to carry these circulating current. Under this condition, the brushes are to carry only the load current.

For making equaliser connections, the number of coils should be multiples of the number of poles and at the same time, the number of coils per pole should be divisible by a small number 2, 3 or 4.

* The current flowing in various paths may also differ due to difference in their resistances, but this would not pose serious effects.

For instance, consider a four-pole, 16-slot double layer, lap wound armature winding having 32 coil sides. Its developed winding diagram is shown in Fig. 4.32. Here, the number of coil sides per pole are 8. The equaliser connections are shown in Fig. 4.32. The following points are worth noting:

1. That every 3rd coil is connected to an equaliser. Each coil-side (or coil) connected to the equaliser occupies the same position relative to the poles such that same emf is induced in all the coils at every instant.
2. The number of connections to each equalising ring is equal to the number of pair of poles.
3. The number of equalising rings is equal to the number of coils under one pair of poles (i.e., $8/2 = 4$).
4. Here, alternate coils have been connected to the equalising ring and as such it is said that the winding is equalised by 50%. If all the coils would have been connected to the equalisers it would have been said that the winding is 100% equalised.

Example 4.4

A six-pole DC armature with lap connected winding has 72 slots and 2 coil-sides per slot. Determine the winding pitches and connections to the 6 equalising rings.

Solution:

Number of poles, $P = 6$

Number of slots = 72

Number of coil sides, $Z = 72 \times 2 = 144$

Number of parallel path, $A = P = 6$ (for simplex lap winding)

$$\text{Pole pitch, } Y_P = \frac{Z}{P} = \frac{144}{6} = 24$$

$$\text{Back pitch, } Y_B = Y_P + 1 = 24 + 1 = 25$$

$$\text{Front pitch, } Y_F = Y_B - 2 = 25 - 2 = 23$$

Distance between the coils having same potential i.e.,

$$Y_{eq} = \frac{\text{Total number of coils}}{\text{Pair of poles}} = \frac{Z / 2}{P / 2} = \frac{144 / 2}{6 / 2} = 24$$

Total number of tapings = No. of equaliser rings $\times$ pair of poles

$$= n_r \times \frac{P}{2} = 6 \times \frac{6}{2} = 18$$

$$\text{Distance between adjacent tapings} = \frac{\text{Total No. of coils}}{\text{Total No. of taps}} = \frac{144 / 2}{18} = 4$$

Hence, the equaliser rings are to be arranged as per the following table:

Ring No.	I	II	III	IV	V	VI
Coil No.	1	5	9	13	17	21
	25	29	33	37	41	45
	49	53	57	61	65	69

Example 4.5

Calculate the different pitches for 4 pole, lap wound DC machine having 24 slots each has 2 coils-sides.

Solution:

Here, $P = 4$; No. of slots = 24; No. of coil sides/slot = 2

$$\therefore Z = 24 \times 2 = 48; \text{ Pole pitch, } Y = \frac{Z}{P} = \frac{48}{4} = 12$$

Back pitch, $Y_B = Y_{B+1} = 12 + 1 = 13$; Front pitch, $Y_F = Y_P - 1 = 12 - 1 = 11$

Resultant pitch, $Y_R = Y_B - Y_F = 13 - 11 = 2$; commutator pitch, $Y_C = 1$

4.13 Simplex Wave Winding

A simplex* wave winding is shown in Fig. 4.33. In lap winding a coil side under one pole is connected directly to a coil side at the back which occupies almost corresponding positioned coil side under the next pole and the finish end of that coil is connected to a commutator segment and to the start end of the adjacent coil situated under the same original pole. But in the wave winding the coil side is not connected back rather progresses forward to another coil side placed under the next pole, as shown in Fig. 4.33. In this way, the winding progresses, passing successively every North and South pole till it returns to the coil side from where it was started. It clearly shows that the connections of wave winding always progresses in the same direction around the armature instead of moving forward and backward alternately like that of lap winding. As the shape of winding is wavy, it is named as *wave winding*.

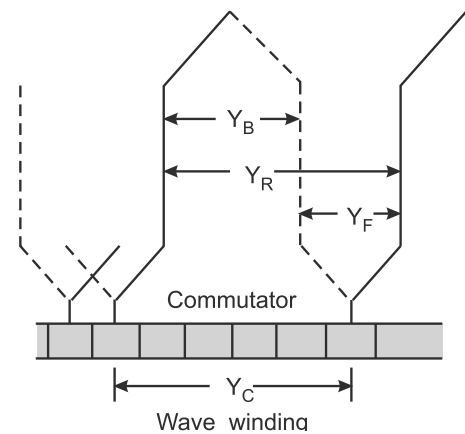


Fig. 4.33 Wave winding

The wave winding may be classified as progressive wave winding or retrogressive wave winding.

Progressive wave winding. If after completing one round of the armature, the winding falls in a slot to the right of its starting point the winding is known as *progressive wave winding*.

Retrogressive wave winding. If after completing one round of the armature. The winding falls in a slot to the left of its starting point, the winding is known as *retrogressive wave winding*.

The wave winding may also be a multiplex winding (double, triple or more).

A simplex wave winding has only two parallel paths irrespective of the number of pair of poles of the machine. However, a multiplex wave winding has $2m$ parallel paths, where m is the multiplicity.

* Like lap winding, a wave winding may also be multiplex winding i.e., duplex, triplex and so on...

Regarding wave winding, the following points are worth noting:

(a) *Simplex wave winding*

1. Both back and front pitches must be odd.
2. Both back and front pitches must be nearly equal to pole pitch. They may be equal to each other or may differ by 2 i.e.,

$$Y_F = Y_B \text{ or } Y_F = Y_B \pm 2$$

3. Commutator pitch, $Y_C = Y_A$ (average pitch)
4. An average pitch Y_A must be an integer given by the relation

$$Y_A = \frac{Y_B + Y_F}{2} = \frac{Z \pm 2}{P} = \frac{Z / 2 \pm 1}{P / 2} = \frac{\text{No. of commutator segments} - 1}{\text{No. of pair of poles}}$$

The wave winding will be closed itself only if the value of average pitch (Y_A) comes out to be a whole number (i.e., integer) and agrees to the above formulae.

It is important to note here that in formulae $Y_A = \frac{Z-2}{P}$, the value ± 2 has been taken due to the

reason that after one round of armature the winding falls either short or goes ahead by two conductors from the starting conductor. If it is not done and the average pitch is taken as Z/P then after one round of armature the winding would have been closed without including all coil-sides.

The positive sign provides progressive winding whereas negative sign provides retrogressive winding.

It is mentioned that average pitch (Y_A) must be a whole number, it shows that this winding is not possible with any number of coil-sides. For example, with 32 conductors in a four-pole machine, $Y_A = \frac{32 \pm 2}{4} = 8\frac{1}{2}$ or $7\frac{1}{2}$ is a fractional number, the wave winding is not possible.

5. Resultant pitch, $Y_R = Y_B + Y_F$
6. (a) For even number of pair of pole machines i.e., the machines which are having 2, 4, 6,..... pair of poles;
 - (i) the number of coils must be odd.
 - (ii) the number of commutator segments must be odd.
 - (iii) the average pitch, $Y_A = \frac{Y_B + Y_F}{2}$ may be odd or even.
- (b) For odd number of pair of pole machines i.e., the machines which are having 3, 5, 7,..... pair of poles;
 - (i) the number of coils may be odd or even
 - (ii) the number of commutator segments may be odd or even.
 - (iii) the average pitch must be odd for even number of coils but it must be even for odd number of coils.
- (c) *Multiplex wave winding*
 - (i) $Y_B = Y_F \pm 2m$

Positive sign for progressive winding and negative for retrogressive winding.

(ii) $Y_A = \frac{Z \pm 2m}{P}$ which must be an integer.

(iii) In case of duplex winding

- (a) If No. of pair of poles is odd and average pitch is odd, it must have odd number of commutator segments and coils.

If average pitch is even machine must have an even number of commutator segments and coils.

- (b) If No. of pair of poles is even, the number of commutator segments and coils must be even irrespective whether the average pitch is odd or even.

If average pitch is odd, the winding will be singly re-entrant and if even doubly re-entrant.

4.14 Dummy Coils

While designing wave winding, a particular number of coil-sides are required. To accommodate these coil-sides, the stemming with particular number of slots are needed which may not be available with standard armature punching. In such cases, some coil-sides (or conductors) are placed in the vacant slots. These coil sides are not connected to other coil-sides of the winding and do not participate in the conversion of power. Such coil-sides or coils are called *dummy coil*. These are employed only to make the mechanical balancing of the armature.

Thus, *the coils placed on the armature which do not participate in the conversion of power but are employed only to make mechanical balancing of the armature are known as dummy coils.*

Example 4.6

Draw a developed winding diagram showing position of poles, direction of rotation, polarity and position of brushes of a simplex two-layer wave winding for a four-pole DC generator with 30 armature conductors. Hence point out the characteristics of a simple wave winding.

Solution:

Here, $P = 4$; $Z = 30$

$$\text{Average pitch, } Y_A = \frac{Z \pm 2}{P} = \frac{30 \pm 2}{4} = 8^{**} \text{ or } 7$$

If Y_A is taken odd i.e., 7, then $Y_B = Y_F$

Starting from 1st coil-side, connect coil-side 1 to $1 + 7 = 8$ at the back and 8 to $8 + 7 = 15$ at the front through commutator segment 8. The first coil side is connected to commutator segments 1 at the front. Thus $Y_C = 8 - 1 = 7$. The coil side 15 is further connected to coil side $15 + 7 = 22$ at the back and $22 + 7 = 29$ at the front and so on, as per the table given below, till winding is closed.

* If Y_A is taken as 8, then $Y_B = 9$ and $Y_F = 7$ or $Y_F = 9$ and $Y_B = 7$. However, it is important to note that if $Y_C = 7$ the armature will rotate in one direction and if $Y_C = 8$, it will rotate in opposite direction.

Back-end Connections	Front-end Connections	Through Segment No.
1 to $(1 + 7) = 8$	8 to $(8 + 7) = 15$	8
15 to $(15 + 7) = 22$	22 to $(22 + 7) = 29$	15
29 to $(29 + 7) = 36 = 6$	6 to $(6 + 7) = 13$	7
13 to $(13 + 7) = 20$	20 to $(20 + 7) = 27$	14
27 to $(27 + 7) = 34 = 4$	4 to $(4 + 7) = 11$	6
11 to $(11 + 7) = 18$	18 to $(18 + 7) = 25$	13
25 to $(25 + 7) = 32 = 2$	2 to $(2 + 7) = 9$	5
9 to $(9 + 7) = 16$	16 to $(16 + 7) = 23$	12
23 to $(23 + 7) = 30$	30 to $(30 + 7) = 37 = 7$	4
7 to $(7 + 7) = 14$	14 to $(14 + 7) = 21$	11
21 to $(21 + 7) = 28$	28 to $(28 + 7) = 35 = 5$	3
5 to $(5 + 7) = 12$	12 to $(12 + 7) = 19$	10
19 to $(19 + 7) = 26$	26 to $(26 + 7) = 33 = 3$	2
3 to $(3 + 7) = 10$	10 to $(10 + 7) = 17$	9
17 to $(17 + 7) = 24$	24 to $(24 + 7) = 31 = 1$	1

The developed winding diagram, as per table, is shown in Fig. 4.34.

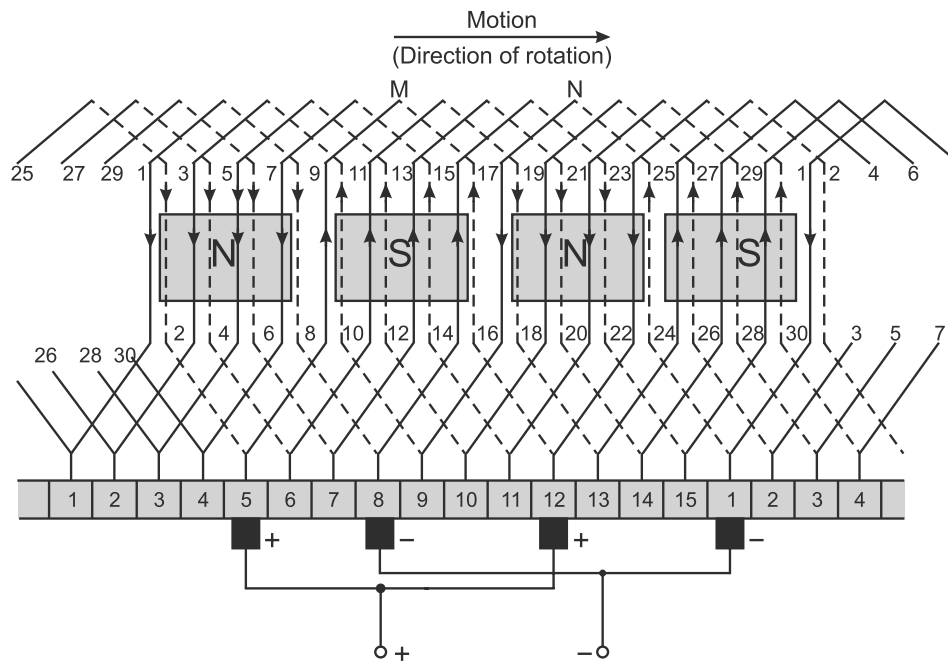


Fig. 4.34 Developed winding diagram

The table shows that winding connections started from coil side number 1 finishes at the same coil side, thus, form a closed circuit.

The ring or spiral winding diagram of a wave wound armature is shown in Fig. 4.35.

Brush Position

1. The direction of induced *emf* in various coil-sides is marked as per the following grouping (see Fig. 4.34)

Downward (N-Pole)	Upward (S-Pole)	Downward (N-Pole)	Upward (S-Pole)
1–8	9–16	17–23	24–30
(8)	(8)	(7)	(7)

2. The direction of induced *emf* in various coil-sides is also marked in the spiral winding diagram shown in Fig. 4.35.

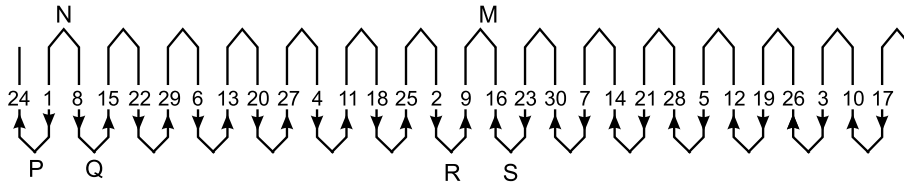


Fig. 4.35 Spiral winding

3. Figure 4.35 shows that whole winding is divided into two portions i.e., between *N* to *M* and to *M* to *N*.
4. Here *N* is a point where induced emfs are separating, but this position is at the back and does not fall at the commutator end. Therefore, the negative brush may be placed either at position *P* or *Q* i.e., either at commutator segment number 1 or 8.
5. Similarly, it is clear that *M* is a point where induced emfs are meeting, but this position is at the back and does not fall at the commutator end. Therefore, the positive brush may be placed either at position *R* or *S* i.e., either at commutator segment number 5 or 12.
6. Here, conductors 24, 1, 8, 15, 2, 9, 16, 23 fall in between the poles, no *emf* is induced in them and the brushes can be placed at their junctions.
7. If negative brush is placed at *P*, the positive brush can be placed at *R* or *S*. Let the negative brush be placed at *P* and the positive brush is placed at *R*, the armature winding will form two parallel paths as shown in Fig. 4.36.

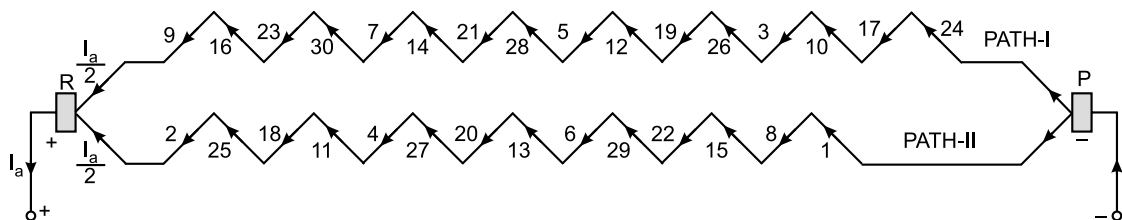


Fig. 4.36 Parallel paths

8. If in all, 4 brushes (two positive and two negative) are used and are placed in both alternative positions, then the loops lying between the brushes of same polarity are being short circuited as shown in Fig. 4.37, but the number of parallel paths remain only two.

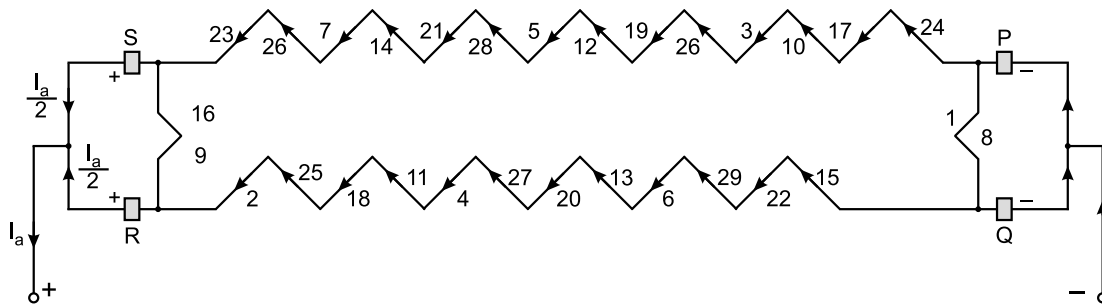


Fig. 4.37 Path formation with four brushes

9. The ring diagram with brush position is shown in Fig. 4.38.

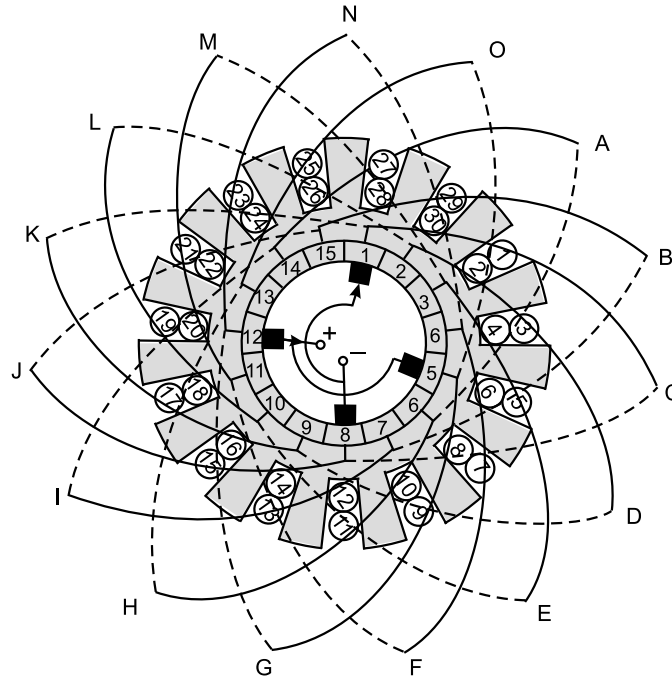


Fig. 4.38 Ring diagram

From the above explanation, it is summarised that:

- (i) Only two brushes are necessary (at position P and R , see Fig. 4.36), although their number may be kept equal to the number of poles (at position $P-Q$, negative and $R-S$, positive; see Fig. 4.38).

Note: Only two brushes are necessary, however, parallel brushes may be added to make their number equal to the number of poles. The parallel brush arrangement reduces the current per brush set which reduces the axial length of commutator and consequently reduces the cost of commutator or machine. This arrangement is used in large machines, for small machines only two brushes (one set) is sufficient.

- (ii) Wave wound armature winding has only two parallel paths irrespective of the number of poles of the machine. That is why, this winding is sometimes called ‘two circuit winding’ or ‘series winding’.

(iii) The total generated emf, $E_g = e_{av} \times Z/2$

where e_{av} = average induced emf/conductor and

$Z/2$ = No. of conductors connected in series in each parallel path.

(iv) The current carried by each parallel path or each armature conductor will be $I_a/2$ where I_a is the total armature current.

Example 4.7

Draw a developed winding diagram for a wave wound, six-pole DC armature having 16 slots with 2 coil-sides per slot, each coil has single turn.

Solution:

Here, $P = 6$; $Z = 16 \times 2 = 32$

$$\text{Average pitch, } Y_A = \frac{Z \pm 2}{P} = \frac{32 - 2}{6} = 5 \text{ (add number)}$$

Starting from 1st coil-side, connect coil-side 1 to $1 + 5 = 6$ at the back and 6 to $6 + 5 = 11$ at front through commutator segment No. 6. The first coil-side is connected to commutator segment No. 1 at the front. Thus $Y_C = 6 - 1 = 5$. To complete the winding, connect coil-side 11 to $11 + 5 = 16$ at the back and 16 to $16 + 5 = 21$ at the front and so on, as per the table given below:

Back-end Connections	Front-end Connections	Through Segment No.
1 to $(1 + 5) = 6$	6 to $(6 + 5) = 11$	6
11 to $(11 + 5) = 16$	16 to $(16 + 5) = 21$	11
21 to $(21 + 5) = 26$	26 to $(26 + 5) = 31$	16
31 to $(31 + 5) = 36 = 4$	4 to $(4 + 5) = 9$	5
9 to $(9 + 5) = 14$	14 to $(14 + 5) = 19$	10
19 to $(19 + 5) = 24$	24 to $(24 + 5) = 29$	15
29 to $(29 + 5) = 34 = 2$	2 to $(2 + 5) = 7$	4
7 to $(7 + 5) = 12$	12 to $(12 + 5) = 17$	9
17 to $(17 + 5) = 22$	22 to $(22 + 5) = 27$	14
27 to $(27 + 5) = 32$	32 to $(32 + 5) = 37 = 5$	3
5 to $(5 + 5) = 10$	10 to $(10 + 5) = 15$	8
15 to $(15 + 5) = 20$	20 to $(20 + 5) = 25$	13
25 to $(25 + 5) = 30$	30 to $(30 + 5) = 35 = 3$	2
3 to $(3 + 5) = 8$	8 to $(8 + 5) = 13$	7
13 to $(13 + 5) = 18$	18 to $(18 + 5) = 23$	12
23 to $(23 + 5) = 28$	28 to $(28 + 5) = 33 = 1$	1

The table shows that winding connections stated from coil-side No. 1 finishes at the same coil side, thus, form a closed circuit.

The ring or spiral winding diagram of a wave wound armature is shown in Fig. 4.40.

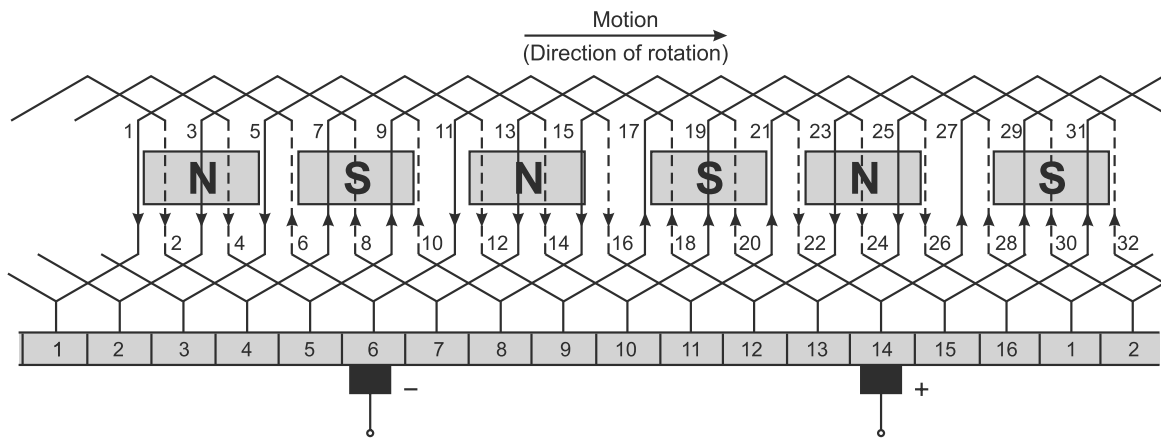


Fig. 4.39 Developed winding diagram

Brush Position

- The direction of induced *emf* in various coil-sides is marked as per the following grouping (see Fig. 4.39):

Downward (N-Pole)	Upward (S-Pole)	Downward (N-Pole)	Upward (S-Pole)	Downward (N-Pole)	Upward (S-Pole)
1–5	6–10	11–16	17–21	22–26	27–32
(5)	(5)	(6)	(5)	(5)	(6)
- The direction of induced emfs in various coil-sides is also marked in the spiral winding diagram, shown in Fig. 4.40.

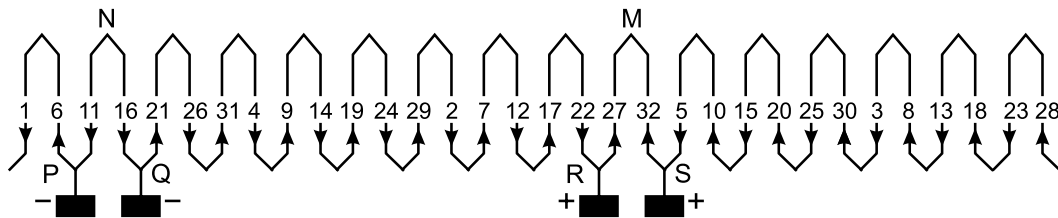


Fig. 4.40 Spiral winding

- Figure 4.40 shows that whole winding is divided into two portions between *N* to *M* and *M* to *N*.
- From Fig. 4.40, it is clear that point *N* is a position where induced emfs are separating, but this position is at the back and does not fall at the commutator end. Therefore, negative brush may be placed either at position *P* or *Q* i.e., either at commutator segment number 6 or 11.
- Similarly, from Fig. 4.40, it is clear that point *M* is a position where induced emfs are meeting, but this position is at the back and does not fall at the commutator end. Therefore, positive brush may be placed either at position *R* or *S* i.e., either at commutator segment number 14 or 3.
- If negative brush is placed at *P*, the corresponding position of positive brush will be *R*. However, if the negative brush is placed at *Q*, the corresponding position of positive brush will be *S*.
- The two parallel paths thus formed are shown in Fig. 4.41.

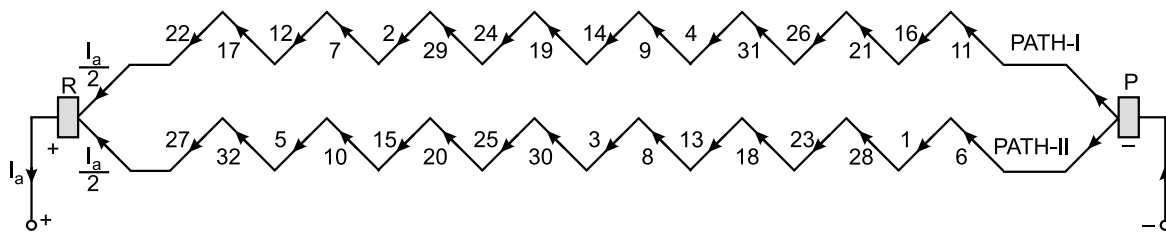


Fig. 4.41 Parallel paths

8. It is important to note that the direction of induced emf marked in coil-side number 11 and 27 is opposite when shown in the circuit diagram (see Fig. 4.41) in comparison to developed winding diagram shown in Fig. 4.39.

In fact, these two coil-sides, at this particular instant, are passing through magnetic neutral axis and the induced emf in these conductors is zero. Hence, they do not affect the system.

4.15 Applications of Lap and Wave Windings

The lap winding contains more number of parallel paths and provides large current. Hence, this winding is applied to the generators which are to deliver more current. Wave winding is more suitable for small generators specially these are meant for 500–600 V circuits.

The main advantage of wave winding is that it gives more emf than lap winding for given number of poles and armature conductors, whereas, the lap winding would require large number of conductors for the same emf. This will result in higher cost of winding and less utilisation of space in the armature slots.

Moreover, in wave winding, equalising connections are not necessary, whereas in lap winding these are required definitely. It is because, in wave winding the conductors of the two paths are distributed in such a way that they lie under all the poles, therefore, any inequality of pole fluxes affects two paths equally, hence their induced emfs are equal. But, in lap winding, each parallel path contains conductors which lie under one pair of poles, hence unequal voltages are produced which set-up a circulating current causing sparking at the brushes.

Thus, in general practice, wave winding is preferred, the lap winding is only used for low-voltage, high-current machines.

Section Practice Problems

Numerical Problems

1. Draw a developed winding diagram of progressive lap winding for 4 pole, 24 slot with one coil side per slot, single layer winding showing there in position of poles, direction of motion, direction of induced emf and position of brushes.
2. Design and draw a 2 layer progressive duplex lap winding for a 4 pole DC generator with 16 slots. Show the position of brushes and their polarity. Also draw a diagram representing number of parallel paths thus formed.
3. Prepare a winding diagram for a four-pole wave connected armature of a DC generator having 22 coil sides.

Short Answer Type Questions

Q.1. Define statically and dynamically induced emf.

Ans. When flux linking with the coil changes an emf is induced in the coil is called statically induced emf, in this case both coil and magnetic field system are stationary.

When a conductor cuts across the magnetic field an emf is induced in the conductor is called dynamically induced emf, in this case either conductor or the magnetic field system is moving (or rotating).

Q.2. Why is commutator employed in DC machines?

Ans. Commutator is employed in DC machines:

1. To convert AC into DC, in generator action, to deliver DC electric power to the load.
2. To convert DC into AC, in motor action, to develop unidirectional torque in armature.

Q.3. Define coil pitch and coil span.

Ans. *Coil pitch or Coil span:* The distance between two sides of the same coil is called coil pitch or coil span. The coil-pitch is usually expressed in terms of number of armature conductor or number of slots between two sides of the same coil.

The coil span is usually expressed in terms of angular displacement (electrical angle) between the two sides of the same coil.

Q.4. Define resultant pitch.

Ans. The distance in terms of number of armature conductor or number of slots between the start of one coil and the start of next coil to which it is connected is called resultant pitch.

Q.5. Explain the difference between integral slot and fractional slot winding.

Ans. The winding in which the number of armature slots per pole give an integer (whole number), the winding is called integral slot winding.

The winding in which the number of armature slots per pole gives fractional value, the winding is called fractional slot winding.

Q.6. Define the factors and state benefits of short pitched coils.

Ans. The advantage of short pitched winding is that in this case the copper used for end connections is reduced substantially which reduces the cost of machine. It also improves the commutation (reduction of sparking at brushes) because inductance of overhang connections is reduced. Moreover, it reduces the copper losses and improves the efficiency to some extent. Hence, many a times short pitched winding is used.

Q.7. What are equaliser rings and why are they used?

Ans. *Equaliser rings and their use:* An equaliser is a copper wire having very low resistance and is used to connect the points of different parallel paths of armature winding which should have same potential under ideal conditions. These equaliser rings carry the circulating current and relieve the brushes to carry these circulating current. Under this condition, the brushes are to carry only the load current.

Q.8. What is the basic principle on which a generator operates?

Ans. A generator operates on the basic principle of production of dynamically induced emf (electro-magnetic induction).

Q.9. Why is the pole shoe section of a DC machine made larger than pole core?

Ans. The pole shoe is made larger because it is to support the field coils and spreads out the flux over the armature periphery more uniformly. The larger x-section area reduces the reluctance of the magnetic path.

Q.10. Is it necessary to use a large number of coils and commutator segments with the coils evenly distributed around the surface of the armature of a DC machine?

Ans. Yes, it is necessary it provides practically constant unidirectional voltage at the brushes.

Q.11. Why the armature of a DC machine is made of laminated silicon steel?

Ans. To reduce hysteresis and eddy current loss.

Q.12. In large DC machines electro-magnets are preferred over permanent magnets, why?

Ans. On account of their greater magnetic effect and field strength regulation.

Q.13. In small DC machine, cast iron yokes are preferred, why?

Ans. Because of their low cost.

Q.14. Why fractional pitch winding is preferred over full pitch winding?

Ans. To effect saving in the copper of end connections and to have improved commutation by reducing inductance effect of overhang.

Q.15. What for brushes are employed in DC generator.

Ans. The brushes are employed to collect current from the commutator and supply it to the external load circuit.

Q.16. For what type of DC machine, wave winding is employed?

Ans. For low current and high voltage rating machine.

Q.17. Which are the different types of armature windings commonly used in DC machines?

Ans. Lap and wave windings.

Q.18. For what type of DC machine lap winding is employed?

Ans. For high current and low voltage rating machine.

Q.19. Why equaliser rings are used?

Ans. Equaliser rings are used in lap wound machines to avoid unequal distribution of current at the brushes, thus reducing sparking at the brushes.

Q.20. In which type of armature winding equaliser connections are used?

Ans. In lap winding.

4.16 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, $t = 60/N$ second

$\therefore$ Average induced emf in one conductor,

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

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,

$$E = \frac{P\phi N}{60} \times \frac{Z}{A} = \frac{PZ\phi N}{60A} \text{ volt} \quad \dots(4.4)$$

or
$$E = \frac{PZ\phi n}{A} \text{ where } n \text{ in speed in r.p.s.}$$

i.e.,
$$n = \frac{N}{60}$$

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

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

or
$$E = K_1\phi N \text{ where } K_1 = \frac{PZ}{60A} \text{ is another constant or } E \propto \phi N \quad \dots(4.5)$$

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

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 i.e., brushes is reversed, but when both are reversed the polarity does not change.

This induced emf is fundamental phenomenon to all DC machines whether they are working as 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., $E_g = \frac{PZ\phi N}{60A}$ volt.

Whereas, in case the machine is working as a *motor*, this induced emf is called back emf as it acts opposite to the supply voltage V . Then $E_b = \frac{PZ\phi N}{60A}$ volt.

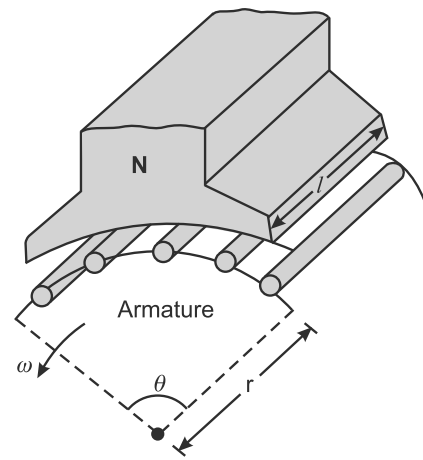


Fig. 4.42 A portion of a DC machine

4.17 Torque Equation

We know that when a current carrying conductor is placed in the magnetic field a force is exerted on it which exerts turning moment or torque ($F \times r$) (see Fig. 4.43). This torque is produced due to electro-magnetic effect, hence is called *electromagnetic torque*.

Let P = No. 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 = No. of parallel paths.

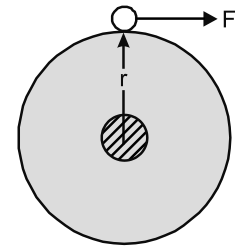


Fig. 4.43 Conductor placed on armature of radius 'r'

Average force on each conductor, $F = Bil$ newton

Torque due to one conductor = $F \times r$ newton metre

Total torque developed in the armature,

$$T = ZFr \text{ newton metre}$$

or $T = ZB i l r$

Now, current in each conductor, $i = I_a / A$

*Average flux density, $B = \phi/a$

where 'a' is the X- sectional area of flux path at radius r .

Obviously, $a = \frac{2\pi r l}{P} \text{ m}^2 \therefore B = \frac{\phi P}{2\pi r l} \text{ tesla}$

Substituting these values in equation (i), we get

$$T = Z \times \frac{\phi P}{2\pi r l} \times \frac{I_a}{A} \times l \times r \text{ or } T = \frac{PZ \phi I_a}{2\pi A} \text{ Nm} \quad \dots(4.6)$$

Alternately; The power developed in the armature is given as

$$EI_a = \omega T \text{ or } EI_a = \frac{2\pi N}{60} \times T$$

or $\frac{\phi ZNP}{60A} \times I_a = \frac{2\pi N}{60} \times T \text{ or } T = \frac{PZ \phi N}{2\pi A} \text{ Nm (As above)}$

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

$$\therefore T = K \frac{\phi I_a}{2\pi} \text{ where } K = \frac{PZ}{A} \text{ is a constant}$$

The constant K for a given machine is the same for the emf equation as well as the torque equation.

Also, $T = K_2 \phi I_a$ where $K_2 = \frac{PZ}{2\pi A}$ is another constant. Thus, $T \propto \phi I_a \quad \dots(4.7)$

* If B = flux density in tesla; θ = arc angle subtended by the pole shoe; l = length of pole shoe; r = radius of pole shoe. Then,
 $\phi = B \times a = B \times 2\pi r \frac{\theta}{360} \times l \text{ weber}$

Thus, we conclude that torque produced in the armature is directly proportional to flux per pole and armature current. Moreover, the direction of electromagnetic torque developed in the armature depends upon the direction of flux or magnetic field and the direction of flow of current in armature conductors. The direction of torque produced and hence the direction of rotation is reversed if either of the two is reversed. But when both are reversed the direction of torque does not change.

Example 4.8

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

Solution:

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

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

$$A = P = 8 \text{ (lap winding)}$$

$$\therefore E_g = \frac{40 \times 10^{-3} \times 960 \times 400 \times 8}{60 \times 8} = \mathbf{256 \text{ V (Ans.)}}$$

Example 4.9

A 4-pole, DC machine is having 500 wave wound conductors and running at 1000 rpm. The flux per pole is 30 m Wb. What will be the voltage induced in the armature winding.

Solution:

Here, $P = 4$; $A = 2$ (Wave wound); $Z = 500$; $N = 1000 \text{ rpm}$;

$$\phi = 30 \text{ m Wb} = 30 \times 10^{-3} \text{ Wb}$$

$$\text{Generated voltage, } E_g = \frac{\phi ZNP}{60A} = \frac{30 \times 10^{-3} \times 500 \times 1000 \times 4}{60 \times 2} = \mathbf{1500 \text{ V (Ans.)}}$$

Example 4.10

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

Solution:

Here, $P = 4$; $A = P = 4$ (Lap wound); $\phi = 20 \text{ m Wb} = 20 \times 10^{-3} \text{ Wb}$; $N = 720 \text{ rpm}$

No. of slots = 144 with 2 coil sides per slot and each coil has two turns

$$\therefore Z = 144 \times 2 \times 2 = 576$$

$$\text{Induced emf across armature, } E_g = \frac{\phi ZNP}{60A} = \frac{20 \times 10^{-3} \times 576 \times 720 \times 4}{60 \times 4} = \mathbf{138.24 \text{ V (Ans.)}}$$

$$\text{Voltage across each parallel path} = E_g = \mathbf{138.24 \text{ V (Ans.)}}$$

Example 4.11

A six-pole machine has an armature with 90 slots and 8 conductors per slot, the flux per pole is 0.05 Wb and rms at 1000 rpm. Determine induced emf if winding is (i) lap connected (ii) wave connected.

Solution:

Here, $P = 6$; $\phi = 0.05$ Wb; $N = 1000$ rpm

No. of slots = 90 each slot with 8 conductors

$$\therefore Z = 90 \times 8 = 720$$

(i) When lap connected: $A = P = 6$

$$\text{Induced emf, } E_g = \frac{\phi ZNP}{60A} = \frac{0.05 \times 720 \times 1000 \times 6}{60 \times 6} = \mathbf{600 \text{ V (Ans.)}}$$

(ii) When wave connected: $A = 2$

$$\text{Induced emf, } E_g = \frac{\phi ZNP}{60A} = \frac{0.05 \times 720 \times 1000 \times 6}{60 \times 2} = \mathbf{1800 \text{ V (Ans.)}}$$

Example 4.12

A DC generator carries 600 conductors on its armature with lap connections. The generator has 8 poles with 0.06 Wb useful flux. What will be the induced emf at its terminals if it is rotated at 1000 rpm? Also determine the speed at which it should be driven to induce the same voltage with wave connections?

Solution:

Here, $P = 8$; $Z = 600$; $\phi = 0.06$ Wb; $N = 1000$ rpm.

$$A = P = 8 \text{ (when lap wound)}$$

$$\text{Induced emf, } E_g = \frac{\phi ZNP}{60A} = \frac{0.06 \times 600 \times 1000 \times 8}{60 \times 8} = \mathbf{600 \text{ V (Ans.)}}$$

when wave wound, let the speed be N' rpm but $E_g = 600$ V

$$\text{Now, } N' = \frac{E_g \times 60A}{\phi ZP} = \frac{600 \times 60 \times 2}{0.06 \times 600 \times 8} = \mathbf{250 \text{ rpm (Ans.)}}$$

Example 4.13

A wave wound armature of an eight-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; No. 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

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

$$\therefore \text{Speed, } N = \frac{300 \times 60 \times 2}{0.05 \times 816 \times 8} = \mathbf{110.3 \text{ rpm (Ans.)}}$$

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

$$E_g = \frac{0.05 \times 816 \times 110.3 \times 8}{60 \times 8} = \mathbf{75 \text{ V (Ans.)}}$$

Example 4.14

A six-pole lap wound armature rotating at 350 rpm is required to generate 260 V. The effective flux per pole is about 0.05 Wb. If the armature has 120 slots, determine the suitable number of conductors per slot and hence determine the actual value of flux required to generate the same voltage.

Solution:

Here, $P = 6$; $A = P = 6$; $N = 350$ rpm; $E_g = 260$ V; $\phi = 0.05$ Wb

$$\text{Now, } E_g = \frac{\phi ZNP}{60A} \text{ or } 260 = \frac{0.05 \times Z \times 350 \times 6}{60 \times 6}$$

$$\text{or } Z = \frac{260 \times 60 \times 6}{0.05 \times 350 \times 6} = \frac{260 \times 24}{7}$$

$$\text{No. of conductors/slot} = \frac{Z}{\text{No. of slots}} = \frac{260 \times 24}{7 \times 120} = 7.43 \cong 8 \text{ (an integer)}$$

For 8 conductors/slot, $Z = 120 \times 8 = 960$

$$\text{Actual value of flux required, } \phi = \frac{E_g \times 60A}{ZNP} = \frac{260 \times 60 \times 6}{960 \times 350 \times 6} = \mathbf{0.0464 \text{ Wb (Ans.)}}$$

Example 4.15

The emf generated by a 4 pole DC generation is 400 V, when the armature is driven at 1200 rpm. Calculate the flux per pole if the wave wound generator has 39 slots having 16 conductors per slot.

Solution:

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

where, $P = 4$; $E_g = 400$ V; $N = 1200$ rpm; $Z = 39 \times 16 = 624$; $A = 2$ (wave winding)

$$\therefore \text{Flux per pole, } \phi = \frac{E_g \times 60A}{ZNP} = \frac{400 \times 60 \times 2}{624 \times 1200 \times 4} = 0.016 \text{ Wb} = \mathbf{16 \text{ mWb (Ans.)}}$$

Example 4.16

The armature of a four-pole 250 V, lap wound generator has 500 conductors and runs at 400 rpm. Determine the useful flux per pole. If the number of turns in each field coil is 1000, what is the average induced emf in each field coil on breaking its connection if the magnetic flux set-up by it dies away completely in 0.1 second?

Solution: Here, $P = 4$; $E_g = 250$ V; $Z = 500$; $A = P = 4$; $N = 400$ rpm

$$\phi = \frac{E_g \times 60A}{ZNP} = \frac{250 \times 60 \times 4}{500 \times 400 \times 4} = \mathbf{0.075 \text{ Wb (Ans.)}}$$

No. of turns of exciting winding, $N_t = 1000$

$$e = N_t \frac{d\phi}{dt} = 1000 \times \frac{0.075 - 0}{0.1} = \mathbf{750 \text{ V (Ans.)}}$$

Example 4.17

A four-pole generator has an induced emf of 250 V when driven at 500 rpm. The armature is lap wound and has 600 conductors. The radius of the pole shoe is 20 cm and it subtends an angle of 60° . Calculate the flux density in the air-gap if the length of pole shoe is 18 cm.

Solution:

Here, $P = 4$; $E_g = 250$ V; $N = 500$ rpm; $A = P = 4$; $Z = 600$

$$\text{Flux per pole, } \phi = \frac{E_g \times 60A}{ZNP} = \frac{250 \times 60 \times 4}{600 \times 500 \times 4} = 0.05 \text{ Wb}$$

$$\text{Pole shoe arc} = 2\pi r \times \frac{\theta}{360} = 2\pi \times 0.2 \times \frac{60}{360} = 0.21 \text{ m}$$

$$\text{Pole shoe area} = \text{Pole shoe arc} \times l = 0.21 \times 0.18 = 0.0378 \text{ m}^2$$

$$\text{Flux density in air gap} = \frac{\phi}{\text{area}} = \frac{0.05}{0.0378} = \mathbf{1.323 \text{ tesla (Ans.)}}$$

Example 4.18

A four-pole wave wound DC generator has 51 slots on its armature and each slot has 24 conductors. The flux per pole is 0.01 weber. 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; $Z = 51 \times 24 = 1224$; $E = 220$ V; $P = 4$; $A = 2$ (wave winding).

$$\therefore 220 = \frac{0.01 \times 1224 \times N \times 4}{60 \times 2}$$

$$\text{or } N = \frac{220 \times 60 \times 2}{0.01 \times 1224 \times 4} = \mathbf{539.21 \text{ rpm (Ans.)}}$$

For lap winding, $A = P = 4$;

$$E_g = \frac{0.01 \times 1224 \times 539.21 \times 4}{60 \times 4} = \mathbf{110 \text{ V (Ans.)}}$$

Example 4.19

A four-pole, wave wound DC armature has a bore diameter of 84 cm. It has 600 conductors and the ratio of pole arc to pole pitch is 0.8. If the armature is running at 360 rpm and the flux density in the air gap is 1.2 tesla, determine the induced emf in the armature if the effective length of armature is 20 cm.

Solution:

Here $P = 4$; $A = 2$ (wave wound); $Z = 600$; $N = 360$ rpm

Armature bore diameter, $D = 84$ cm = 0.84 m

$$\text{Pole pitch} = \frac{\pi \times \text{bore diameter}}{\text{No. of poles}} = \frac{\pi \times 0.84}{4} = 0.66 \text{ m}$$

$$\text{Pole shoe arc} = \text{Pole pitch} \times \frac{\text{Pole arc}}{\text{Pole pitch}} = 0.66 \times 0.8 = 0.528 \text{ m}$$

Pole shoe area, $a = \text{Pole shoe arc} \times \text{Pole length}$

$$= 0.528 \times 0.2 = 0.1056 \text{ m}^2$$

Flux per pole, $\phi = B \times a = 1.2 \times 0.1056 = 0.12672$ Wb

$$\text{Induced emf, } E_g = \frac{\phi ZNP}{60A} = \frac{0.12672 \times 600 \times 360 \times 4}{60 \times 2} = \mathbf{912.4 \text{ V (Ans.)}}$$

Example 4.20

A four-pole DC generator has rated armature current of 200 A. If the armature is lap-wound, determine the current flowing through each parallel path of the armature. What will be its value if the armature is wave wound?

Solution:

Here, $P = 4$; $A = P = 4$ (lap winding); $I_a = 200$ A

For lap-wound machine, current in each parallel path

$$= \frac{I_a}{A} = \frac{200}{4} = \mathbf{50 \text{ A (Ans.)}}$$

For wave-wound machine, current in each parallel path

$$= \frac{I_a}{A} = \frac{200}{2} = \mathbf{100 \text{ A (Ans.)}}$$

Example 4.21

A four-pole lap-connected DC machine has an armature resistance of 0.15 ohm. The total armature conductors are 48. Find the armature resistance of the machine when rewound for wave connections.

Solution:

Here, $P = 4$; $R_a = 0.15$ ohm; $Z = 48$

For lap-winding, $A = P = 4$

$\therefore$ Resistance of each parallel path, $R_1 = R_a \times A = 0.15 \times 4 = 0.6 \Omega$

No. of conductors in each parallel path = $\frac{Z}{A} = \frac{48}{4} = 12$

Resistance of each conductor = $\frac{0.6}{12} = 0.05 \Omega$

For wave-winding, $A = 2$

No. of conductors in each parallel path = $\frac{48}{2} = 24$

Resistance of each parallel path = $24 \times 0.05 = 1.2 \Omega$

Armature resistance, $R_a = \frac{1.2}{2} = 0.6 \Omega$ (Ans.)

Example 4.22

A DC machine running at 750 rpm has an induced emf of 200 V. Calculate the speed at which the induced emf will be 250 V (ii) the percentage increase in main field flux for an induced emf of 250 V at a speed of 700 rpm.

Solution:

Here, $E_1 = 200$ V; $N_1 = 750$ rpm

(i) $E_2 = 250$ V; $N_2 = ?$

(ii) $E_3 = 250$ V, $N_3 = 700$ rpm, $\phi_3 = ?$

We know $E \propto N\phi$

$$(i) \therefore \frac{N_2}{N_1} = \frac{E_2}{\phi_2} \times \frac{\phi_1}{E_1} \text{ as } \phi_2 = \phi_1$$

$$N_2 = \frac{250}{200} \times 750 = 937.5 \text{ rpm.}$$

$$(ii) \frac{N_3}{N_1} = \frac{E_3}{\phi_3} \times \frac{\phi_1}{E_1} \text{ or } \frac{\phi_3}{\phi_1} = \frac{E_3}{E_1} \times \frac{N_1}{N_3} = \frac{250}{200} \times \frac{750}{700} = 1.34$$

$\therefore$ %age increase in flux = **1.34%** (Ans.)

Example 4.23

A 50 HP, 400 V, 4 pole, 1000 rpm, DC motor has flux per pole equal to 0.027 Wb. The armature having 1600 conductors is wave connected. Calculate the gross torque when the motor takes 70 ampere.

Solution:

$$\text{Torque developed, } T = \frac{P\phi ZI_a}{2\pi A}$$

Where, $P = 4$; $\phi = 0.027$ Wb; $Z = 1600$; $I_a = 70$ A; $A = 2$ (wave connected)

$$T = \frac{4 \times 0.027 \times 1600 \times 70}{2 \times \pi \times 2} = 963 \text{ Nm (Ans.)}$$

Example 4.24

The induced emf in a DC machine is 220 volts at a speed of 1500 rpm. Calculate the electromagnetic torque developed at an armature current of 20 A.

Solution:

Here $E = 220$ V; $N = 1500$ rpm; $I_a = 20$ A

Power developed in the armature

$$\omega T_e = E_b I_a$$

or
$$T_e = \frac{E_b I_a}{\omega} = \frac{E_b I_a}{2\pi N / 60} = \frac{220 \times 20 \times 60}{2\pi \times 1500} = \mathbf{23.87 \text{ Nm (Ans.)}}$$

Example 4.25

The electromagnetic torque developed in a DC machines is 80 Nm for an armature current of 20 A. Find the torque for a current of 30 A. What is the induced emf for a speed of 900 rpm?

Solution:

$$T_{e1} \propto \phi_1 I_{a1} \text{ and } T_{e2} \propto \phi_2 I_{a2}$$

or
$$\frac{T_{e2}}{T_{e1}} = \frac{I_{a2}}{I_{a1}} \quad (\text{Assuming flux remains constant})$$

$$T_{e2} = 80 \times \frac{30}{20} = \mathbf{120 \text{ Nm (Ans.)}}$$

Now
$$T_{e2} = \frac{k}{2\pi} \phi_2 I_{a2}$$

$$\therefore k \phi_2 I_{a2} = 2\pi T_{e2} \text{ or } k \phi_2 = \frac{2\pi \times 120}{30} = 8\pi$$

$$\text{Now } E = kn\phi = \frac{8\pi \times 900}{60} = \mathbf{376.8 \text{ volt (Ans.)}} \quad (\because \phi_2 = \phi_1 = \phi)$$

4.18 Armature Reaction

When a DC generator is loaded, a current flows through the armature conductor in the same direction as that of the induced (or generated) emf. The armature conductors carrying current, produce their own magnetic field called armature field.

The effect of armature field produced by the armature current carrying conductors on the main magnetic field is known as **armature reaction**.

Let us see the effect of armature field on the main magnetic field when the generator is loaded.

Consider a bipolar generator. At no-load, no current flows through the armature conductors and the flux distribution in the armature is shown in Fig. 4.44. The vector OF_m represents the mmf produced by the main field. It is observed that the Magnetic Neutral Axis (MNA), which are perpendicular to the main field passing through the armature, and the Geometrical Neutral Axis (GNA) coincide with each other. The brushes (B_1 and B_2) are always placed at MNA. Here, they are shown as touching

the armature conductors directly, but in reality they touch the commutator segments connected to these conductors.

Geometrical Neutral Axis: The line passing through the geometrically central point between the two adjacent opposite magnetic poles is called **geometrical neutral axis (GNA)**.

Magnetic Neutral Axis: The line passing through the magnetically neutral position between the two adjacent opposite magnetic poles is called **magnetic neutral axis (MNA)**. When a conductor (or coil) passes through these axis, no emf is induced in the conductor (or coil).

When load is applied to the generator, current* flows through the armature conductors which sets up armature field as shown in Fig. 4.45. The vector OF_A represents the mmf produced by the armature field.

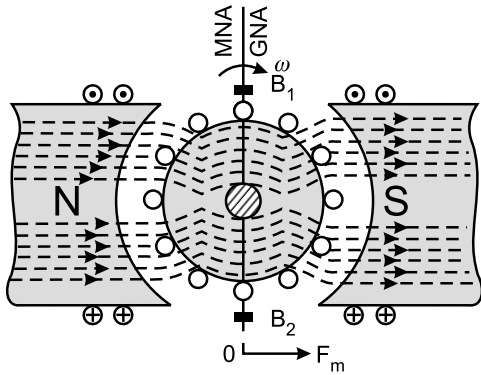


Fig. 4.44 Main field produced by main poles

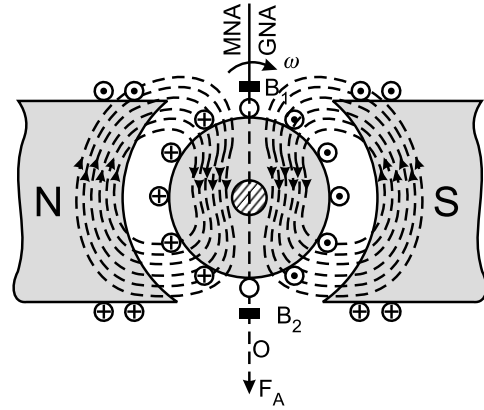


Fig. 4.45 Field produced by armature conductors

This armature flux interacts with the main flux and a resultant flux is set up in the armature as shown in Fig. 4.46. It can be observed that the resultant flux is no longer uniform. It is concentrated (becomes stronger) at the trailing pole tips and is rare (becomes weaker) at the leading pole tips.

The resultant mmf is shown by the vector OF which is the vector sum of OF_m and OF_A . Thus, the MNA are shifted to new position displaced from its original position by an angle θ .

The new position of magnetic neutral axis i.e., the shifting of axis by an angle θ depends upon the magnitude of load applied on the generator. Larger the load, larger will be the shift or larger will be the value of angle θ . It means the shifting of MNA is not constant, it varies and depends upon the magnitude of load applied on the machine. Moreover, the shift is in the direction of rotation. (in generating action).

As per the new position of MNA , the distribution of armature flux is shown in Fig. 4.47. The vector OF_{AR} represents the new position of mmf producing resultant armature field. This armature field has two component (i) OF_C which is perpendicular to the main mmf OF_m and produces the cross magnetising effect. (ii) OF_D which opposes the main mmf OF_m and produces the demagnetising effect.

* The direction of flow of current in armature conductors is determined by Fleming's right hand rule. The direction of induced emf and direction of flow of current is the same.

Thus the armature magnetic field produces.

- (i) Cross magnetising effect which creates a magnetic field in between the two adjacent opposite poles where brushes are placed for commutation.
- (ii) Demagnetising effect which weakens the main magnetic field and changes the flux distribution such that at trailing pole tips the flux is strengthened and at leading pole tips the flux is weakened.

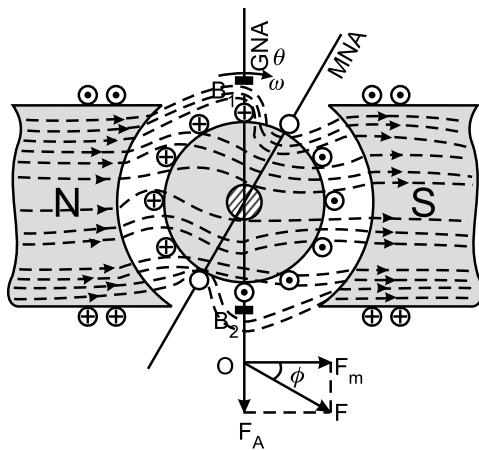


Fig. 4.46 Resultant field

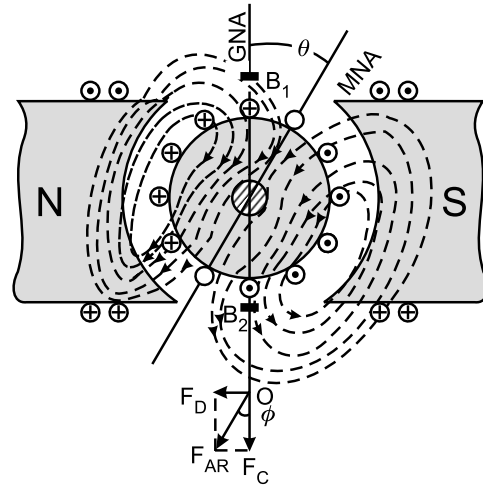


Fig. 4.47 New position of MNA

III-effects of armature reaction

The above two effects caused by the armature reaction lead to poor commutation (increases sparking at the brushes or at the commutator surface) and increases iron losses. Let us see how it happens;

- (i) *Sparking at brushes:* During commutation i.e., when a coil is short circuited by the brushes through commutator segments should have zero emf induced in it. That is why the brushes are usually placed along the interpolar axis where the flux cut by the coil is zero and no emf is induced in it. But due to armature reaction the magnetic neutral axis (MNA) are shifted and the coil which undergoes commutation induces some emf causing sparking at the brushes. At heavy loads, the induced emf in the commutating coil may be so high that it may produce a spark that may spread around the commutator surface forming a ring of fire. By all means, it has to be avoided otherwise it would damage the commutator surface and brushes.
- (ii) *Iron losses:* The flux density in the leading and trailing pole tips is changing due to change in load on the generator or due to armature reaction. This change in flux density causes more iron losses in the pole shoes.

4.19 Calculations for Armature Ampere-turns

Armature reaction causes demagnetising and cross-magnetising effect. Due to armature reaction, let the MNA be shifted ahead by an angle θ . The new position of MNA is represented by line AB. Draw another line CD making the same angle θ with GNA but in opposite direction as shown in Fig.

4.48. It may be observed that all the conductors lying between AOC and BOD carry current in such a direction mmf produced by them in opposite to the main mmf . These conductors cause demagnetising effect and these turns are known as *demagnetising turns*.

All other turn lying between angle AOD and COB produce cross magnetising mmf and are called *cross-magnetising turns*.

Let Z = total number of armature conductors

A = No. of parallel paths

θ^* (mech.) = angle by which MNA is shifted

P = No. of poles

I_a = armature current

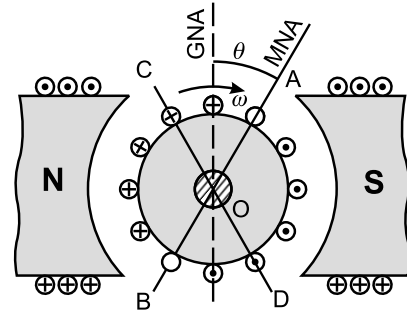


Fig. 4.48 Angle of shift due to armature reaction

Current per parallel path or current in each conductor, $I_c = \frac{I_a}{A}$

$$\text{Total armature ampere-turns} = \frac{I_c Z}{2} \left(\text{since turns} = \frac{Z}{2} \right)$$

$$\text{Total ampere-turns per pole} = \frac{I_c Z}{2P} \quad \dots(4.8)$$

Demagnetising ampere-turns = ampere-turns lying with in the angle $(AOC + BOD)$

$$= \frac{I_c Z}{2} \cdot \left(\frac{2\theta + 2\theta}{360} \right) = \frac{I_c Z}{2} \cdot \frac{4\theta}{360} = I_c Z \frac{2\theta}{360}$$

$$\text{Demagnetising ampere-turns/pole, } AT_d = \frac{I_c Z}{2} \cdot \frac{2\theta}{360} = I_c Z \cdot \frac{\theta}{360} \quad \dots(4.9)$$

$$\text{Cross magnetising ampere-turns/pole, } AT_c = \frac{I_c Z}{2P} - \frac{I_c Z \theta}{360} = I_c Z \left(\frac{1}{2P} - \frac{\theta}{360} \right) \quad \dots(4.10)$$

Example 4.26

A six-pole generator has 600 wave wound conductors on its armature. It delivers 100 ampere at full-load. If the brush lead is 6° mechanical, calculate the armature demagnetising and cross-magnetising ampere-turns per pole.

Solution:

Here, $P = 4$; $A = 2$ (wave-wound); $Z = 600$; $I_a = 100$ A; $\theta = 6^\circ$

$$\text{Current in each conductor, } I_c = \frac{I_a}{A} = \frac{100}{2} = 50 \text{ A}$$

$$\text{Demagnetising ampere-turns/pole, } AT_d = I_c Z \cdot \frac{\theta}{360} = 50 \times 600 \times \frac{6}{360} = \mathbf{500 \text{ (Ans.)}}$$

* In a bipolar machine mechanical angle is 360° and the electrical angle is also 360° , whereas, in four-pole machine mech. angle is 360° but the electrical angle is 720° i.e., electrical angle = $2 \times$ mech. angle or electrical angle = $\frac{P}{2}$ mech. angle.

$$\begin{aligned}\text{Cross-magnetising ampere-turns/pole, } AT_c &= I_c Z \cdot \left(\frac{1}{2P} - \frac{\theta}{360} \right) \\ &= 50 \times 600 \times \left(\frac{1}{2 \times 6} - \frac{6}{360} \right) = \mathbf{2000} \text{ (Ans.)}\end{aligned}$$

Example 4.27

A 250 kW, 500 V, 4 pole lap wound armature has 720 conductors. It is given a brush lead of 3° mechanical from its geometrical neutral axis (GNA). Calculate demagnetising and cross magnetising ampere-turns per pole. Neglect shunt field current.

Solution:

Here, Load = 250 kW; $V = 500$ V; $P = 4$; $Z = 720$; $\theta = 3^\circ$ (mech.)

$$\text{Load current, } I_L = \frac{250 \times 1000}{500} = 500 \text{ A}$$

Armature current $I_a = I_L = 500$ A (shunt field current neglected)

No. of parallel paths, $A = P = 4$ (lap wound)

$$I_c = \frac{I_a}{A} = \frac{500}{4} = 125 \text{ A}$$

Demagnetising ampere-turns/pole,

$$AT_d = I_c Z \cdot \frac{\theta}{360} = 125 \times 720 \times \frac{3}{360} = \mathbf{750} \text{ (Ans.)}$$

Cross-magnetising ampere-turns/pole,

$$AT_c = I_c Z \left(\frac{1}{2P} - \frac{\theta}{360} \right) = 125 \times 720 \times \left(\frac{1}{2 \times 4} - \frac{3}{360} \right) = \mathbf{10500} \text{ (Ans.)}$$

Example 4.28

A four-pole motor has a wave wound armature with 720 conductors. The brushes are displaced backward through 4 degree mechanical from GNA. If the total armature current is 80A, calculate demagnetising and cross-magnetising ampere-turns per pole.

Solution:

Here, $P = 4$; $A = 2$; $Z = 720$; $\theta = 4$; $I_a = 80$ A

$$\text{Current in each conductor, } I_c = \frac{I_a}{A} = \frac{80}{2} = 40 \text{ A}$$

$$\text{Demagnetising ampere-turns/pole, } AT_d = I_c Z \cdot \frac{\theta}{360} = 40 \times 720 \times \frac{4}{360} = \mathbf{320} \text{ (Ans.)}$$

$$\begin{aligned}\text{Cross-magnetising ampere-turns/pole, } AT_c &= I_c Z \left(\frac{1}{2P} - \frac{\theta}{360} \right) \\ &= 40 \times 720 \times \left(\frac{1}{2 \times 4} - \frac{4}{360} \right) = \mathbf{3280} \text{ (Ans.)}\end{aligned}$$

Example 4.29

A 250 V, 10 kW, 8 pole DC generator has single turn coils. The armature is wave-wound with 90 commutator segments. If the brushes are shifted by 2 commutator segments at full-load, calculate (i) total armature reaction ampere-turns (ii) demagnetising ampere-turns and (iii) cross-magnetising ampere-turns.

Solution:

Here, Load = 10 kW; $V = 250$ V; $P = 8$; $A = 2$ (wave wound)

No. of commutator segments = 90

Brush shift = 2 commutator segments

$$\text{Load current; } I_L = \frac{10 \times 1000}{250} = 40 \text{ A}$$

$$\text{Armature current, } I_a = I_L = 40 \text{ A}$$

$$\text{Current per conductor, } I_c = \frac{I_a}{2} = \frac{40}{2} = 20 \text{ A}$$

Total armature conductors, $Z = \text{No. of commutator segment} \times \text{No. of parallel path} = 90 \times 2 = 180$

$$\text{Brush shift, } \theta = \frac{2}{90} \times 360 = 8^\circ \text{ (mech.)}$$

$$(i) \text{ Total armature-reaction ampere-turns/pole} = \frac{I_c Z}{2P} = \frac{40 \times 180}{2 \times 8} = \mathbf{450} \text{ (Ans.)}$$

$$(ii) \text{ Demagnetising ampere-turns/pole} = I_c Z \cdot \frac{\theta}{360} = 40 \times 180 \times \frac{8}{360} = \mathbf{160} \text{ (Ans.)}$$

$$(iii) \text{ Cross-magnetising ampere-turns/pole} = \frac{I_c Z}{2P} - \frac{I_c Z \cdot \theta}{360} = 450 - 160 = \mathbf{290} \text{ (Ans.)}$$

Example 4.30

A 150 kW, 250 V, 6 pole lap wound generator has 600 conductors on its armature. Due to armature reaction if the MNA are shifted by 18° electrical, determine (i) demagnetising ampere-turns (ii) cross-magnetising ampere-turns (iii) series turns required to balance the demagnetising component neglecting magnetic leakage.

Solution:

Here, Load = 150 kW; $V = 250$ V; $P = 6$; $A = P = 6$; $Z = 600$; $\theta = 18^\circ$ electrical

$$\text{Load current, } I_L = \frac{150 \times 1000}{250} = 600 \text{ A}$$

$$\text{Armature current, } I_a = I_L = 600 \text{ A}$$

$$\text{Current per conductor, } I_c = \frac{I_a}{A} = \frac{600}{6} = 100 \text{ A}$$

$$\text{Brush shift, } \theta = \frac{\text{electrical angle}}{P / 2} = \frac{18}{6 / 2} = 6^\circ \text{ (mechanical)}$$

$$(i) \text{ Demagnetising ampere-turns, } AT_d = I_c Z \cdot \frac{\theta}{360^\circ} = 100 \times 600 \times \frac{6}{360} = \mathbf{1000} \text{ (Ans.)}$$

$$(ii) \text{ Cross-magnetising ampere-turns, } AT_c = I_c Z \cdot \left(\frac{1}{2P} - \frac{\theta}{360} \right)$$

$$= 100 \times 600 \times \left(\frac{1}{2 \times 6} - \frac{6}{360} \right) = \mathbf{4000} \text{ (Ans.)}$$

$$(iii) \text{ Series turns required to balance the demagnetising component} = \frac{AT_d}{I_a} = \frac{1000}{600}$$

$$= \frac{5}{3} = \mathbf{1.67} \text{ (Ans.)}$$

4.20 Commutation

In a DC machine, one of the major function is the delivery of current from the armature (rotating part) to the external circuit (stationary part) or vice-versa. This operation is conducted with the help of brushes and commutator.

During this operation one of the armature coil moves from the influence of one pole to the other and consequently the current in this coil is reversed. While moving from one pole to the other the coil is short circuited by the brushes through commutator segments for fraction of a second (say about $\frac{1}{500}$ second). This operation is called *commutation*.

Thus, *the process in which a coil is short circuited by the brushes through commutator segments while it passes from the influence of one pole to the other is called **commutation***. In this process the current in the coil is reversed.

*The duration for which a coil remains short circuited is called **commutation period**.*

Explanation

For better understanding, consider a machine having ring winding, a part of which is shown in Fig. 4.49. Assume that the width of brush is equal to the width of commutator segment and the insulation between the segments is very thin (negligibly small). The current per conductor is I_c and the armature is rotating in such a direction, that coils are moving from left to right. Let the coil 'B' undergoes commutation. Step-wise explanation is given below:

1. As shown in Fig. 4.49 (a), the brush is in contact with commutator segment 'a' and collects current $2I_c$ coming equally from both the sides.
2. As the armature is moving, in the first step as shown in Fig. 4.49(b), the brush contact with segment 'b' starts increasing and contact with segment 'a' starts decreasing. Consequently, the current flowing towards the brush via segment 'b' starts increasing* and through segment 'a' starts decreasing.

* It may be noted that at first instant the current in segment 'b' is zero but at second instant its value is $I_c - x$ and at the next instant it will become I_c which will be more than $(I_c - x)$. Similarly, at first instant current in segment 'a' was $2I_c$ (i.e., $I_c + I_c = 2I_c$) which is reduced to $I_c + x$ and at the next instant it will be reduced to I_c only.

It may be noted that current in coil 'B' decreases from I_c to x .

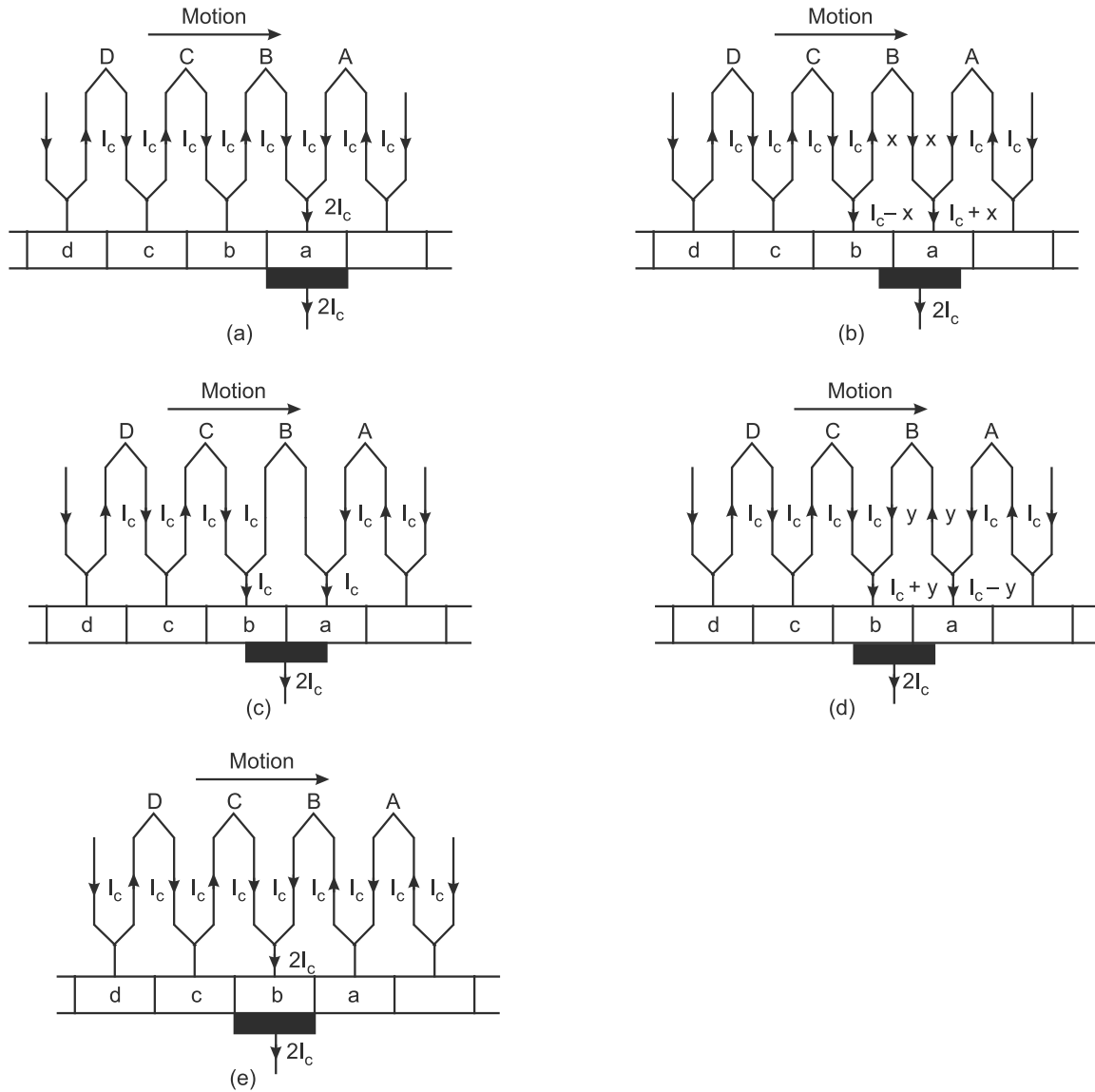


Fig. 4.49 Commutation during brush shifts from segment 'a' to 'b'

3. At the next instant, as shown in Fig. 4.49(c), the brush is at the centre of both the segments 'b' and 'a' and covers half of the area of both the segments. At this instant brush is drawing equal current (I_c) from both the segments 'b' and 'a' and its total value is $2I_c$.

It may be noted that current in the coil 'B' at this instant reduces to zero.

4. Further at the next instant, as shown in Fig. 4.49(d), larger area of segment 'b' has come in contact with the brush than segment 'a'. Accordingly, brush draws more current ($I_c + y$) from segment 'b' and draws smaller current ($I_c - y$)* from segment 'a'.

* It may be noted that at each instant current drawn by the brush is $2I_c$. First instant, $2I_c$; second instant ($I_c - x + I_c + x = 2I_c$); third instant ($I_c + I_c = 2I_c$); fourth instant ($I_c + y + I_c - y = 2I_c$).

It may be noted that current in the coil 'B' has reversed and starts increasing.

5. At the next (final) instant, as shown in Fig. 4.49(e), the brush completely comes in contact with segment 'b' and draws equal current I_c from both the sides.

It may be noted that current in the coil 'B' has totally reversed and obtains its rated value I_c .

Thus, the commutation process is completed for coil 'B'. The same process continues for the next coils to come (i.e., coil C, D and so on.....).

The reversal of current through a coil undergoing commutation may occur in any of the following manners (see Fig. 4.50):

Curve-1. Shows *linear commutation*, where current changes from $+I_c$ to $-I_c$ uniformly. It is an ideal commutation and provides uniform current density at the brush contact surface. In this case, the power loss at the brush contact is minimum.

Curve-2. Shows *sinusoidal commutation*. It results in satisfactory commutation.

Curve-3. Shows an *accelerated* or *over-commutation* where the current attains its final value with a zero (quick) rate of change at the end of commutation period. Usually, it provides a satisfactory commutation.

Curve 4. Shows a *retarded* or *under-commutation* where the final rate of change of current is very high. In such conditions sparking at the trailing edge of the brush is inevitable.

Curve 5. Shows sharply *accelerated commutation* where the current may reach to its proper final value without a spark but it involves very high localised current densities at the brush contact leading to sparking and heating which further leads to deterioration of brushes.

Curve 6. Shows sharply *retarded commutation* where current reaches to its final value which causes excessive current density under brushes resulting in sparking at the brushes.

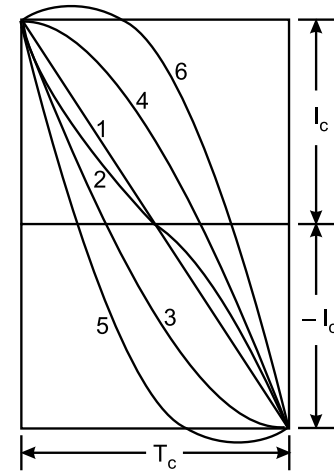


Fig. 4.50 Curves for reversal of current

Conclusion

From the above discussion, it is concluded that for *satisfactory commutation*, the current in the coil which undergoes commutation must be reversed completely during its commutation period T_c .

4.21 Cause of Delay in the Reversal of Current in the Coil going through Commutation and its Effect

The main cause of delay in the reversal of current in the coil undergoing commutation is its inductive property. It is apparent that the coils placed in the armature may have large number of turns embedded in the magnetic core having high permeability, due to which it possesses appreciable amount of self-inductance.

The inductive property of the coil undergoing commutation gives rise to a voltage called *reactance voltage*. This voltage opposes the reversal of current in it. Although, this voltage is very small, it

produces a large current in the coil whose resistance is very small under short circuit. Due to this, heavy **sparking** occur at the brushes.

Thus, it is observed that even though the brushes are set at such a position that coils undergoing short-circuit are in the magnetic neutral axis where they are not cutting any flux and hence no emf is induced in them due to rotation of armature but there will be an emf induced due to self-inductance which causes severe sparking at the brushes.

How to Offset this Reactance Voltage?

To offset this reactance voltage, a voltage is produced in each coil as it passes through commutating period. This voltage is produced in the coil in such a direction that it offsets the reactance voltage and helps in reversing the current in the coil. Such a voltage is called the *commutating emf*.

The necessary commutating emf can be produced either (i) by shifting the brushes in non-interpolar machines, beyond the position of *MNA* which is selected to neutralise the armature reaction. or (ii) by strengthening the inter-poles more than that is necessary to neutralise the armature reaction flux.

4.22 Magnitude of Reactance Voltage

An approximate value for inductance (L) of a coil placed in the armature can be determined by Hobart's formula. Hobart gave an experimental rule for determining inductance of a coil, i.e.,

$$L = n^2 (8 l_e + 0.8 l_f) \times 10^{-6} \text{ henry} \quad \dots(4.11)$$

where, l_e = embedded length of coil in metre

l_f = free length (over hang) of coil in metre

n = number of turns of a coil

Induced emf in a coil due to self-inductance, i.e.,

$$\text{Reactance voltage} = L \frac{di}{dt} \quad \dots(4.12)$$

where, di = Change of current during commutation

$$= I_c - (-I_c) = 2I_c$$

$$dt = T_c \text{ (time for which the coil is short circuited)}$$

$$T_c = \frac{W_b - W_m}{v_c} \text{ second} \quad \dots(4.13)$$

Here,

W_b = brush width in metre

W_m = width (or thickness) of mica insulation

v_c = linear velocity of commutator $\frac{\pi DN}{60}$

$$\text{Hence, reactance voltage} = n^2 (8l_e + 0.8l_f) \cdot \frac{2I_c}{T_c} \times 10^{-6} \text{ volt} \quad \dots(4.14)$$

The above voltage is developed when only one coil is short circuited by the brush width. If brush width is such that it is short circuiting m coils, then

$$\text{reactance voltage} = m n^2 (8l_e + 0.8l_f) \cdot \frac{2I_c}{T_c} \times 10^{-6} \text{ V} \quad \dots(4.15)$$

Example 4. 31

A four-pole lap-wound DC machine has an armature of 20 cm diameter and runs at 1500 rpm. If the armature current is 120 A, thickness of the brush is 10 mm and the self-inductance of each coil is 0.15 mH, determine the average emf induced in each coil during commutation.

Solution:

Here, $P = 4$; $A = P = 4$; $D = 20 \text{ cm} = 0.2 \text{ m}$; $I_a = 120 \text{ A}$;

$$L = 0.15 \text{ mH} = 0.15 \times 10^{-3} \text{ H}; W_b = 10 \text{ mm} = 0.01 \text{ m}$$

$$\text{Linear velocity, } v_c = \frac{\pi DN}{60} = \frac{\pi \times 0.2 \times 1500}{60} = 15.71 \text{ ms}^{-1}$$

$$\begin{aligned} \text{Commutation time, } T_c &= \frac{W_b - W_m}{V_c} = \frac{0.01 - 0}{15.71} = (W_m = 0 \text{ not given}) \\ &= 636 \times 10^{-3} = 0.636 \text{ ms} \end{aligned}$$

$$\text{Current per conductor, } I_c = \frac{I_a}{A} = \frac{120}{4} = 30 \text{ A}$$

$$\begin{aligned} \text{Average reactance voltage} &= L \cdot \frac{2I_c}{T_c} = 0.15 \times 10^{-3} \times \frac{2 \times 30}{0.636 \times 10^{-3}} \\ &= \mathbf{14.15 \text{ V (Ans.)}} \end{aligned}$$

Example 4. 32

Calculate the reactance voltage for a six-pole wave connected generator if its speed is 300 rpm, diameter of commutator 1.4 metre, number of commutator segments 440, brush width 3 cm, length of each conductor 1 m, length of core 40 cm, turns per commutator segment 2 and armature current is 500 ampere.

Solution:

Here, $P = 6$; $A = 2$; $N = 300 \text{ rpm}$; $D = 1.4 \text{ m}$; $W_b = 3 \text{ cm}$; $I_a = 500 \text{ A}$; $n = 2$

Linear or peripheral velocity,

$$v_c = \frac{\pi DN}{60} = \frac{\pi \times 1.4 \times 300}{60} = 22 \text{ ms}^{-1}$$

$$\text{Period of commutation, } T_c = \frac{W_b - W_m}{v_c} = \frac{0.03 - 0}{22} = \frac{0.03}{22} \text{ second}$$

$$\text{Current per conductor, } I_c = \frac{I_a}{A} = \frac{500}{2} = 250 \text{ A}$$

$$\text{Length of conductor} = 1 \text{ m}$$

$$\text{Embedded length of conductor} = 40 \text{ cm} = 0.4 \text{ m}$$

$$\text{Free length of conductor} = 1 - 0.4 = 0.6 \text{ m}$$

$$\text{Embedded length per turn, } l_e = 2 \times 0.4 = 0.8 \text{ m}$$

$$\text{Free length per turn, } l_f = 2 \times 0.6 = 1.2 \text{ m}$$

$$\text{Width of each segment} = \frac{\pi D}{\text{No. of segments}} = \frac{\pi \times 1.4}{440} = 0.01 \text{ m}$$

$$\text{Brush width, } W_b = 3 \text{ cm} = 0.03 \text{ m}$$

$$\text{No. of segments short circuited by the brush, } m = \frac{0.03}{0.01} = 3$$

$$\text{No. of turns per coil, } n = 2$$

$$\begin{aligned} \therefore \text{Self-inductance, } L &= mn^2 (8 l_e + 0.8 l_f) \times 10^{-6} \text{ H} \\ &= 3 \times 2^2 \times (8 \times 0.8 + 0.8 \times 1.2) \times 10^{-6} \text{ H} \\ &= 88.32 \times 10^{-6} \text{ H} \end{aligned}$$

$$\text{Reactance voltage} = L \times \frac{2I_c}{T_c} = 88.32 \times 10^{-6} \times \frac{2 \times 250}{0.032 / 22} = \mathbf{32.38 \text{ V (Ans.)}}$$

4.23 Good Commutation and Poor Commutation

Good Commutation

Good commutation means no sparking at the brushes and the commutator surface remains unaffected during continuous operation of DC machines. Efforts are made to obtain good commutation.

Poor Commutation (Causes of sparking at brushes)

A machine is said to have poor commutation if there is sparking at the brushes and the commutator surface gets damaged during its operation. Sparking at the brushes results in overheating at the commutator brush contact and pitting of commutator. These effects are cumulative, since any sparking impairs the contact which increases heating and further aggravates the situation.

Poor commutation may be caused by mechanical or electrical conditions. The mechanical conditions for poor commutation may be due to uneven surface of the commutator, non-uniform brush pressure or vibrations of brushes in the brush holder etc. By making proper mechanical arrangements, the sparking due to mechanical conditions can be avoided (or eliminated).

The electrical conditions for poor commutation is development of emf in the coils undergoing commutation which may be due to armature reaction or inductance effect of the coil.

The production of emf due to armature reaction in the coil undergoing commutation can be eliminated by providing interpoles or compensating winding on the machine. The production of emf due to inductance can be counter balanced either (i) by strengthening the interpoles more than that is necessary to neutralise the armature reaction flux or (ii) by shifting the brushes beyond the position of MNA which is selected to neutralise the armature reaction.

4.24 Interpoles and their Necessity

The narrow poles placed in between the main poles of a DC machine are called interpoles or commutating poles.

Necessity

Interpoles are provided in between the main poles of DC machine and are energised to such an extent that they must neutralise the armature field produced by the armature winding when machine is loaded. At the same time they must neutralise the emf induced due to inductance in the coil undergoing commutation.

For illustration,

Consider a coil ab placed on the armature, rotating in a uniform magnetic field. At this instant, when the induced emf in the coil ab which undergoes short circuit must be zero as shown in Figs. 4.51 (a) and (b). Then no current flows and there is no sparking at the brushes which are slipping from one commutator segment to the next.

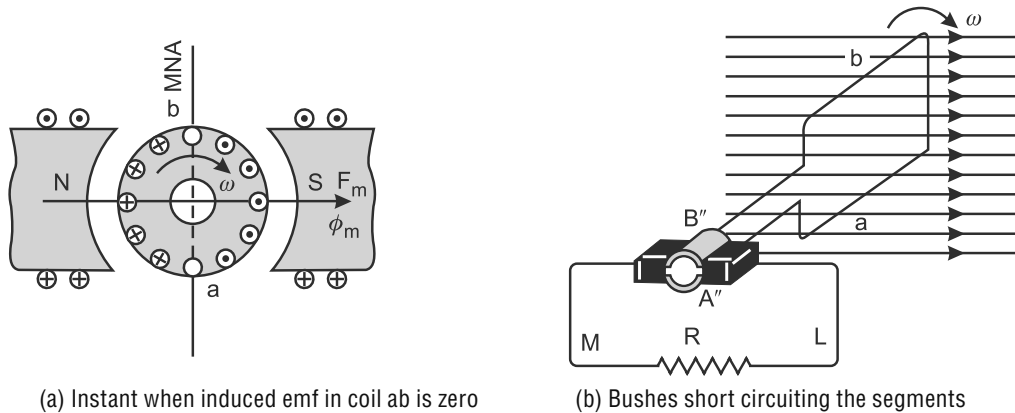


Fig. 4.51 Armature rotating in uniform magnetic field

When load is applied, the armature conductors also carry current and produce their own magnetic field ϕ_A in the direction shown in Fig. 4.52(a). Thus coil ab undergoing commutation, this coil is short circuited for a small period. Although it is moving parallel to main field ϕ_m but at the same time it is cutting the armature field ϕ_A at right angles. Hence, an emf is induced in the short circuited coil

ab as shown in Fig. 4.52(a). This produces lot of current in the coil and hence causes sparking at the brushes.

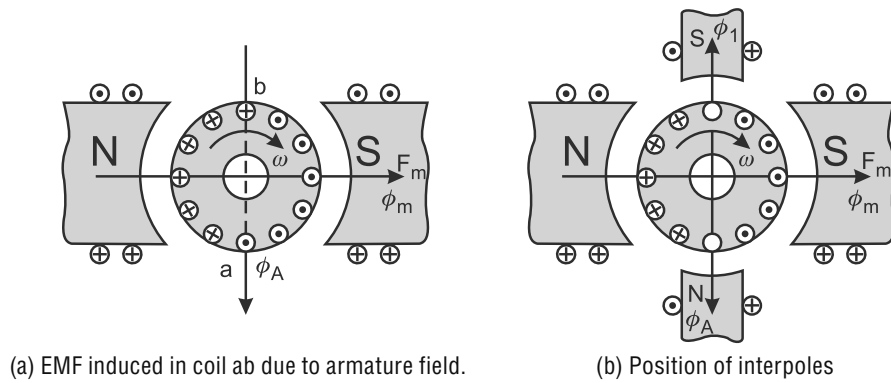


Fig. 4.52 Interpoles neutralising the armature field

The sparking at the brushes can be avoided by neutralising the armature field. For this, interpoles are provided in the DC machines which are placed in between the main poles as shown in Fig. 4.52(b). The flux produced by the interpoles, i.e., ϕ_i must be equal to that of armature field ϕ_A . As ϕ_A is proportional to I_a , therefore, the winding of the interpoles is connected in series with the armature as shown in Fig. 4.53(a) and 4.53(b). Usually, the interpoles are tapered in order to ensure that there may not be saturation at the root of the pole at heavy overloads. At the same time the air-gap under the interpoles is kept larger (1.5 to 1.7 times) than that under the main poles in order to avoid saturation in the interpoles.

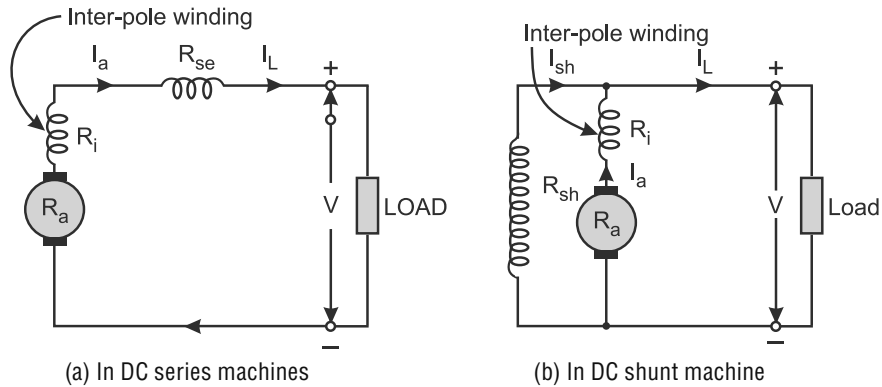


Fig. 4.53 Connections of interpole winding

4.25 Compensating Winding and its Necessity

An armature reaction produces a demagnetising and cross-magnetising effect. The demagnetising effect is compensated by incorporating a *few extra turns* to the main-field winding, whereas, to neutralise the cross-magnetising effect a compensating winding is used.

In this case, a number of conductors or coils are embedded in the slots of the pole shoes and are connected in series with the armature winding in such a way that current flowing through these conductors or coils sets up a magnetic field which neutralises the cross-magnetising effect of armature field. This winding is known as *compensating winding*, as shown in Fig. 4.54.

When current flows through this winding, it sets up magnetic field which is equal and opposing to the cross-magnetising effect of armature field and neutralises it. Thus, no emf is induced in the coil passing through *MNA* and hence sparking at the brushes is eliminated. Thus, a sparkless or good commutation is obtained.

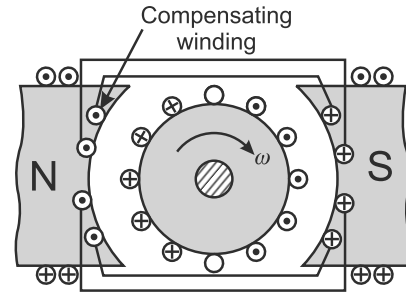


Fig. 4.54 Compensating winding

Example 4.33

Estimate the number of turns needed on each commutating pole of six-pole generator delivering 200 kW at 200 V, given that the number of armature conductors is 540 and the winding is lap connected interpole air-gap is 1.0 cm and the flux density in the interpole air-gap is 0.3 Wb/m². Neglect the effect of iron parts of the circuit and of leakage.

Solution:

Here, Load = 200 kW; $V = 200$ V; $Z = 540$; $A = P = 6$

$$l_{ig} = 1.0 \text{ cm} = 0.01 \text{ m}; B_{ig} = 0.3 \text{ Wb/m}^2$$

$$\text{Load current, } I_L = \frac{\text{kW} \times 1000}{V} = \frac{200 \times 1000}{200} = 1000 \text{ A}$$

$$\text{Armature current, } I_a = I_L = 1000 \text{ A}$$

$$\text{Current per conductor, } I_c = \frac{I_a}{A} = \frac{1000}{6} = 166.7 \text{ A}$$

$$\text{Armature reaction ampere turns per pole} = \frac{I_c Z}{2P} = \frac{166.7 \times 540}{2 \times 6} = 7500$$

$$\text{Ampere-turns for air gap flux per pole, } AT_{ig} = \frac{l_{ig} B_{ig}}{\mu_0} = \frac{0.01 \times 0.3}{4\pi \times 10^{-7}} = 2386$$

$$\text{Total ampere-turns required for each interpole, } AT_{ip} = 7500 + 2386 = 9886$$

$$\text{No. of turns for each interpole} = \frac{AT_{ip}}{I_a} = \frac{9886}{1000} = \mathbf{9.886 \text{ (Ans.)}}$$

Example 4.34

A four-pole, 20 kW, 400 V DC generator has a wave wound armature with 600 conductors. The mean flux density in the air gap of interpole is 0.5 tesla on full-load. If the air gap under interpole is 4 mm, calculate the number of turn required on each interpole.

Solution:

Here $P = 4$; $A = 2$ (wave-wound); load = 20 kW; $V = 400$ V; $Z = 600$; $B_{ig} = 0.5$ T; $l_{ig} = 4$ mm = 4×10^{-3} m

$$\text{Load current, } I_L = \frac{kW \times 1000}{V} = \frac{20 \times 1000}{400} = 50 \text{ A}$$

$$\text{Armature current, } I_a = I_L = 50 \text{ A}$$

$$\text{Current in each conductor, } I_c = \frac{I_a}{A} = \frac{50}{2} = 25 \text{ A}$$

$$\text{Armature reaction ampere-turns per pole} = \frac{I_c Z}{2P} = \frac{25 \times 600}{2 \times 4} = 1875$$

$$\text{Ampere-turns for air-gap, } AT_{ig} = \frac{B_{ig} l_{ig}}{\mu_0} = \frac{0.5 \times 4 \times 10^{-3}}{4\pi \times 10^{-7}} = 1591$$

$$\text{Total interpole ampere-turns, } AT_{ip} = 1875 + 1591 = 3466$$

$$\text{Number of turns on each interpole} = \frac{AT_{ip}}{I_a} = \frac{3466}{50} = \mathbf{69.32} \text{ (Ans.)}$$

Example 4.35

A four-pole, lap wound DC generator carries 360 armature conductors and delivers a full-load current of 400 A. Determine the number of turns of each Interpole if the air-gap flux of the interpole is 0.5 tesla and the effective air-gap length is 3 mm. Assuming that the number of ampere-turns required for the remaining magnetic circuit is only one-tenth of the air-gap.

Solution:

Here, $P = 4$; $A = P = 4$ (lap winding); $Z = 360$; $I_a = 400$ A

$$\text{Current per conductor, } I_c = \frac{I_a}{A} = \frac{400}{4} = 100 \text{ A}$$

$$\text{Armature reaction ampere-turns per pole, } AT = \frac{I_c Z}{2P} = \frac{100 \times 360}{2 \times 4} = 4500$$

$$\text{Inter-pole air gap, } l_{ig} = 3 \text{ mm} = 3 \times 10^{-3} \text{ m}$$

$$\text{Flux density in the inter-pole air gap, } B_{ig} = 0.5 \text{ T}$$

$$\text{Ampere-turns required for inter-pole air gap} = \frac{B_{ig} l_{ig}}{\mu_0} = \frac{0.5 \times 3 \times 10^{-3}}{4\pi \times 10^{-7}} = 1193.2$$

$$\text{Ampere-turns required for remaining magnetic circuit} = 10\% \text{ of } 1193.2 = \frac{10}{100} \times 1193.2 = 119.3$$

$$\text{Total ampere-turns required for the interpole} = 4500 + 1312.5 = 5812.5$$

$$\text{Number of turn on each interpole} = \frac{5812.5}{400} = \mathbf{14.53} \text{ (Ans.)}$$

Example 4.36

A four-pole, 25 kW, 250 V wave-wound generator has 42 slots with 10 conductors per slot. The brushes are given a lead of 8° mechanical when the generator delivers full-load current. Calculate the number of turns on the compensating winding if the ratio of pole arc to pole pitch is 0.8.

Solution:

Here, $P = 4$; $A = 2$ (wave-winding); Load = 25 kW; $V = 250$ V; $Z = 42 \times 10 = 420$; $\theta = 8^\circ$ (mech.)

$$\text{Load current, } I_L = \frac{kW \times 1000}{V} = \frac{25 \times 1000}{250} = 100 \text{ A}$$

$$\text{Armature current, } I_a = I_L = 100 \text{ A}$$

$$\text{Current per conductor, } I_c = \frac{I_a}{A} = \frac{100}{2} = 50 \text{ A}$$

$$\text{Total armature reaction ampere-turns} = \frac{I_c Z}{2P} = \frac{50 \times 420}{2 \times 4} = 2625$$

Ampere-turns per pole for compensating winding

$$= \frac{I_c Z}{2P} \times \frac{\text{Pole arc}}{\text{Pole pitch}} = 2625 \times 0.8 = 2100$$

$$\text{Turns per pole for compensating winding} = \frac{\text{ATs for each pole face}}{I_a} = \frac{2100}{100} = \mathbf{21} \text{ (Ans.)}$$

4.26 Methods of Improving Commutation

Commutation may be improved by employing following methods.

- 1. By use of high resistance brushes.** High resistance carbon brushes help the current to be reversed in the coil undergoing commutation and reduces sparking at the brushes.
- 2. By shifting of brushes.** In this method, brushes are shifted to the new position of MNA so that no emf be induced in the coil undergoing commutation. Thus, the sparking at the brushes is eliminated. But in this case, the position of MNA changes with the change in load on the machine and simultaneously the position of brushes cannot be changed.
Hence, this method is employed in the machine which we do not have interpoles and the load on the machine remain almost constant.
- 3. By use of interpoles or commutating poles.** In this method, narrow poles are placed in between the main poles of a DC machine which re-energised to such an extent that they neutralise the field produced by the armature under load. Hence, no emf is induced in the coil which undergoes commutation.
- 4. By use of compensating winding.** In this method, a number of conductors or coils are embedded in the slots provided at the pole shoes faces and carry current of such a magnitude and direction that field produced by them neutralises the armature field and improve commutation.

Section Practice Problems

Numerical Problems

1. A four-pole, lap wound DC machine is having 500 conductors on its armature and running at 1000 rpm. The flux per pole is 30 m Wb Calculate the voltage induced in the armature winding. What will be induced emf if the armature is rewound for wave winding?
(Ans. 250 V; 500 V)
2. A 4-pole machine has an armature with 90 slots and 8 conductors per slot, the flux per pole is 0.05 Wb and runs at 1200 rpm. Determine induced emf if winding is (i) lap connected (ii) wave connected.
(Ans. 720 V; 1440 V)
3. A wave wound armature of a six-pole generator has 51 slots. Each slot contains 20 conductors. The voltage required to be generated is 250 V. What would be the speed of coupled prime mover if flux per pole is 0.07 Wb.
If the armature is rewound as lap wound machine and run by same prime mover, what will be the generated voltage.
(Ans. 70 rpm; 83.3 V)
4. The armature of a four-pole 200 V, lap wound generator has 400 conductors and rms of 300 rpm. Determine the useful flux per pole. If the number of turns in each field coil is 900, what is the average induced emf in each field coil on breaking its connection if the magnetic flux set-up by it dies away completely in 0.1 second?
(Ans. 0.1 Wb; 900 V)
5. A four-pole, lap wound DC armature has a bore diameter of 70 cm. It has 540 conductors and the ratio of pole arc to pole pitch is 0.72. If the armature is running at 500 rpm and the flux density in the air gap is 1.2 tesla, determine the induced emf in the armature if the effective length of armature is 20 cm.
(Ans. 427.68 V)
6. The armature resistance of a four-pole, lap wound DC machine is 0.18 ohm. What will be the value of armature resistance if the machine is rewound for wave connections.
(Ans. 0.72 Ω)
7. A current of 72A is supplied by a four-pole lap wound DC generator with 480 conductors on its armature. The brushes are given an actual lead of 12° (mechanical). Calculate the cross-magnetising ampere-turns per pole.
(Ans. 792)
8. A four-pole DC generator supplies a current of 100A at full load. It has wave wound armature with 722 conductors. If the brush lead is 8° calculate the armature demagnetising and cross-magnetising ampere-turns per pole.
(Ans. 802; 3710.5)
9. A four-pole wave wound DC machine has an armature of 25 cm diameter and runs at 1200 rpm. If the armature current is 140 A, thickness of brush is 12 mm and the self inductance of each armature coil is 0.14 mH, calculate the average emf induced in each coil during commutation.
(Ans. 25.64 V)
10. Determine the number of turns on each commutating pole of a 6-pole machine if the flux density in the air gap of the commutating pole is 0.5 Wb/m² at full-load and the effective length of the airgap is 4 mm. The full load current is 600 A and the armature is lap wound with 540 conductors. Assume the number of ampere-turns required for the remainder of the magnetic circuit to be one-tenth of that of the air-gap.
(Ans. 10.4)
11. A 420 V, four-pole, 25 kW DC generator has a wave-connected armature winding with 846 conductors. The mean flux density in the air-gap under the interpoles is 0.5 Wb/m² on full load and the radial gap length is 0.4 cm. Calculate the number of turns required on each interpole.
(Ans. 79.62)

Short Answer Type Questions

Q.1. What is armature reaction?

Ans. The effect of magnetic field set up by the armature current carrying conductors on the distribution of flux set-up by the main poles of a DC machine is called armature reaction.

Q.2. Mention two unwanted effects of armature reaction?

Or

State the effects of armature reaction in DC machines.

Ans. Demagnetisation or weakening of main field and cross-magnetisation or distortion of main field.

Q.3. How will you define magnetic neutral plane (mnp)?

Ans. The plane through the axis, along which no emf is induced in the armature conductors, is known as magnetic neutral plane.

Q.4. Give the relation between electrical and mechanical angle in case of rotating machine.

Ans. In a multipolar machine, the electrical angle completed in one revolution is $\frac{P}{2} \times 360^\circ$, whereas mechanical angle is only 360° .

$$\therefore \theta_{elect.} = \frac{P}{2} \theta_{mech}$$

Q.5. In a DC machine without interpole to get improved commutation, whether the brush shift should be varied with change in load or brush shift should be fixed?

Ans. Brush shift has to be varied with the change in load in a DC machine so as to lie along *MNA* to provide sparkless commutation.

Q.6. Explain bad commutation.

Ans. A machine is said to have poor or bad commutation if there is sparking at the brushes and commutator surface. The bad commutation may be caused by mechanical or electrical conditions. The mechanical conditions may be due to uneven commutator surface non uniform brush pressure, vibration of brushes in the brush holder etc. The electrical conditions include development of *emf* in the coil undergoing commutation due to armature reaction or due to inductance.

Q.7. What is linear commutation?

Ans. When current in a coil undergoing commutation changes from $+I_c$ to $-I_c$ uniformly, it is called linear commutation. It is an ideal commutation.

Q.8. Name the factor that opposes reversal of current in a coil undergoing commutation.

Ans. Self-inductance of the coil undergoing commutation opposes the reversal of current.

Q.9. Why are the interpoles of a DC machine tapered?

Ans. Interpoles are tapered in order to ensure that there may not be saturation at the root of the pole at heavy overloads.

Q.10. What is the function of compensating winding in a DC machine?

Ans. The compensating winding is used to neutralise the effect of armature reaction outside the influence of the interpoles. It also maintains uniform flux distribution under the faces of the main poles.

Q.11. In what way compensating winding is connected to the armature?

Ans. The compensating winding is connected in series with the armature in a manner so that the direction of current through the compensating winding conductors in any pole face will be opposite the field produced by the armature current carrying conductors.

Q.12. What is the role of interpoles and compensating winding in DC machine?

Ans. Both are used to neutralise the armature field produced by the current carrying conductors of the armature when machines are loaded.

Q.13. What are disadvantages of armature reaction?

Ans. Armature reaction produces demagnetising and cross-magnetising effect on the main magnetic field. Because of armature reaction, the *MNA* are shifted due to which an emf is induced in the coil undergoing commutation which causes heavy sparking at brushes.

4.27 Types of DC Generators

D.C. generators are generally classified according to the methods of their field excitation. On the basis of this criteria, they can be classified as:

1. Separately excited DC generators
2. Self excited DC generators – these are further classified as:
 - (i) Shunt wound DC generators
 - (ii) Series wound DC generators
 - (iii) Compound wound DC generators.
 - (a) Long shunt compound wound generators
 - (b) Short shunt compound wound generators.

Except the above, there are also permanent magnet type DC generators. In these generators, no field winding is placed around the poles. These machines have fairly constant magnetic field. Although these machines are very compact but are used only in small sizes like dynamos in automobiles etc. The main disadvantages of these machine is that the flux produced by the magnets deteriorates with the passage of time which changes the characteristics of the machine.

4.28 Separately-excited DC Generators

A DC generator in which current is supplied to the field winding from an external DC source is called a separately excited DC generator. The flux produced by the poles depends upon the field current with in the unsaturated region of magnetic material of the poles (i.e., $\phi \propto I_f$), but in the saturated region, the flux remains constant. Its conventional diagram is shown in Fig. 4.55.

Important relations: Here, $I_a = I_L$ (4.16)

where I_a is armature current and I_L is the line current.

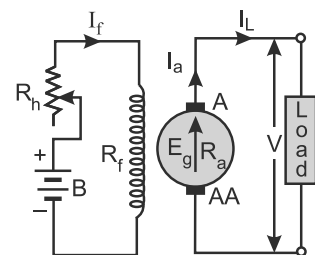


Fig. 4.55 Circuit diagram for separately excited DC generator

$$\text{Terminal voltage, } V = E_g - I_a R_a$$

If contact brush drop per brush (v_b) is known,

$$V = E_g - I_a R_a - 2 v_b \quad \dots(4.17)$$

$$\text{Power developed} = E_g I_a;$$

$$\text{Power output} = VI_L = VI_a$$

4.29 Self-excited DC Generators

A DC generator whose field winding is excited by the current supplied by the generator itself is called a *self-excited DC generator*.

In a self-excited DC generator, the field coils may be connected in parallel with the armature, in series with the armature or partly in series and partly in parallel with the armature winding. Accordingly, the self-excited generators may be classified as

- (i) Shunt wound generators
- (ii) Series wound generators
- (iii) Compound wound generators.

(i) Shunt Wound Generators

In a shunt wound generator, the field winding is connected across the armature winding forming a parallel or shunt circuit. Therefore, full terminal voltage is applied across the field winding. A very small current I_{sh} flows through it because this winding has many turns of fine wire having very high resistance R_{sh} (of the order of 100 ohm). Its conventional diagram is shown in Fig. 4.56.

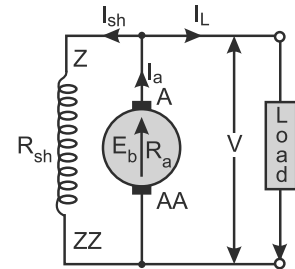


Fig. 4.56 Circuit diagram for DC shunt generator

Important relations:

$$\text{Shunt field current, } I_{sh} = V/R_{sh} \quad \dots(4.18)$$

Where R_{sh} is the shunt field winding resistance. The field current I_{sh} is practically constant at all loads, therefore, the DC shunt machine is considered to be constant flux machine.

$$\text{Armature current, } I_a = I_L + I_{sh} \quad \dots(4.19)$$

$$\text{Terminal voltage, } V = E_g - I_a R_a$$

$$\text{Including brush contact drop, } V = E_g - I_a R_a - 2v_b \quad \dots(4.20)$$

$$\text{Power developed} = E_g I_a; \text{ Power output} = VI_L$$

(ii) Series Wound Generators

In a series wound generator, the field winding is connected in series with the armature winding forming a series circuit. Therefore, full line current I_L or armature current I_a flows through it. Since the series field winding carries full load current, it has a few turns of thick wire having low resistance (usually of the order of less than one ohm). Its conventional diagram is shown in Fig. 4.57.

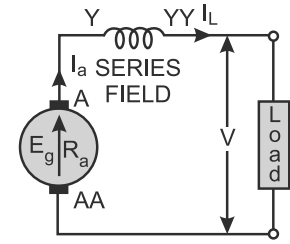


Fig. 4.57 Circuit diagram for DC series generator

Important relations:

Series field current,
$$I_{se} = I_L = I_a \dots (4.21)$$

Series field winding resistance = R_{se}

Terminal voltage,
$$V = E_g - I_a R_a - I_{se} R_{se} = E_g - I_a (R_a + R_{se})$$

Including brush contact drop,
$$V = E_g - I_a (R_a + R_{se}) - 2v_b \dots (4.22)$$

Power developed = $E_g I_a$; Power output = $VI_L = VI_a$

Note: The flux developed by the series field winding is directly proportional to the current flowing through it (i.e., $\phi \propto I_{se}$). But it is only true before magnetic saturation, after saturation flux becomes constant even if the current flowing through it is increased.

(iii) Compound Wound Generators

In a compound wound generator, there are two sets of field windings on each pole. One of them is connected in series (having few turns of thick wire) and the other is connected in parallel (having many turns of fine wire) with armature. A compound wound generator may be;

- (a) *Long shunt* in which the shunt field winding is connected in parallel with the combination of both armature and series field winding. The conventional diagram of lone shunt compound generator is shown in Fig. 4.58.

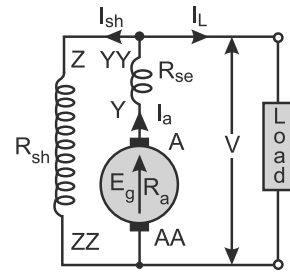


Fig. 4.58 Circuit diagram for long shunt DC compound generator

Important relations

Shunt field current,
$$I_{sh} = \frac{V}{R_{sh}}$$

Series field current,
$$I_{se} = I_a = I_L + I_{sh} \dots (4.23)$$

Terminal voltage,
$$\begin{aligned} V &= E_g - I_a R_a - I_{se} R_{se} \\ &= E_g - I_a (R_a + R_{se}) \end{aligned}$$

Including brush contact drop,
$$V = E_g - I_a (R_a + R_{se}) - 2v_b \dots (4.24)$$

Power developed = $E_g I_a$; Power output = VI_L

- (b) *Short shunt* in which the shunt field winding is connected in parallel with only armature winding. The conventional diagram of short shunt compound generator is shown in Fig. 4.59.

Important relations

Series field current, $I_{se} = I_L$

Shunt field current,
$$I_{sh} = \frac{V + I_L R_{se}}{R_{sh}} = \frac{E_g - I_a R_a}{R_{sh}} \quad \dots(4.25)$$

$$I_a = I_L + I_{sh}$$

Terminal voltage, $V = E_g - I_a R_a - I_L R_{se}$

Including brush contact drop, $V = E_g - I_a R_a - I_L R_{se} - 2v_b \quad \dots(4.26)$

$$\text{Power developed} = E_g I_a; \text{Power output} = VI_L$$

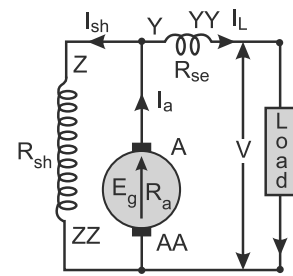


Fig. 4.59 Circuit diagram for short shunt DC compound generator

Cumulatively and Differentially Compound-wound Generators

In compound wound DC generators, the field is produced by the shunt as well as series winding. Generally the shunt field is stronger than the series field. When the series field *assist* the shunt field, the generator is called as **cumulatively compound wound generator** [see Fig. 4.60(a)]. However, when the series field *opposes* the shunt field, the generator is known as **differentially compound wound generator** [see Fig. 4.60(b)].

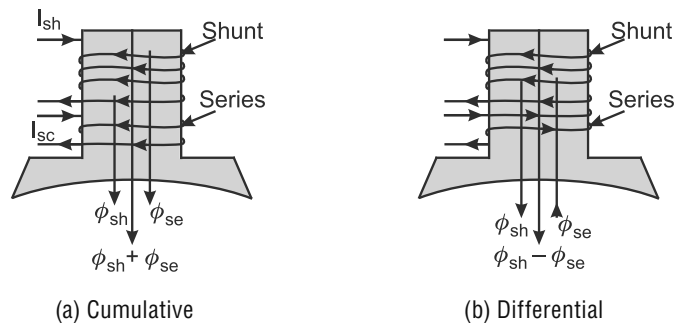


Fig. 4.60 Winding position and direction of flow of current in shunt and series winding

4.30 Voltage Regulation of a DC Shunt Generator

At no-load, the voltage at the terminals of a shunt generator is maximum and is called no-load generated emf. When load is applied on the generator, the terminal voltage decreases due to drop in the armature circuit.

Generated voltage or voltage at the terminals at no-load

$$E_g = E_0 \frac{P\phi ZN}{60A}$$

At full load, the terminal voltage is

$$V = E_g - I_{a(fl)} R_a - V_b$$

Where, $I_{a(fl)}$ = Full-load armature current

R_a = Armature resistance

V_b = Total voltage drop at the brushes

*The rise in terminal voltage from full-load to no-load at constant speed of a DC generator is called its **voltage regulation**. It is expressed as a percentage of full-load terminal voltage i.e.,*

$$\% \text{ Voltage regulation} = \frac{E_0 - V}{V} \times 100 \quad \dots(4.27)$$

Example 4.37

A 12 kW, six-pole DC generator develops an emf of 240 at 1500 rpm. The armature has a lap connected winding. The average flux density over the pole pitch is 1.0 T. The length and diameter of the armature is 30 cm and 25 cm respectively. Calculate flux per pole, total number of active armature conductors. Power generated in the armature and torque developed when the machine is delivering 50 A current to the load.

Solution:

Here, $P = 6$; $V = 240$ V; $N = 1500$ rpm; $A = P = 6$;

$B = 1.0$ T; $D = 0.25$ m; $l = 0.3$ m; $I_a = I_L = 50$ A

$$\text{Flux per pole, } \phi = B \times \frac{\pi D}{P} \times l = 1.0 \times \frac{\pi \times 0.25}{6} \times 0.3 = \mathbf{0.0393 \text{ Wb}} \text{ (Ans.)}$$

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

$$\therefore Z = \frac{E_g \times 60A}{\phi \times N \times P} = \frac{240 \times 60 \times 6}{0.0393 \times 1500 \times 6} = \mathbf{244} \text{ (Ans.)}$$

Power developed in the armature, $P_g = E_g I_a = 240 \times 50 = \mathbf{12000 \text{ W}}$ (Ans.)

$$\text{Torque developed, } T = \frac{P_g}{\omega} = \frac{P_g}{2\pi N / 60} = \frac{12000 \times 60}{2\pi \times 1500} = \mathbf{76.4 \text{ Nm}} \text{ (Ans.)}$$

Example 4.38

A 12-pole DC shunt generator has 50 slots on its armature with 12 conductors per slot with wave winding. The armature and field winding resistance is 0.5 ohm and 60 ohm respectively. The generator is supplying a resistive load of 15 ohm at terminal voltage of 300 V when running at a speed of 625 rpm. Find the armature current, the generated emf and the flux per pole.

Solution:

The conventional diagram is shown in Fig. 4.61.

$$I_L = \frac{V}{R_L} = \frac{300}{15} = 20 \text{ A};$$

$$I_{sh} = \frac{V}{R_{sh}} = \frac{300}{60} = 5 \text{ A}$$

Armature current, $I_a = I_L + I_{sh} = 20 + 5 = \mathbf{25 \text{ A (Ans.)}}$

Generated emf, $E_g = V + I_a R_a$

$$= 300 + 25 \times 0.5 = \mathbf{312.5 \text{ V (Ans.)}}$$

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

where, $Z = 50 \times 12 = 600$; $N = 625 \text{ rpm}$; $P = 12$; $A = 2$;

$$\therefore 312.5 = \frac{f \times 600 \times 625 \times 12}{60 \times 2}$$

or $\phi = \mathbf{8.33 \text{ m Wb (Ans.)}}$

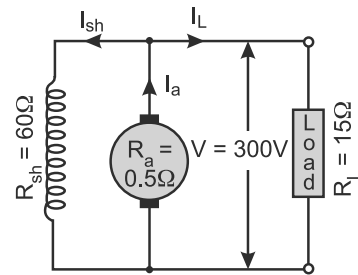


Fig. 4.61 Circuit diagram for shunt generation

Example 4.39

A four-pole shunt generator with lap connected armature has field and armature resistance of 50Ω and 0.1Ω respectively. The generator is supplying a load of 2.4 kW at 100 V . Calculate the armature current, current in each conductor and generated emf.

Solution:

Load current, $I_L = \frac{2.4 \times 1000}{100} = 24 \text{ A}$

Shunt field current; $I_{sh} = \frac{V}{R_{sh}} = \frac{100}{50} = 2 \text{ A}$

Armature current, $I_a = I_L + I_{sh} = 24 + 2 = \mathbf{26 \text{ A (Ans.)}}$

Current in each conductor, $I_c = \frac{I_a}{A} = \frac{26}{6} = \mathbf{4.33 \text{ A (Ans.)}}$

Generated emf, $E_g = V + I_a R_a$

$$= 100 + 26 \times 0.1 = \mathbf{102.6 \text{ V (Ans.)}}$$

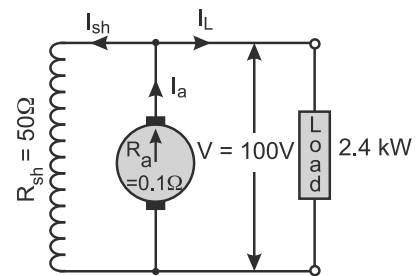


Fig. 4.62 Circuit diagram

Example 4.40

The useful flux of a four-pole, lap wound DC generator is 0.07 Wb . Its armature carries 220 turns and each turn has 0.004 ohm resistance, if its armature current is 50 A , running at a speed of 900 rpm , determine its terminal voltage.

Solution:

Here, $P = 4$; $A = 4$ (lap – wound); $\phi = 0.07 \text{ Wb}$; $N = 900 \text{ rpm}$; $I_a = 50 \text{ A}$

No. of armature conductors, $Z = 2 \times \text{No. of turns} = 2 \times 220 = 440$

Induced emf,
$$E = \frac{PZ\phi N}{60A} = \frac{4 \times 400 \times 0.07 \times 900}{60 \times 4} = 462 \text{ V}$$

No. of turns connected in each parallel path = $\frac{220}{4} = 55$

Resistance of each parallel path = $55 \times 0.004 = 0.22 \text{ ohm}$

Four resistances, each of 0.22 ohm, are connected in parallel as shown in Fig. 4.63(a).

$\therefore$ Armature resistance, $R_a = \frac{0.22}{4} = 0.055 \Omega$

Terminal voltage, $V = E - I_a R_a$ (generator action)

$$= 462 - 50 \times 0.055$$

$$= \mathbf{459.25 \text{ V (Ans.)}}$$

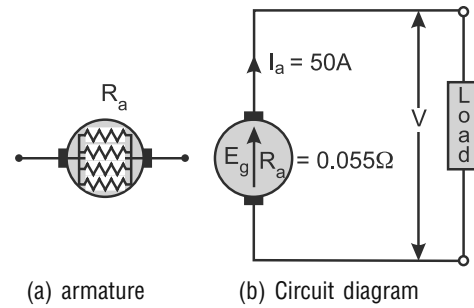


Fig. 4.63 Circuit diagram

Example 4.41

A four-pole DC shunt generator with a wave wound armature having 390 conductors has to supply a load of 500 lamps each of 100 W at 250 V. Allowing 10 V for the voltage drop in the connecting leads between the generator and the load and brush drop of 2 V. Calculate the speed at which the generator should be driven. The flux per pole is 30 m Wb and the value of $R_a = 0.05 \Omega$ and $R_{sh} = 65 \Omega$.

Solution:

The conventional circuit diagram of the DC shunt generator is shown in Fig. 4.64.

Total load = $500 \times 100 \text{ W}$

$$I_L = \frac{500 \times 100}{250} = 200 \text{ A}$$

Voltage drop in leads, $V_L = 10 \text{ V}$

Voltage across shunt field winding,

$$V_{sh} = V + V_L = 250 + 10 = 260 \text{ V}$$

$$I_{sh} = V_{sh}/R_{sh} = 260/65 = 4 \text{ A}$$

$$I_a = I_L + I_{sh} = 200 + 4 = 204 \text{ A}$$

Armature drop = $I_a R_a = 204 \times 0.05 = 10.2 \text{ V}$

Total brush drop, $2v_b = 2 \text{ V}$

Generated emf,
$$E_g = V + I_a R_a + V_L + 2v_b$$

$$= 250 + 10.2 + 10 + 2 = 272.2 \text{ V}$$

Now,
$$E_g = \frac{P\phi NZ}{60A} \text{ or } 272.2 = \frac{4 \times 30 \times 10^{-3} \times N \times 390}{60 \times 2}$$

or
$$N = \frac{272.2 \times 60 \times 2}{4 \times 30 \times 10^{-3} \times 390} = \mathbf{698 \text{ rpm (Ans.)}}$$

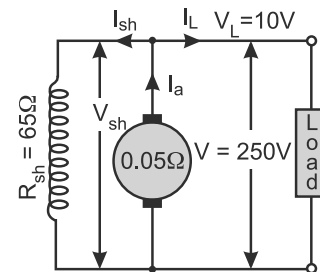
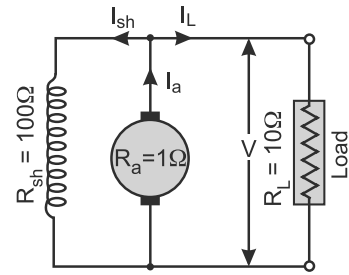


Fig. 4.64 Circuit diagram

Example 4.42

The armature of a four-pole DC shunt generator has 378 wave connected conductors. The armature and shunt winding resistance of the generator is 1 ohm and 100 ohm respectively. The flux per pole is 0.02 Wb. If a load resistance of 10 ohm is connected across the armature terminals and the generator is driven at 1000 rpm, calculate the power absorbed by the load.

**Fig. 4.65** Circuit diagram**Solution:**

The conventional circuit is shown in Fig. 4.65.

$$\text{Generated emf, } E_g = \frac{PZ\phi N}{60 A} = \frac{4 \times 378 \times 0.02 \times 1000}{60 \times 2} = 252 \text{ V}$$

$$\text{Line current, } I_L = \frac{V}{R_L} = \frac{V}{10} \text{ (where } V \text{ is terminal voltage)}$$

$$\text{Shunt field current, } I_{sh} = \frac{V}{R_{sh}} = \frac{V}{100}$$

$$\text{Armature current, } I_a = I_L + I_{sh} = \frac{V}{10} + \frac{V}{100} = (0.11 V)$$

$$\begin{aligned} \text{Using the relation, } E_g &= V + I_a R_a; \\ 252 &= V + 0.11 V \times 1.0 \end{aligned}$$

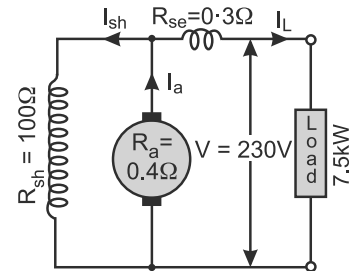
$$\therefore \text{ Terminal voltage, } V = 227 \text{ volt}$$

$$\therefore \text{ Load current, } I_L = \frac{V}{R_L} = \frac{227}{10} = 22.7 \text{ A}$$

$$\text{Power absorbed by the load, } P = VI_L = 227 \times 22.7 = 5.153 \text{ kW (Ans.)}$$

Example 4.43

A load of 7.5 kW at 230V is supplied by a short-shunt cumulatively compound DC generator. If the armature, series and shunt field resistances are 0.4, 0.3 and 100 ohm respectively. Calculate the induced emf and the load resistance.

**Fig. 4.66** Circuit diagram**Solution:**

Refer to Fig. 4.66.

$$I_L = \frac{7.5 \times 1000}{230} = 32.61 \text{ A}$$

$$I_{sh} = \frac{V + I_L R_{se}}{R_{sh}} = \frac{230 + 32.61 \times 0.3}{100} = 2.39 \text{ A}$$

$$I_a = I_L + I_{sh} = 32.61 + 2.39 = 35 \text{ A}$$

$$\begin{aligned} \text{Induced emf, } E_g &= V + I_L R_{se} + I_a R_a \\ &= 230 + 32.61 \times 0.3 + 35 \times 0.4 = 253.78 \text{ V (Ans.)} \end{aligned}$$

$$\text{Load resistance, } R_L = \frac{V^2}{P} = \frac{(230)^2}{7 \cdot 5 \times 1000} = 7.053 \text{ ohm (Ans.)}$$

Example 4.44

A load of 20 kW at 230 V is supplied by a compound DC generator. If the series, shunt field and armature resistances are 0.05, 115 and 0.1 ohm respectively. Calculate the generated emf when the generator is connected as long shunt.

Solution:

$$\text{Load} = 20 \text{ kW} = 20 \times 10^3 \text{ W}$$

$$V = 230 \text{ V}; R_a = 0.1 \text{ } \Omega; R_{se} = 0.05 \text{ } \Omega; R_{sh} = 115 \text{ } \Omega$$

$$\text{Line current, } I_L = \frac{20 \times 10^3}{230} = 86.96 \text{ A}$$

$$\text{Shunt field current, } I_{sh} = \frac{V}{R_{sh}} = \frac{230}{115} = 2 \text{ A}$$

$$\text{Armature current, } I_a = I_L + I_{sh} = 86.96 + 2 = 88.96 \text{ A}$$

$$\begin{aligned} \text{Generated emf, } E_g &= V + I_a R_a + I_a R_{se} \\ &= 230 + 88.96 \times 0.1 + 88.96 \times 0.05 \\ &= \mathbf{243.3 \text{ V (Ans.)}} \end{aligned}$$

4.31 Characteristics of DC Generators

To determine the relation between different quantities of a DC generator, the following are the important characteristics of DC generators:

- 1. No-load characteristics.** It is also known as magnetic characteristics or open-circuit characteristics (O.C.C.). It shows the relation between the no-load generated emf in the armature (E_0) and the field current (i.e., exciting current) I_f at a specified speed.
- 2. External characteristics.** It is also called the performance characteristics. It shows the relation between the terminal voltage (V) and the load current I_L .
- 3. Internal Characteristics.** It is also known as total characteristics. It gives the relation between the emf actually induced in the armature (E_g) and the armature current I_a .

4.32 No-load Characteristics of DC Generators or Magnetisation Curve of DC Generator

It shows the relation between the no-load generated emf in the armature (E_0) and the field current I_f at a specified speed. To obtain this characteristics, proceed as follows:

Open the field winding of the generator and connect it to a separate DC source through a rheostat as shown in Fig. 4.67. Connect an ammeter in the field circuit and a voltmeter across the armature. Reduce the field current to zero and run the armature at a specified speed. Get the reading of voltmeter and mark the point 'a' on the graph. To plot the characteristics take field current I_f along X-axis and no-load generated emf (E_0) along Y-axis. Increase the field current in steps and get the corresponding voltmeter readings. Plot these values on the graph. The curve thus obtained (shown in Fig. 4.68) shows the no-load characteristics or open circuit characteristics (O.C.C.) of the generator.

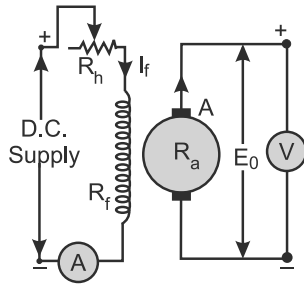


Fig. 4.67 Circuit diagram

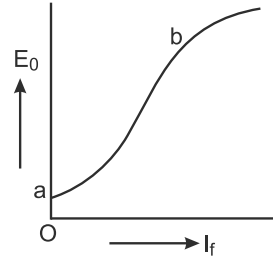


Fig. 4.68 No-load characteristics

Analysis of the curve

While analysing the curve, the following points are worth noting:

1. The curve starts from point 'a' instead of 'O' when the field current is zero. It is because of the residual magnetism of the poles.
2. The initial part of the curve (ab) is almost a straight line because at this stage the magnetic material is unsaturated and it has high permeability.
3. After point 'b' the curve bends and the generated emf (E_0) becomes almost constant. It is because after point 'b', the poles (magnetic material) starts getting saturated.

4.33 Voltage Build-up in Shunt Generators

The shunt generator is a self-excited DC generator whose field winding is supplied current from the output of the generator itself. But question arises how it can supply current to the field winding before the voltage being generated? And if the field current is not supplied, how can the voltage be generated? Let us find out its answer from the following explanation.

The open circuit characteristics of a DC shunt generator is shown in Fig. 4.69(b). The shunt field resistance is represented by a straight line OX. When armature is rotated at a constant speed of ω rad/sec, the small *residual flux* of the poles is cut by the armature conductors, and very small *emf* (oa) is induced in the armature. If now key (K) connected in the shunt field winding, as shown in Fig. 4.69(a), is closed, current ob flows in the field winding. This current increases the flux produced by the poles and voltage generated in the armature is increased to oc which further increases the field current to od which further builds up the voltage. This building up action comes to an end at point f where the o.c.c. intersects the shunt field resistance line OX. It is, because beyond this point, the

induced voltage is less than that required to maintain the corresponding field current. Thus, the final current in the field winding is ef and the final voltage build up by the generator for a given *O.C.C.* is oe as shown in Fig. 4.69(b).

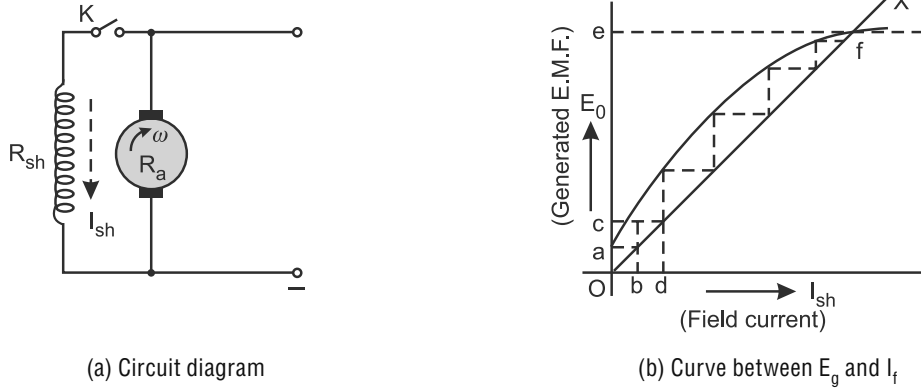


Fig. 4.69 Open circuit voltage built-up

4.34 Critical Field Resistance of a DC Shunt Generator

The open circuit characteristic of a DC shunt generator are shown in Fig. 4.70. The line OX is drawn in such a way that its slope gives the field winding resistance, i.e.,

$$R_{sh} = \frac{OB \text{ (in volt)}}{OC \text{ (in ampere)}}$$

In this case, the generator can build up a maximum voltage OB with a shunt field resistance R_{sh} . A line OY represents a smaller resistance. With this resistance, the generator can build up a maximum voltage OF which is slightly more than OB . If the field resistance is increased, the slope of the resistance line increases. Consequently the maximum voltage which the generator can build up, at a specified speed, decreases. If the value of R_{sh} is increased to such an extent that the resistance line does not cut the no-load characteristics at all (OZ), then it is apparent that the voltage will not be built-up (i.e., the generator fails to excite).

If the resistance line (OP) just coincide with the slope of the curve, at this value of field resistance, the generator will *just excite*. This resistance, given by the tangent to the *O.C.C.* is called the **critical resistance** at a specified speed.

Thus, *the slope of the tangent drawn on the O.C.C. is called critical resistance.*

Critical resistance of a field winding. It is that maximum value resistance of a field winding which is required to build-up voltage in a generator. If the value of field resistance is more than this value, the generator would not build-up the voltage.

Critical load resistance. The minimum value of load resistance on a DC shunt generator with which it can be in position to build-up is called its critical load resistance.

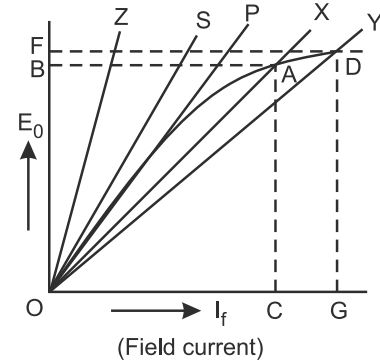


Fig. 4.70 Critical resistance

Critical speed of a DC shunt generator. It is the speed of a DC shunt generator at which shunt field resistance will represent the critical field resistance.

4.35 Load Characteristics of Shunt Generator

It is also called external or performance characteristics of shunt generator. It shows relation between the terminal voltage V on load and the load current I_L . To obtain this characteristics, proceed as follows:

Connect an ammeter A_1 and rheostat in the field circuit and an ammeter A_2 and voltmeter V on the load side as shown in Fig. 4.71. Apply a variable load across the terminals. At start switch off the load and run the generator at rated speed. No-load emf (generated voltage E_g) will appear across the voltmeter. Then switch on the load through switch S and increase the load gradually keeping field current (ammeter reading A_1) constant with the help of rheostat R_h . Take the readings of voltmeter V and ammeter A_2 at various instants and plot the curve. The curve so obtained is shown in Fig. 4.71.

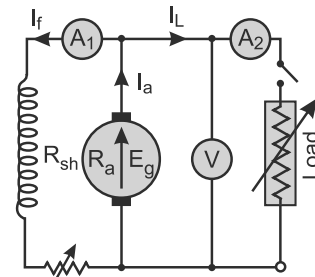


Fig. 4.71 Circuit diagram

Analysis of the Curve

While analysis the curve, the following points are highlighted:

1. At no-load, the voltage across the terminals is maximum and is considered to be equal to generated emf E_g .
2. As the load is increased gradually, the load current I_L increases but the terminal voltage decreases. The decrease in voltage is because of the following reasons:
 - (i) Due to increase in voltage drop in the armature resistance ($I_a R_a$)
 - (ii) Due to armature reaction, when load current or armature current I_a increases, the demagnetising effect of the armature field increases on the main field which reduced the induced emf. Consequently the terminal voltage decreases.
 - (iii) The drop in terminal voltage further causes decreases in field current. This will, in turn, causes the decrease in induced emf which reflects the drop in terminal voltage. However, the field current can be kept constant by adjusting the rheostat connected in the field circuit.
3. During initial portion of the curve AB , the tendency of the voltage drop due to armature resistance is more than armature reaction.
4. At point B these two effects neutralise each other.
5. After point B , armature reaction dominates and the curve turns back (BC portion of the curve), as shown in Fig. 4.72.
6. The point C at which the external characteristic cuts the current axis corresponds to a gradual short circuit.

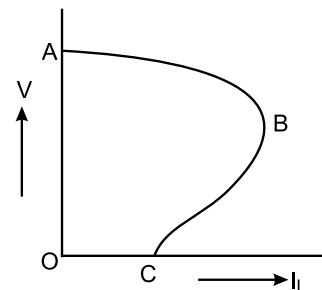


Fig. 4.72 Curve between V and I_L

4.36 Load Characteristics of Series Generators

In this generator, the field winding is connected in series with the armature and load (see Fig. 4.73). Therefore, full armature current I_a flows through it. When load increases, I_a increases which increases flux and consequently generated emf is also increased. This, correspondingly increases the terminal voltage V . Thus, a series generator has a rising characteristic (curve OA) as shown in Fig. 4.73.

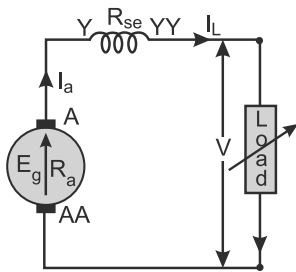


Fig. 4.73 Circuit diagram

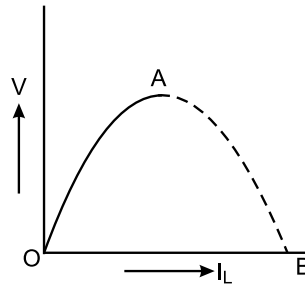


Fig. 4.74 Curve between V and I_L

However, at higher loads, the terminal voltage begins to reduce because of the excessive demagnetising effects of armature reaction. Ultimately, the terminal voltage reduces to zero at load current OB as shown in Fig. 4.74.

4.37 Load Characteristics of Compound Generator

There are some applications where constant terminal voltage is essential. At such places, shunt generator is not suitable, because its terminal voltage decreases with the increase in load on it.

However it can be made suitable for such applications by connecting a few turns in series with the armature as shown in Fig. 4.75. The field produced by these series turns assist the field produced by the shunt winding. Such generators are known as compound generators. In such generators when load current increases, the flux increases which increases the induced emf. This extra induced emf compensates the voltage drop in the armature resistance and the demagnetising effect due to armature reaction. Hence, the terminal voltage V remains substantially constant.

Degree of Compounding

A cumulatively – compound wound generator is shown in Fig. 4.75. Its level of compounding can be changed by varying the amount of current passing through the series field winding by connecting a by-pass rheostat R_h .

When the field current is adjusted such that the terminal voltage V on full load remains the same as that on no-load, the generator is called to be *level* or *flat compounded generator* (see Fig. 4.76).

When the terminal voltage on full-load is more than its terminal voltage at no-load, the generator is called to be an over compounded generator.

On the other hand, when the terminal voltage on full-load is less than no-load voltage, the generator is called to be as under compounded generator.

However, if the field produced by the series field winding acts in opposite direction to the field produced by the shunt field winding, the generator is called to be differentially compounded (see Fig. 4.76).

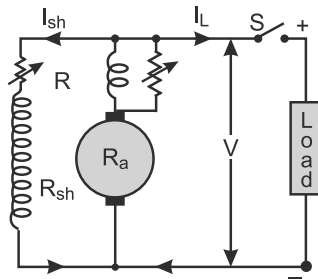


Fig. 4.75 Circuit diagram

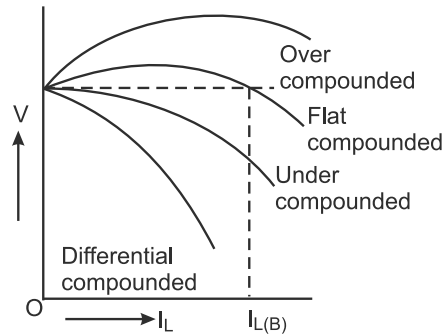


Fig. 4.76 Load characteristics of compound generator

4.38 Causes of Failure to Build-up Voltage in a Generator

There may be one or more of the following reasons due to which a generator fails to build-up voltage:

1. When the residual magnetism in the field system is destroyed.
2. When the connections of the field winding are reversed. This, in fact, destroys the residual magnetism due to which generator fails to build up voltage.
3. In case of shunt-wound generators, the other causes may be
 - (i) the resistance of shunt field circuit may be more than the critical resistance.
 - (ii) the resistance of load circuit may be less than critical resistance.
 - (iii) the speed of rotation may be below the rated speed.
4. In case of series-wound generators, the other causes may be
 - (i) the load circuit may be open: it may be due to faulty contact between brushes and commutator or commutator surface may be greasy or dirty and making no contact with the brushes.
 - (ii) the load circuit may have high resistance.

Rectification: If the generator is not building up because of absence of residual magnetism due to any reason, the *field coils should be connected to a DC source for a small period in order to magnetise the poles.*

4.39 Applications of DC Generators

Depending upon the characteristics of various types of DC generators, their important applications are given below:

1. **Separately excited DC generators.** Although, these generators are more costly than self excited generators as they require a separate source for their field excitation. But their response to the

change in field resistance is more quick and precise. Therefore, these are employed where quick and definite response to control is important such as Ward–Leonard System of speed control.

2. **Shunt-wound DC generators.** As they provide constant terminal voltage, they are best suited for battery charging. Along with field regulators, they are also used for light and power supply purposes.
3. **Series-wound DC generators.** These generators have very few applications. Their best application is in the DC locomotives, where they supply field current for regenerative braking. They are also employed in series arc lighting. Another application of these generators is as series boosters for increasing DC voltage across the feeders.
4. **Compound-wound DC generators**
 - (i) *Over-compounded type.* These are more suited for lighting and power services, as they compensate for the voltage drop in the lines and voltage at the terminals of the load remains constant.
 - (ii) *Differential-compounded type.* They are usefully employed as are welding sets. In such cases, generator is practically short-circuited every time the electrode touches the metal plates to be welded.

4.40 Losses in a DC Generator

While conversion of mechanical energy into electrical energy, *a part of energy dissipated in the form of heat in surrounding air is called losses in the generator.*

These losses affect the efficiency of the generator. A reduction in these losses leads to higher efficiency. Thus, the major objective in the design of a DC machine is the reduction of these losses. The various losses occurring in a DC machine can be sub-divided as:

1. Copper losses.
2. Iron losses
3. Mechanical losses.

1. **Copper losses.** The various windings of the DC machine, made of copper, have some resistance. When current flows through them, there is power loss proportional to the square of their respective currents. *These power losses are called copper losses.*

In general, the various copper losses in a DC machine are:

- (i) Armature copper loss = $I_a^2 R_a$
- (ii) Shunt field copper loss = $I_{sh}^2 R_{sh}$
- (iii) Series field copper loss = $I_{se}^2 R_{se}$
- (iv) Interpole winding copper loss = $I_i^2 R_i = I_a^2 R_i$
- (v) Brush contact loss = $I_a^2 R_b$ or $2I_a v_b$
- (vi) Compensating winding copper loss = $I_a^2 R_c$

The brush contact drop is generally included in armature copper losses.

2. Iron losses. The losses which occur in the iron parts of a DC generator are known as *iron losses* or *core losses* or *magnetic loss*. These losses consist of the following:

- (i) **Hysteresis loss.** Whenever a magnetic material is subjected to reversal of magnetic flux, this loss occurs. It is due to retentivity property of the material. It is expressed with reasonable accuracy by the following expression: $P_h = K_h V f B_m^{1.6} \dots (4.28)$

where, K_h = hysteresis constant in J/m^3 i.e., energy loss per unit volume of magnetic material during one magnetic reversal, its value depends upon nature of material;

V = Volume of magnetic material in m^3 ;

f = frequency of magnetic reversal in cycle/second and

B_m = maximum flux density in the magnetic material in tesla.

It occurs in the rotating armature. To minimise this loss, the armature core is made of silicon steel which has low hysteresis constant.

- (ii) **Eddy current loss.** When flux linking with the magnetic material changes (or flux is cut by the magnetic material) an emf is induced in it which circulates eddy currents through it. These eddy currents produce eddy current loss in the form of heat. It is expressed with reasonable accuracy by the expression:

$$P_e = K_e V f^2 t^2 B_m^2 \dots (4.29)$$

where, K_e = constant called co-efficient of eddy current, its value depends upon the nature of magnetic material;

t = thickness of lamination in m ;

V, f and B_m are the same as above.

The major part of this loss occur in the armature core. To minimise this loss, the armature core is laminated into thin sheets (0.3 to 0.5 mm) since this loss is directly proportional to the square of thickness of the laminations.

3. Mechanical losses. As the armature of a DC machine is a rotating part, some power is required to overcome:

- (i) Air friction of rotating armature (windage loss)
(ii) Friction at the bearing and friction between brushes and commutator (friction loss).

*These losses are known as **mechanical losses**.* To reduce these losses proper lubrication is done at the bearings.

4.41 Constant and Variable Losses

The losses in a DC generator may also be sub-divided into:

1. Constant losses; 2. Variable losses

1. Constant losses. The losses in a DC machine which remain the same at all loads are called *constant losses*. The constant losses in a DC machine are:

(i) Iron losses; (ii) Mechanical losses; (iii) Shunt field copper losses

2. Variable losses. The losses in DC machine which vary with load are called *variable losses*. The variable losses in a DC machine are;

(i) Armature copper loss; (ii) Series field copper loss (iii) Interpole winding copper loss and (iv) Compensating winding copper loss.

4.42 Stray Losses

The sum of the iron losses and mechanical losses in a DC machine are known as *stray losses* i.e.,

$$\text{Stray losses} = \text{Iron losses} + \text{Mechanical losses}.$$

4.43 Power Flow Diagram

The mechanical power (ωT_m) is supplied to the generator which is converted into electrical power (VI_L). While conversion, various losses occur in the machine. The power flow diagram for a DC generator is shown in Fig. 4.77.

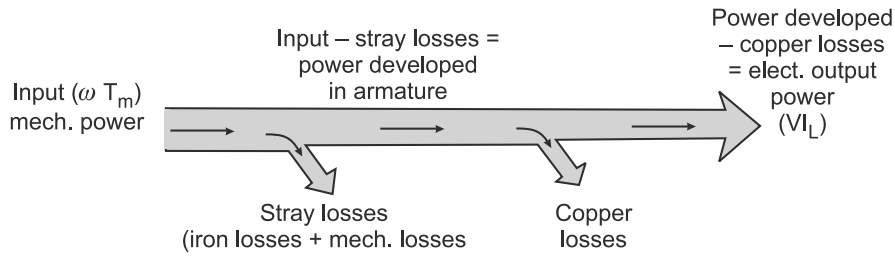


Fig. 4.77 Power flow diagram of a DC generator

4.44 Efficiency of a DC Generator

The ratio of output power to the input power of a DC generator is called its *efficiency*.

$$\text{Efficiency, } \eta = \frac{\text{output}}{\text{Input}}; \text{ where, Power output} = VI_L \text{ watt}$$

$$\text{Power input} = \text{Power output} + \text{Variable losses} + \text{Constant losses}$$

Since the shunt field current I_{sh} is very small as compared to line current,

therefore, $I_L \cong I_a$ (neglecting I_{sh})

$$\therefore \text{Variable losses} = I_L^2 R_a$$

$$\text{Constant losses} = P_c \text{ (say)}$$

$$\text{Then, power output} = VI_L + I_L^2 R_a + P_c$$

$$\therefore \eta = \frac{VI_L}{VI_L + I_L^2 R_a + P_c} \quad \dots(4.30)$$

4.45 Condition for Maximum Efficiency

The efficiency of a DC generator is given as:

$$\begin{aligned}\eta &= \frac{\text{output}}{\text{output} + \text{variable losses} + \text{constant losses}} \\ &= \frac{VI_L}{VI_L + I_L^2 R_a + P_c} = \frac{1}{1 + \frac{I_L R_a}{V} + \frac{P_c}{VI_L}} \quad \dots(4.31)\end{aligned}$$

Now, efficiency will be maximum when the denominator of eq. (i) is minimum i.e.,

$$\frac{d}{dI_L} \left(1 + \frac{I_L R_a}{V} + \frac{P_c}{VI_L} \right) = 0$$

or
$$\frac{R_a}{V} - \frac{P_c}{VI_L^2} = 0 \text{ or } \frac{R_a}{V} = \frac{P_c}{VI_L^2} \text{ or } I_L^2 R_a = P_c$$

i.e., **Variable losses = Constant losses**

Hence, *the efficiency of a DC machine will be maximum when the line current is such that constant loss is equal to the variable loss.*

The line current at which the efficiency of DC machine is maximum.

$$I_L = \sqrt{\frac{P_c}{R_a}} \quad \dots(4.32)$$

Example 4.45

A DC generator is connected to a 220 V DC mains. The current delivered by the generator to the mains is 100 A. The armature resistance is 0.1 ohm. The generator is driven at a speed of 500 rpm Calculate (i) the induced emf (ii) the electromagnetic torque (iii) the mechanical power input to the armature neglecting iron, winding and friction losses, (iv) Electrical power output from the armature, (v) armature copper loss.

Solution:

(i) The induced emf, $E_g = V + I_a R_a = 220 + 0.1 \times 100 = \mathbf{230 \text{ V}}$ (Ans.)

(ii) Using the relation, $\omega T = E_g I_a$

$$\begin{aligned}\text{Electromagnetic torque, } T &= \frac{E_g I_a}{\omega} = \frac{E_g I_a}{2\pi N} \times 60 \quad \left[\because \omega = \frac{2\pi N}{60} \right] \\ &= \frac{230 \times 100 \times 60}{2\pi \times 500} = \mathbf{439.27 \text{ Nm}} \text{ (Ans.)}\end{aligned}$$

(iii) Neglecting iron, winding and friction losses,

$$\begin{aligned}\text{Input to armature} &= \omega T \text{ (or } E_g I_a) \\ &= \frac{2\pi NT}{60} = \frac{2\pi \times 500 \times 439.27}{60} = \mathbf{23000 \text{ W}} \text{ (Ans.)}\end{aligned}$$

(iv) Electrical power output = $VI_a = 220 \times 100 = \mathbf{22000\ W}$ (Ans.)

(v) Armature copper losses = $I_a^2 R_a = (100)^2 \times 0.1 = \mathbf{1000\ W}$ (Ans.)

Example 4.46

A shunt generator supplies 195 A at 220 V. Armature resistance is 0.02 ohm, shunt field resistance is 44 ohm. If the iron and friction losses amount to 1600 watt, find (i) emf generated; (ii) copper losses; (iii) b.h.p. of the engine driving the generator.

Solution:

The conventional circuit is shown in Fig. 4.78.

Shunt field current,

$$I_{sh} = \frac{V}{R_{sh}} = \frac{220}{44} = 5\text{ A}$$

Armature current, $I_a = I_L + I_{sh} = 195 + 5 = 200\text{ A}$

Generated or induced emf,

$$E_g = V + I_a R_a = 220 + 200 \times 0.02 = \mathbf{224\ V} \text{ (Ans.)}$$

Armature copper loss;

$$= I_a^2 R_a = (200)^2 \times 0.02 = 800\text{ W}$$

$$\text{Shunt field copper loss} = I_{sh}^2 R_{sh} = (5)^2 \times 44 = 1100\text{ W}$$

$$\text{Total copper losses} = 800 + 1100 = \mathbf{1900\ W} \text{ (Ans.)}$$

$$\text{Output power} = VI_L = 220 \times 195 = 42900\text{ W}$$

$$\text{Input power} = 42900 + 1600 + 1900 = 46400\text{ W}$$

$$\text{B.H.P. of the engine driving the generation} = \frac{46400}{735.5} = \mathbf{63.08\ H.P.} \text{ (Ans.)}$$

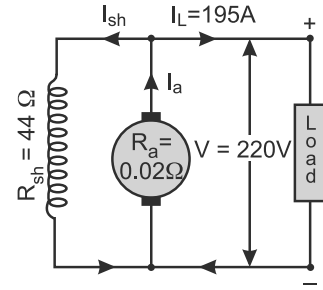


Fig. 4.78 Circuit diagram

Example 4.47

A 400 V shunt generator has full-load current of 200 A. Its armature resistance is 0.06 ohm, field resistance is 100 ohm and the stray losses are 2000 watt. Find the h.p. of prime-mover when it is delivering full load, and find the load for which the efficiency of the generator is maximum.

Solution:

The conventional circuit is shown in Fig. 4.79.

$$\text{Shunt field current, } I_{sh} = \frac{V}{R_{sh}} = \frac{400}{100} = 4\text{ A}$$

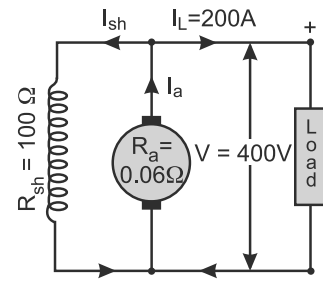


Fig. 4.79 Circuit diagram

$$\text{Armature current, } I_a = I_L + I_{sh} = 200 + 4 = 204 \text{ A}$$

$$\text{Armature copper loss; } = I_a^2 R_a = (204)^2 \times 0.06 = 2497 \text{ W}$$

$$\text{Shunt field copper loss} = I_{sh}^2 R_{sh} = (4)^2 \times 100 = 1600 \text{ W}$$

$$\text{Total losses} = 2497 + 1600 + 2000 = 6097 \text{ W}$$

$$\text{Output power} = VI_L = 400 \times 200 = 80000 \text{ W}$$

$$\text{Input power} = \text{Output power} + \text{losses}$$

$$= 80000 + 6097 = 86097 \text{ W}$$

$$\text{Horse power of prime-mover} = \frac{\text{Input power}}{735.5} = \frac{86097}{735.5} = \mathbf{17.06 \text{ H.P. (Ans.)}}$$

$$\text{Constant losses} = \text{stray losses} + \text{shunt field copper loss} = 2000 + 1600 = 3600 \text{ W}$$

Condition for maximum efficiency is,

$$\text{Variable losses} = \text{constant losses.}$$

Let, I_L' be the load current at which the efficiency is maximum and armature current is I_a'

$$\therefore I_a'^2 R_a = 3600 \quad \text{or} \quad I_a' = \sqrt{\frac{3600}{0.06}} = 245 \text{ A}$$

$$\text{Load current, } I_L' = I_a' - I_{sh} = 245 - 4 = 241 \text{ A}$$

$$\text{Load for which the efficiency is maximum} = I_L' V = 241 \times 400 = \mathbf{96.4 \text{ kW (Ans.)}}$$

Section Practice Problems

Numerical Problems

1. The armature of a four-pole DC generator has 90 slots on its armature with 6 conductors per slot. If the armature is lap-wound, flux per pole is 6×10^{-2} Wb and running at 1000 rpm, determine its induced emf. Also determine the electrical power output of the machine if the current per conductor is 100 ampere.
(Ans. 540 V; 216 kW)
2. A 10 kW, six-pole DC generator develops an emf of 200 V at 1500 rpm. The armature has a lap-connected winding. The average flux density over a pole pitch is 0.9 T. The length and diameter of the armature are 0.25 m and 0.2 m respectively. Calculate (a) the flux per pole (b) the total number of active conductors in the armature and (c) the torque developed by the machine when the armature supplies a current of 60 A.
(Ans. 23.6 mWb, 340, 76.4 Nm)
3. The field and armature resistance of a four-pole shunt generator with lap-connected armature is 50Ω and 0.1Ω respectively. It is supplying a 2400 W load at a terminal voltage of 100 V. Calculate the total armature current, the current per armature path and the generated emf.
(Ans. 26A; 6.5 A; 102.6 V)

4. A DC shunt generator supplies a load of 100 A at 200 V. The generator has four-pole and its shunt field and armature resistance is 80 ohm and 0.1 ohm respectively. Find (i) total armature current (ii) current per conductor and (iii) generated emf. **(Ans. 102.5 A, 25.6A; 210.25 V)**
5. An eight-pole DC shunt generator supplies a load of 12.5 ohm at 250 V. Its armature carries wave connected 778 conductors and its armature and field winding resistances are 0.24 ohm and 250 ohm respectively. Find the armature current, the induced emf and the flux per pole. **(Ans. 821 A; 255.04 V; 9.834 m Wb)**
6. A six-pole, 12 kW, 240 V DC machine is wave-connected. If the same machine is lap-connected, all other data remaining same, calculate its voltage, current and power ratings. **(Ans. 80V; 150 A; 12 kW)**
7. The induced voltage of a shunt generator is 254 V. When the machine is loaded, the terminal voltage drops down to 240 V. Determine the load current, if the armature resistance is 0.04 Ω , and the field circuit resistance is 24 Ω ohm neglecting armature reaction. **(Ans. 340 A)**
8. A four-pole, lap-wound DC shunt generator has field and armature resistances of 100 Ω and 0.1 Ω respectively. It supplies power to 50 lamps rated for 100 volt, 60 watt each. Calculate the total armature current and the generated emf by allowing a contact drop of 1 volt per brush. **(Ans. 105.1V)**
9. Find the resistance of the load which takes a power of 5 kW from a DC shunt generator whose external characteristic is given by the equation: $V = 250 - 0.5 I_L$. **(Ans. 11.48 Ω)**
10. A four-pole DC generator is having useful flux of 0.07 Wb per pole, it carries 220 turns each of 0.004 ohm resistance. The shunt and series winding resistance is 100 ohm and 0.02 ohm respectively. If the generator carries an armature current of 50 A and running at a speed of 900 rpm find its terminal voltage and power delivered by it. **(Ans. 458.25 V; 20.814 W)**
11. A 500 V shunt generator has a full load current of 100 A and stray losses being 1.5 kW. Armature and field resistances are 0.3 and 250 ohm respectively. Calculate the input power and efficiency. **(Ans. 55.621 kW; 89.89%)**

Short Answer Type Questions

Q.1. What are the requirements of self-excited DC machine?

Or

What are the conditions to be fulfilled for a DC shunt generator to build-up emf.

Ans. Following are the requirements of a self-excited DC machine:

1. Its poles must have residual magnetism.
2. The field winding must be connected in such a way that field produced by the field winding must add to the residual magnetism. It should never be connected in reverse direction.
3. The field resistance should not be more than critical resistance.
4. The armature should not be rotated in reverse direction.
5. The resistance of the load circuit must not be below the critical resistance.

Q.2. Define critical resistance of DC shunt generator.

Ans. Critical resistance of a DC shunt generator. The maximum value of a shunt field winding resistance required to build-up voltage in a DC generator is called critical resistance. If the value of field winding resistance is more than this value, the generator will not be in position to built-up the voltage.

Q.3. What are the different methods by which flux is established in the magnetic circuit of a DC generator?

Ans. The magnetic flux in a DC generator, can be established by the following methods:

- (i) by means of permanent magnets.
- (ii) By the field coils excited by some external source
- (iii) By the field coils excited by the generator itself.

Q.4. How can you differentiate between the excitation system of a DC series generator and that of a DC shunt generator?

Ans. In a series wound generator, the field winding is connected in series with the armature winding so that whole current flows through it and the load. In a shunt wound generator the field winding is connected across the armature winding forming a parallel or shunt circuit.

Q.5. Why is field coils of a DC shunt generator are wound with a large number of turns of fine wire.

Ans. The field coils of a DC shunt generator are wound with a large number of turns of fine wire so as to have high resistance in order to keep shunt field current as low as possible as well as to provide required mmf.

Q.6. What type of current flows in field winding and armature winding of a DC shunt generator? [A.M.I.e., Winter 2003]

Ans. In field winding, it is DC whereas in armature winding it is AC.

Q.7. What is meant by OCC of a DC generator?

Ans. OCC mean open circuit characteristics. The curve drawn between generated emf at no-load and the field current, when the machine is running at a specified speed is known as magnetic characteristic or open-circuit characteristic (OCC) of a DC generator.

Q.8. What is the critical resistance of field circuit?

Ans. The maximum value of resistance of field circuit of a DC shunt generator with which the DC shunt generator will be able to excite it is called critical resistance.

Q.9. In what respect the separately excited DC generator is superior to self excited DC generator?

Ans. The separately excited DC generator provides stable operation with any field excitation in comparison to self excited generators.

Q.10. What is critical speed in a DC shunt generator?

Ans. It is the speed of a DC generator at which shunt field resistance will represent the critical field resistance.

Q.11. A DC shunt generator is developing rated terminal voltage at some speed. For this generator,

- (i) If only the direction of rotation is reversed, will the generator build-up?
- (ii) If the direction of rotation and also the residual magnetism are reversed simultaneously will the generator build up?

Ans. (i) The generator will not build up. When the direction of rotation is reversed, the polarity of the generated emf will be reversed. the direction of field current will also be reversed and hence the residual magnetism present in the poles will be wiped off and the generator will fail to build up.

- (ii) When the direction of rotation and the residual magnetism both are reversed simultaneously then it is obvious that a small emf will be produced initially which will further strengthen the field and hence the generator will build up voltage.

Q.12. What kind of generator can be expected to have no-load voltage and full load voltage to be same?

Ans. It can be expected in case of flat-compounded DC generator.

Q.13. If the terminal voltage of a DC generator at full load is more than its open-circuit voltage. What is the mode of excitation of the generator?

Ans. It can happen only if the machine is cumulatively compound wound.

Q.14. What type of DC generator can be used for battery charging?

Ans. DC shunt wound generator.

Q.15. What type of DC generator can be used for general power supply?

Ans. Cumulative compound wound is the most suitable.

Q.16. A DC series generator is not considered suitable for general electric supply?

Ans. Because DC series generators provide rising V-I characteristics.

Q.17. A six-pole, 12 kW, 240 V DC machine is wave-connected. If this machine is now lap-connected, all other things remaining the same, calculate the voltage and current ratings.

Ans. We know $E_g = \frac{\phi ZNP}{60A}$

If all other factors are same only the winding connections are being changed

$$E_g \propto \frac{1}{A}$$

i.e.,

$$E_{g_{wave}} \propto \frac{1}{A_{wave}} \text{ and } E_{g_{lap}} = \frac{1}{A_{lap}}$$

$$\frac{E_{g_{lap}}}{E_{g_{wave}}} = \frac{A_{wave}}{A_{lap}} \text{ or } E_{g_{lap}} = \frac{2}{P} \times E_{g_{wave}} = \frac{2}{6} \times 240 = 80 \text{ V (Ans.)}$$

$$\text{Current, } I = \frac{\text{Power}}{V} = \frac{12 \times 1000}{80} = 150 \text{ A (Ans.)}$$

Review Questions

1. Name the various parts of a DC machine and give their function.
2. Explain the principle of action of a DC generator. Describe briefly its important parts.
3. What is the principle commercially adopted to transform mechanical energy to electrical energy? Illustrate in the case of a simple DC generator. How can the generator be made to supply DC?
4. Explain how commutator works in a DC machine to generate DC voltage.
5. Define: pole pitch, front pitch, back pitch, resultant pitch, average pitch and commutator pitch. Illustrate them with the help of neat sketches.

6. Explain what do you understand by (i) lap and wave windings (ii) duplex windings.
7. What is meant by duplex winding? If a duplex winding does not close after one passage around the armature, is the number of commutator segments even or odd. Explain.
8. Illustrate with suitable diagrams the patterns of (i) lap winding and (ii) wave winding of the armature of a DC machine. Explain the relative merits and the applications of the two types of windings.
9. What are the similarities and dissimilarities between lap and wave windings in a DC machine?
10. Explain why equaliser connections are used in lap windings and dummy coils are sometimes used in wave windings.
11. What are the ordinary types of armature windings for DC machines? Explain the essential difference between them and give their advantages, disadvantages and applications.
12. Highlight the factors on which the choice of type of armature winding of a DC machine will depend.
13. Find the expression for the equivalent armature resistance of a P -pole, lap wound armature, when there are total Z conductors, the length of each conductor being l cm. Assume cross-sectional area as a cm² and specific resistance of a conductor material as ρ ohm-cm.
14. Write short notes on the following:
 - (i) Principle of operation of DC generator.
 - (ii) Construction and function of commutator.
 - (iii) Lap winding.
 - (iv) Wave winding-merits and demerits over lap winding.
15. Derive emf equation of a DC generator (or DC machine).
16. Explain how will you distinguish between a lap and wave winding. How can you recognise the winding of a DC machine by counting its brushes?
17. What are the different types of excitation employed in DC machines?
18. Explain the principle of action of a DC shunt generator.
19. Explain what is meant by armature reaction of a DC machine. Describe different methods for minimising armature reaction.
20. Explain what you would understand by "armature reaction" in a DC generator. What are its effects?
21. How demagnetising and cross-magnetising ampere-turns per pole are calculated in a DC machine?
22. "As brushes in a DC machines are shifted, magnetising/demagnetising ampere-turns appears". Explain with the help of a diagram.
23. Develop an expression for the demagnetising and cross magnetising armature ampere-turns in a DC generator.
24. What are the types of commutation possible in a DC machine? Explain them with graph.
25. Explain what do you mean by commutation in a DC machine. Mention the methods of improving it.
26. What do you mean by good commutation and bad commutation?
27. Briefly describe the function of interpoles in a DC machine.
28. Define *O.C.C.* (no-load characteristics) of a DC generator. Explain how it is obtained for a given generator.
29. Explain how a shunt generator builds up. What limits the voltage to which a generator can build up?

30. What is critical field resistance in a DC generator?
31. Discuss the internal and external characteristics of a shunt generator.
32. Mention the different reasons for the drop in the terminal voltage of a shunt generator when it is loaded.
33. Sketch the load characteristic of (i) DC shunt and (ii) DC series generator. Give reasons for the particular shape in each case.
34. Explain the load characteristics of a level-compounded DC generator. What do you mean by cumulative and differential compounding? Mention their applications.
35. Write a short note on external characteristics of series, shunt and compound wound DC generators.
36. Under what circumstances does a DC shunt generator fails to build up.
37. What are the various energy losses in a DC machine and how do they vary with load?
38. Derive a condition for maximum efficiency of a DC generator.

Multiple Choice Questions

1. The direction of electro-magnetic torque developed in the armature of a DC machine can be reversed by reversing the direction of

(a) rotation	(b) field flux
(c) armature current	(d) either field flux or armature current.
2. A thicker wire is used in the DC series field winding than DC shunt field winding in DC machines.

(a) to prevent mechanical vibrations.	(b) to produce large flux.
(c) because it carries the load current which is much higher than shunt field current for the same rating of DC machines.	(d) to provide strength.
3. The brushes for commutator are made of

(a) Copper	(b) Aluminium
(c) Cast iron	(d) Carbon.
4. In DC generators, dummy coil are provided

(a) to reduce eddy current losses	(b) to enhance flux density
(c) to amplify voltage	(d) to mechanically balance the rotor.
5. A shunt generator produces 445 A at 250V. The resistances of shunt field and armature are 50 Ω and 0.025 ohm respectively. The armature voltage drop will be

(a) 5 V	(b) 11.25 V
(c) 22.5 V	(d) 25 V
6. Eddy current loss varies

(a) inversely as the thickness of the laminations	(b) inversely as the square of the thickness of the laminations
(c) directly as thickness of laminations.	(d) directly as the square of the thickness of laminations.

7. Hysteresis loss in a DC machine depends upon
 - (a) volume and grade of iron
 - (b) maximum value of flux density
 - (c) frequency of magnetic reversals
 - (d) all of the above.
8. Iron losses in a DC machine take place in
 - (a) yoke
 - (b) commutator
 - (c) main body
 - (d) armature rotor.
9. The main requirement of a DC armature winding is that it must be
 - (a) a wave winding
 - (b) a lap winding
 - (c) a closed one
 - (d) drum winding
10. For full-pitch winding in a four-pole, 36-slot DC machine, the coil occupies _____ slot.
 - (a) 1 and 9
 - (b) 1 and 10
 - (c) 3 and 11
 - (d) 4 and 12
11. In a long-shunt DC generator, the series field winding is excited by _____ current.
 - (a) shunt
 - (b) armature
 - (c) load
 - (d) external
12. A DC generator with wave winding is used for _____ current, _____ voltage.
 - (a) low, high
 - (b) low, low
 - (c) high, low
 - (d) high, high
13. The emf induced in the armature of a DC generator is inversely proportional to
 - (a) pole flux
 - (b) field current
 - (c) number of armature parallel paths
 - (d) number of dummy coils
14. The external characteristic of a shunt generator can be obtained directly from its _____ characteristics.
 - (a) internal
 - (b) open-circuit
 - (c) closed-circuit
 - (d) performance
15. The O.C.C. of a self-excited DC generator starts with some minimum voltage instead of zero due to
 - (a) residual pole flux
 - (b) high armature speed
 - (c) magnetic inertia
 - (d) high field circuit resistance
16. If residual magnetism of a shunt generator is destroyed due to any reason, it may be restored by connecting its shunt field
 - (a) to earth
 - (b) to a DC source
 - (c) to neutral
 - (d) to an AC source
17. A DC generator is considered to be an ideal one if it has _____ voltage regulation.
 - (a) low
 - (b) zero
 - (c) positive
 - (d) negative
18. In a DC generator, compensating winding is provided to
 - (a) compensate for decrease in main flux
 - (b) neutralise armature mmf
 - (c) neutralise cross-magnetising flux
 - (d) maintain uniform flux distribution.
19. Which statement is not true for the interpoles in the following.
 - (a) these are smaller in size spaced in between the main poles
 - (b) their field windings are connected in parallel with the armature so that they carry part of the armature current

- (c) their polarity, in the case of generators is the same as that of the main pole ahead
 (d) they automatically neutralise not only reactance voltage but cross-magnetisation as well
- 20.** In a DC generator, the effect of armature reaction on the main field is to
 (a) reverse it (b) distort it
 (c) reduce it (d) both (b) and (c)
- 21.** In a loaded DC generator, to reduce sparking, brushes have to be shifted.
 (a) clockwise (b) counterclockwise
 (c) either (a) or (b) (d) in the direction of rotation.
- 22.** The commutation process in a DC generator basically involves
 (a) passage of current from moving armature to a stationary load
 (b) reversal of current in an armature coil as it crosses MNA
 (c) conversion of reactance voltage
 (d) all of above

Keys to Multiple Choice Questions

1. d	2. c	3. d	4. d	5. b	6. d	7. d	8. d	9. c	10. b
11. b	12. a	13. c	14. b	15. a	16. b	17. b	18. c	19. d	20. d
21. d	22. d								

DC Motors

Chapter Objectives

After the completion of this unit, students/readers will be able to understand:

- ✓ What is a DC motor and how does it convert electrical energy into mechanical energy?
- ✓ What is back emf and its significance?
- ✓ What are the factors on which torque developed in a DC motor depends?
- ✓ How DC motors are classified on the basis of their field excitation?
- ✓ What are the performance characteristics of DC motors and how are they selected for different applications?
- ✓ What is the need of a starter and how do starters limit the in-rush flow of starting current and protect the motor?
- ✓ How is a four point starter for DC shunt motor different than a three point starter?
- ✓ How are the steps of a starting resistance designed?
- ✓ Which type of starter is used for starting of DC series motors?
- ✓ What are the factors on which the speed of a DC motor depends and how can we control the speed of DC motors as per the requirement?
- ✓ How is speed of electric trains controlled?
- ✓ What is electric braking? How is it superior to mechanical braking and what are the different methods by which electric motors or drives are stopped?
- ✓ What are the various losses of a DC machine, how these are categorised?
- ✓ How to determine various losses of a DC machine with the help of different tests?
- ✓ How to calculate the efficiency of a DC machine once the losses are determined?
- ✓ How to prepare maintenance schedule of a DC machine to improve its reliability and performance?

Introduction

A machine that converts mechanical power into DC electrical power is called a DC generator. The same machine when used to convert DC electrical power into mechanical power, it known as a DC motor. From construction point of view there is no difference between a DC generator and motor.

The DC motors are very useful where wide range of speeds and perfect speed regulation is required such as electric traction.

5.1 DC Motor

An electro-mechanical energy conversion device (electrical machine) that converts DC electrical energy or power (EI) into mechanical energy or power (ωT) is called a **DC motor**.

Electric motors are used for driving industrial machines, e.g., hammers, presses, drilling machines, lathes, rollers in paper and steel industry, blowers for furnaces, etc., and domestic appliances, e.g., refrigerators, fans, water pumps, toys, mixers, etc. The block diagram of energy conversion, when the electro-mechanical device works as a motor, is shown in Fig. 5.1.

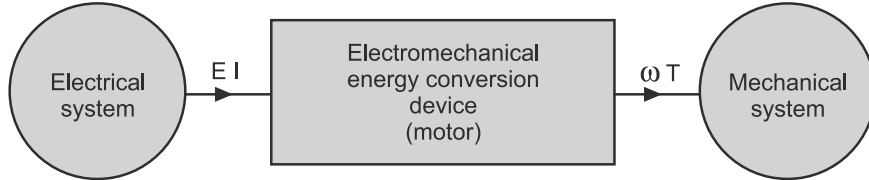


Fig. 5.1 Block diagram of electromagnetic energy conversion (motor action)

5.2 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. 5.2(a)]. When DC supply is connected to the coil, current flows through it which sets up its own field as shown in Fig. 5.2(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 Fig. 5.2(c). The tendency of this is to come to its original position i.e., in straight line due to which force is exerted on the two coil sides and torque develops which rotates the coil.

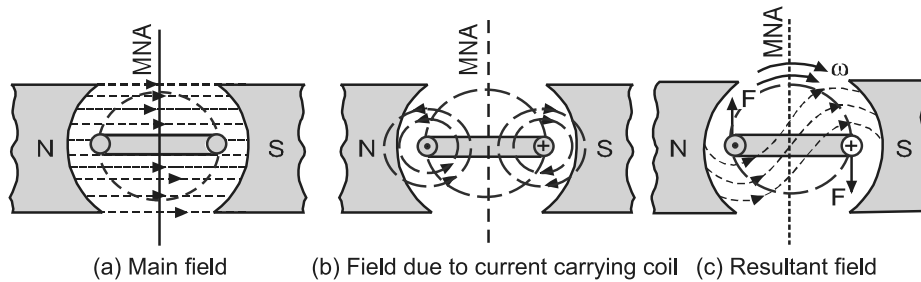


Fig. 5.2 Working principle of a motor

Alternately, it can be said that the main poles produce a field F_m . Its direction is marked in Fig. 5.3. 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 develops in clockwise direction as marked in Fig. 5.3.

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). Whereas, the other conductors placed under the influence of other pole i.e., south pole, carry the current in opposite direction as shown in Fig. 5.4. A resultant rotor field is produced. Its direction is marked by the arrow-head F_r . This rotor field F_r tries to come in line with the main field F_m and torque (T_e) develops. Thus, rotor rotates.

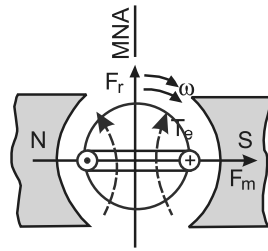


Fig. 5.3 Position of main field F_m and rotor field F_r

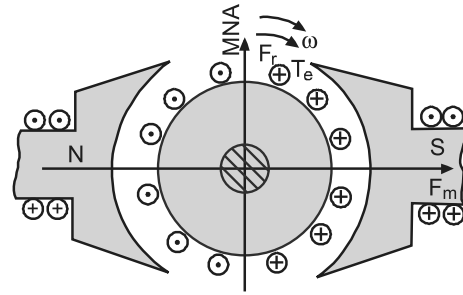


Fig. 5.4 Motor action

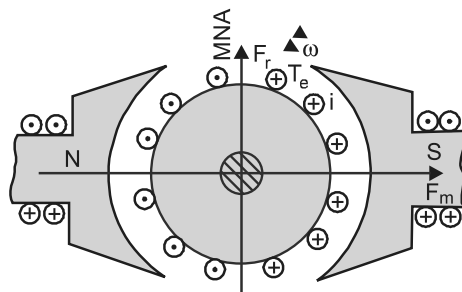
It can be seen that to obtain a continuous torque, the direction of flow of current in each conductor or coil side must be reversed when it passes through the magnetic neutral axis (MNA). This is achieved with the help of a commutator.

Function of a Commutator

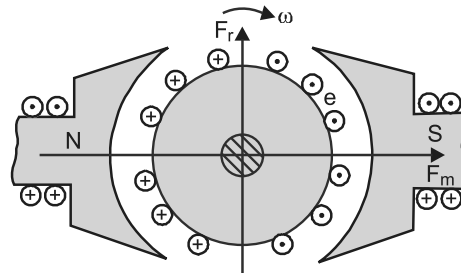
The function of a commutator in DC motors is to reverse the direction of flow of current in each armature conductor when it passes through the *M.N.A.* to obtain continuous torque.

5.3 Back emf

It has been seen that when current is supplied to the armature conductors, as shown in Fig. 5.5(a), placed in the main magnetic field, torque develops and 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 Fig. 5.5(b).



(a) Torque development due to alignment of rotor field with main field



(b) Production of E_b

Fig. 5.5 Back emf

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;

$$E_b = \frac{PZ\phi N}{60 A}$$

or
$$E_b = \frac{ZP}{60 A} \phi N \text{ or } E_b \propto \phi N \quad \left(\text{since } \frac{ZP}{60 A} \text{ are constant}\right) \dots(5.1)$$

Also, $N \propto \frac{E_b}{\phi}$ 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 Fig. 5.6. 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; $E_b = V - I_a R_a$.

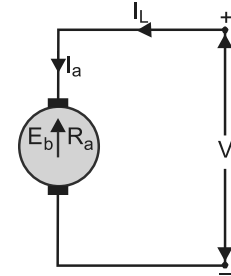


Fig. 5.6 Circuit diagram ($E_b < V$)

Significance of Back emf

The current flowing through the armature is given by the relation:

$$I_a = \frac{V - E_b}{R_a}$$

When mechanical load applied on the motor increases, its speed decreases which reduces the value of E_b . As a result the value $(V - E_b)$ increases which 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.

5.4 Electro-magnetic Torque Developed in DC Motor

The electrical power which is supplied to a DC motor is converted into mechanical power. The conversion of power takes place in the armature as stated below:

The power developed in the armature is given as

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

or
$$\frac{\phi ZNP}{60A} \times I_a = \frac{2\pi N}{60} \times T_e \quad \text{or} \quad T_e = \frac{PZ\phi N}{2\pi A} \text{ Nm}$$

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

$\therefore T = K \frac{\phi I_a}{2\pi}$ where $K = \frac{PZ}{A}$ is a constant

The constant K for a given machine is the same for the emf equation as well as the torque equation.

As well as, $T = K_2 \phi I_a$ where $K_2 = \frac{PZ}{2\pi A}$ is another constant or $T \propto \phi I_a \dots(5.2)$

Thus, it is concluded that torque produced in the armature of a DC machine is directly proportional to flux per pole and armature current. Moreover, the direction of electromagnetic torque developed in the armature depends upon the direction of flux or magnetic field and the direction of flow of current in the armature conductors. If either of the two is reversed the direction of torque produced is reversed and hence the direction of rotation. But when both are reversed the direction of torque (or rotation) does not change.

5.5 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 case of DC motors, the actual torque available at the shaft for doing useful mechanical work is known as **shaft torque**.

Brake Horse Power (B.H.P.)

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

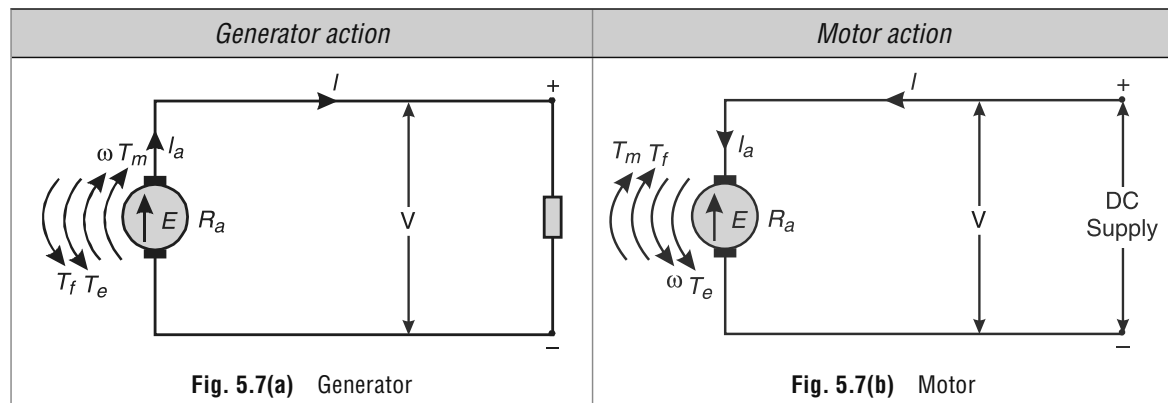
$$\text{Useful output power} = \omega T_{sh} = 2\pi N T_{sh}/60 \text{ watt}$$

$$\text{Output in B.H.P.} = \frac{2\pi N T_{sh}}{60 \times 735.5} \quad \dots(5.3)$$

5.6 Comparison of Generator and Motor Action

It has been seen that the same machine can be used as a DC generator or as a DC motor. When it converts mechanical energy (or power) into electrical energy (or power), it is called a DC generator and when it is used for reversed operation, it is called a DC motor.

The comparison of generator and motor action is given below:



1. In generating action, the rotation is due to mechanical torque, therefore, T_m and ω are in the same direction. 2. The frictional torque T_f acts in opposite direction to rotation ω . 3. Electromagnetic torque T_e acts in opposite direction to mechanical torque T_m so that $\omega T_m = \omega T_e + \omega T_f$. 4. In generating action, an emf is induced in the armature conductors which circulates current in the armature when load is connected to it. Hence, e and i both are in the same direction. 5. In generator action, $E > V$ 6. In generating action, the torque angle θ is leading. 7. In generating action, mechanical energy is converted into electrical energy.	1. In motoring action, the rotation is due to electromagnetic torque, therefore, T_e and ω are in the same direction. 2. The frictional torque T_f acts in opposite direction to rotation ω . 3. Mechanical torque T_m acts in opposite direction to electromagnetic torque T_e so that $\omega T_e = \omega T_m + \omega T_f$. 4. In motoring action, current is impressed to the armature against the induced emf (e), therefore current flows in opposite direction to that of induced emf. 5. In motor action, $E < V$ 6. In motoring action, the torque angle θ is lagging. 7. In motoring action, electrical energy is converted into mechanical energy.
--	--

Example 5.1

A 50 HP, 400 V, 4 pole, 1000 rpm, DC motor has flux per pole equal to 0.027 Wb. The armature having 1600 conductors is wave connected. Calculate the gross torque when the motor takes 70 ampere.

Solution:

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

Where, $P = 4$; $\phi = 0.027$ Wb; $Z = 1600$; $I_a = 70$ A; $A = 2$ (wave connected)

$$T = \frac{4 \times 0.027 \times 1600 \times 70}{2 \times \pi \times 2} = \mathbf{963 \text{ Nm (Ans.)}}$$

Example 5.2

The induced emf in a DC machine is 200 V at a speed of 1200 rpm. Calculate the electromagnetic torque developed at an armature current of 15 A.

Solution:

Here, $E_b = 200$ V; $N = 1200$ rpm; $I_a = 15$ A

Now power developed in the armature,

$$\omega T_e = E_b I_a$$

$$\begin{aligned} \text{or } T_e &= \frac{E_b I_a}{\omega} = \frac{E_b I_a}{2\pi N} \times 60 & \left(\because \omega = \frac{2\pi N}{60} \right) \\ &= \frac{200 \times 15}{2\pi \times 1200} \times 60 = \mathbf{23.87 \text{ Nm (Ans.)}} \end{aligned}$$

Example 5.3

A four-pole DC motor has a wave-wound armature with 594 conductors. The armature current is 40 A and flux per pole is 7.5 m Wb. Calculate H.P. of the motor when running at 1440 rpm

Solution:

$$\text{Torque developed, } T = \frac{PZ\phi I_a}{2\pi A} = \frac{4 \times 594 \times 7.5 \times 10^{-3} \times 40}{2\pi \times 2} = \mathbf{56.72 \text{ Nm (Ans.)}}$$

$$\text{Power developed} = \omega T \text{ watt; where } \omega = \frac{2\pi N}{60}$$

$$H.P. = \frac{\text{power developed}}{735.5}; H.P. = \frac{\omega T}{735.5} = \frac{2\pi NT}{60 \times 735.5}$$

$$\text{or } H.P. = \frac{2 \times 1440 \times 56.72}{60 \times 735.5} = \mathbf{11.63 \text{ (Ans)}}$$

Example 5.4

A DC motor has 6-poles with lap wound armature. What will be its brake horse power when it draws a current of 340 A and rotates at 400 rpm. The flux per pole is 0.05 Wb and the armature carries 864 turns, Neglect mechanical losses.

Solution:

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

$$\phi = 0.05 \text{ Wb; No. of turns} = 864$$

$$Z = 864 \times 2 = 1728$$

$$\text{Back emf, } E_b = \frac{\phi ZNP}{60A} = \frac{0.05 \times 1728 \times 400 \times 6}{60 \times 6} = 576 \text{ V}$$

$$\text{Armature current, } I_a = I_L = 340 \text{ A}$$

$$\text{Power developed} = E_b \times I_a = 576 \times 340 = 195840 \text{ W}$$

$$\text{Neglecting losses, brake HP} = \frac{E_b I_a}{735.5} = \frac{195840}{735.5} = \mathbf{266.27 \text{ (Ans.)}}$$

5.7 Types of DC Motors

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

1. **Separately excited DC motors:** The conventional diagram of a separately excited DC motor is shown Fig. 5.8. Its voltage equation will be;

$$E_b = V - I_a R_a - 2v_b \quad (\text{where } v_b \text{ is voltage drop per brush}) \quad \dots(5.4)$$

2. **Self excited DC motors:** These motors can be further classified as;

- (i) **Shunt motors:** Their conventional diagram is shown in Fig. 5.9.

Important relations:

$$I_{sh} = V/R_{sh} \quad \dots(5.5)$$

$$I_a = I_L - I_{sh} \quad \dots(5.6)$$

$$E_b = V - I_a R_a - 2v_b \quad (\text{where } v_b \text{ is voltage drop per brush}) \quad \dots(5.7)$$

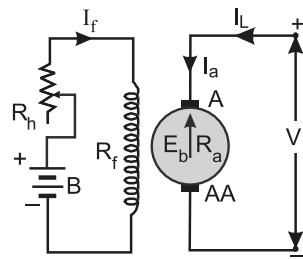


Fig. 5.8 Circuit diagram of separately excited DC motor

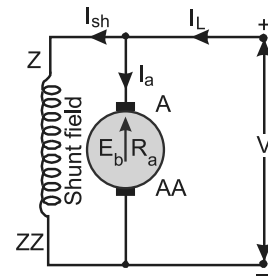


Fig. 5.9 DC shunt motor

(ii) **Series motor:** Its conventional diagram is shown in Fig. 5.10.

Important relations:

$$I_L = I_a = I_{se} \quad \dots(5.8)$$

$$E_b = V - I_a (R_a + R_{se}) - 2v_b \quad \dots(5.9)$$

(iii) **Compound motor:** Its conventional diagram (for long shunt) is shown in Fig. 5.11.

$$I_{sh} = \frac{V}{R_{sh}}; I_a = I_L - I_{sh}; E_b = V - I_a (R_a + R_{se}) - 2v_b \quad \dots(5.10)$$

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

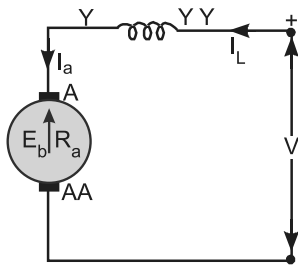


Fig. 5.10 DC series motor

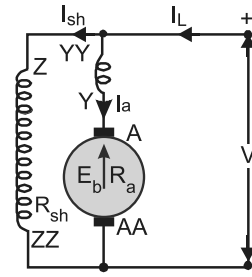


Fig. 5.11 DC compound motor

The compound motor can be further subdivided as;

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

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

(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, i.e.,

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

Example 5.5

The armature resistance of a DC shunt motor is 0.5 ohm, it draws 20 A from 220 V mains and is running at a speed of 80 radian per second. Determine (i) Induced emf (ii) Electromagnetic torque (iii) Speed in rpm.

Solution:

Here, $V = 220 \text{ V}$; $I_a = 20 \text{ A}$; $R_a = 0.5 \Omega$; $\omega = 80 \text{ rad/s}$

$$\text{Induced emf, } E = V - I_a R_a = 220 - 20 \times 0.5 = \mathbf{210 \text{ V (Ans.)}}$$

$$\text{Electromagnetic torque, } T = \frac{EI_a}{\omega} = \frac{210 \times 20}{80} = \mathbf{52.5 \text{ Nm (Ans.)}}$$

$$\text{Speed in rpm, } N = \frac{60\omega}{2\pi} = \frac{60 \times 80}{2 \times \pi} = \mathbf{764 \text{ rpm (Ans.)}}$$

Example 5.6

A 400 V DC motor takes an armature current of 100 A when its speed is 1000 rpm. If the armature resistance is 0.25 ohm, calculate the torque produced in Nm.

Solution:

Here, $V = 400 \text{ V}$; $I_a = 100 \text{ A}$; $R_a = 0.25 \Omega$; $N = 1000 \text{ rpm}$

$$\begin{aligned} \text{Induced emf, } E &= V - I_a R_a \text{ (motor action)} \\ &= 400 - 100 \times 0.25 = 375 \text{ V} \end{aligned}$$

Using the relation, $\omega T = EI_a$

$$\frac{2\pi NT}{60} = EI_a \quad \left[\text{Because } \omega = \frac{2\pi N}{60} \right] \quad \text{or}$$

$$\therefore \text{Torque produced, } T = \frac{60EI_a}{2\pi N} = \frac{60 \times 375 \times 100}{2\pi \times 1000} = \mathbf{358.1 \text{ Nm (Ans.)}}$$

Example 5.7

The armature and series field winding resistance of a 220 V, four-pole DC series motor is 0.75 ohm. It has 782 wave wound armature conductors. If it draws 40 A from the supply mains and has a flux of 25 mWb, determine its speed and gross torque developed.

Solution:

Here, $V = 250 \text{ V}$; $P = 4$; $A = 2$ (wave winding); $Z = 782$;

$$R_a + R_{se} = 0.75 \Omega; I = 40 \text{ A}; \phi = 25 \times 10^{-3} \text{ Wb}$$

$$E = V - I(R_a + R_{se}) = 250 - 40 \times 0.75 = 220 \text{ V}$$

$$E = \frac{\phi ZNP}{60A}$$

$$\text{or } N = \frac{60AE}{\phi ZP} = \frac{60 \times 2 \times 220}{25 \times 10^{-3} \times 782 \times 4} = \mathbf{337.6 \text{ rpm (Ans.)}}$$

$$T_a = \frac{\phi ZPI_a}{2\pi A} = \frac{25 \times 10^{-3} \times 782 \times 4 \times 40}{2\pi \times 2} = \mathbf{248.9 \text{ Nm (Ans.)}}$$

Example 5.8

The armature and shunt field resistance of a four-pole, lap wound DC shunt motor is 0.05 ohm and 25 ohm respectively. If its armature contains 500 conductors, find the speed of the motor when it takes 120 A from a DC mains of 100 V supply. Flux per pole is $2 \times 10^{-2} \text{ Wb}$.

Solution:

The circuit is shown in Fig. 5.12;

$$I_{sh} = \frac{V}{R_{sh}} = \frac{100}{25} = 4 \text{ A};$$

$$I_a = I_L - I_{sh} = 120 - 4 = 116 \text{ A}$$

$$E_b = V - I_a R_a = 100 - 116 \times 0.05 = 94.2 \text{ V}.$$

Now,

$$E_b = \frac{P \phi Z N}{60 A}$$

or

$$94.2 = \frac{6 \times 2 \times 10^{-2} \times 500 \times N}{60 \times 6}$$

or

$$N = \mathbf{565.2 \text{ rpm (Ans.)}}$$

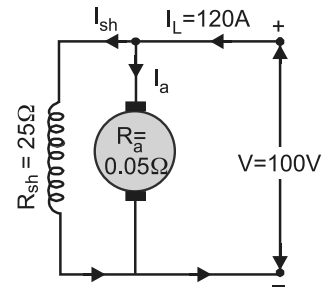


Fig. 5.12 Circuit diagram

Example 5.9

A 6-pole, 440 V DC motor has 936 wave wound armature conductors. The useful flux per pole is 25 m Wb. The torque developed is 45.5 kg-m. Calculate the following, if armature resistance is 0.5 ohm; (i) Armature current (ii) Speed

Solution:

Here,

$$P = 6; Z = 936; \phi = 25 \text{ m Wb} = 25 \times 10^{-3} \text{ Wb}$$

$$A = 2 \text{ (wave wound armature); } V = 440 \text{ V; } R_a = 0.5 \text{ ohm;}$$

Torque developed,

$$T = 45.5 \text{ kg-m} = 45.5 \times 9.81 = 446.35 \text{ Nm}$$

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

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

(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 $\frac{2\pi N}{60} \times I = EI_a$

Speed $N = \frac{60 \times EI}{\pi T} = \frac{60 \times 420 \times 39.95}{2\pi \times 446.35} = \mathbf{359 \text{ rpm (Ans.)}}$

Example 5.10

The electromagnetic torque developed in a DC machine is 80 Nm for an armature current of 30 A. What will be the torque for a current of 15 A? Assume constant flux. What is the induced emf at a speed of 900 rpm and an armature current of 15 A?

Solution:

Torque developed, $T_1 = 80 \text{ Nm}$

Armature current, $I_{a1} = 30 \text{ A}$

Armature current, $I_{a2} = 15 \text{ A}$

Let the torque developed is $T_2 \text{ Nm}$ when the armature current is 15 A .

Now $T \propto \phi I_a$

When flux ϕ is constant, $T \propto I_a$

$$\therefore \frac{T_2}{T_1} = \frac{I_{a2}}{I_{a1}}$$

$$\text{or } T_2 = \frac{I_{a2}}{I_{a1}} \times T_1 = \frac{15}{30} \times 80 = \mathbf{40 \text{ Nm (Ans.)}}$$

Power developed in the armature = $E_2 I_{a2} = \omega_2 T_2$

$$\text{where } \omega_2 = \frac{2\pi N_2}{60} = \frac{2\pi \times 900}{60} = 30\pi$$

$$\therefore \text{Induced emf} = E_2 = \frac{\omega_2 T_2}{I_{a2}} = \frac{30\pi \times 40}{15} = \mathbf{251.33 \text{ V (Ans.)}}$$

5.8 Characteristics of DC Motors

The performance of a DC motor can be easily judged from its characteristic curves, known as motor *characteristics*. The characteristics of a motor are those curves which show relation between the two quantities. On the basis of these quantities, the following characteristics can be obtained:

- 1. Speed and Armature current i.e., N – I_a Characteristics:** It is the curve drawn between speed N and armature current I_a . It is also known as *speed characteristics*.
- 2. Torque and Armature current i.e., T– I_a Characteristics:** It is the curve drawn between torque developed in the armature T and armature current I_a . It is also known as *electrical characteristic*.
- 3. Speed and Torque i.e., N–T characteristics:** It is the curve drawn between speed N and torque developed in the armature T . It is also known as *mechanical characteristics*.

The following important relations must be kept in mind while discussing the motor characteristics:

$$E_b \propto N \phi \quad \text{or} \quad N \propto \frac{E_b}{\phi} \quad \text{and} \quad T \propto \phi I_a$$

5.9 Characteristics of Shunt Motors

The conventional diagram of this motor is shown in Fig. 5.13. In these motors, the shunt field current $I_{sh} = V/R_{sh}$ remains constant since the supply voltage V is constant. Hence, the flux in DC shunt motors is practically constant (although at heavy loads, somewhat flux decreases due to armature reaction).

1. $N - I_a$ characteristics

We know that,
$$N \propto \frac{E_b}{\phi}$$

Since flux is constant;
$$N \propto E_b \text{ or } N \propto V - I_a R_a$$

If the armature drop ($I_a R_a$) is negligible, the speed of the motor will remain constant for all values of load as shown by the dotted line AB in Fig. 5.14. But strictly speaking, as the armature current increases due to the increase of load, armature drop $I_a R_a$ increases and speed of the motor decreases slightly as shown by the straight line AC in Fig. 5.14 (neglecting armature reaction). Moreover, the characteristic curve does not start from a point of zero armature current because a small current, no-load armature current I_{a0} , is necessary to maintain rotation of the motor at no-load.

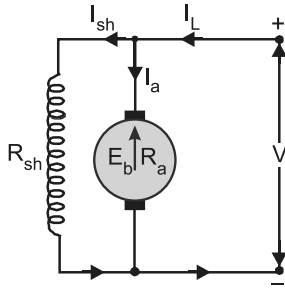


Fig. 5.13 Circuit for shunt motor

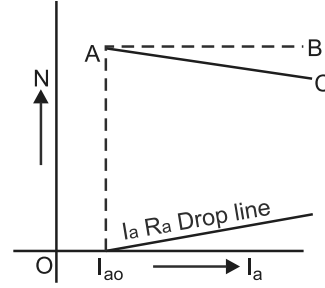


Fig. 5.14 $N - I_a$ characteristics of shunt motor

Since there is no appreciable change in the speed of a DC shunt motor from no-load to full load that is why it is considered to be a constant speed motor. This motor is best suited where almost constant speed is required and the load may be thrown off totally and suddenly.

2. $T - I_a$ Characteristics

We know that,
$$T \propto \phi I_a$$

Since flux is constant,
$$T \propto I_a$$

Hence, the electrical characteristic (i.e., $T - I_a$) is a straight line passing through the origin as shown in Fig. 5.15. It is clear from the characteristic curve that a large armature current is required at the start if machine is on heavy load. Thus, shunt motor should never be started on load.

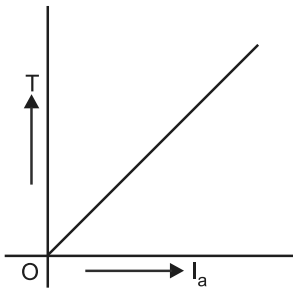


Fig. 5.15 $T - I_a$ characteristics of shunt motor

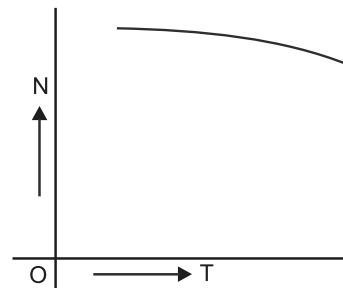


Fig. 5.16 $N - T$ characteristics of shunt motor

3. N – T Characteristics

The $N-T$ characteristic is derived from the first two characteristics. When load torque increases, armature current I_a increases but speed decreases slightly. Thus with the increase in load or torque, the speed decreases slightly as shown in Fig. 5.16.

5.10 Characteristics of Series Motors

The conventional diagram a series motor is shown in Fig. 5.17. In these motors, the series field winding carries the armature current. Therefore, the flux produced by the series field winding is proportional to the armature current before magnetic saturation, but after magnetic saturation flux becomes constant.

1. $N - I_a$ Characteristics

We know that
$$N \propto \frac{E_b}{\phi}$$

where, $E_b = V - I_a (R_a + R_{se})$

When armature current increases, the induced emf (back emf) E_b decreases, due to $I_a (R_a + R_{se})$ drop whereas flux ϕ increases as $\phi \propto I_a$ before magnetic saturation. However, under normal conditions $I_a (R_a + R_{se})$ drop is quite small and may be neglected.

Considering E_b to be constant,

$$N \propto \frac{1}{\phi} \propto \frac{1}{I_a}$$

Thus, before magnetic saturation, the $N-I_a$ curve follows the hyperbolic path as shown in Fig. 5.18.

In this region, the speed decreases abruptly with the increase in load or armature current.

After magnetic saturation, flux becomes constant, then

$$N \propto E_b \propto V - I_a (R_a + R_{se})$$

Thus, after magnetic saturation, the $N-I_a$ curve follows a straight line path and speed decreases slightly as shown in Fig. 5.18.

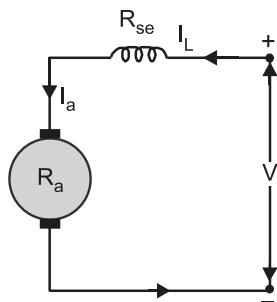


Fig. 5.17 Circuit diagram of series motor

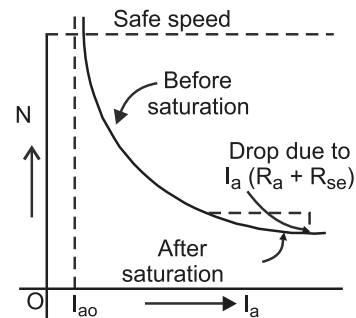


Fig. 5.18 $N-I_a$ characteristics of DC series motor

From this characteristic, it is concluded that the series motor is a variable speed motor, i.e., its speed changes when the armature current (or load) changes. As the load on this motor decreases, speed increases. If this motor is connected to the supply without load, armature current will be very small and hence speed will be dangerously high which may damage the motor due to heavy centrifugal forces.

Therefore, a series motor is never started on no-load. However, to start a series motor, mechanical load (not belt driven load because belt slips over the pulley) is put on it first then started.

2. $T - I_a$ Characteristics

We know that, $T \propto \phi I_a$

In series motors, before magnetic saturation $\phi \propto I_a$

Hence, before magnetic saturation the electromagnetic torque produced in the armature is proportional to the square of the armature current. Therefore, this portion of the curve (OA) is a parabola passing through the origin as shown in Fig. 5.19.

However, after magnetic saturation, the flux ϕ becomes constant.

$\therefore T \propto I_a$

Hence, after magnetic saturation, the curve (AB) becomes a straight line.

It is seen that before magnetic saturation $T \propto I_a^2$. When load is applied to this motor at start, it takes large current and heavy torque is produced which is proportional to square of this current. Thus, this motor is capable to pick up heavy loads at the start and best suited for electric traction.

3. $N - T$ Characteristics

This characteristic is derived from the first two characteristics. At low value of load, I_a is small, torque is small but the speed is very high. As load increases, I_a increases, torque increases but the speed decreases rapidly. Thus for increasing torque, speed decreases rapidly as shown in Fig. 5.20.

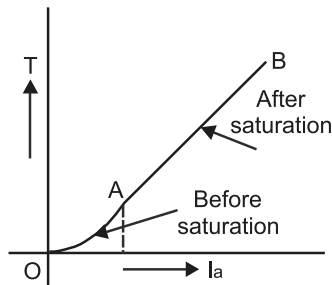


Fig. 5.19 $T - I_a$ characteristics of DC series motor

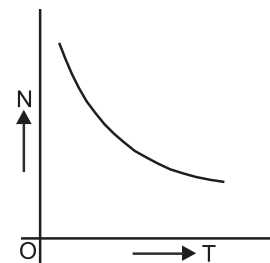


Fig. 5.20 $N - T$ characteristics of DC series motor

5.11 Characteristics of Compound Motors

There are two types of compound wound DC motors namely; cumulative compound motors and differential compound motors. Cumulative compound motors are most common. The characteristics of

these motors lies between the shunt and series motors. The $N-I_a$ characteristics, $T-I_a$ characteristics and $N-T$ characteristics are shown in Figs. 5.21(a), (b) and (c), respectively.

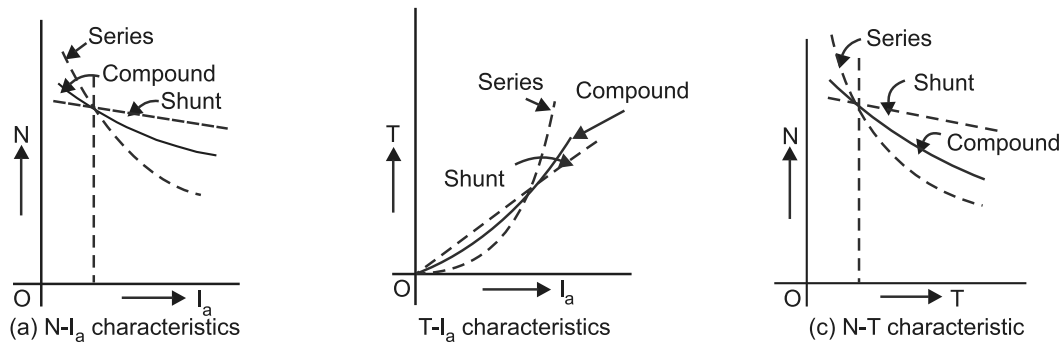


Fig. 5.21 Characteristics of cumulatively compound DC motor

However the $N-I_a$, $T-I_a$ and $N-T$ characteristics of a differentially compound motor are shown in Figs. 5.22(a), (b) and (c), respectively.

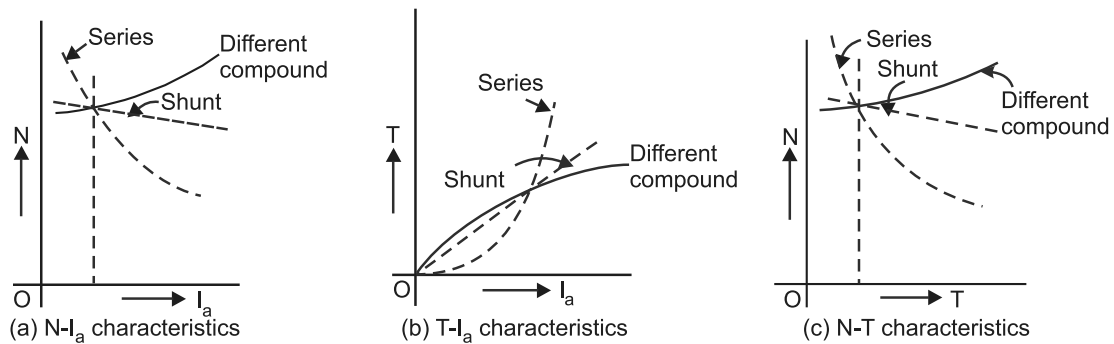


Fig. 5.22 Characteristics of differentially compound DC motor

5.12 Applications and Selection of DC Motors

5.12.1 Applications of DC Motors

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

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. It is, therefore, used;
 - (i) Where the speed between no-load to full load has to be maintained almost constant.
 - (ii) 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, line shafts in the group drive*, etc.

- 3. Series motors:** The characteristics of a series motor reveal that it is variable speed motor i.e., the speed is low at higher torques and vice-versa. Moreover, at light loads or at no-load, the motor attains dangerously high speed. It is, therefore, employed:

- (i) Where high torque is required at the time of starting to accelerate heavy loads quickly.
- (ii) 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.

Note: The series motors are always directly coupled with loads or coupled through gears. Belt loads are never applied to series motor, because the belt may slip over the pulley or it may break. Then the motor will operate at light loads or at no-load and will attain dangerously high speed which may damage the motor.

- 4. Compound motors:** The important characteristic of this motor is that the speed falls appreciably on heavy loads as in a series motor, but at light loads, the maximum speed is limited to safe value. It is, therefore, used;

- (i) Where high torque is required at the time of starting and where the load may be thrown off suddenly.
- (ii) 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.

5.12.2 Selection of DC Motors

While selecting a DC motor for a particular work, one is to consider the following points:

- 1. Selection of power rating:** If the size (*HP* or *kW* capacity) of a motor is more than the load to be picked-up by it then it will operate at lighter load than its rating. Hence, there will be more losses (i.e., motor will operate at poor efficiency) and unnecessarily there will be wastage of power. Thus extra expenditure will incur during operation. At the same time its initial cost will be more.

On the other hand, if the size of the motor is less than the load to be picked-up by it, then it will be over loaded and it will be heated-up beyond its limits. Hence the motor may be damaged if operated continuously. Otherwise, also the protective devices will disconnect the motor under over-load conditions and this affect the production.

Thus, a motor should be chosen of a size for its maximum power utilisation. During operation, it should be heated-up within the permissible temperature limits and it should never be over-heated. But at the same time it should be capable to take-up the over-loads temporarily.

- 2. Characteristics of the motor:** For satisfactory operation, selection of power rating of a motor is not only the criteria, rather one should know the characteristics of a motor (i.e., behaviour of a motor under different load conditions) so that a work can be done quickly and efficiently without any breakdown. Therefore, before selection of motor, one should know the following particulars of the work

- (i) Torque requirement during starting and running at different loads.
- (ii) Requirement of accelerating and braking torque
- (iii) Frequency of switching
- (iv) Temperature at the work place
- (v) Environmental conditions, etc.

After knowing the above particulars at the work place, a suitable motor (with proper enclosures) to meet with the requirements is selected.

5.13 Starting of DC Motors

To start a DC motor, when it is switched-ON to the supply with full rated voltage, it draws heavy current during starting period (more than its rated value). This excessive current overheats the armature winding and may even damage the winding insulation. Therefore, during starting period a resistance called starter is connected in series with the armature circuit to limit the starting current.

5.14 Necessity of Starter for a DC Motor

Under normal operating conditions, the voltage equation for a motor is given as

$$E_b = V - I_a R_a \quad \text{or} \quad I_a R_a = V - E_b$$

The armature current is given by the relation;

$$I_a = \frac{V - E_b}{R_a}$$

When the motor is at rest, the induced emf E_b in the armature is zero ($E_b \propto N$). Consequently, if full voltage is applied across the motor terminals, the armature will draw heavy current ($I_a = V/R_a$) because armature resistance is relatively small. This *heavy starting current* has the following effects:

- (i) It will blow out the fuses and prior to that it may damage the insulation of armature winding due to excessive heating effect if starting period is more.
- (ii) Excessive voltage drop will occur in the lines to which the motor is connected. Thus, the operation of the appliances connected to the same line may be impaired and in some cases they may refuse to work.

To avoid this heavy current at start, a variable resistance is connected in series with the armature, as shown in Fig. 5.23, called a **starting resistance or starter**, and thus the armature current is limited to safe value $\left(I_a = \frac{V}{R_a + R} \right)$. Once the motor picks up speed, emf is built up and current is reduced

$\left(I_a = \frac{V - E_{b1}}{R_a + R} \right)$. After that the starting resistance is gradually reduced. Ultimately, whole of the resistance is taken out of circuit when the motor attains normal speed.

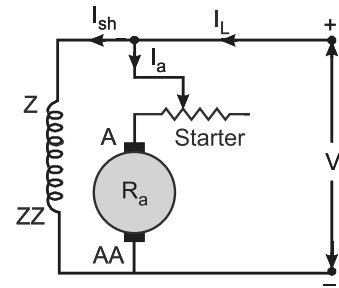


Fig. 5.23 DC shunt motor starter

Another important feature of a starter is that it contains protective devices such as overload protection coil (or relay) which provides necessary protection to the motor against over loading and no-volt release coil.

5.15 Starters for DC Shunt and Compound Wound Motors

The basic function of a starter is to limit the current in the armature circuit during starting or accelerating period. Starters are always rated on the basis of output power and voltage of the motor with which they are to be employed, e.g., 10 HP, 250 V shunt motor starter). A simplest type of starter is just a variable resistance (a rheostat) connected in series with the armature alone (not with the motor as a whole) as shown in Figs. 5.24(a) and (b).

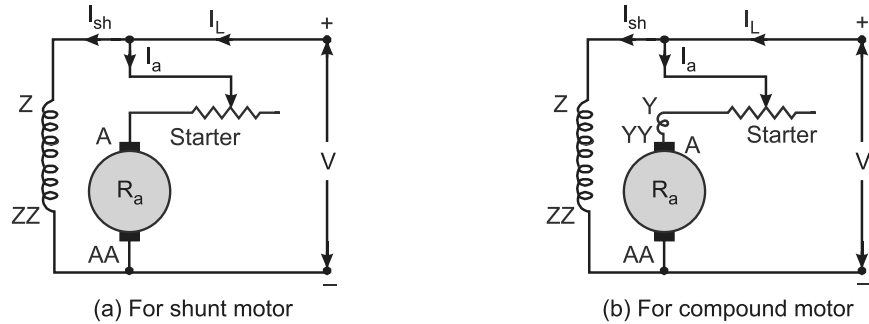


Fig. 5.24 DC Series and Compound motor starter

It may be noted that shunt field is kept independent of starting resistance. It is because when supply is connected, it receives normal rated voltage and sets-up maximum (rated) flux. A higher value of flux results in a low operating speed and a higher motor torque for a particular value of starting current since speed is inversely proportion to flux per pole $\left(N \propto \frac{1}{\phi}\right)$ whereas motor torque is

proportional to product of flux per pole and armature current ($T \propto \phi I_a$). Hence, for a given load torque, the motor will accelerate quickly and reduces the starting period. Thus, the heating effect to armature winding is reduced.

For all practical application, this starter is further modified which includes protective devices such as over-load release and no-volt release. The over-load release protects the motor against over-loading i.e., when the motor is over-loaded (or short circuited) this relay brings the plunger to its *OFF* position. On the other hand, the no-volt release brings the plunger to its *OFF* position so that the motor may not start again without starter. For shunt and compound motors there are two standard types of starters named as (a) three point starter and (b) four point starter.

5.16 Three-point Shunt Motor Starter

The schematic connection diagram of a shunt motor starter is shown in Fig. 5.25. It consists of starting resistance R divided into several sections. The tapping points of starting resistance are connected

to number of studs. The last stud of the starting resistance is connected to terminal A to which one terminal of the armature is connected. The + ve supply line is connected to the line terminal L through main switch. From line terminal, supply is connected to the starting lever SL through over load release coil OLRC. A spring S is placed over the lever to bring it to the off position, when supply goes off. A soft iron piece SI is attached with the starting lever which is pulled by the no volt release coil under normal running condition. The far end of the brass strip BS is connected to the terminal Z through a no volt release coil NVRC. One end of the shunt field winding is connected to Z terminal of the starter. An iron piece is lifted by OLRC under abnormal condition to short circuit the no-volt release coil. The negative supply line is connected directly to the other ends of shunt field winding and armature of the DC shunt motor.

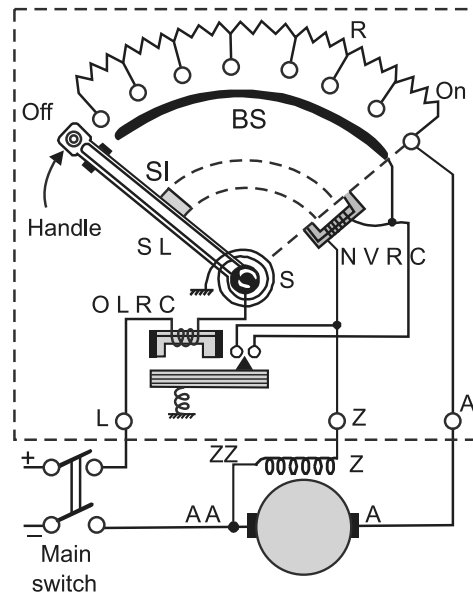


Fig. 5.25 Three-point shunt motor starter

Operation

First of all the main switch is closed with starting lever resting in off position. The handle is then turned clockwise to the first stud and brass strip. As soon as it comes in contact with first stud, whole of the starting resistance R is inserted in series with the armature and the field winding is directly connected across the supply through brass strip. As the handle is turned further the starting resistance is cut out of the armature circuit in steps and finally entire starting resistance is cut out of armature circuit.

No-volt Release Coil and its Function

A no-volt release coil is a small electromagnet having many turns of fine wire. It is connected in series with shunt field winding and therefore, carries a small field current. When the handle is turned to on position, the no-volt release coil is magnetised by the field current and holds the starting lever at on position. In case of failure or disconnection of the supply, this coil is demagnetised and the lever

comes to the off position due to spring tension. Consequently. The motor is disconnected from the supply. If the spring with the no-volt release coil is not used the lever would remain in *ON*-position in case of supply failure. And again, when the supply comes, the motor would be connected directly to the lines without starter.

The other important advantage of connecting the no-volt release coil in series with the shunt field winding is that due to an accident if the circuit of field winding becomes open, the *NVRC* will be demagnetised and the starting lever is immediately pulled back to off position by the spring. Otherwise the motor would have attained dangerously high speed.

Over-load Release Coil and its Function

An over-load release coil is an electromagnet having small number of turns of thick wire. It is connected in series with the motor and carries the line current. When the motor is over loaded (or short circuited), a heavy current more than predetermined value will flow through it. Then, the iron piece (armature or plunger) is lifted and short circuits the no-volt release coil. Hence the starting lever is released and pulled back to the off position due to spring tension. Thus the motor is disconnected from the supply and is protected against over loading.

5.17 Four-point Starter

For speed control of DC shunt or compound motors, a rheostat (variable resistor R_h) is connected in series with the field winding, as shown in Fig. 5.26. In this case, if a three-point starter is used and the value of R_h is so adjusted that the current flowing through the shunt field winding is very small. It may be seen that the same current flows through the no-volt release coil, then the magnetic strength of the coil may be insufficient to hold the plunger at its *ON* position. This is an undesirable feature of a three-point starter. This feature makes a three-point starter unsuitable for such applications. Accordingly, a four-point starter is designed, as shown in Fig. 5.26, in which the current flowing through the no-volt release coil is made independent of the shunt field circuit. Figure 5.26(a) shows a four-point starter used with a shunt wound motor whereas Fig. 5.26(b) shows a starter used with a compound wound machine.

Operation

The working of a four-point starter is similar to a three-point starter with slight changes.

In this case, when the plunger touches the first stud, the line current is divided into the following three parts:

- (i) First part passes through starting resistance and armature (as well as in series field for compound motors).
- (ii) Second part passes through the field winding (and speed control resistance if applied) and
- (iii) The third part passes through no-volt release coil and protective resistance connected in series with the coil.

5.18 Calculation of Step Resistances Used in Shunt Motor Starter

For starting a motor from stand still to its rated speed, it is normally desirable to increase the speed gradually to maintain the angular acceleration constant during the starting period. The angular acceleration is proportional to the net torque, which is in turn nearly proportional to the product of flux (ϕ) and armature current I_a i.e., $T \propto \phi I_a$. The flux ϕ will remain constant provided line voltage remains constant. Hence it follows that substantially constant angular acceleration calls for constant armature current during starting period.

We know, $\text{Speed, } N \propto \frac{E_b}{\phi} \propto \frac{V - I_a R}{\phi}$

where R = resistance of armature plus the resistance of starter.

Since I_a and ϕ are to be kept constant, therefore, for increasing the speed (N) gradually, R should be varied (reduced) in such a way that the above relation must be satisfied. For different values of armature current, the value of R is given by the expression, d

$$R = \frac{V - KN}{I_a} \text{ where } K \text{ is a constant}$$

Note the Steps: $N \propto \frac{V - I_a R}{\phi}$ or $\phi N \propto V - I_a R$
 or $KN = V - I_a R$ or $R = \frac{V - KN}{I_a}$

In starters, usually the value of R is changed in steps and, therefore, armature current will change in two extreme values. Accordingly, the steps of the starter are designed in such a way that armature current varies in between these limits so that torque may not change to a greater degree.

The fuse or *MCB* placed in the motor circuit is usually not larger than 150% of the motor full-load current.

Let I_1 and I_2 be the maximum and minimum value of the current drawn by the motor during starting. Let the starter has n -sections each having a resistance as $r_1, r_2, r_3, \dots, r_n$ as shown in Fig. 5.27. Let the total resistance of armature circuit when the starting arm is kept at stud No. 1, 2, 3, $\dots$ n and $n + 1$ be $R_1, R_2, R_3, \dots, R_n$ and R_{n+1} (where $R_{n+1} = R_a$), respectively.

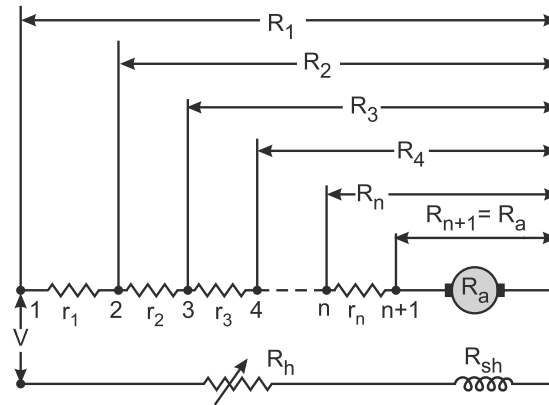


Fig. 5.27 Design of shunt motor starter

Just at the time of starting when the starting arm is brought in contact with stud-1, the motor is stationary and there is no back emf, the maximum value of current drawn by the motor,

$$I_1 = \frac{V}{R_1} \quad \dots(5.11)$$

The motor starts rotating and picks up speed N_1 which develops a back emf E_{b1} (where $E_{b1} \propto N_1$) and the current drops to I_2 (the starting arm is still at stud-1), therefore,

$$I_2 = \frac{V - E_{b1}}{R_1} \quad \dots(5.12)$$

Now the starting arm is shifted to stud-2, the speed of the motor is still N_1 and the back emf is also E_{b1} but the circuit resistance is reduced to R_2 due to this the current again attains its maximum value I_1 , i.e.,

$$I_1 = \frac{V - E_{b1}}{R_2} \quad \dots(5.13)$$

The motor picks-up speed further and its value reaches to N_2 which develops a back emf E_{b2} ($E_{b2} \propto N_2$) and the current drops to I_2 (the starting arm is still at stud-2), therefore,

$$I_2 = \frac{V - E_{b2}}{R_2} \quad \dots(5.14)$$

Further, starting arm is shifted to stud-3, the speed is still N_2 and back emf is E_{b2} but the circuit resistance is reduced to R_3 , thus the current again attains its maximum value I_1 , i.e.,

$$I_1 = \frac{V - E_{b2}}{R_3} \quad \dots(5.15)$$

Dividing eqn. (5.13) by (5.12) and eqn. (5.15) by (5.14), we get,

$$\frac{I_1}{I_2} = \frac{V - E_{b1}}{R_2} \times \frac{R_1}{V - E_{b1}} = \frac{V - E_{b2}}{R_3} \times \frac{R_2}{V - E_{b2}}$$

$$\text{or} \quad \frac{I_1}{I_2} = \frac{R_1}{R_2} = \frac{R_2}{R_3} = K \text{ (say)} \quad \dots(5.16)$$

$$\text{and} \quad \frac{R_1}{R_2} \times \frac{R_2}{R_3} = K^2 \quad \text{or} \quad \frac{R_1}{R_3} = K^2$$

Similarly, the starting arm is shifted to next studs in sequence and ultimately reaches to stud number $(n + 1)$, then we get,

$$\frac{R_1}{R_2} = \frac{R_2}{R_3} = \frac{R_3}{R_4} = \dots = \frac{R_{n-1}}{R_n} = \frac{R_n}{R_a} = K$$

$$\text{and} \quad \frac{R_1}{R_2} \times \frac{R_2}{R_3} \times \frac{R_3}{R_4} \times \dots \times \frac{R_{n-1}}{R_n} \times \frac{R_n}{R_a} = K^n$$

$$\text{or} \quad \frac{R_1}{R_a} = K^n \quad \text{or} \quad K = \left(\frac{R_1}{R_a} \right)^{\frac{1}{n}} \quad \dots(5.17)$$

If the values of armature resistance R_a , limiting currents I_1 (max. value) and I_2 (min. value) are known, the value of R_1 and K can be determined from eqn. (5.11) and (5.16) respectively. At the same time, the number of section (n) can be determined by using eqn. (5.17).

By knowing the value of R_1 and K , one can determine the values of $R_2, R_3, R_4, \dots R_n$ by using the eqn. (vi) and then the value of resistance of each step can be determined. i.e., $r_1 = R_1 - R_2$; $r_2 = R_2 - R_3$; $r_3 = R_3 - R_4$; $\dots$; $r_n = R_n - R_a$

Example 5.11

A 152 V DC shunt motor has an armature resistance of 0.3Ω , a brush voltage drop of 2 V, the rated full load current is 70 A. Calculate (i) the current at the instant of starting as a percentage of full load current (ii) the value of starting resistance to limit the motor current at the instant of starting to 150 percent of the rated load current.

Solution:

Here, $V = 152 \text{ V}$; $R_a = 0.3 \Omega$; $I_{fl} = 70 \text{ A}$

(i) Starting current with no-additional resistance in the armature circuit,

$$I_s = \frac{V - \text{brush contact drop}}{R_a} = \frac{152 - 2}{0.3} = 500 \text{ A}$$

$$I_s \text{ as a \%age of full-load} = \frac{I_s}{I_{fl}} \times 100 = \frac{500}{70} \times 100 = 714.3$$

Let the total resistance required in the armature circuit to limit the starting current to 150 per cent of the rated load current be R_1 , then

$$R_1 = \frac{V - \text{brush contact drop}}{1.5 \times I_{fl}} = \frac{152 - 2}{1.5 \times 70} = 1.43 \text{ ohm}$$

(ii) Additional resistance required for starting

$$R = R_1 - R_a = 1.43 - 0.3 = \mathbf{1.13 \Omega (Ans.)}$$

Example 5.12

A 10 b.h.p. (7.46 kW), 200-V shunt motor has full-load efficiency of 85%. The armature has a resistance of 0.238Ω . Calculate the value of the starting resistance necessary to limit the starting current to 1.5 times the full-load current at the moment of first switching on. The shunt current may be neglected. Find also the back emf of the motor, when the current has fallen to its full-load value, assuming that the whole of the starting resistance is still in circuit.

Solution:

$$\text{Full load motor current, } I_{fl} = \frac{7.46 \times 1000}{200 \times 0.85} = 43.88 \text{ A}$$

$$\text{Starting current, } I_1 = 1.5 \times 43.88 = 65.83 \text{ A}$$

$$R_1 = \frac{V}{I_1} = \frac{200}{65.83} = 3.038 \Omega; R_a = 0.238 \Omega$$

$$\therefore \text{Starting resistance} = R_1 - R_a = 3.038 - 0.238 = \mathbf{2.8 \Omega (Ans.)}$$

Now, full-load current, $I_{fl} = 43.88 \text{ A} = I_a$

Now,
$$I_a = \frac{V - E_b}{R_1}$$

$$\therefore E_b = V - I_a R_1 = 200 - (43.88 \times 3.038) = \mathbf{67 \text{ V (Ans.)}}$$

Example 5.13

A 230 V shunt motor has an armature resistance of 0.4Ω . The starting armature current must not exceed 45 A. If the number of sections are 5, calculate the values of resistance steps to be used in the starter.

Solution:

Number of sections of the starter, $n = 5$

Resistance of armature circuit at the starting instant

$$R_1 = \frac{V}{I_{\max}} = \frac{230}{45} = 5.11 \Omega$$

Ratio of maximum to minimum current during starting,

$$\frac{I_{\max}}{I_{\min}} = K = \left(\frac{R_1}{R_a} \right)^{1/n} = \left(\frac{5.11}{0.4} \right)^{1/5} = 1.6645$$

$$\text{Resistance, } R_2 = \frac{R_1}{K} = \frac{5.11}{1.6645} = 3.07 \Omega ; \text{ Resistance, } R_3 = \frac{R_2}{K} = \frac{3.07}{1.6645} = 1.844 \Omega$$

$$\text{Resistance, } R_4 = \frac{R_3}{K} = \frac{1.844}{1.6645} = 1.108 \Omega ; \text{ Resistance, } R_5 = \frac{R_4}{K} = \frac{1.108}{1.6645} = 0.666 \Omega$$

$$\text{Resistance of 1st to 5th section } r_1 = R_1 - R_2 = 5.11 - 3.07 = \mathbf{2.04 \Omega (Ans.)}$$

$$r_2 = R_2 - R_3 = 3.07 - 1.844 = \mathbf{1.226 \Omega (Ans.)}$$

$$r_3 = R_3 - R_4 = 1.844 - 1.108 = \mathbf{0.736 \Omega (Ans.)}$$

$$r_4 = R_4 - R_5 = 1.108 - 0.666 = \mathbf{0.442 \Omega (Ans.)}$$

$$r_5 = R_5 - R_a = 0.666 - 0.4 = \mathbf{0.266 \Omega (Ans.)}$$

Example 5.14

A 220-V shunt motor has an armature resistance of 0.5Ω . The armature current of starting must not exceed 40 A. If the number of sections is 6, calculate the values of the resistor steps to be used in this starter.

Solution:

Here, $V = 220 \text{ V}$; $R_a = 0.5 \Omega$; $I_{\max} = 40 \text{ A}$; $n = 6$

Now,
$$R_1 = \frac{220}{40} = 5.5 \Omega,$$

$$\frac{R_1}{R_a} = K^n \text{ or } R_1 = R_a K^n$$

∴

$$5.5 = 0.4 K^6 \text{ or } K^6 = 5.5/0.4 = 13.75$$

$$6 \log_{10} K = \log_{10} 13.75 = 1.1383; K = 1.548$$

Now,

$$R_2 = \frac{R_1}{K} = \frac{5.5}{1.548} = 3.553 \Omega$$

$$R_3 = \frac{R_2}{K} = \frac{3.553}{1.548} = 2.295 \Omega$$

$$R_4 = \frac{2.295}{1.548} = 1.482 \Omega$$

$$R_5 = \frac{1.482}{1.548} = 0.958 \Omega$$

$$R_6 = \frac{0.958}{1.548} = 0.619 \Omega$$

Resistance of various (1st to 6th) sections;

$$r_1 = R_1 - R_2 = 5.5 - 3.553 = \mathbf{1.947 \text{ W (Ans.)}}$$

$$r_2 = R_2 - R_3 = 3.553 - 2.295 = \mathbf{1.258 \text{ W (Ans.)}}$$

$$r_3 = R_3 - R_4 = 2.295 - 1.482 = \mathbf{0.813 \Omega (Ans.)}$$

$$r_4 = R_4 - R_5 = 1.482 - 0.958 = \mathbf{0.524 \Omega (Ans.)}$$

$$r_5 = R_5 - R_6 = 0.958 - 0.619 = \mathbf{0.339 \Omega (Ans.)}$$

$$r_6 = R_6 - R_a = 0.619 - 0.4 = \mathbf{0.219 \Omega (Ans.)}$$

Example 5.15

A 250 V DC shunt motor has an armature resistance of 0.125 ohm and a full load current of 150 ampere. Calculate the number and values of resistance elements of a starter to start the motor on full load, the maximum current not to exceed 200 A.

Solution:

As the motor is to start against its full load, hence the minimum current is its full load current i.e., 150 A.

$$I_{\max} = 200 \text{ A}; I_{\min} = 150 \text{ A}$$

∴

$$K = \frac{I_{\max.}}{I_{\min.}} = \frac{200}{150} = \frac{4}{3}$$

Now

$$R_1 = \frac{V}{I_{\max.}} = \frac{250}{200} = 1.25 \text{ ohm and } R_a = 0.125 \text{ ohm} \quad (\text{given})$$

Now

$$\left(\frac{I_{\max}}{I_{\min}} \right)^n = \frac{R_1}{R_a} \quad \text{or} \quad \left(\frac{4}{3} \right)^n = \frac{1.25}{0.125} = 10$$

Taking logs on both sides, we have

$$n. \log \frac{4}{3} = \log 10 \text{ or } n \times 0.1248 = 1 \text{ or } n = \mathbf{8 (Ans.)}$$

$$R_2 = \frac{R_1}{K} = 1.25 \times \frac{3}{4} = 0.938 \, \Omega \quad ;$$

$$R_3 = \frac{R_2}{K} = 0.938 \times \frac{3}{4} = 0.703 \, \Omega$$

$$R_4 = \frac{R_2}{K} = 0.703 \times \frac{3}{4} = 0.527 \, \Omega \quad ;$$

$$R_5 = \frac{R_4}{K} = 0.527 \times \frac{3}{4} = 0.395 \, \Omega$$

$$R_6 = \frac{R_5}{K} = 0.395 \times \frac{3}{4} = 0.296 \, \Omega \quad ;$$

$$R_7 = \frac{R_6}{K} = 0.222 \times \frac{3}{4} = 0.222 \, \Omega$$

$$R_8 = \frac{R_7}{K} = 0.222 \times \frac{3}{4} = 0.167 \, \Omega \quad ;$$

$$R_9 = \frac{R_8}{K} = 0.167 \times \frac{3}{4} = 0.125 \, \Omega = R_a$$

Resistance of various steps in the order of 1st to 8th,

$$r_1 = R_1 - R_2 = 1.25 - 0.931 = \mathbf{0.312 \, \Omega} \quad ;$$

$$r_2 = R_2 - R_3 = 0.938 - 0.703 = \mathbf{0.235 \, \Omega}$$

$$r_3 = R_3 - R_4 = 0.703 - 0.527 = \mathbf{0.176 \, \Omega} \quad ;$$

$$r_4 = R_4 - R_5 = 0.527 - 0.395 = \mathbf{0.132 \, \Omega}$$

$$r_5 = R_5 - R_6 = 0.395 - 0.296 = \mathbf{0.099 \, \Omega} \quad ;$$

$$r_6 = R_6 - R_7 = 0.296 - 0.222 = \mathbf{0.074 \, \Omega}$$

$$r_7 = R_7 - R_8 = 0.222 - 0.167 = \mathbf{0.055 \, \Omega} \quad ;$$

$$r_8 = R_8 - R_9 = 0.167 - 0.125 = \mathbf{0.042 \, \Omega}$$

Example 5.16

Find the value of the step resistance in a 6-stud starter for a 5 h.p. (3.73 kW), 200-V shunt motor. The maximum current in the line is limited to twice the full-load value. The total Cu loss is 50% of the total loss. The normal field current is 0.6 A and the full-load efficiency is found to be 88%.

Solution:

$$\text{Output} = 3730 \, \text{W}$$

$$\text{Input} = \frac{\text{Output}}{\eta} = \frac{3730}{88} \times 100 = 4238 \, \text{W}$$

$$\text{Total loss} = 4238 - 3730 = 508 \, \text{W}$$

$$\text{Armature Cu loss} = \frac{508}{2} = 254 \, \text{W}$$

$$\text{Input current} = \frac{\text{Input}}{V} = \frac{4238}{200} = 21.19 \, \text{A}$$

$$\text{Armature current, } I_a = I_L - I_{sh} = 21.19 - 0.6 = 20.59 \, \text{A}$$

$$\text{Now} \quad (20.59)^2 R_a = 254$$

$$\therefore R_a = \frac{254}{(20.59)^2} = 0.5989 \, \Omega$$

$$\text{Permissible input current} = 21.19 \times 2 = 42.38 \, \text{A}$$

$$\text{Permissible armature current} = 42.38 - 0.6 = 41.78 \, \text{A}$$

$$\therefore R_1 = \frac{200}{41.78} = 4.787 \, \Omega; n = 5; \frac{R_1}{R_a} = K^5$$

$$\therefore 4.787 = K^5 \times 0.5989$$

$$\therefore K^5 = 4.787/0.5989 = 7.993$$

$$\text{or } 5 \log K = \log 7.993 = 0.9027$$

$$\therefore \log K = 0.1805; K = 1.516$$

$$\text{Now } R_2 = \frac{R_1}{K} = \frac{4.789}{1.516} = 3.159 \, \Omega ; \quad R_3 = \frac{R_2}{K} = \frac{3.159}{1.516} = 2.084 \, \Omega$$

$$R_4 = \frac{R_3}{K} = \frac{2.084}{1.516} = 1.376 \, \Omega ; \quad R_5 = \frac{R_4}{K} = \frac{1.376}{1.516} = 0.908 \, \Omega$$

Resistance in 1st step – $R_1 - R_2 = 4.787 - 3.159 = \mathbf{1.628 \, \Omega}$. (Ans.)

Resistance in 2nd step – $R_2 - R_3 = 3.159 - 2.084 = \mathbf{0.075 \, \Omega}$. (Ans.)

Resistance in 3rd step – $R_3 - R_4 = 2.084 - 1.376 = \mathbf{0.708 \, \Omega}$. (Ans.)

Resistance in 4th step – $R_4 - R_5 = 1.376 - 0.908 = \mathbf{0.468 \, \Omega}$. (Ans.)

Resistance in 5th step – $R_5 - R_a = 0.908 - 0.5989 = \mathbf{0.309 \, \Omega}$. (Ans.)

5.19 Series Motor Starter

A series motor starter is also called a two-point starter. Its internal and external connections are shown in Fig. 5.28.

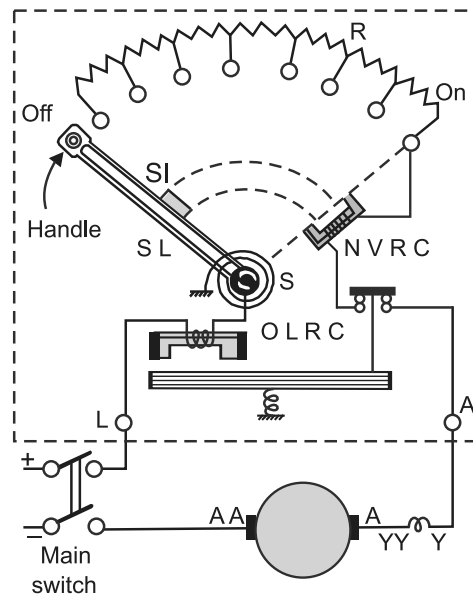


Fig. 5.28 Two-point series motor starter

Here, for starting the motor, the control arm or plunger is moved in clockwise direction from its *OFF* position to *ON* position against the spring tension. In the beginning, all the sections of the starting resistance are connected in series with the armature to limit the current to predetermined value. As the starting arm moves, various steps of the starting resistance are cut out of circuit and

ultimately whole of the starting resistance is cut-out and the control arm is held in the *ON* position by an electromagnet. The hold-on (no-volt release) coil is connected in series with the armature circuit. If the motor loses its load, current drawn by the motor decreases which decreases the strength of the hold-on coil. Immediately the arm goes back to the *OFF* position due to strong spring tension; thus preventing the motor from over-speed. The control arm or plunger also goes back to the *OFF* position when supply goes *OFF* or when the supply voltage decreases appreciably. *L* and *Y* are the two points of the starter through which supply line terminal and the motor (series field) terminal is connected.

For stopping the motor, the line switch should always be opened rather than bringing the control arm back to its *OFF* position. If it is done a heavy sparking occurs at the last stud placed near the *OFF* position. This sparking occurs due to dissipation of energy stored in the magnetic field of series field winding.

Example 5.17

A 240 V series motor takes 40 A when giving its rated output at 1500 rpm. Its armature and series field resistance is 0.18 Ω and 0.12 Ω respectively. Find the external resistance which must be added to obtain rated torque (i) at starting and (ii) at 1000 rpm.

Solution:

Since torque remains the same in both the cases, the current drawn by the motor remains constant at 40 A, because $T \propto \Phi I$.

We know, current drawn by the motor,
$$I = \frac{V - E_b}{R_a + R_{se} + R}$$

where R is external resistance connected in series with motor at start

$$\therefore 40 = \frac{240 - 0}{0.18 + 0.12 + R} \quad (\text{since at start } E_b = 0)$$

$$\text{or } R = \frac{240}{40} - 0.3 = \mathbf{5.7 \Omega (Ans.)}$$

$$\text{Back emf, } E_{b_1} = V - I(R_a + R_{se}) = 240 - 40 \times (0.18 + 0.12) = 228 \text{ V}$$

$$\text{Back emf, } E_{b_2} = E_{b_1} \times \frac{N_2}{N_1} = 228 \times \frac{1000}{1500} = 152 \text{ V}$$

$$\therefore I = \frac{V - E_b}{R_a + R_{se} + R}, 40 = \frac{240 - 152}{0.18 + 0.12 + R}$$

$$\text{or } R = \frac{88}{40} - 0.3 = \mathbf{1.9 \Omega (Ans.)}$$

Section Practice Problems

Numerical Problems

1. A DC series motor draws 50 A at 230 V. Resistance of armature and series field winding is 0.2 Ω and 0.1 Ω respectively. Calculate (i) brush voltage (ii) back emf, (iii) power wasted in armature, and mechanical power developed. **(Ans. 225V, 215 V, 500 W, 10.75 kW)**

2. The field resistance and armature resistance of a 120 V DC shunt motor is 60 ohm and 0.2 ohm respectively. The motor draws 60 A current at full-load, 1800 rpm. If the brush contact drop is 3V, find the speed of the motor at half load. **(Ans. 1902)**
3. A 250 V DC shunt motor, on no-load draws a current of 5A and runs at 1000 rpm. The armature and field resistance of the motor is 0.025 ohm and 250 ohm respectively. If the motor draws 41 A at full-load what will be the speed of the motor. Assume that the field is weakened by 3% due to armature reaction. **(Ans. 993.67)**
4. A DC series motor draws 80 A at 230 V and rotates at 1000 rpm. The armature and series field resistance is 0.11 ohm and 0.14 ohm respectively. Calculate the speed of the motor when it draws 20 A from the mains assuming that the field is reduced to 0.4 times the previous one. **(Ans. 2678 rpm)**
5. A 220 V DC series motor draws full-load line current of 38 A at the rated speed of 500 rpm. The series field and armature resistance of the motor is 0.2 ohm and 0.4 ohm respectively. Considering brush drop as 3.0 V irrespective of the load and neglecting armature reaction, find:
 - (i) The speed of the motor when the load current drops to 19 A
 - (ii) The speed on removal of load when the motor takes only 1A from supply.
 - (iii) The internal horse power developed in each of the above cases.**(Ans. 1058 rpm; 21172 rpm; 10, 5.31, 0.294)**
6. A belt driven DC shunt generator runs at 1200 rpm delivering 10 kW at 220 V brushes. The belt breaks, following which the machine operates as a motor drawing 2 kW power. What will be its speed as a motor. The armature and field resistance are 0.25 Ω and 55 Ω respectively. Ignore armature reaction and assume the contact drop at each brush to be 1V. **(Ans. 1100)**
7. The field and armature resistance of a DC shunt machine is 60 ohm and 0.015 ohm respectively. When working as a generator it delivers 60 kW at 240 V and 720 rpm. What will be its speed when the same machine works as a motor drawing 60 kW at 240 V assuming that contact voltage drop per brush is 1 V. **(Ans. 686.3 rpm)**
8. A 12 hp, 230 V shunt motor has an armature circuit resistance of 0.5 Ω and a field resistance of 115 Ω . At no-load and rated voltage the speed is 1200 rpm and the armature current is 2A. If the load is applied, the speed drops to 1100 rpm. Determine the armature current, the line current and torque. **(Ans. 40.2 A; 42.2 A; 73.2 Nm)**
9. A 250 V, four-pole shunt motor has wave winding with 500 conductors. The armature circuit resistance is 0.25 Ω , field resistance is 100 Ω and the flux per pole is 0.02 Wb. Armature reaction is neglected. If the motor draws 14.5 A from the mains, then compute speed and the torque developed in the armature. **(Ans. 741 rpm, 38.2 Nm)**
10. The field winding and armature resistance of a 230 V DC shunt motor is 230 ohm and 0.5 ohm respectively. It draws 3 A at no-load and runs at a speed of 1000 rpm. At full load and rated voltage, the current drawn is 23 A and the armature reaction causes a drop of 2% in flux. Determine (i) full-load speed (ii) full-load torque. **(Ans. 976 rpm, 47.15 Nm)**
11. The field and armature resistance of a 200 V DC series motor is 0.2 ohm and 0.3 ohm respectively. It draws 20 A at full-load and runs at 700 rpm. Assuming the magnetic circuit unsaturated, what will be the speed if (i) the load torque is increased by 44% (ii) the motor current is 10A? **(Ans. 577.2 rpm, 1437 rpm)**

12. A 120 V DC shunt motor has an armature and shunt field winding resistance of $0.2\ \Omega$ and $120\ \Omega$ respectively. The brush voltage drop is 2 V. The rated full-load armature current is 75 A. Calculate the current at the instant of starting and its value in terms of percentage of full-load armature current. **(Ans. 591 A; 788%)**
13. A 440 V, 80 A, 1200 rpm DC shunt motor has an armature resistance of $0.55\ \Omega$. Determine the resistance for each step of the starter for accomplishing starting in 4 steps. The maximum armature current should not exceed 150% of the full-load current. Neglect shunt field current being small.
(Ans. $1.3847\ \Omega$, $0.8618\ \Omega$, $0.5364\ \Omega$ and $0.3338\ \Omega$)
14. A 25 hp, 220 V DC shunt motor has an armature resistance of $0.1\ \Omega$. At full-load, it draws an armature current of 95A and runs at a speed of 600 rpm. It is to be braked by plugging. Estimate the value of the resistance which should be placed in series with it to limit the current to 130 A. What should be the initial value of the electric braking torque and value when the speed has fallen to half its full load value?
(Ans. $3.211\ \Omega$; $400.5\ \text{Nm}$; $302.57\ \text{Nm}$)

Short Answer Type Questions

Q.1. How does a DC motor differ from a DC generator in construction?

Ans. Basically, there is no difference in the construction of a DC generator and motor, however the frame of the generator can, as a rule, be open but those of motors should be either partly or totally enclosed.

Q.2. Why the emf generated in the armature of a DC motor is called the back emf?

Ans. Because this induced emf in a DC motor opposes the applied voltage, therefore, it is called back or counter emf.

Q.3. What do you understand by self excitation mode of DC machine? Name two DC machines working in this mode.

Ans. The DC machine in which field winding(s) is/are excited by the current supplied by the machine itself is said to be in its self excited mode. In such machines the field coils are inter-connected with the armature winding.

The self excited machines may be (i) DC shunt machine (ii) DC series machine

Q.4. What will be the effect on direction of rotation of a DC series motor if the supply terminals are reversed?

Ans. There will be no effect, motor will rotate in the same direction, as before the reversal of line terminals.

Q.5. How can the direction of rotation of a DC shunt motor be reversed?

Ans. Direction of rotation of a DC shunt motor can be reversed by reversing the current flow through either the armature winding or the field winding.

Q.6. What do you mean by speed regulation of a DC motor?

Ans. The speed regulation of a DC motor is defined as the change in speed when the load on the motor is reduced from rated load to zero load and is expressed in percentage of rated full-load speed

Q.7. In a DC motor, the brushes are given a backward shift why?

Ans. In a DC motor, the brushes are given backward shift to neutralise the effect of armature reaction and further to reduce sparking at the commutator.

Q.8. What should be the location of interpoles in a (i) motor (ii) generator.

Ans. In case of a motors, the interpoles having the same polarity as that of main poles must be placed behind them, whereas in case of a generators, the interpoles having same polarity as that of the main pole must be placed ahead of them in the direction of rotation.

Q.9. Why large variable speed DC motors are fitted with compensating windings?

Ans. To reduce sparking at brushes due to armature reaction.

Q.10. Why is the starting torque of a DC series motor more than that of a DC shunt motor of the same rating?

Ans. In case of a DC series motor flux ϕ is directly proportional to armature current I_a (before saturation) and, therefore, torque developed $T_e \propto I_a^2$ while in case of a DC shunt motor torque developed $T_e \propto I_a$ (flux being constant). Obviously on the basis of the same kW output and speed, a DC series motor develops the torque more than that of a shunt motor. Hence, series motors are capable to pick heavy loads at start.

Q.11. What would you expect if the field winding of a DC shunt motor gets disconnected while in normal operation?

Ans. The flux will drop to almost zero value (residual value) and, therefore, the speed will increase to a tremendously high value and the motor may get damaged due to heavy centrifugal forces.

Q.12. What is the purpose and location of a series field winding?

Ans. Series field winding is connected in series with the armature and placed over the magnetic pole core to set up necessary flux in the machine for production of torque.

Q.13. A DC shunt motor runs away at heavy loads. Comment.

Ans. The field may be weakened, due to armature reaction at heavy loads, to the extent that the motor runs away.

Q.14. What is difference between cumulative compound and differential compound wound motors?

Ans. In cumulative compound wound DC motors, the field produced by series field winding assists the field produced by shunt field winding, whereas in differential compound wound motors series field opposes the shunt field.

Q.15. A long shunt DC compound motor is cumulatively compounded. Without any change in connection, it is now run as a DC generator. State whether it will now be differentially or cumulatively compounded.

Ans. When a cumulatively compounded long shunt DC motor is run as a generator, the shunt and series field currents produce flux in opposite directions and thus it will operate as a differentially compounded generator.

Q.16. What is the field of application of DC shunt motor and DC series motor.

Ans. DC shunt motors are almost constant speed motors. These motors develop medium starting torque and their speed can be adjusted by using speed control methods. Therefore, shunt motors can be used for the loads which are totally and suddenly thrown off without resulting in excessive speed. Being constant speed motors, they are best suited for driving of line shafts, machine lathes, milling machines, conveyors, fans and for all purposes where constant speed is required.

DC series motors are variable speed motors. These motors develop large starting torque but attain dangerously high speed on no-load. So these motors cannot be operated at no-load. Series motors are best suited for electric traction, elevators, cranes, vacuum cleaners, sewing machines etc.

Q.17. Identify suitable DC motors for the following applications:

(a) Electric traction (b) Vacuum cleaners (c) Paper making (d) Shearing and punching.

Ans. (a) DC series motor (b) DC series motor (c) DC cumulative compound motor (d) DC cumulative compound motor.

Q.18. What would happen if a DC motor is directly switched ON to the supply, without any starter?

Ans. If a DC motor is directly switched *ON* to the supply, it will draw heavy current (about 10 – 12 times its rated value) which may over-heat the motor or damage it, depending upon the starting period.

Q.19. Why a starter is necessary for a DC motor?

Or

Why starters are used for DC motors.

Ans. A starter is employed to limit the starting current and provide necessary safety to the motor.

Q.20. A DC shunt motor is connected to a three-point starter. What would happen if

(i) the starter handle is moved rapidly from 'off to 'on' position;

(ii) the field circuit becomes open-circuited with the motor running at no-load;

(iii) the starter handle is pulled back to stop the motor.

Ans. (i) When the starter handle is moved rapidly from '*OFF*' to '*ON*' position, the resistance connected in series with the armature is being cut out at a faster rate and the speed of the motor is increased at a slow rate. Because of this the armature current will increase to a larger value and the ratio of upper and lower values of currents will not be maintained.

(ii) With the opening of field circuit with motor running at no-load, the field current will reduce to zero. So flux collapses and reduced to zero, in the process, the speed of motor will suddenly starts increasing and continue to increase if the supply is not cut-off.

(iii) Sparking will occur at the last stud due to release of energy stored in the magnetic field of field winding, which may burn it.

Q.21. It is desirable that the starting lever of a motor starter should fall back to off position when the power goes off. Why?

Ans. If the starter arm remains in the "*ON*" position when supply goes off, then on restoring the power supply, the motor will start without starting resistance. Hence, motor will draw heavy current when supply is restored.

Q.22. Discuss the limitations of a three-point starter.

Ans. In a three-point starter, the no-volt release coil is connected in series with the shunt field winding. If the field current is decreased to low value for speed control then magnetic strength of the no-volt release coil decreases to such an extent that spring tension brings the starting arm back to *OFF* position. To overcome this problem a four-point starter is used.

Q.23. Why do you prefer starter to rheostat in starting DC motors?

Ans. The starter also contains protective devices, such as no-volt release, overload release, etc.

Q.24. How does four point DC shunt motor starter differs from three point starter?

Ans. In a four point starter the circuits of no-volt release coil and shunt field are made independent and so the operation of no-volt release is not effected due to variations in field current.

5.20 Speed Control of DC Motors

The speed of a DC motor is given by the relation $N \propto \frac{E_b}{\phi}$ where $E_b = V - I_a R_a$

$$\therefore N \propto \frac{V - I_a R_a}{\phi}$$

From the above equation it is clear that the speed of DC motors can be controlled;

1. By varying flux per pole ϕ . This is known as *flux* or *field control method*.
2. By varying the armature drop, i.e., by varying the resistance of armature circuit. This is known as *armature control method*.
3. By varying the applied voltage. This is known as *voltage control method*.

5.21 Speed Control of Shunt Motors

5.21.1 Field Control Method

The speed of a DC motor can be increased by weakening the field and it can be decreased by strengthening the field. In DC shunt motors, the speed adjustments can be made by field control method by employing any one of the following methods:

1. Field-rheostat control method
2. Reluctance control method
3. Field-voltage control method

1. Field rheostat control method. The flux produced by the shunt field winding depends upon the current flowing through it (i.e., $\phi \propto I_{sh}$ and $I_{sh} = \left(\frac{V}{R_{sh}} \right)$. When a variable resistance R is

connected in series with the shunt field winding as shown in Fig. 5.29(a). The shunt field current $\left(I_{sh} = \frac{V}{R_{sh} + R} \right)$ is reduced and hence the flux ϕ . Consequently, the motor runs at a speed

higher than the normal speed (since $N \propto 1/\phi$), as shown in Fig. 5.29(b) The amount of increase in speed depends upon the value of variable resistance R .

This method is most common since very little power ($I_{sh}^2 R$) is wasted in the shunt field variable resistance due to relatively small value of I_{sh} .

In this method speed can be only increased, thus we can obtain speeds above normal. The other limitations and drawbacks of this method are:

- (i) Speeds below normal cannot be obtained.

- (ii) The speeds above normal can be obtained by weakening the field. The advantage of high speed cannot be considered for increase in power output rather to compensate the power, armature has to draw extra current from the mains.
- (iii) To obtain high speed, the field is very weak, to obtain certain load torque, armature draws extra current which may causes overheating of armature winding; poor commutation and instability.

Hence, the high speeds are restricted to certain extent. High speeds are also restricted due to mechanical considerations such as centrifugal forces developing in the armature conductors and friction occurring at the bearings.

Accordingly there is a limit to the maximum speed obtainable with this method. It is mainly because of poor commutation at weak fluxes. A ratio of maximum to minimum speeds of 6 is fairly common.

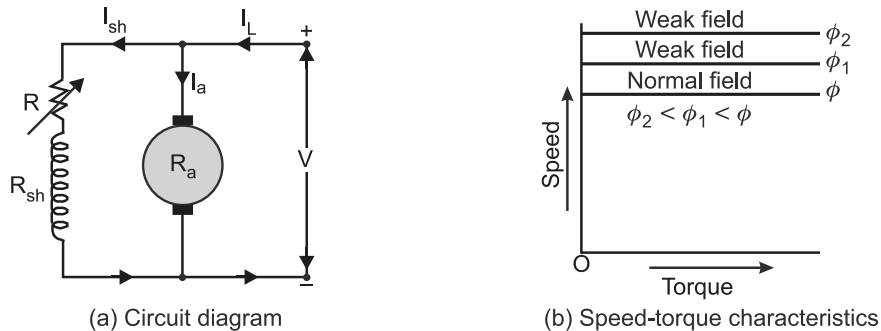


Fig. 5.29 Speed control of DC shunt motor by field control method

2. **Reluctance control method.** The flux or field can also be controlled by controlling the reluctance of the magnetic circuit, but this can only be obtain by employing some special mechanical features which increases the cost of machine. Therefore, practically this method is not employed.
3. **Field-Voltage control method.** The flux or field can also be controlled by supplying variable voltage to the field winding. This can only be achieved by disconnecting the field winding from the armature and supplying variable voltage from some other source. Then the motor is treated as separately excited DC motor.

5.21.2 Armature Control Method

In this method, voltage applied to the armature is changed without altering the field current. This cannot be achieved by just changing the common supply voltage because it will also affect the field simultaneously and the combined effect will have little change in the speed of shunt motor. Hence, to adjust the speed of DC shunt motors by armature control method, different arrangements are made and the methods are known as:

1. Armature-resistance control method
2. Shunted-armature control method
3. Armature terminal-voltage control method

- 1. Armature resistance control method.** In a shunt motor, flux is constant when applied terminal voltage and shunt field resistance are constant. Therefore, speed of the motor is directly proportional to induced emf (i.e., $N \propto E_b$ and $E_b = V - I_a R_a$). The value of E_b depends upon the drop in the armature circuit. When a variable resistance is connected in series with the armature as shown in Fig. 5.30(a) the induced emf [$E_b = V - I_a (R_a + R)$] is reduced and hence the speed. Thus, the motor runs at a speed lower than the normal speed as shown in Fig. 5.30(b).

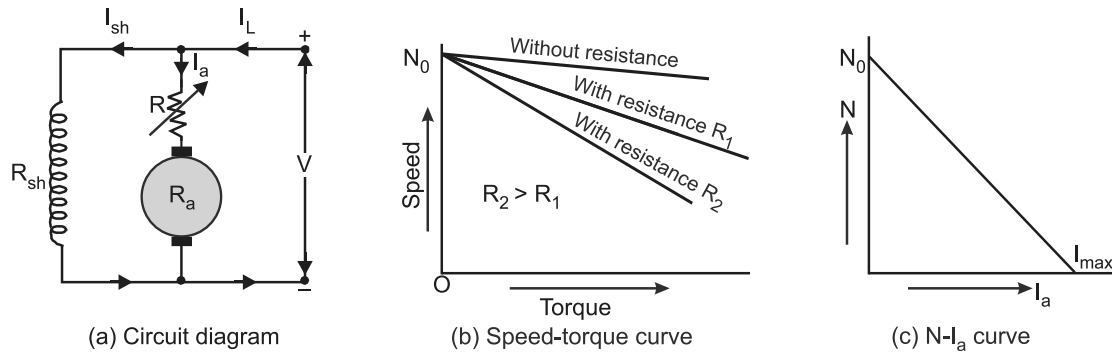


Fig. 5.30 Speed control of DC shunt motor by armature control method

For a constant load, the armature current remains the same so the input to the motor remains the same but the output decreases in proportion to the speed. Therefore, for the loads such as fans and centrifugal pumps where the load torque decreases with the fall in speed, this method of speed control is quite convenient and economical.

By this method, a wide range of speeds (below normal) can be obtained. Moreover, motor develops any desired torque over its operating range since torque depends only upon the armature current (flux remaining unchanged). The major advantage of this method is that the speed of the motor can be reduced to any low value and creeping speed (only a few rpm) can be developed so easily, as shown in Fig. 5.30(c).

The major disadvantage of this method of speed control is that there is heavy loss of power in the control rheostat.

- 2. Shunted-armature control method.** An armature resistance control method is very simple and usually employed when speeds below normal are required. But this method suffers from the drawback that the motor speed changes with every change in load on the machine. It is because the speed variation does not depend only upon the controlling resistance but it also depends upon load current. Because of this reason constant speed cannot be obtained in case of rapidly changing loads. To improve the stability, a shunt diverted is used across the armature in addition to series resistance, as shown in Fig. 5.31(a). By this arrangement, the changes in armature current due to change in load torque will not be so effective to change the voltage across armature and hence the speed of the motor remains almost constant.

Figure 5.31(b) shows the speed-torque characteristics for shunted armature control method. In this method, the ideal no-load speed of the motor (N'_0) will be less than that obtained by conventional series resistance method (N_0). This difference occurs due to the fact that even if no current flows through the motor armature, there is some current in the series resistance and

the diverter. Hence, there is some voltage drop in series resistance which reduces the voltage coming across the armature. Thus, in this arrangement, the voltage coming across the armature is always less than the supply voltage. Whereas in case of conventional series resistance control method, the voltage coming across armature is V . The following three characteristics have been drawn in Fig. 5.31(b).

- (i) Normal speed-torque characteristics – curve-A.
- (ii) Speed-torque characteristics with conventional series resistance control – curve-B
- (iii) Speed-torque characteristics with shunted armature control – curve-C.

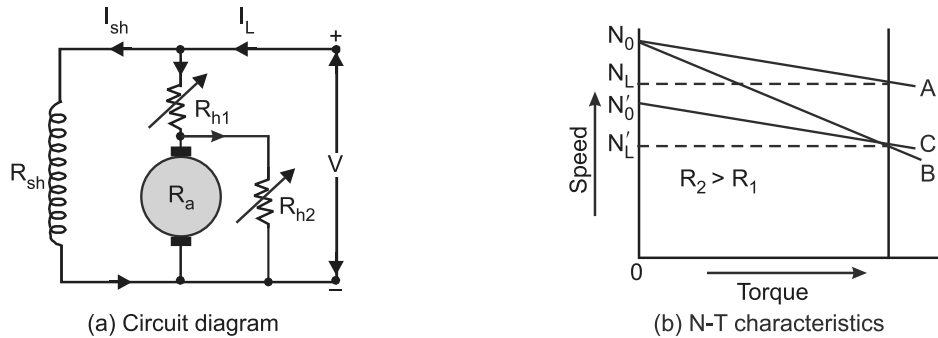


Fig. 5.31 Speed control of DC shunt motors by shunted armature control method.

3. Armature terminal-voltage control method. In this method, speed of a DC shunt motor is changed by changing the voltage applied across the armature. This can be achieved only by providing a separate voltage source. Although this method avoids the disadvantages of poor speed regulation and low efficiency, which are the characteristics of armature-resistance control method, but it is very expensive and has very high initial cost. It is because an adjustable voltage generator or an adjustable electronic regulator is required to supply variable voltage to the armature. Both these machines are very costly.

This method gives a large range of speeds with any desired number of speed points. It is essentially a constant-torque system because the output of the motor decreases with a decrease in applied voltage and a corresponding decrease in speed.

5.22 Speed Control of Separately Excited Motors

Sometimes, it is also called an armature voltage control method of a DC shunt motor. In this case, a separate DC source is used to supply power to the armature of DC shunt motor or separately excited motor and the field winding is excited from a different source. The most common and accurate speed control method of separately excited DC motors is Ward-Leonard system as explained below :

Ward-Leonard System

This system is used to supply variable voltage to the motor. As shown in Fig. 5.32, a DC generator G is mechanically coupled with a prime mover PM which rotates the generator at constant speed. The field winding of the DC generator is connected to a constant voltage DC supply line through a field

regulator and reversing switch. The DC motor M is fed from the generator G and its field winding is connected directly to a constant DC supply line.

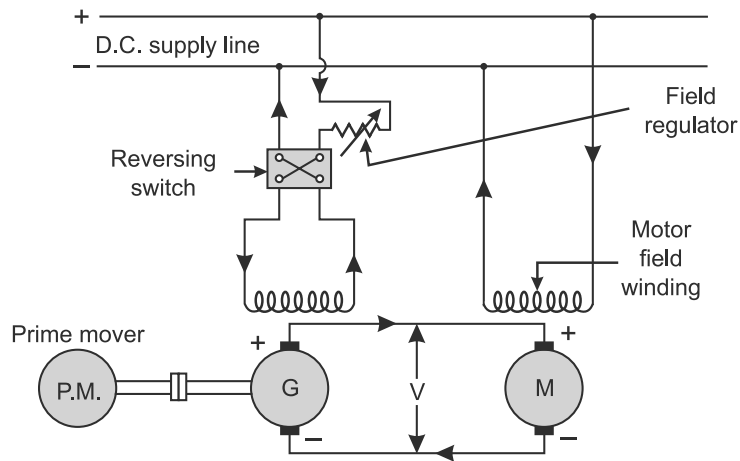


Fig. 5.32 Ward-Leonard method of speed control of DC motors

The voltage of the generator fed to the motor, can be varied from zero to its maximum value by means of its field regulator. By reversing the direction of the field current by means of the reversing switch, the polarity of the generated voltage can be reversed and hence the direction of rotation of motor M . Hence, by this method, the speed and direction of rotation both can be controlled very accurately.

The capital investment in this system is very high as two extra machines (a generator and a prime mover) are required. This system of speed control is best suited where almost unlimited speed control in either direction of rotation is required, e.g., in steel rolling mills, paper machines, elevators, cranes, diesel-electric propulsion of ships, etc.

5.23 Speed Regulation

The *speed regulation of a DC motor is defined as the change in speed from full load to no-load and is expressed as a percentage of the full load speed.*

$$\therefore \% \text{ Speed regulation} = \frac{\text{N.L. speed} - \text{F.L. speed}}{\text{F.L. speed}} \times 100 = \frac{N_0 - N}{N} \times 100 \quad \dots(5.18)$$

Example 5.18

The armature resistance of a 220 V DC generator is 0.4 ohm. It is delivering a load of 4 kW at rated terminal voltage. Now the machine is operated as a motor and draws the same armature current at the same terminal voltage. In this operation, if the flux per pole is increased by 10% what will be the ratio of generator to motor

Solution:

As a generator; $I_{a1} = I_L = \frac{4 \times 1000}{220} = 18.182 \text{ A}$

$$E_g = V + I_{a1}R_a = 220 + 18.182 \times 0.4 = 227.27 \text{ V}$$

As a motor;

$$I_a = I_{a2} = 18.182 \text{ A}$$

$$E_b = V - I_{a2}R_a = 220 - 18.182 \times 0.4 = 212.73 \text{ V}$$

$$\phi_2 = 1.1 \phi_1 \text{ (given)}$$

Now

$$N_1 \propto \frac{E_g}{\phi_1} \text{ and } N_2 \propto \frac{E_b}{\phi_2}$$

∴

$$\frac{N_1}{N_2} = \frac{E_g}{\phi_1} \times \frac{\phi_2}{E_b} = \frac{227.27}{\phi_1} \times \frac{1.1\phi_1}{212.73} = \mathbf{1.175} \text{ (Ans.)}$$

Example 5.19

A 250 V, 8 kW with $R_a = 0.7 \text{ ohm}$ DC shunt motor runs at 1250 rpm. Its field is adjusted at no-load so that its armature carries a current of 16 A. When load is applied, the current drawn by it increases to 40 A and speed falls to 1150 rpm. How much flux per pole reduces due to armature reaction.

Solution:

$$\text{At no-load; } E_{b0} = V - I_{a0}R_a = 250 - 1.6 \times 0.7 = 248.88 \text{ V}$$

$$\text{At full-load; } E_b = V - I_a R_a = 250 - 40 \times 0.7 = 222 \text{ V}$$

$$\text{Now, } N_0 \propto \frac{E_{b0}}{\phi_0} \text{ and } N \propto \frac{E_b}{\phi}$$

$$\text{Therefore } \frac{N}{N_0} = \frac{E_b}{\phi} \times \frac{\phi_0}{E_{b0}}$$

$$\text{or } \phi = \frac{E_b}{E_{b0}} \times \frac{N_0}{N} \times \phi_0$$

$$\text{or } \phi = \frac{222}{248.88} \times \frac{1250}{1150} \times 1 = 0.96956$$

$$\text{Reduction in flux} = 1 - 0.96956 = 0.03044 = \mathbf{3.044 \%} \text{ (Ans.)}$$

Example 5.20

A fan motor whose torque is proportional to the square of the speed is driven by a separately excited DC motor. The motor draws a current of 8 A at 120 V and runs at a speed of 500 rpm. What voltage and current is to be applied to run the motor at 750 rpm. The armature resistance of the motor is 1 ohm and losses are neglected.

Solution:

When 120 V is applied to the armature

$$\text{Armature current, } I_{a1} = 8 \text{ A}$$

$$\text{Back emf, } E_{b1} = V - I_{a1}R_a = 120 - 8 \times 1 = 112 \text{ V}$$

$$\text{Speed, } N_1 = 500 \text{ rpm}$$

Let voltage of V volt be applied to the armature to raise the speed to 750 rpm.

Then,
$$T_2 = T_1 \times \left(\frac{N_2}{N_1} \right)^2 = T_1 \times \left(\frac{750}{500} \right)^2 = 2.25 T_1 \quad (\text{Since } T \propto N^2 \text{ given})$$

or
$$I_{a2} \phi_2 = 2.25 I_{a1} \phi_1 \quad (\text{since } T \propto \phi I_a)$$

Assuming flux as constant

$$I_{a2} = 2.25 \times I_{a1} = 2.25 \times 8 = \mathbf{18 \text{ A}} \quad (\text{Ans.})$$

Now,
$$\frac{E_{b2}}{E_{b1}} = \frac{N_2}{N_1}$$

or
$$E_{b2} = \frac{N_2}{N_1} \times E_{b1} = \frac{750}{500} \times 112 = 168 \text{ V}$$

Applied voltage,
$$V_2 = E_{b2} + I_{a2} R_a = 168 + 18 \times 1 = \mathbf{186 \text{ V}} \quad (\text{Ans.})$$

Example 5.21

A 100 kW belt-driven shunt generator running at 300 rpm on 220 V bus bars continues to run as a motor when the belt breaks then taking 10 kW from the mains. What will be its speed? Armature resistance is 0.025 ohm, field circuit resistance is 60 ohm contact drop per brush is 1 V and ignore armature reaction.

Solution:

Shunt field current,
$$I_{sh} = \frac{220}{60} = 3.67 \text{ A}$$

(i) When the machine runs as a generator (see Fig. 5.33)

$$I_{L1} = \frac{100 \times 1000}{220} = 454.54 \text{ A}$$

$$I_{a1} = I_{L1} + I_{sh} = 454.54 + 3.67 = 458.21 \text{ A}$$

$$\begin{aligned} E_g &= V + I_{a1} R_a + 2v_b \\ &= 220 + 458.21 \times 0.025 + 2 \times 1 = 233.455 \text{ V} \end{aligned}$$

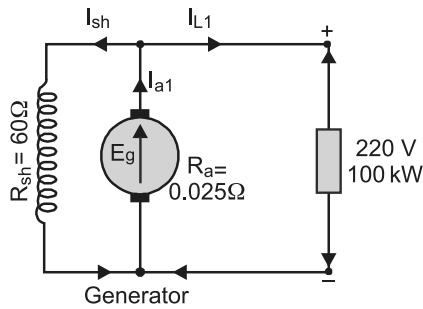


Fig. 5.33 Circuit diagram

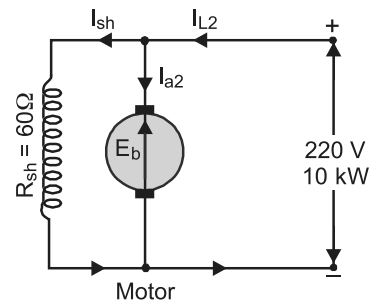


Fig. 5.34 Circuit diagram

(ii) When the machine runs as a motor (see Fig. 5.59.)

$$I_{L2} = \frac{10 \times 1000}{220} = 45.45 \text{ A}; I_{a2} = I_{L2} - I_{sh} = 45.45 - 3.67 = 41.78 \text{ A}$$

$$E_b = V - I_{a2} R_a - 2v_b = 220 - 41.78 \times 0.025 - 2 \times 1 = 216.955 \text{ V}$$

In shunt machines, flux is constant;

$$\therefore N_1 \propto E_g \text{ and } N_2 \propto E_b$$

$$\text{or } \frac{N_2}{N_1} = \frac{E_b}{E_g}$$

$$\text{or } N_2 = \frac{E_b}{E_g} \times N_1 = \frac{216.955}{233.455} \times 300 = \mathbf{278.8 \text{ rpm (Ans)}}$$

Example 5.22

A 240 V DC shunt motor has a field resistance of 400 ohm and an armature resistance of 0.1 ohm. The armature current is 50 A and the speed is 1000 rpm. Calculate the additional resistance in the field to increase the speed to 1200 rpm. Assume that armature current remains the same and the magnetisation curve to be a straight line.

Solution:

When no resistance is added in the shunt field winding

$$\text{Shunt field current, } I_{sh} = \frac{V}{R_{sh}} = \frac{240}{400} = 0.6 \text{ A}$$

$$E_{b1} = E_{b2} = V - I_a R_a = 240 - 50 \times 0.1 = 235 \text{ V (since } I_a \text{ is constant)}$$

$$\text{Now, we know that, } N \propto \frac{E_b}{\phi}$$

$$\therefore N_1 \propto \frac{E_{b1}}{\phi_1} \text{ and } N_2 \propto \frac{E_{b2}}{\phi_2}$$

$$\text{or } \frac{N_2}{N_1} = \frac{E_{b2}}{\phi_2} \times \frac{\phi_1}{E_{b1}} = \frac{\phi_1}{\phi_2} \quad (\because E_{b1} = E_{b2} = 235 \text{ V})$$

As the magnetisation curve is a straight line, $\phi_1 \propto I_{sh1}$ and $\phi_2 \propto I_{sh2}$

$$\therefore \frac{N_2}{N_1} = \frac{I_{sh1}}{I_{sh2}}$$

$$\text{or } I_{sh2} = \frac{N_1}{N_2} \times I_{sh1} = \frac{1000}{1200} \times 0.6 = 0.5 \text{ A}$$

$$\text{or } \frac{240}{400 + R} = 0.5$$

$$\therefore R = \mathbf{80 \Omega (Ans)}$$

Example 5.23

A 250 V shunt motor runs at 1500 rpm at full load with an armature current of 15 A. The total resistance of the armature and brushes is 0.6 Ω . If the speed is to be reduced to 1200 rpm with the same armature current, calculate the amount of resistance to be connected in series with the armature and power lost in this resistor.

Solution:

During normal operating conditions;

$$\text{Armature current, } I_{a1} = 15 \text{ A}$$

$$\text{Back emf, } E_{b1} = V - I_{a1} R_a = 250 - 15 \times 0.6 = 241 \text{ V}$$

$$\text{Speed, } N_1 = 1500 \text{ rpm}$$

Let a resistance R ohm be connected in series with armature, then

$$\text{Speed, } N_2 = 1200 \text{ rpm}$$

$$\text{Back emf, } E_{b2} = V - I_{a2} (R + R_a) = 250 - 15(0.6 + R) = 241 - 15R$$

$$\text{Now, } \frac{E_{b2}}{E_{b1}} = \frac{N_2}{N_1} \text{ (Since flux is constant)}$$

$$\frac{241 - 15R}{241} = \frac{1200}{1500} \text{ or } 241 - 15R = 192.8 \text{ or } R = 3.213 \Omega \text{ (Ans.)}$$

$$\text{Power lost} = I_a^2 R = (15)^2 \times 3.213 = 723 \text{ W (Ans.)}$$

Example 5.24

A DC shunt motor runs at 1000 rpm on 220 V supply. Its armature and field resistances are 0.5 ohm and 110 ohm respectively and the total current taken from the supply is 26 A. It is desired to reduce the speed to 750 rpm keeping the armature and field currents same. What resistance should be inserted in the armature circuit?

Solution:

$$\text{Shunt field current, } I_{sh} = \frac{V}{R_{sh}} = \frac{220}{110} = 2 \text{ A}$$

$$\text{Armature current, } I_a = I_L - I_{sh} = 26 - 2 = 24 \text{ A}$$

When no resistance is connected in series with the armature,

$$\text{Induced emf, } E_{b1} = V - I_a R_a = 220 - 24 \times 0.5 = 208 \text{ V}$$

Let the resistance connected in series with the armature be R ohm, as shown in Fig. 5.35. to reduce the speed to 750 rpm

$$\text{Then, induced emf, } E_{b2} = V - I_a (R_a + R) = 220 - 24 (0.5 + R) = (208 - 24R) \text{ V} \quad \dots(i)$$

$$\text{Now, we know that, } N \propto \frac{E_b}{\phi}$$

Flux ϕ is constant because shunt field current remains the same.

$$\therefore N_1 \propto E_{b1} \text{ and } N_2 \propto E_{b2}$$

$$\text{Taking their ratio, } \frac{E_{b2}}{E_{b1}} = \frac{N_2}{N_1}$$

$$\begin{aligned} \text{or } E_{b2} &= \frac{N_2}{N_1} \times E_{b1} = \frac{750}{1000} \times 208 \\ &= 156 \text{ V} \end{aligned} \quad \dots(ii)$$

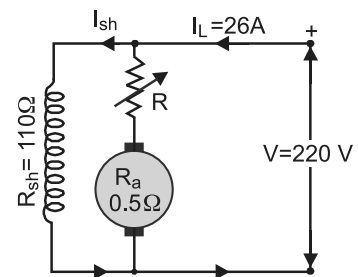


Fig. 5.35 Circuit diagram

Equating eq. (i) and (ii), we get,

$$208 - 24 R = 156 \quad \text{or} \quad R = \mathbf{2.167 \Omega} \text{ (Ans)}$$

Example 5.25

The armature resistance of a 200 V DC shunt motor is 0.5 ohm. When it draws an armature current of 30 A, it runs at a speed of 750 rpm. In order to reduce the speed to 450 rpm, what resistance must be added in the armature circuit keeping armature current constant. Further, what will be the speed of motor if its additional armature resistance is kept the same but armature current is reduced to 15 A.

Solution:

When no resistance is added in the armature circuit,

$$\text{Armature current, } I_{a1} = 30 \text{ A}$$

$$\text{Back emf, } E_{b1} = V - I_{a1} R_a = 200 - 30 \times 0.5 = 185 \text{ V}$$

$$\text{Speed, } N_1 = 750 \text{ rpm}$$

When a resistance (say R ohm) is connected in series with armature

$$\text{Armature current, } I_{a2} = I_{a1} = 30 \text{ A}$$

$$\text{Back emf, } E_{b2} = V - I_{a2} (R_a + R) = 200 - 30(0.5 + R) = (185 - 30R) \text{ volt.}$$

$$\text{Speed, } N_2 = 450 \text{ rpm}$$

$$\text{Now, } \frac{E_{b2}}{E_{b1}} = \frac{N_2}{N_1} \quad \text{(assuming flux as constant)}$$

$$\text{or} \quad \frac{185 - 30R}{185} = \frac{450}{750}$$

$$\text{or} \quad R = \frac{185 - 0.6 \times 185}{30} = \mathbf{2.467 \Omega} \text{ (Ans.)}$$

When armature current (say I_{a3}) changes to 15A.

$$\text{Back emf, } E_{b3} = V - I_{a3} (R + R_a) = 200 - 15(0.5 + 2.467) = 155.5 \text{ V}$$

$$\text{Speed } N_3 = N_1 \times \frac{E_{b3}}{E_{b1}} = 750 \times \frac{155.5}{185} = \mathbf{630.4 \text{ rpm}} \text{ (Ans.)}$$

Example 5.26

A 230 V shunt motor is taking a current of 50 A. Resistance of shunt field is 46 Ω and the resistance of the armature is 0.02 Ω . There is a resistance of 0.6 Ω in series with the armature and the speed is 900 rpm. What alternation must be made in the armature circuit to raise the speed to 1000 rpm, the torque remaining the same.

Solution:

$$\text{Line current, } I_{L1} = 50 \text{ A and } N_1 = 900 \text{ rpm}$$

$$\text{Shunt field current, } I_{sh} = \frac{V}{R_{sh}} = \frac{230}{46} = 5 \text{ A}$$

$$\text{Armature current, } I_{a1} = I_L - I_{sh} = 50 - 5 = 45 \text{ A}$$

$$\text{Back emf, } E_{b1} = V - I_a (R_a + R) = 230 - 45 (0.02 + 0.6) = 202.1 \text{ V}$$

Let the series resistance be reduced from 0.6Ω to R_1 ohm to raise the speed to 1000 rpm.

Since load torque is constant

$$\therefore T_2 = T_1 \text{ or } I_{a2} \phi_2 = I_{a1} \phi_1 \quad (\text{since } T \propto \phi I_a)$$

$$\text{or } I_{a2} = I_{a1} \times \frac{\phi_1}{\phi_2} = I_{a1} = 45 \text{ A} \quad (\text{assuming flux unchanged})$$

$$\text{Speed, } N_2 = 1000 \text{ rpm}$$

$$\text{Back emf, } E_{b2} = V - I_{a2} (R_a + R_1) = 230 - 45 (0.02 + R_1) = 229.1 - 45R_1$$

$$\text{Also } E_{b2} = E_{b1} \times \frac{N_2}{N_1} \quad (\text{since flux is constant})$$

$$\text{or } 229.1 - 45 R_1 = 202.1 \times \frac{1000}{900}$$

$$\text{or } R_1 = \mathbf{0.1 \Omega} \text{ (Ans.)}$$

i.e., Additional resistance of 0.6Ω will have to be reduced to 0.1Ω in order to raise the motor speed from 900 rpm to 1000 rpm. (Ans.)

Example 5.2

A 250 V shunt motor has an armature current of 20 A when running at 1000 rpm against full-load torque. The armature resistance is 0.5Ω . What resistance must be inserted in series with the armature to reduce the speed to 800 rpm at the same torque, and what will be the speed if the load torque is halved with this resistance in the circuit. Assume the flux to remain constant throughout and neglect brush contact drop.

Solution:

At normal conditions; $I_{a1} = 20 \text{ A}$; $N_1 = 1000 \text{ rpm}$

$$\text{Back emf, } E_{b1} = V - I_{a1} R_a = 250 - 20 \times 0.5 = 240 \text{ V}$$

Let R be the resistance connected in series with the armature circuit to reduce the speed to 800 rpm, i.e., $N_2 = 800 \text{ rpm}$

$$\text{Load torque, } T_2 = T_1 \quad (\text{given})$$

$$\text{or } I_{a2} \phi_2 = I_{a1} \phi_1 \quad (\text{since } T \propto \phi I_a)$$

$$\text{or } I_{a2} = I_{a1} = 20 \text{ A} \quad (\text{flux } \phi \text{ being constant})$$

$$\text{Back emf } E_{b2} = V - I_{a2} (R_a + R) = 250 - 20 (0.5 + R) = 240 - 20 R$$

$$\text{Now, } \frac{E_{b2}}{E_{b1}} = \frac{N_2}{N_1} \quad (\phi \text{ being constant})$$

$$\text{or } \frac{240 - 20R}{240} = \frac{800}{1000}$$

or $R = 2.4 \Omega$ (Ans.)

When load torque is reduced to half

i.e., $T_3 = 0.5 T_1$ or $I_{a3} \phi_3 = 0.5 I_{a1} \phi_1$

or $I_{a3} = 0.5 I_{a1} = 0.5 \times 20 = 10 \text{ A}$ (since ϕ is constant)

Back emf, $E_{b3} = V - I_{a3} (R + R_a) = 250 - 10 (2.4 + 0.5) = 221 \text{ V}$

$$\frac{N_3}{N_1} = \frac{E_{b3}}{E_{b1}} \quad (\phi \text{ being constant})$$

or $N_3 = N_1 \times \frac{E_{b3}}{E_{b1}} = 1000 \times \frac{221}{240} = \mathbf{920.8 \text{ rpm}}$ (Ans.)

Example 5.28

The field winding resistance and armature resistance of a 240 V DC shunt motor is 120 ohm and 0.1 ohm respectively. It draws 24 A at rated voltage to run at 1000 rpm. Find the value of additional resistance required in the armature circuit to reduce the speed to 800 rpm when (i) the load torque is proportional to speed (ii) the load torque varies as the square of the speed.

Solution:

At normal conditions; $I_{L1} = 24 \text{ A}$ and $N_1 = 1000 \text{ rpm}$

$$\text{Shunt field current, } I_{sh} = \frac{V}{R_{sh}} = \frac{240}{120} = 2 \text{ A}$$

$$\text{Armature current, } I_{a1} = I_{L1} - I_{sh} = 24 - 2 = 22 \text{ A}$$

$$\text{Back emf, } E_{b1} = V - I_{a1} R_a = 240 - 22 \times 0.1 = 237.8 \text{ V}$$

- (i) Let R be the additional resistance required to be connected in armature circuit to reduce the speed to 800 rpm when the load torque is proportional to speed, i.e., $T_1 \propto N_1$ and $T_2 \propto N_2$

$$\therefore T_2 = T_1 \times \frac{N_2}{N_1} = T_1 \times \frac{800}{1000} = 0.8 T_1$$

$$\text{or } I_{a2} \phi_2 = 0.8 I_{a1} \phi_1 \text{ (since } T \propto \phi I_a \text{)}$$

$$\text{or } I_{a2} = 0.8 \times 22 = 17.6 \text{ (since } \phi_2 = \phi_1 = \text{constant)}$$

$$E_{b2} = V - I_{a2} (R_a + R) = 240 - 17.6 (0.1 + R) = 238.24 - 17.6 R$$

$$\text{Since } \frac{E_{b2}}{E_{b1}} = \frac{N_2}{N_1},$$

$$\text{or } \frac{238.24 - 17.6 R}{237.8} = \frac{800}{1000}$$

$$\text{or } 238.24 - 17.6R = 190.24 \text{ or } \mathbf{R = 2.73 \Omega}$$
 (Ans.)

- (ii) Let R_1 be the additional resistance required in the armature circuit to reduce the speed to 800 rpm when the load torque varies as the square of the speed

$$T_3 = T_1 \times \left(\frac{N_2}{N_1} \right)^2 = T_1 \times \left(\frac{800}{1000} \right)^2 = 0.64 T_1$$

$$\text{or } I_{a3} \phi_3 = 0.64 I_{a1} \phi_1 \quad (\text{since } T \propto \phi I_a)$$

$$\text{or } I_{a3} = 0.64 \times 22 = 14.08 \text{ A} \quad (\text{since } \phi_3 = \phi_1 = \text{constant})$$

$$E_{b3} = V - I_a (R_1 + R_a) = 240 - 14.08 (R_1 + 0.1) = 238.592 - 14.08 R_1$$

$$\text{Also, } \frac{E_{b3}}{E_{b1}} = \frac{N_3}{N_1} \quad \text{or} \quad \frac{238.592 - 14.08 R_1}{237.8} = \frac{800}{1000}$$

$$238.592 - 14.08 R_1 = 190.24 \text{ or } R_1 = \mathbf{3.434 \Omega} \text{ (Ans.)}$$

5.24 Speed Control of DC Series Motors

The speed of DC series motors can be controlled by any one of the following methods:

- (i) Armature control method
- (ii) Field control method
- (iii) Series – parallel control method

5.24.1 Armature Control Method

By making various adjustments in the armature circuit of a DC series motor its speed can be controlled. According to the adjustments made, these methods are known as;

1. Armature series resistance control method
2. Shunted armature control method
3. Armature terminal voltage control method.

1. Armature series resistance control method. In this method, a variable resistance is connected in series with the armature or motor as shown in Fig. 5.36(a). If the load and torque developed by the machine is constant, the speed of the motor depends upon back emf i.e., $N \propto E_b$. When no additional resistance is connected in series with the armature, then $E_{b1} = V - I_a (R_a + R_{se})$. However, when an additional resistance R is connected in series with the armature, then back emf, $E_{b2} = V - I_a (R_a + R_{se} + R)$. Obviously $E_{b2} < E_{b1}$ accordingly $N_2 < N_1$. Hence, by connecting an additional resistance in series with the armature we can obtain speeds below normal.

The speed-torque characteristics of a DC series motor without additional resistance and with additional series resistance is shown in Fig. 5.36(b). The maximum range of speed control of about 3: 1 will be available depending upon the load.

This is the most common method employed for the speed control of series motors. The power loss in the control resistance for many applications of DC series motors is not too serious, since in these applications the control is utilised for a large portion of time for decreasing the speed under light loads.

The major applications of this method of speed-control are for driving cranes, hoists, trains, etc., because such drives operate intermittently.

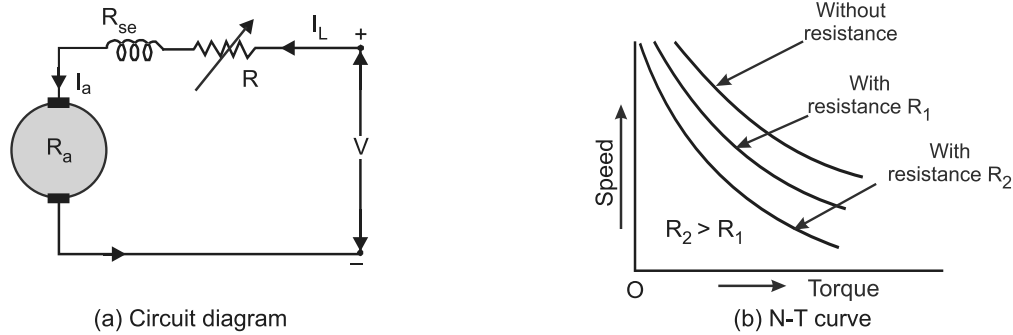


Fig. 5.36 Speed control of DC series motors by armature control method

- 2. Shunt armature control method.** In this method, combination of a rheostat R_2 shunting the armature and a rheostat R_1 in series with armature, as shown in Fig. 5.37 is used. It provides slow speeds at light loads. This is an arrangement which accomplishes the speed control both by lowering the voltage applied to the armature and by varying the flux. In fact, the voltage applied to the armature terminals is varied by varying series rheostat R_1 whereas the exciting current is varied by varying the shunting rheostat R_2 keeping the armature current constant.

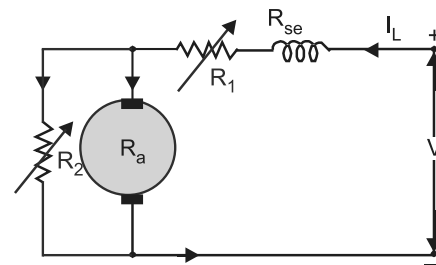


Fig. 5.37 Circuit diagram for shunted armature control method

In this method, by the insertion of armature diverter R_2 , armature current reduces, then flux ϕ must increase because torque developed ($T \propto I_a$) by the armature remains the same. This causes increase in current drawn from the supply mains which increases the field and decreases the speed.

Thus, by this method, speeds below normal can be obtained. A wide range of speeds below normal can be obtained by taking different ratios of R_1 and R_2 .

The application of this method is restricted to the places where speed control for short intervals is required because this method is not so economical due to considerable power losses in speed controlling resistance.

- 3. Armature terminal voltage control method.** In this method, a variable voltage power supply is used to change the supply voltage which changes the speed of a DC series motor. But the cost of such equipment is so high that this method is rarely applied.

5.24.2 Field Control Method

The speed of series motors can be controlled by varying the flux produced by the series field winding. The variation of flux can be brought about by anyone of the following ways;

- 1. Field diverters:** In this method, a variable resistance R is connected in parallel with the series field winding as shown in Fig. 5.38. Its effect is that it diverts the path of the current I_L drawn by the motor. A part of the current I_D flows through diverter and the current flowing through the series field winding is reduced which reduces the flux ϕ . Consequently, the speed of the motor is increased ($N \propto I/\phi$). Thus by this method, only speeds above normal can be obtained.
- 2. Armature diverter:** In this method, variable resistance R is connected in parallel with the armature is shown in Fig. 5.39. Its effect is that it diverts the path of the line current I_L . Some of the current I_D flows through the diverter and reduces the armature current I_a . For a given constant load torque, if I_a is reduced then ϕ must increase ($T \propto \phi I_a$). This results in increase in current drawn by the motor and a fall in speed ($N \propto 1/\phi$). By adjusting the value of diverter resistance, any speed below normal can be obtained by this method.

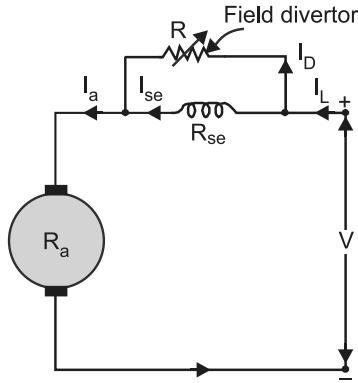


Fig. 5.38 Circuit diagram for field diverter method

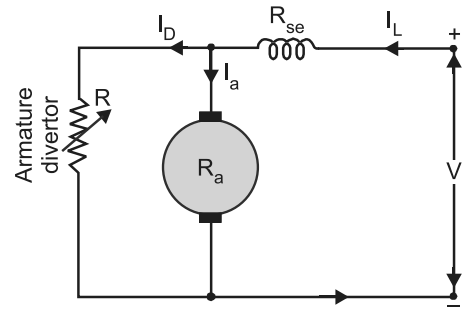


Fig. 5.39 Circuit diagram for armature diverter

- 3. Tapped field control:** In this method, the number of turns of the series field winding can be changed by short circuiting a part of it as shown in Fig. 5.40. We know that flux produced by the winding depends upon the ampere-turns (i.e., $\phi \propto I_{se} \times \text{No. of turns}$). As the number of turns are reduced, the speed of the motor is increased ($N \propto 1/\phi$). Thus, only speeds above normal can be obtained by this method.

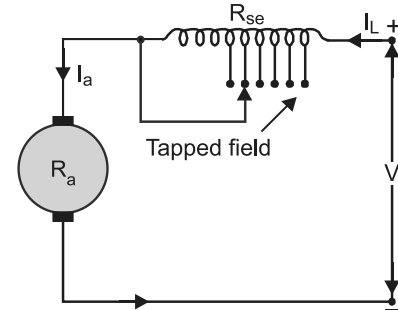


Fig. 5.40 Circuit diagram for tapped field

5.24.3 Voltage Control Method

In this method, the voltage across the series motors are changed by connecting them in series or in parallel or the combination of both. This is widely used in electric traction.

To explain this method, let us consider only two similar series motors (for simplicity) whose shafts are mechanically coupled. Firstly they are connected in series and then in parallel as shown in Figs. 5.41(a) and (b), respectively. The current flowing through each motor and the voltage across it is shown in Fig. 5.41.

When in series:

$$\text{Speed, } N_1 \propto \frac{E_{b1}}{\phi_1} \propto \frac{V/2 - I_a(R_a + R_{se})}{I_a}$$

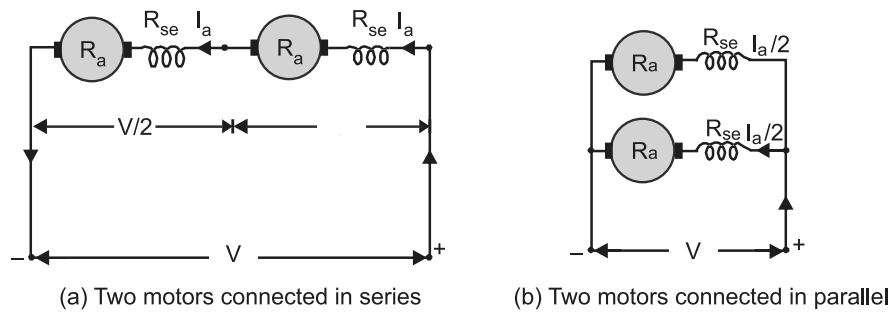


Fig. 5.41 Voltage control method

Neglecting drops,
$$N_1 \propto \frac{V/2}{I_a} \propto \frac{V}{2I_a} \quad \dots(5.19)$$

When in parallel:
$$\text{Speed, } N_2 \propto \frac{E_{b2}}{\phi_2} \propto \frac{V - \frac{I_a}{2}(R_a + R_{se})}{I_a/2} \propto \frac{2V}{I_a} \quad \dots(5.20)$$

From eq. (i) and (ii), we get,
$$\frac{N_2}{N_1} = \frac{2V}{I_a} \times \frac{2I_a}{V} = 4 \text{ or } N_2 = 4N_1 \quad \dots(5.21)$$

Thus, when the motors are connected in series, low speeds are obtained and when they are connected in parallel high speeds (nearly 4 times to that of first case) are obtained. Many speeds can be obtained by having more number of motors and connecting them in series, in parallel or the combination of both.

Usually, this method is employed in electric locomotives for controlling the speed of trains. In this case, combination of series-parallel and resistance control method is employed. The sequence of connections are shown in Fig. 5.42:

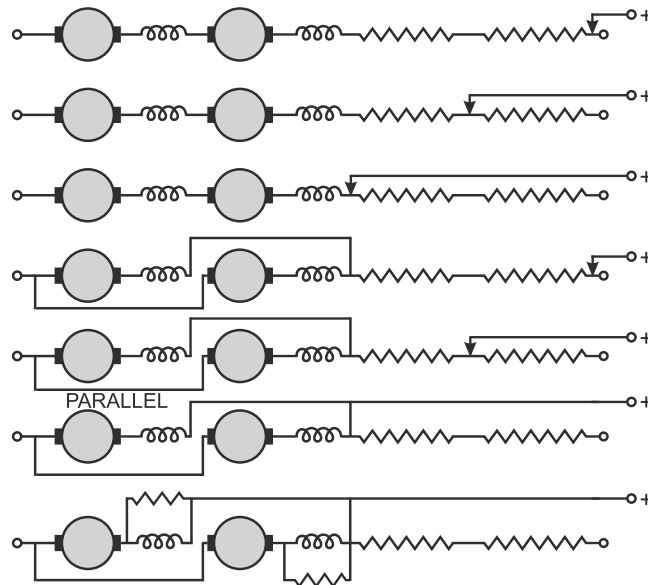


Fig. 5.42 Combination of series-parallel and resistance control of DC series motors

Example 5.29

The armature and field resistance of a 230 V DC series motor is 0.15 ohm and 0.1 ohm respectively. It runs at a speed of 800 rpm when connected to rated voltage drawing a current of 100 A. What will be its speed when it draws 25 A from the supply considering that its flux is only 45 percent at this current as compared to 100 A.

Solution:

Here $N_1 = 800$ rpm; $I_1 = 100$ A; $V = 230$ V; $R_a = 0.15 \Omega$

$$R_{se} = 0.1 \Omega; I_2 = 25 \text{ A}; \phi_2 = 0.45 \phi_1$$

We know, $N \propto \frac{E_b}{\phi}$ or $N_1 \propto \frac{E_{b1}}{\phi_1}$

and $N_2 \propto \frac{E_{b2}}{\phi_2}$ or $\frac{N_2}{N_1} = \frac{E_{b2}}{\phi_2} \times \frac{\phi_1}{E_{b1}}$

Where,

$$E_{b1} = V - I_{a2} (R_a + R_{se})$$

$$= 230 - 100 (0.15 + 0.1) = 230 - 25 = 205 \text{ V}$$

$$E_{b2} = V - I_{a2} (R_a + R_{se})$$

$$= 230 - 25 (0.15 + 0.1) = 230 - 6.25 = 223.75 \text{ V}$$

$\therefore$ Speed, $N_2 = \frac{E_{b2}}{\phi_2} \times \frac{\phi_1}{E_{b1}} \times N_1$

$$\frac{223.75}{0.45\phi_1} \times \frac{\phi_1}{205} \times 800 = \mathbf{1940.4 \text{ rpm (Ans.)}}$$

Example 5.30

The field and armature resistance of a 220 V DC series motor is 0.2 ohm and 0.4 ohm. At full-load it draws 38 A and runs at a speed of 600 rpm. Assume that brush voltage drop is 3 volt. (i) What will be the speed of motor when its intake current is reduced to 19 A (ii) What will be its speed if the load is removed and the motor draws only 1 A from the mains. (iii) Also determine the horse power developed by the motor in each case. While determining the values neglect effect of saturation and armature reaction.

Solution:

Since saturation is neglected, $\phi \propto I_a$

$$E_{b1} = V - I_{a1} (R_a + R_{se}) = 220 - 38 (0.4 + 0.2) = 197.2 \text{ V}$$

$$E_{b2} = V - I_{a2} (R_a + R_{se}) = 220 - 19 (0.4 + 0.2) = 208.6 \text{ V}$$

Now, $N_1 \propto \frac{E_{b1}}{\phi_1} \propto \frac{E_{b1}}{I_{a1}}$ and $N_2 \propto \frac{E_{b2}}{\phi_2} \propto \frac{E_{b2}}{I_{a2}}$

$$N_2 = \frac{E_{b2}}{I_{a2}} \times \frac{I_{a1}}{E_{b1}} \times N_1 = \frac{208.6 \times 38}{19 \times 197.2} \times 600 = \mathbf{1269.37 \text{ rpm (Ans.)}}$$

$$E_{b3} = V - I_{a3} (R_a + R_{se}) = 220 - 1 (0.4 + 0.2) = 219.4 \text{ V}$$

$$\therefore N_3 = \frac{E_{b3}}{I_{a3}} \times \frac{I_{a1}}{E_{b1}} \times N_1 = \frac{219.4 \times 38}{1 \times 197.2} \times 600 = \mathbf{25366 \text{ rpm (Ans.)}}$$

Internal horse power developed in each case;

$$HP_1 = \frac{E_{b1} I_{a1}}{735.5} = \frac{197.2 \times 38}{735.5} = \mathbf{10.19 \text{ (Ans.)}}$$

$$HP_2 = \frac{E_{b2} I_{a2}}{735.5} = \frac{208 \cdot 6 \times 19}{735.5} = \mathbf{5.39 \text{ (Ans.)}}$$

$$HP_3 = \frac{E_{b3} I_{a3}}{735.5} = \frac{219 \cdot 4 \times 1}{735.5} = \mathbf{0.298 \text{ (Ans.)}}$$

Example 5.31

A series motor with unsaturated magnetic circuit and with negligible resistance when running at a certain speed, on a given load takes 50 A at 500 V. If the load torque varies as cube of the speed, find the resistance necessary to reduce the speed by 20%.

Solution:

In series motors, $T \propto \phi I_a$; $T \propto I_a^2$ ($\because \phi \propto I_a$)

Given that, $T \propto N^3$

$$\therefore I_{a1}^2 \propto N_1^3 \text{ and } I_{a2}^2 \propto N_1^3$$

$$\text{or } \frac{I_{a2}}{I_{a1}} = \left(\frac{N_2}{N_1} \right)^{1.5}$$

$$\text{or } I_{a2} = \left(\frac{N_2}{N_1} \right)^{1.5} \times I_{a1}$$

$$\text{Now, } N_2 = 0.8 N_1$$

$$I_{a2} = (0.8)^{1.5} \times 50 = 35.777 \text{ A}$$

$$\text{Circuit resistance in first case, } R_1 = \frac{V}{I_{a1}} = \frac{500}{50} = 10 \Omega$$

$$\text{Circuit resistance in second case, } R_2 = \frac{V}{I_{a2}} = \frac{500}{35.777} = 13.975 \Omega$$

Additional resistance required to reduce the speed;

$$R = R_2 - R_1 = 13.975 - 10 = \mathbf{3.975 \Omega \text{ (Ans.)}}$$

Example 5.32

A 240 V, DC series motor has a resistance of 0.2 ohms, when the line current is 40 A, speed is 1800 rpm. Find the resistance to be added in series with the motor (i) to make the motor run at 900 rpm when line current is 60A (ii) to limit the speed to 3600 rpm when line current is 10 A (iii) speed of motor when it is connected directly to mains and line current is 60 A. Assume flux at 60A is 1.8 times of flux at 40A.

Solution:

Here, $V = 240 \text{ V}$; $R_m = 0.2 \Omega$; $I_{a1} = 40 \text{ A}$; $N_1 = 1800 \text{ rpm}$

$$\text{Back emf } E_{b1} = V - I_{a1} R_m = 240 - 40 \times 0.2 = 232 \text{ V}$$

$$\text{For } I_{a1} = 40 \text{ A; flux} = \phi_1$$

$$\text{For } I_{a2} = 60 \text{ A; flux} = \phi_2 \text{ where } \phi_2 = 1.8 \phi_1$$

$$(i) \ N_2 = 900 \text{ rpm; } I_{a2} = 60 \text{ A; then } \phi_2 = 1.8 \phi_1$$

Let R be the resistance added in motor circuit

$$\begin{aligned} E_{b2} &= V - I_{a2} (R_m + R) = 240 - 60 (0.2 + R) \\ &= 240 - 12 - 60 R = 228 - 60 R \end{aligned}$$

$$\text{Now} \quad N \propto \frac{E_b}{\phi} \quad \text{or} \quad \frac{N_2}{N_1} = \frac{E_{b2}}{\phi_2} \times \frac{\phi_1}{E_{b1}}$$

$$\text{or} \quad \frac{900}{1800} = \frac{(228 - 60R)}{1.8 \phi_1} \times \frac{\phi_1}{232}$$

$$\text{or} \quad 228 - 60 R = \frac{1.8 \times 232 \times 900}{1800}$$

$$\text{or} \quad 228 - 60R = 208.8 \quad \text{or} \quad R = \mathbf{0.32 \Omega} \text{ (Ans.)}$$

$$(ii) \ N_3 = 3600 \text{ rpm; } I_{a3} = 10 \text{ A; } \phi_3 \propto I_{a3} \text{ and } \phi_1 \propto I_{a1}$$

Let R_1 be the resistance added in series with the motor

$$\begin{aligned} E_{b3} &= V - I_{a3} (R_m + R_1) = 240 - 10 (0.2 + R_1) \\ &= 240 - 2 - 10 R_1 = 238 - 10 R_1 \end{aligned}$$

$$N \propto \frac{E_b}{\phi}; \quad \frac{N_3}{N_1} = \frac{E_{b3}}{\phi_3} \times \frac{\phi_1}{E_{b1}}$$

$$\frac{N_3}{N_1} = \frac{E_{b3}}{E_{b1}} \times \frac{I_{a1}}{I_{a3}} \quad \text{(Considering linear magnetisation)}$$

$$\frac{3600}{1800} = \frac{(238 - 10R_1)}{232} \times \frac{40}{10}$$

$$\text{or} \quad 238 - 10R_1 = \frac{3600 \times 10 \times 232}{1800 \times 40}$$

$$\text{or} \quad 238 - 10R_1 = 116 \text{ or } R_1 = \mathbf{12.2 \Omega} \text{ (Ans.)}$$

$$(iii) \ N_4 = ?; I_{a4} = 60 \text{ A and } \phi_4 = 1.8 \phi_1$$

$$E_{b4} = V - I_{a4} (R_m) = 240 - 60 \times 0.2 = 228 \text{ V}$$

$$\frac{N_4}{N_1} = \frac{E_{b4}}{\phi_2} \times \frac{\phi_1}{E_{b1}}$$

or
$$N_4 = \frac{228}{1.8\phi_1} \times \frac{\phi_1}{232} \times 1800$$

or
$$N_4 = \mathbf{982.76 \text{ rpm (Ans.)}}$$

Example 5.33

A 400 V series motor has a total resistance of 0.25 ohm, when running at 1200 rpm it draws a current 25A. When a regulating resistance of 2.75 ohm is included in the armature circuit, it draws a current of 15A. Find the speed and ratio of the two mechanical outputs. Assume that the flux with 15A is 70% of that with 25A.

Solution:

$$E_{b1} = V - I_{a1} (R_a + R_{se}) = 400 - 25 \times 0.25 = 393.75 \text{ V}$$

$$E_{b2} = V - I_{a2} [R_a + R_{se}] + R] = 400 - 15 [0.25 + 2.75] = 355 \text{ V}$$

$$\phi_2 = 0.75 \phi_1$$

Now,
$$N_1 \propto \frac{E_{b1}}{\phi_1} \text{ and } N_2 \propto \frac{E_{b2}}{\phi_2}$$

$$\therefore N_2 = \frac{E_{b2}}{\phi_2} \times \frac{\phi_1}{E_{b1}} \times N_1 = \frac{355}{0.75\phi_1} \times \frac{\phi_1}{393.75} \times 1200 = \mathbf{1442.54 \text{ rpm (Ans.)}}$$

Mechanical power developed in two cases;

$$P_1 = E_{b1} I_{a1} = 393.75 \times 25 = \mathbf{9843.75 \text{ W (Ans.)}}$$

$$P_2 = E_{b2} I_{a2} = 355 \times 15 = \mathbf{5325 \text{ W (Ans.)}}$$

Example 5.34

The field and armature resistance of a 200 V DC series motor is 0.3 ohm and 0.5 ohm respectively. The motor runs at a speed of 700 rpm when drawing a current of 25 A. What value of additional series resistance is required to reduce the speed to 350 rpm keeping intake current constant.

Solution:

Motor input current, $I_1 = 25 \text{ A}$

$$\text{Back emf, } E_{b1} = V - I_1 (R_a + R_{se}) = 200 - 25 (0.5 + 0.3) = 180 \text{ V}$$

$$\text{Speed, } N_1 = 700 \text{ rpm}$$

Let R be the resistance connected in series with the motor to reduce the speed to

$$N_2 = 350 \text{ rpm}$$

Motor input current, $I_2 = I_1 = 25 \text{ A}$

$$\begin{aligned} \text{Back emf, } E_{b2} &= V - I_2 (R + R_a + R_{se}) \\ &= 200 - 25 (R + 0.5 + 0.3) = 180 - 25 R \end{aligned}$$

Since
$$N \propto \frac{E_b}{\Phi},$$

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\Phi_1}{\Phi_2} = \frac{E_{b2}}{E_{b1}} \quad (\phi_2 = \phi_1 \text{ as field current remains the same})$$

or
$$\frac{350}{700} = \frac{180 - 25R}{180}$$

or
$$R = \mathbf{3.6 \text{ ohm}} \text{ (Ans.)}$$

Example 5.35

The field and armature resistance of a 500 V DC series motor is 0.2 ohm and 0.3 ohm respectively. The motor runs at 500 rpm when drawing a current of 49 A. If the load torque varies as the square of the speed, determine the value of the external resistance to be added in series with the armature for the motor to run at 450 rpm Assume linear magnetisation.

Solution:

Here, $N_1 = 500 \text{ rpm}$; $I_{a1} = 40 \text{ A}$; $V = 600 \text{ V}$; $N_2 = 450 \text{ rpm}$

$$T \propto N^2; R_a = 0.3 \Omega; R_{se} = 0.2 \Omega; \phi \propto I_a$$

$$E_{b1} = V - I_{a1} (R_a + R_{se}) = 600 - 40 (0.3 + 0.2) = 580 \text{ V}$$

$$T \propto \phi I_a \text{ or } T \propto I_a^2$$

and
$$T \propto N^2$$

$\therefore$
$$I_a^2 = N^2$$

and
$$\left(\frac{I_{a2}}{I_{a1}} \right)^2 = \left(\frac{N_2}{N_1} \right)^2$$

or
$$I_{a2} = \frac{N_2}{N_1} \times I_{a1} = \frac{450}{500} \times 40 = 36 \text{ A}$$

Let R be the resistance added in series with the armature

$$E_{b2} = V - I_{a2} (R_a + R_{se} + R) = 600 - 36 (0.3 + 0.2 + R) = 582 - 36R$$

Now
$$\frac{N_2}{N_1} = \frac{E_{b2}}{\phi_2} \times \frac{\phi_1}{E_{b1}} \text{ or } \frac{N_2}{N_1} = \frac{E_{b2}}{I_{a2}} \times \frac{I_{a1}}{E_{b1}}$$

or
$$\frac{450}{500} = \frac{(582 - 36R)}{36} \times \frac{40}{580}$$

or
$$582 - 36R = \frac{450 \times 36 \times 580}{500 \times 40}$$

or
$$582 - 36R = 469.8 \text{ or } R = \mathbf{3.117 \Omega} \text{ (Ans.)}$$

Example 5.36

A 240 V DC series motor takes 40 A when giving its rated output at 1200 rpm. The combined value of armature and series field resistance is 0.3 Ω . Find what resistance must be added to obtain the rated torque (a) at starting (b) at 800 rpm.

Solution:

Rated voltage, $V = 240 \text{ V}$

Rated current, $I_1 = 40 \text{ A}$

Rated speed, $N_1 = 1200 \text{ rpm}$

Back emf, $E_{b1} = V - I_a R_m = 240 - 40 \times 0.3 = 228 \text{ V}$

- (i) At start when speed is zero, the back emf E_{b2} will be zero and rated torque will be developed when current drawn by the motor is of rated value i.e.,

Current, $I_2 = 40 \text{ A}$

Back emf, $E_{b2} = V - I_2 (R_1 + R_m)$

$$\therefore \text{additional resistance, } R_1 = \frac{V - E_{b2}}{I_2} - R_m = \frac{240 - 0}{40} - 0.3 = \mathbf{5.7 \text{ ohm (Ans.)}}$$

- (ii) At 800 rpm, the rated torque will be developed only when current drawn by the motor is rated one i.e.,

$I_3 = 40 \text{ A}$

Since field current remains the same, back emf will be proportional to speed i.e.,

$$E_{b2} = E_{b1} \times \frac{N_3}{N_1} = 228 \times \frac{800}{1200} = 152 \text{ V}$$

$$\therefore \text{required additional resistance, } R_2 = \frac{V - E_{b3}}{I_3} - R_m = \frac{240 - 152}{40} - 0.3 = \mathbf{1.9 \Omega (Ans.)}$$

Example 5.37

A DC series motor, connected to a 440 V supply, runs at 1500 rpm when taking a current of 50 A. Calculate the value of resistance which when inserted in series with motor will reduce the speed to 1000 rpm, the gross torque being then half the previous value. The resistance between the terminals of the motor is 0.2Ω . Assume linear magnetisation.

Solution:

Here, $V = 440 \text{ V}$; $I_1 = 50 \text{ A}$; $R_m = 0.2 \Omega$; $N_1 = 1500 \text{ rpms}$; $N_2 = 1000 \text{ rpm}$

Back emf, $E_{b1} = V - I_1 R_m = 440 - 50 \times 0.2 = 430 \text{ V}$

Let R be the resistance connected in series to reduce the speed.

$$\text{Now } T_2 = \frac{1}{2} T_1 \text{ (given)}$$

$$\text{or } I_2 \phi_2 = \frac{1}{2} I_1 \phi_1 \quad (\text{since } T \propto \phi I)$$

$$\text{or } I_2^2 = \frac{1}{2} I_1^2 \text{ (since } \phi \propto I)$$

$$\text{or } I_2 = \sqrt{\frac{1}{2}} I_1 = \frac{50}{\sqrt{2}} = 35.35 \text{ A}$$

Back emf, $E_{b2} = V - I_2 (R + R_m) = 440 - 35.35 (0.2 + R) = 432.93 - 35.35 R$

We know,
$$\frac{E_{b2}}{E_{b1}} = \frac{N_2}{N_1} \times \frac{\phi_2}{\phi_1},$$

$$\frac{432.93 - 35.35 R}{430} = \frac{1000}{1500} \times \frac{35.35}{50} \quad \left(\text{since } \frac{\phi_2}{\phi_1} = \frac{I_2}{I_1} = \frac{35.35}{50} \right)$$

or
$$R = \mathbf{6.51 \, \Omega \, (Ans.)}$$

Example 5.38

A DC series motor has the following rating: 200 V, 20 A and 1200 rpm. Armature and series field resistances are $0.1 \, \Omega$ and $0.2 \, \Omega$ respectively. Magnetic circuit can be assumed to be linear.

At what speed the motor will run at rated torque if a resistance of $20 \, \Omega$ is placed in parallel with the armature?

Solution:

Here, $V = 200 \, \text{V}$; $I_1 = 20 \, \text{A}$; $R_a = 0.1 \, \Omega$; $R_{se} = 0.2 \, \Omega$; $N_1 = 1200 \, \text{rpm}$; $R_D = 20 \, \Omega$

$$\begin{aligned} \text{Back emf, } E_{b1} &= V - I_1(R_a + R_{se}) \\ &= 200 - 20(0.1 + 0.2) = 214 \, \text{V} \end{aligned}$$

When a resistance of $20 \, \Omega$ is connected parallel to armature, as shown in Fig. 5.43, let the motor input current be I_2 ampere.

$$\text{Voltage across armature} = V - I_2 R_{se} = 200 - 0.2 I_2$$

$$\text{Diverter current, } I_D = \frac{200 - 0.2 I_2}{20} = 10 - 0.01 I_2$$

$$\text{Armature current, } I_{a2} = I_2 - I_D = I_2 - (10 - 0.01 I_2) = 1.01 I_2 - 10$$

$$\text{At rated torque i.e., } T_2 = T_1$$

$$\text{or } I_{a2} \Phi_2 = I_{a1} \Phi_1 \quad (\text{since } T \propto \Phi I_a)$$

$$\text{or } I_{a2} = I_{a1} \times \frac{\Phi_1}{\Phi_2}$$

$$\text{or } 1.01 I_2 - 10 = I_1 \times \frac{I_1}{I_2} \quad (\text{series } \Phi \propto I)$$

$$\text{or } 1.01 I_2 - 10 = \frac{20 \times 20}{I_2}$$

$$\text{or } I_2 = 25.45 \, \text{A}$$

$$\text{Armature current, } I_{a2} = 1.01 I_2 - 10 = 1.01 \times 25.45 - 10 = 15.7 \, \text{A}$$

$$\text{Back emf, } E_{b2} = V - I_2 R_{se} - I_{a2} R_a = 200 - 25.25 \times 0.2 - 15.7 \times 0.1 = 193.34 \, \text{V}$$

$$\text{Then, } N_2 = N_1 \times \frac{E_{b2}}{E_{b1}} \times \frac{\Phi_1}{\Phi_2} = 1200 \times \frac{193.34}{214} \times \frac{20}{25.45} = \mathbf{852 \, \text{rpm} \, (Ans.)}$$

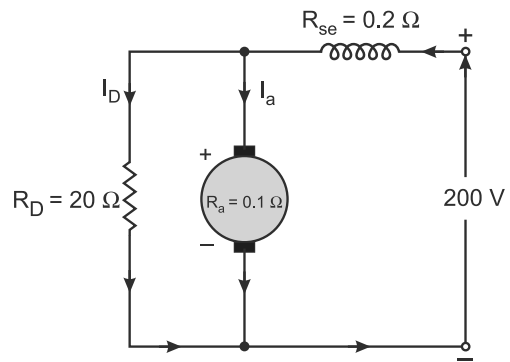


Fig. 5.43 Circuit diagram

Example 5.39

A series motor runs at 800 rpm when taking a current of 60 A at 460 V. The resistance of the armature circuit is 0.2Ω and that of the field winding is 0.1Ω . Calculate the speed when a 0.15Ω diverter is connected in parallel with the field winding. Assume the torque to remain unaltered and the flux to be proportional to the field current.

Solution:

At normal conditions, when no diverter is connected

$$\text{Armature current, } I_{a1} = I_{se1} = I_{L1} = 60 \text{ A}$$

$$E_{b1} = V - I_{a1} R_a - I_{se1} R_{se} = 460 - 60 \times 0.2 - 60 \times 0.1 = 442 \text{ V}$$

When a diverter of 0.15Ω is connected parallel to series field winding as shown in Fig. 5.44, let the speed be N_2 and the line current be I_{L2} .

$$\text{Armature current, } I_{a2} = I_{L2}$$

$$\text{Series field current, } I_{se2} = I_{L2} \frac{R_D}{R_{se} + R_D} = I_{L2} \frac{0.15}{0.1 + 0.15} = \frac{3}{5} I_{L2}$$

Since torque remains the same,

$$T_2 = T_1$$

$$\text{or } I_{a2} \Phi_2 = I_{a1} \Phi_1 \quad (\text{Since } \Phi \propto I_{se})$$

$$\text{or } I_{a2} I_{se2} = I_{a1} I_{se1}$$

$$\text{or } I_{L2} \times \frac{3}{5} I_{L2} = 60 \times 60$$

$$\text{or } I_{L2} = \sqrt{\frac{3600 \times 5}{3}} = 77.46 \text{ A}$$

$$I_{se2} = \frac{3}{5} \times I_{L2} = \frac{3}{5} \times 77.46 \text{ A} = 46.48 \text{ A}$$

$$\text{Back emf } E_{b2} = V - I_{a2} R_a - I_{se2} R_{se} = 460 - 77.46 \times 0.2 - 46.48 \times 0.1 = 440.06 \text{ V}$$

$$\text{Speed, } N_2 = N_1 \times \frac{E_{b2}}{E_{b1}} \times \frac{\Phi_1}{\Phi_2}$$

$$= N_1 \times \frac{E_{b2}}{E_{b1}} \times \frac{I_{se1}}{I_{se2}} = 800 \times \frac{440.06}{442} \times \frac{46.48}{60}$$

$$= \mathbf{617.6 \text{ rpm (Ans.)}}$$

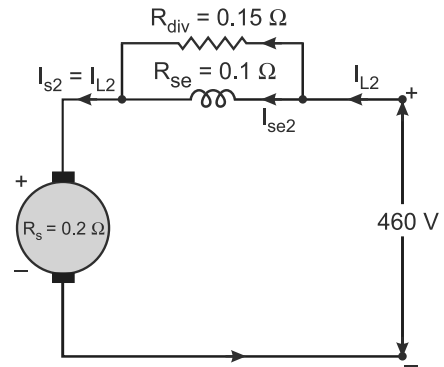


Fig. 5.44 Circuit diagram

5.25 Electric Braking

When load is removed from an electric motor and supply is disconnected, it continues to run for some time due to inertia. This continuous rotation may cause damage to equipment or to the manufactured product and even loss of human life. Therefore, quick stopping of a motor is essential in such cases.

Thus, *the method by which an electric motor or drive is brought to rest quickly when load on it is removed and supply is disconnected is called **braking**.*

Braking may be employed to bring the drive to rest or it may be employed to lower down the speed when load is reduced. The device employed for braking has to absorb the kinetic and potential energy of the moving parts.

Objectives of Braking

While stopping the drive, braking may be used for any one of the following objectives:

- (i) Reducing the time of stopping i.e., reducing the time of continuous running when drive is switched – *OFF*.
- (ii) Stopping the drive exactly at specified point, e.g., in lifts; for safety reasons, the drive has to be stopped at a specific point.
- (iii) For feeding back some of the energy to the supply system.

Essential Features of Braking

- (i) It should be quick and reliable in action.
- (ii) Braking force should be controllable.
- (iii) Suitable means must be provided for dissipating the stored energy of the rotating parts.
- (iv) A failure of any part of the braking system should result in the application of brakes.

Braking Systems

Broadly, in electric drives, two systems of braking can be applied:

- 1. Mechanical braking:** In mechanical braking the stored energy of rotating parts is dissipated in the form of heat where frictional torque acts against the rotation. The motor may be stopped by using a brake shoe or brake band or brake drum.
- 2. Electrical braking:** In electrical braking, the kinetic energy of the motor is converted into electrical energy and is dissipated as heat in a resistance or returned to the supply system.

Advantages and Disadvantages of Electrical Braking over Mechanical Braking

Before dealing with electric braking, let us try to find out the advantages and disadvantages of electric braking over mechanical braking.

Advantages

- (i) *Saving; no replacement cost:* In case of mechanical braking, due to friction there is excessive wear on brake lining which needs frequent and costly replacement. But in electric braking no such replacement is required hence saves money.
- (ii) *Small maintenance cost:* In case of mechanical braking there is more wear and tear which increases the maintenance cost. There is no wear and tear in case of electric braking which reduces the maintenance cost to very low value.

- (iii) *Energy saving:* In regenerative braking, a part of energy is returned to the supply this reduces the operating cost. This is only possible in electric braking.
- (iv) *Reliability:* In case of mechanical braking, the heat produced at brake blocks may result in failure of brakes. But in case of electric braking, the heat produced does not affect the braking system this improves its reliability.
- (v) *Smooth operation:* Mechanical braking may produce jerks but electric braking never produces jerks.
- (vi) *System Capacity:* By employing electric braking the capacity of the system can be increased by way of higher speeds and handling of heavy loads.

Disadvantages or Limitations

- (i) *It cannot hold the machine or load stationary:* In case of electric braking, the driving motor starts working as a generator during braking period. But at stand-still the machine (motor) cannot work as generator. Therefore, an electric brake can reduce the speed of the machine or load and bring it to almost at stand-still condition but it cannot hold it stationary. Hence, electric brake alone cannot fulfil the purpose, friction (mechanical) brake is always provided in addition to it.
- (ii) *Cost:* Addition equipment employed for electric braking increases the cost.
- (iii) *Choice of motor is limited:* In case of electric braking system, the motor has to function as a generator and must have suitable braking characteristics. Thus, the choice of motor is limited.

Electric braking is superior to mechanical braking since it is much quicker and eliminates the cost of maintenance of mechanical brakes. However, in order to finally bring the motor to a stand still position and hold it there, friction brakes are also essential.

5.26 Types of Electric Braking

There are three types of electric braking.

- (i) Plugging
- (ii) Rheostatic braking
- (iii) Regenerative braking.

5.26.1 Plugging

This is also called a counter-current braking. It is simplest type of braking and involves the reversing of the connections to the armature of the motor so that it tends to run in the reverse direction. In order to stop the machine, a special device must be installed to cut off the supply as soon as it comes to rest. This method can be applied to DC motors, induction motors and synchronous motors. It is particularly suitable where the drive has to be rapidly reversed such as in planning machines, etc.

- (a) **Plugging applied to DC Shunt motors:** The direction of rotation of DC shunt motor can be reversed by reversing the current flowing through the armature. The expression for the armature current is $I_a = \frac{V - E_b}{R_a}$.

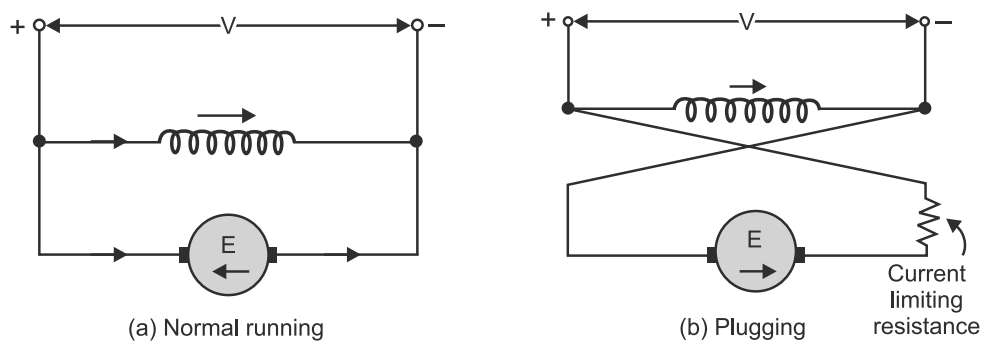


Fig. 5.45 Plugging with shunt motor

During normal running, the back $emf E_b$ is opposite to the applied voltage ' V ' but at the instant of reversal a voltage equal to $V + E_b$ is impressed across armature. This will cause a great rush of current (almost double the normal) in the armature circuit. To prevent this the starting resistance is reinserted in the circuit as shown in Fig. 5.45.

- (b) **Plugging applied to DC series motors:** The method is same as in case of DC shunt motor. The changeover of connections is shown in Fig. 5.46.

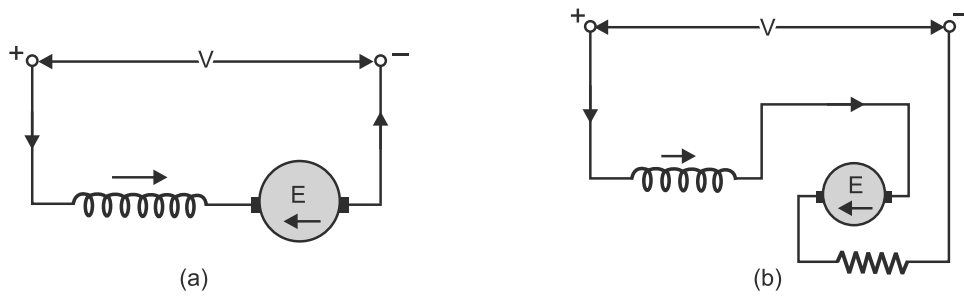


Fig. 5.46 Plugging with series motor

In both cases, the motor must be disconnected from the supply when it comes to rest otherwise it may rotate in the opposite direction.

5.26.2 Rheostatic Braking

This is also called a dynamic braking. With this method of braking the motor is disconnected from the supply and used as a generator driven by the momentum of the equipment to be braked and supplying current to resistance; DC or synchronous motors can be braked in this way. The induction motors, however, require a separate source of DC excitation during this type of braking. This type of braking is applied to different motors as explained below;

- (a) **DC shunt motors:** The armature is disconnected from the supply and a resistance is connected across it, as shown in Fig. 5.47(b). The motor then works as a separately excited generator and the braking torque is applied by the current flowing in the resistance as shown in Fig. 5.47.

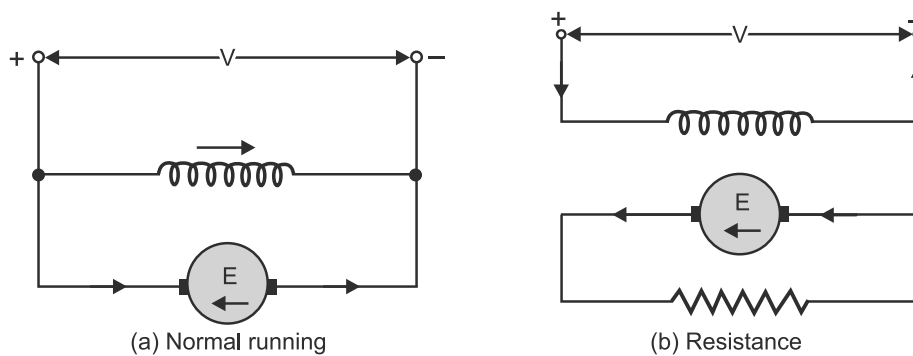


Fig. 5.47 Rheostatic braking of shunt motors

The magnitude of the braking effect can be controlled by varying either the resistance in the armature circuit or the field current. The braking is not effective if the supply fails during this period.

- (b) **DC series motors:** The motor after being disconnected from the supply mains, works as a self excited series generator. Sometimes, in order to build up more field flux the connections of armature are reversed as shown in Fig. 5.48(b).

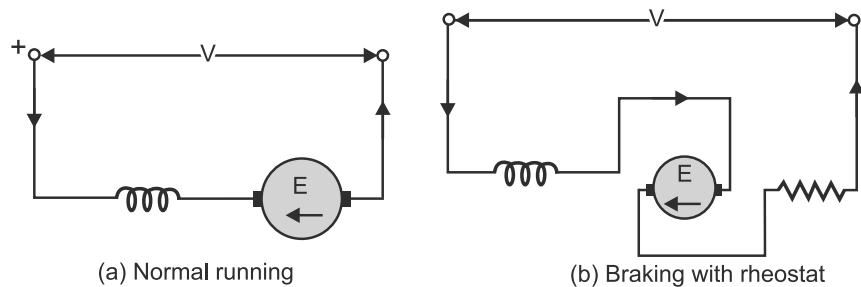


Fig. 5.48 Rheostatic braking of series motors

In such cases if the resistance is above a certain critical value equal to the initial slope of the current-voltage characteristics, the machine will not be self excited, therefore, resistance should be low enough.

5.26.3 Regenerative Braking

This type of braking is mostly employed in electric traction. The kinetic energy of the motor is converted into electrical energy, which is fed back to the supply lines instead of wasting it in a rheostat. This method can be applied to DC motors and induction motors.

- (a) **DC shunt motors:** If the emf generated by the motor is greater than the supply voltage, power will be fed back to the supply. The emf in a shunt motor depends upon the field flux and speed. During this type of braking the field is disconnected from the armature and connected to a separate supply as shown in Fig. 5.49. The field current is so adjusted that $E > V$ and this is returned to the mains.

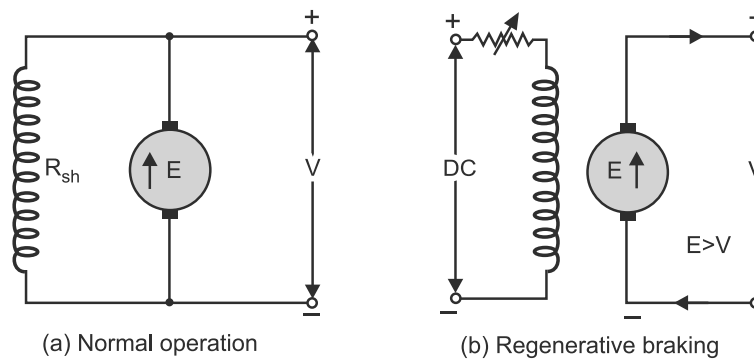


Fig. 5.49 Regenerative braking with shunt motors

Alternatively, if the field excitation does not change but the load causes the speed to increase, the induced *emf* may become more than the supply voltage and power will be fed back to the supply.

- (b) **DC series motors:** Regenerative braking cannot be applied to DC series motors in an ordinary way. For regenerative braking, the motor should work as a generator this is achieved by reversing the connections of series field. But even if the field connections are reversed at the exact moment, this method would still be not successful, because at the instant of reversal, the *emf* induced in the motor will be small, so the current will flow through the field winding in wrong direction, which will reverse the field and cause the motor *emf* to help the supply voltage. This will result in short circuit of supply. Due to these complications, this method is not used for common industrial purposes. However, regenerative braking can be applied with series motors used for traction purposes but in this case, either the field windings are modified or the machines are supplied with separate exciting windings.

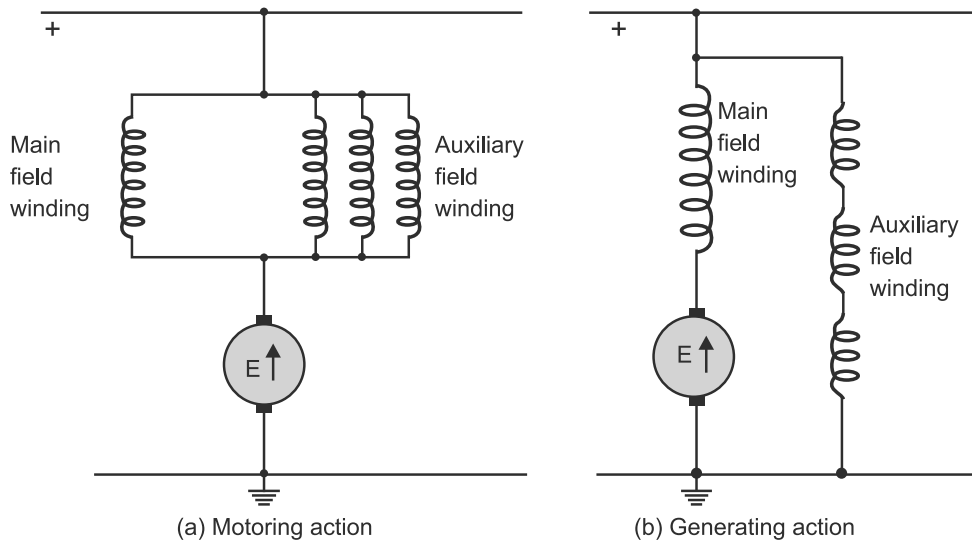


Fig. 5.50 Regenerative braking with series motors

One method of regenerative braking with series motors is French method. If there is a single series motor, it is provided with one main series field winding and 2 or 3 auxiliary field windings.

During normal running the main and auxiliary field windings are placed in parallel with each other as shown in Fig. 5.50(a). During regenerative braking, the auxiliary windings are placed in series with each other and combination is connected in parallel across the armature and main series field winding as shown in Fig. 5.50(b). In this case the machine works as a differentially compound generator and sends back power to supply lines.

In locomotives there are four to six motors and therefore, no auxiliary windings are required. The regenerative braking can be applied in this case as shown in Fig. 5.51.

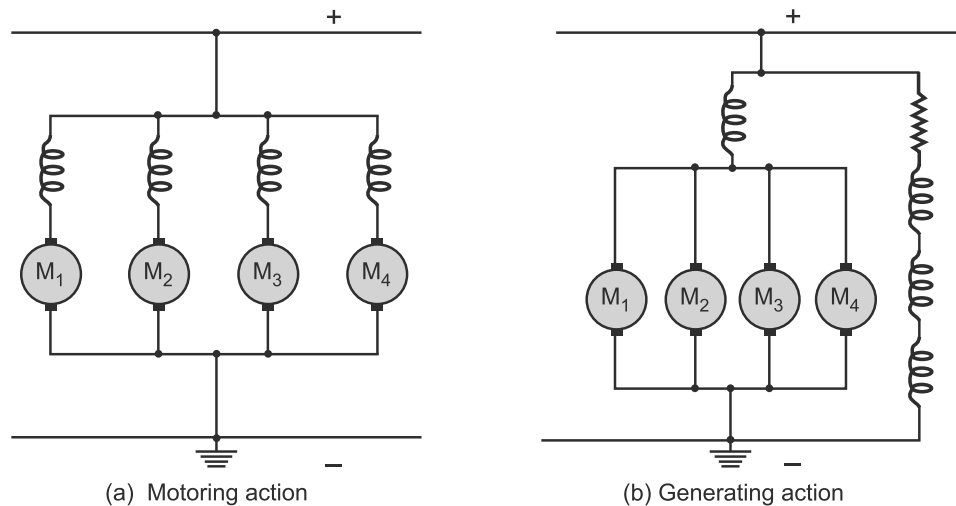


Fig. 5.51 Regenerative braking

An alternative method of regenerative braking is applied by using an exciter for controlling the excitation of the field windings during regeneration.

Section Practice Problems

Numerical Problems

1. A 220 V DC shunt motor takes armature current of 48 A and runs at 760 rpm. Find the resistance to be added in the field circuit to increase the speed to 950 rpm at an armature current of 78 A. Assume flux is proportional to field current. The armature and field winding resistance is $0.15\ \Omega$ and $240\ \Omega$ respectively. **(Ans. $66.48\ \Omega$)**
2. A 500 V DC shunt motor is running at 700 rpm. Its speed is to be raised to 1000 rpm by weakening the field but the total torque remaining unchanged. The armature and field resistances are $0.8\ \Omega$ and $750\ \Omega$ respectively and the current at the lower speed is 12 A. Calculate the additional shunt field resistance required assuming the magnetic circuit to be unsaturated. Neglect all losses. **(Ans. $330\ \Omega$)**
3. The armature resistance of 250 V DC shunt motor is $0.5\ \text{ohm}$. Its armature current is 20 A when running at 1200 rpm and develops full-load torque. What resistance must be inserted in series with the armature to reduce the speed to 600 rpm at the same torque, and what will be the speed if the load torque is halved with this resistance in the circuit. Assume the flux to remain constant throughout and neglect brush contact drop. **(Ans. $6\ \Omega$, 925 6 rpm)**

4. A 230 V DC shunt motor draws a current of 50 A. Resistance of shunt field winding and the armature is $46\ \Omega$ and $0.02\ \Omega$ respectively. When there is a resistance of $0.6\ \Omega$ in series with the armature, the speed of motor is 800 rpm. What alteration must be made in the armature circuit to raise the speed to 850 rpm, the torque remaining the same.
(Ans. $0.6\ \Omega$ resistance connected in series with armature has to be reduced to $0.319\ \Omega$)
5. The armature resistance of a 220 V DC shunt motor is 0.5 ohm. Its armature draws a current of 30 A at full-load and runs at a speed of 800 rpm. If a resistance of $1.0\ \Omega$ is placed in the armature circuit, find the speed at (a) full-load torque (b) double full-load torque.
(Ans. 683 rpm, 507 rpm)
6. The field and armature resistance of a 220 V DC series motor is 0.3 and 0.5 ohm respectively. When connected to rated voltage, at certain load it draws 25 A and runs at 1000 rpm. If the current remains constant, calculate the resistance necessary to reduce the speed to 500 rpm.
(Ans. $3.6\ \Omega$)
7. The total resistance of armature circuit of a 600 V DC series motor is 0.5 ohm. It takes 40 A from the mains and runs at 1200 rpm. Assuming linear magnetisation and load torque as square of the speed, determine the value of the external resistance to be added in series with the armature for the motor to run at 1080 rpm. The load torque varies as the square of the speed. Assume linear magnetisation and take total resistance of armature circuit as $0.5\ \Omega$.
(Ans. $3.1167\ \Omega$)
8. A 240 V DC series motor takes 40 A when giving its rated output at 750 rpm. Its resistance is $0.3\ \Omega$. Find what resistance must be added to obtain the rated torque (a) at starting (b) at 500 rpm.
(Ans. $5.7\ \Omega$, $1.9\ \Omega$)
9. A series motor runs at 800 rpm when taking a current of 60 A at 460 V. The resistance of the armature circuit is $0.2\ \Omega$ and that of the field winding is $0.1\ \Omega$. Calculate the speed when a $0.15\ \Omega$ diverter is connected in parallel with the field winding. Assume the torque to remain unaltered and the flux to be proportional to the field current.
(Ans. 617.6 rpm)
10. A DC series motor having a resistance of $0.4\ \Omega$ and runs at 2000 rpm when connected to 250 V supply and drawing a current of 20 A.
 - (i) What resistance must be added in order to limit the speed to 4000 rpm when armature current is 5A? Assume flux varies linearly.
 - (ii) What resistance must be added to limit the speed to 1000 rpm when armature current is 30 A? Assume that the flux at 30 A is 20% more than that at 20A.
 - (iii) At what speed the motor will run if it is connected directly to 250 V supply when the load is such that the current drawn is 30 A?
(Ans. (i) $25.4\ \Omega$, (ii) $3.093\ \Omega$, (iii) 1640 rpm)

Short Answer Type Questions

Q.1. List various methods of controlling speed of DC shunt motors.

Or

Name the methods used for speed control of DC motors.

Ans. (i) Field control (ii) Armature control (iii) Voltage control method

Q.2. What are the factors that affect the speed of a DC motor?

Ans. We know, speed, $N \propto \frac{E_b}{\phi} \propto \frac{V - I_a R_a}{\phi}$

Hence, the factors influencing the speed of a DC motor are:

(i) Applied or terminal voltage (ii) Flux per pole ϕ (ii) Resistance of armature circuit and (iv) armature current or load.

Q.3. In a field rheostat control method what factors do limit the increase of speed of DC shunt motors?

Ans. In field rheostat control method, the factors which limit the increase of speed of DC shunt motors are; (i) demagnetising effect of armature reaction on the field, (ii) commutation problems at high speeds, (iii) friction at bearings and (iv) large centrifugal forces developed at high speed.

Q.4. Which method is adopted to control the speed of a DC shunt motor above its base speed?

Ans. To obtain speeds above base speed, field control method is adopted.

Q.5. A DC shunt motor is running at rated speed with a resistance R in series with the armature, will the speed of the motor increase or decrease if additional resistance of finite value is connected (a) across R and (b) in series with R ?

Ans. (a) When resistance R is connected across R , its effective value will decrease hence speed will increase
(b) On the other hand when a resistance R is connected in series with the existing resistance R , its effective value will increase, then the speed of motor will decrease.

Q.6. While controlling the speed of a DC shunt motor what should be done to achieve a constant torque drive?

Ans. We know $T \propto \phi I_a$, therefore, while controlling the speed of a DC shunt motor, the product value of field and armature current must remain the same.

Q.7. In the armature circuit of DC motor, an external resistance is introduced. How shall it affect the speed of the motor?

Ans. The speed of motor will decrease.

Q.8. List different methods of speed control employed for DC series motors.

Ans. The various methods of speed control of DC series motor are:

1. Armature control methods. These may be sub-divided as

- (i) Armature series resistance control method
- (ii) Shunted armature control method
- (iii) Armature terminal voltage control method

2. Field control Methods. These may be sub-divided as

- (i) Field diverter method.
- (ii) Armature diverter method
- (iii) Tapped field control method

3. Voltage control Method

Q.9. Do the series motors run faster in series combination or parallel combination?

Ans. Series motors will run faster in parallel combination.

Q.10. Why the power loss in control resistance for many applications of DC series motors is not too serious as in case of DC shunt motors?

Ans. Because in case of DC series motors, the control is utilised for long duration while reducing the speed under light load conditions and it is only employed intermittently while carrying full load.

Q.11. How plugging of a DC motor is done?

Ans. In DC motors plugging is obtained by reversing the supply terminals to the armature of the motor.

Q.12. Why rheostatic braking is economical to plugging?

Ans. In rheostatic braking, energy required from the supply to brake the motor is eliminated as compared to the plugging.

5.27 Losses in a DC Machine

A DC machine is used to convert mechanical energy into electrical energy or vice-versa. While doing so, the whole of input energy does not appear at the output but a part of it is lost in the form of heat in the surroundings. This wasted energy is called *losses in the machine*.

These losses affect the efficiency of the machine. A reduction in these losses leads to higher efficiency. Thus, the major objective in the design of a DC machine is to reduce these losses. The various losses occurring in a DC machine can be sub-divided as:

1. Copper losses.
2. Iron losses.
3. Mechanical losses

1. **Copper losses:** The various windings of the DC machine, made of copper, have some resistance. When current flows through them, there will be power loss proportional to the square of their respective currents. *These power losses are called **copper losses**.*

In general, the various copper losses in a DC machine are:

- (i) Armature copper loss = $I_a^2 R_a$
- (ii) Shunt field copper loss = $I_{sh}^2 R_{sh}$
- (iii) Series field copper loss = $I_{se}^2 R_{se}$
- (iv) Interpole winding copper loss = $I_i^2 R_i = I_a^2 R_i$
- (v) Brush contact loss = $I_a^2 R_b = 2 I_a v_b$
- (vi) Compensating winding copper loss = $I_a^2 R_c$

The loss due to brush contact is generally included in armature copper loss.

2. **Iron losses:** *The losses which occur in the iron parts of a DC machine are called iron losses or core losses or magnetic losses.* These losses consist of the following:

- (i) **Hysteresis loss:** Whenever a magnetic material is subjected to reversal of magnetic flux, this loss occurs. It is due to retentivity (a property) of the magnetic material. It is expressed with reasonable accuracy by the following expression:

$$P_h = K_h V f B_m^{1.6}$$

where,

K_h = hysteresis constant in J/m³ i.e., energy loss per unit volume of magnetic material during one magnetic reversal, its value depends upon nature of material;

V = Volume of magnetic material in m^3 .

f = frequency of magnetic reversal in cycle/second and

B_m = maximum flux density in the magnetic material in Tesla.

It occurs in the rotating armature. To minimise this loss, the armature core is made of silicon steel which has low hysteresis constant.

- (ii) **Eddy current loss:** When flux linking with the magnetic material changes (or flux is cut by the magnetic material) an emf is induced in it which circulates eddy currents through it. These eddy currents produce eddy current loss in the form of heat. It is expressed with reasonable accuracy by the expression:

$$P_e = K_e V f^2 t^2 B_m^2$$

where,

K_e = constant called co-efficient of eddy current, its value depends upon the nature of magnetic material;

t = thickness of lamination in m; V, f and B_m are the same as above.

The major part of this loss occurs in the armature core. To minimise this loss, the armature core is laminated into thin sheets (0.3 to 0.5 mm) since this loss is directly proportional to the square of thickness of the laminations.

3. **Mechanical losses:** As the armature of a DC machine is a rotating part, some power is required to overcome:

(i) Air friction of rotating armature (windage loss).

(ii) Friction at the bearing and friction between brushes and commutator (friction loss).

These losses are known as **mechanical losses**. To reduce these losses proper lubrication is done at the bearings.

5.28 Constant and Variable Losses

The losses in a DC machine may also be sub-divided into two categories, i.e.,

1. Constant losses;
2. Variable losses.

1. **Constant losses:** The losses in a DC machine which remain the same at all loads are called *constant losses*. The constant losses in a DC machine are:

(i) Iron losses; (ii) Mechanical losses; (iii) Shunt field copper losses.

2. **Variable losses:** The losses in a DC machine which vary with load are called *variable losses*.

The variable losses in a DC machine are:

(i) Armature copper loss; (ii) Series field copper loss; (iii) Interpole winding copper loss.

5.29 Stray Losses

The sum of the iron loss and mechanical loss in a DC machine are known as *stray losses* i.e.,

$$\text{Stray losses} = \text{Iron loss} + \text{Mechanical loss}.$$

5.30 Power Flow Diagram

(i) When machine is working as a generation

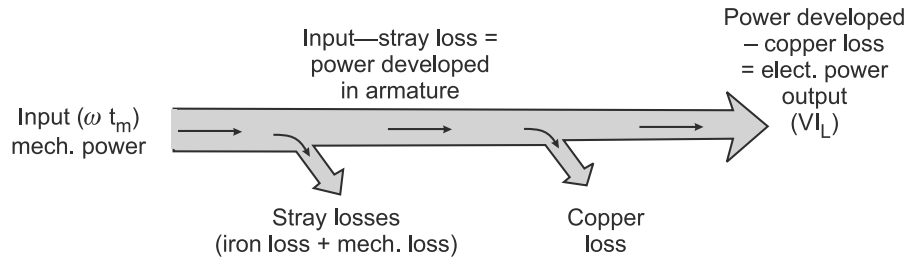


Fig. 5.52 Power flow diagram (Generator action)

The mechanical power (ωT_m) is supplied to the generator which is converted into electrical power ($V_L I_L$). While conversion, various losses occur in the machine. The power flow diagram for a DC generator is shown in Fig. 5.52.

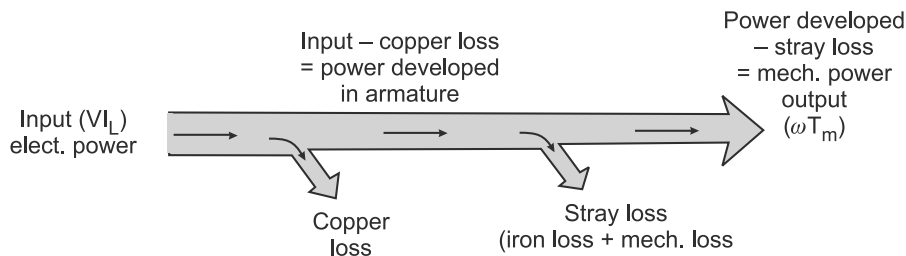


Fig. 5.53 Power flow diagram (Motor action)

Although losses in a DC machine are the same whether it works as a generator or as a motor but the flow of power is opposite. The power flow diagram for a DC motor is shown in Fig. 5.53.

5.31 Efficiency of a DC Machine

The ratio of output power to the input power of a DC machine is called its *efficiency***.

$$\text{Efficiency, } \eta = \frac{\text{Output}}{\text{Input}} ;$$

* The ratio of output to input of a DC motor is called its commercial efficiency, i.e., $\eta = \frac{\text{output}}{\text{input}}$. The ratio of mechanical power output to the power developed in the armature is called its mechanical efficiency, i.e., $h_m = \frac{\text{mech. power output}}{\text{mech. power developed in the armature}}$. The ratio of electrical power developed in the armature to the electrical power input is called electrical efficiency of the motor, i.e., $h_e = \frac{\text{power developed in the armature}}{\text{electrical power input}}$.

Also, commercial efficiency, $h = h_m \times h_e$

(i) When machine is working as a generator

$$\text{Power output} = VI_L \text{ watt}$$

$$\text{Power input} = \text{Power output} + \text{Variable losses} + \text{Constant losses}$$

Since the shunt field current I_{sh} is very small as compared to line current,

We may consider, $I_L \cong I_a$ (neglecting I_{sh})

$$\therefore \text{Variable losses} = I_L^2 R_a ; \text{Constant losses} = P_c \text{ (say)}$$

$$\text{Then, power input} = VI_L + I_L^2 R_a + P_c \quad \therefore \quad \eta = \frac{VI_L}{VI_L + I_L^2 R_a + P_c} \quad \dots(5.22)$$

(ii) when machine is working as a motor.

$$\text{Power input} = VI_L$$

$$\text{Power output} = \text{Power input} - \text{Variable losses} - \text{constant losses} = VI_L - I_L^2 R_a - P_c$$

$$\therefore \quad \eta = \frac{VI_L - I_L^2 R_a - P_c}{VI_L} \quad \dots(5.23)$$

5.32 Condition for Maximum Efficiency

The efficiency of a DC generator is given as:

$$\begin{aligned} \eta &= \frac{\text{output}}{\text{output} + \text{variable losses} + \text{constant losses}} \\ &= \frac{VI_L}{VI_L + I_L^2 R_a + P_c} = \frac{1}{1 + \frac{I_L R_a}{V} + \frac{P_c}{VI_L}} \end{aligned} \quad \dots(5.24)$$

Now, efficiency will be maximum when the denominator of eq. (5.24) in minimum i.e.,

$$\begin{aligned} \frac{d}{dI_L} \left(1 + \frac{I_L R_a}{V} + \frac{P_c}{VI_L} \right) &= 0 \\ \text{or} \quad \frac{R_a}{V} - \frac{P_c}{VI_L^2} &= 0 \quad \text{or} \quad \frac{R_a}{V} = \frac{P_c}{VI_L^2} \quad \text{or} \quad I_L^2 R_a = P_c \end{aligned} \quad \dots(5.25)$$

i.e., **Variable losses = Constant losses**

Hence, the efficiency of a DC machine will be maximum when the line current is such that constant loss is equal to the variable loss.

$$\text{The line current at which the efficiency of DC machine is maximum. } I_L = \sqrt{\frac{P_c}{R_a}} \quad \dots(5.26)$$

Example 5.40

A DC generator is connected to a 220 V DC mains. The current delivered by the generator to the mains is 100 A. The armature resistance is 0.1 ohm. The generator is driven at a speed of 500 rpm. Calculate (i) the induced emf (ii) the electromagnetic torque (iii) the mechanical power input to

the armature neglecting iron, windage and friction losses, (iv) Electrical power output from the armature, (v) armature copper loss.

Solution:

(i) The induced emf, $E_g = V + I_a R_a$
 $= 220 + 0.1 \times 100 = \mathbf{230 \text{ V (Ans.)}}$

(ii) Using the relation, $\omega T = E_g I_a$
 Electromagnetic torque, $T = \frac{E_g I_a}{\omega} = \frac{E_g I_a}{2\pi N} \times 60 \quad \left[\because \omega = \frac{2\pi N}{60} \right]$
 $= \frac{230 \times 100 \times 60}{2\pi \times 500} = \mathbf{439.27 \text{ Nm (Ans.)}}$

(iii) Neglecting iron, windage and friction losses,

$$\begin{aligned} \text{Input to armature} &= \omega T \quad \text{or} \quad E_g I_a \\ &= \frac{2\pi N T}{60} = \frac{2\pi \times 500 \times 439.27}{60} = \mathbf{23000 \text{ W (Ans.)}} \end{aligned}$$

(iv) Electrical power output $= V I_a = 220 \times 100 = \mathbf{22000 \text{ W (Ans.)}}$

(v) Armature copper losses $= I_a^2 R_a = (100)^2 \times 0.1 = \mathbf{1000 \text{ W (Ans.)}}$

Example 5.41

A shunt generator supplies 195 A at 220 V. Armature resistance is 0.02 ohm, shunt field resistance is 44 ohm. If the iron and friction losses amount to 1600 watt, find (i) emf generated; (ii) copper losses; (iii) b.h.p. of the engine driving the generator. (iv) commercial, mechanical and electrical efficiency.

Solution:

The conventional circuit is shown in Fig. 5.54.

Shunt field current, $I_{sh} = \frac{V}{R_{sh}} = \frac{220}{44} = 5 \text{ A}$

Armature current, $I_a = I_L + I_{sh} = 195 + 5 = 200 \text{ A}$

(i) Generated or induced emf, $E = V + I_a R_a$
 $= 220 + 200 \times 0.02$
 $= \mathbf{224 \text{ V (Ans.)}}$

Armature copper loss $= I_a^2 R_a = (200)^2 \times 0.02 = 800 \text{ W}$

Shunt field copper loss $= I_{sh}^2 R_{sh} = (5)^2 \times 44 = 1100 \text{ W}$

(ii) Total copper losses $= 800 + 1100 = \mathbf{1900 \text{ W (Ans.)}}$

Output power $= V I_L = 220 \times 195 = 42900 \text{ W}$

Input power $= 42900 + 1600 + 1900 = 46400 \text{ W}$

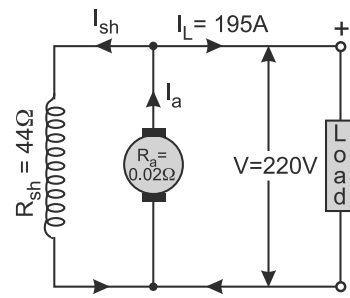


Fig. 5.54 Circuit diagram

(iii) B.H.P. of the engine driving the generator = $\frac{46400}{735 \cdot 5} = \mathbf{63.08 \text{ H.P.}}$ (Ans.)

(iv) Commercial efficiency, $\eta = \frac{\text{final output of machine}}{\text{input to machine}}$
 $= \frac{42900}{46400} \times 100 = \mathbf{92.45\%}$ (Ans.)

Mechanical efficiency, $\eta_m = \frac{\text{Power developed in armature}}{\text{Power input}}$
 $= \frac{E_g I_a}{46400} \times 100 = \frac{224 \times 200}{46400} \times 100 = \mathbf{96.55\%}$ (Ans.)

Electrical efficiency, $\eta_e = \frac{\text{Electrical Power output}}{\text{Power generated in armature}}$
 $= \frac{V I_L}{E_g I_a} \times 100 = \frac{220 \times 195}{224 \times 200} \times 100 = \mathbf{95.76\%}$ (Ans.)

Alternatively, commercial efficiency,

$$\eta = \eta_m \times \eta_e$$

$$= \frac{96.55}{100} \times \frac{95.76}{100} \times 100 = 92.45\% \text{ (True as above)}$$

Example 5.42

A 10 kW, 250 V DC self excited shunt generator driven at 1000 rpm has armature resistance 0.15 ohm and field current 1.64 A. Find rated load, armature induced emf, torque developed and efficiency when the rotational losses are 540 watt. Assume constant speed operation.

Solution:

Here, output power = 10 kW = $10 \times 1000 \text{ W}$

$$R_a = 0.15 \Omega; I_{sh} = 1.64 \text{ A}; V = 250 \text{ V}; N = 1000 \text{ rpm}$$

$$\text{Load current, } I_L = \frac{10 \times 1000}{250} = \mathbf{40 \text{ A}} \text{ (Ans.)}$$

$$\text{Armature current, } I_a = I_L + I_{sh} = 40 + 1.64 = 41.64 \text{ A}$$

$$\text{Induced or generated emf, } E_g = V + I_a R_a$$

$$= 250 + 41.64 \times 0.15 = \mathbf{256.246 \text{ V}} \text{ (Ans.)}$$

$$\text{Power developed in the armature, } \omega T = E_g I_a$$

$$\therefore \text{Torque developed, } T = \frac{E_g I_a}{\omega} = \frac{256.246 \times 41.64 \times 60}{2\pi \times 1000} \left(\text{since } \omega = \frac{2\pi N}{60} \right)$$

$$= \mathbf{101.89 \text{ Nm}} \text{ (Ans.)}$$

$$\text{Power developed} = E_g I_a = 256.246 \times 41.64 = 10670 \text{ W}$$

$$\text{Mechanical losses} = 540 \text{ W}$$

$$\text{Power input} = 10670 + 540 = 11210 \text{ W}$$

$$\text{Power output} = 10 \text{ kW} = 10 \times 1000 \text{ W}$$

$$\text{Efficiency, } \eta = \frac{\text{output}}{\text{input}} \times 100 = \frac{10 \times 1000}{11210} \times 100 = \mathbf{89.2\%} \text{ (Ans.)}$$

Example 5.43

A 200 V shunt motor has $R_a = 0.1 \text{ ohm}$, $R_f = 240 \text{ ohm}$ and rotational loss = 236 W. On full load the line current is 9.8 A with the motor running at 1450 rpm. Determine

- (a) the mechanical power developed
- (b) the power output
- (c) the load torque (d) the full load efficiency

Solution:

Here, $V = 200 \text{ V}$; $R_a = 0.1 \text{ } \Omega$; $R_{sh} = 240 \text{ } \Omega$; (Mech. + Iron loss) = 236 W

$$I_L = 9.8 \text{ A}; N = 1450 \text{ rpm}$$

$$\text{Shunt field current, } I_{sh} = \frac{V}{R_{sh}} = \frac{200}{240} = 0.833 \text{ A}$$

$$\text{Armature current, } I_a = I_L - I_{sh} = 9.8 - 0.833 = 8.967 \text{ A}$$

$$E_b = V - I_a R_a = 200 - 8.967 \times 0.1 = 199.1 \text{ V}$$

$$(a) \quad \text{Mechanical power developed} = E_b \times I_a = 199.1 \times 8.967 = 1785.33 \text{ W}$$

$$(b) \quad \begin{aligned} \text{Power output} &= \text{Mech. power developed} - \text{rotational losses} \\ &= 1785.33 - 236 = 1549.33 \text{ W} \end{aligned}$$

$$(c) \quad \text{Now} \quad \frac{2\pi NT}{60} = \text{Power output}$$

$$\text{or} \quad \text{Load torque, } T = \frac{\text{Power output} \times 60}{2\pi N}$$

$$\text{or} \quad \text{Load torque, } T = \frac{1549.33 \times 60}{2\pi \times 1450} = \mathbf{10.2 \text{ Nm (Ans.)}}$$

$$(d) \quad \text{Input to the motor} = VI_L = 200 \times 9.8 = 1960 \text{ W}$$

$$\text{Full-load efficiency, } \eta = \frac{\text{Power output}}{\text{Input}} \times 100 = \frac{1549.3}{1960} \times 100 = \mathbf{79.04\% (Ans.)}$$

Example 5.44

A long shunt dynamo running at 1000 rpm supplies 22 kW at a terminal voltage 220 V. The resistance of armature, shunt field and series field are 0.05, 110 and 0.06 ohm respectively. The overall efficiency at above load is 88%. Find (a) copper losses (b) iron and friction losses.

Solution:

The circuit is shown in Fig. 5.55; Here, Power $P = 22 \text{ kW}$; $V = 220 \text{ V}$; $R_a = 0.05 \text{ } \Omega$

$$R_{sh} = 110 \, \Omega; R_{se} = 0.06 \, \Omega; \eta = 88\%$$

$$\text{Output current, } I_L = \frac{\text{Power output}}{V} = \frac{22 \times 1000}{220} = 100 \, \text{A}$$

$$I_{sh} = \frac{V}{R_{sh}} = \frac{220}{110} = 2 \, \text{A}$$

$$I_a = I_L + I_{sh} = 100 + 2 = 102 \, \text{A}$$

$$\text{Armature copper loss} = I_a^2 R_a = (102)^2 \times 0.05 = 520.2 \, \text{W}$$

$$\text{Series field copper loss} = I_{se}^2 R_{se} = (102)^2 \times 0.06 = 624.24 \, \text{W}$$

$$\text{Shunt field copper loss} = I_{sh}^2 R_{sh} = (2)^2 \times 110 = 440 \, \text{W}$$

$$\text{Total copper losses} = I_a^2 R_a + I_{se}^2 R_{se} + I_{sh}^2 R_{sh} = 520.2 + 624.24 + 440$$

$$= \mathbf{1584.44 \, \text{W (Ans.)}}$$

$$\text{Power input} = \frac{\text{Power output}}{\eta} = \frac{22 \times 1000}{0.88} = 25000 \, \text{W}$$

$$\text{Total loss, } P_T = \text{Power input} - \text{power output} = 25000 - 22000 = 3000 \, \text{W}$$

$$\text{Iron and friction losses, } P_S = P_T - \text{copper losses} = 3000 - 1584.44 = \mathbf{1415.56 \, \text{W (Ans.)}}$$

Example 5.45

A 220 V DC series motor takes 50 A. Armature resistance 0.1 ohm, series field resistance 0.08 ohm. If the iron and friction losses are equal to copper losses at this load, find the B.H.P. and efficiency.

Solution:

The circuit is shown in Fig. 5.56;

$$\text{Armature current, } I_a = I_L = 50 \, \text{A}$$

$$\text{Copper losses} = I_a^2 (R_a + R_{se}) = (50)^2 \times (0.1 + 0.08) = 450 \, \text{W}$$

$$\text{Iron and friction losses} = \text{copper losses} = 450 \, \text{W}$$

$$\text{Total losses} = \text{Iron and friction losses} + \text{copper losses}$$

$$= 450 + 450 = 900 \, \text{W}$$

$$\text{Input power} = V I_L = 220 \times 50 = 11000 \, \text{W}$$

$$\text{Output power} = \text{Input power} - \text{Total losses}$$

$$= 11000 - 900 = 10100 \, \text{W}$$

$$\therefore \text{B.H.P.} = \frac{\text{output power}}{\text{Input power}} = \frac{10100}{735.5} = \mathbf{13.732 \, \text{H.P. (Ans.)}}$$

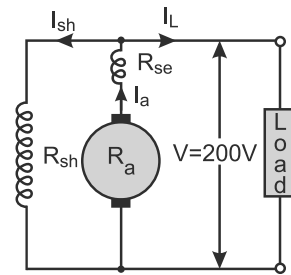


Fig. 5.55 Circuit diagram

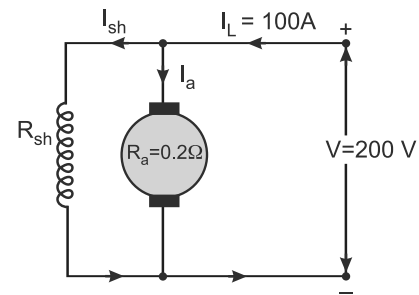


Fig. 5.56 Circuit diagram

$$\text{Efficiency, } \eta = \frac{\text{output power}}{\text{input power}} \times 100 = \frac{10100}{11000} \times 100 = \mathbf{91.82 \% (Ans.)}$$

Example 5.46

A 200V shunt motor takes 10A when running on no-load. At higher loads the brush drop is 2V and at light load it is negligible. The stray load loss at a line current of 100 A is 50% of the no-load loss. Calculate the efficiency at a line current of 100A if armature and field resistance are 0.2 Ω and 100 Ω respectively.

Solution:

Here, $V = 200$ V; $I_{L0} = 10$ A; $V_{bf} = 2$ V; $V_{b0} = 0$ V

Stray load loss = 50% of no-load loss; $R_a = 0.2 \Omega$; $R_{sh} = 100 \Omega$

$$\text{Input at no-load} = V \times I_{L0} = 200 \times 10 = 2000 \text{ W}$$

$$I_{sh} = \frac{V}{R_{sh}} = \frac{200}{100} = 2 \text{ A}$$

$$\text{Shunt field Cu loss} = I_{sh}^2 R_{sh} = (2)^2 \times 100 = 400 \text{ W}$$

$$\text{Stray loss} = \frac{50}{100} \times 2000 = 1000 \text{ W}$$

At load, armature current, $I_a = I_L - I_{sh} = 100 - 2 = 98 \text{ A}$

$$\text{Armature copper loss} = I_a^2 R_a = (98)^2 \times 0.2 = 1920.8 \text{ W}$$

$$\text{Loss at brushes} = V_{bf} \times I_a = 2 \times 98 = 196 \text{ W}$$

$$\begin{aligned} \text{Total losses} &= \text{Stray loss} + \text{Armature Cu loss} + \text{Shunt field Cu loss} \\ &\quad + \text{Brush contact loss} \\ &= 1000 + 1920.8 + 400 + 196 = 3516.8 \text{ W} \end{aligned}$$

$$\text{Input to motor} = V \times I_L = 200 \times 100 = 20000 \text{ W}$$

$$\begin{aligned} \text{Motor efficiency, } \eta &= \frac{\text{output}}{\text{input}} = \frac{\text{Input} - \text{Losses}}{\text{Input}} \times 100 \\ &= \frac{20000 - 3516.8}{20000} \times 100 = \mathbf{82.416\% (Ans.)} \end{aligned}$$

Example 5.47

A shunt generator has a full-load current of 195 A at 250 V. The stray losses are 720 W and the shunt field coil resistance is 50 Ω . It has a full-load efficiency of 88%. Find the armature resistance. Also find the current corresponding to maximum efficiency.

Solution:

$$\text{Generator rated output} = V \times I_L = 250 \times 195 = 48750 \text{ W}$$

$$\text{Input power to generator} = \frac{\text{Rated power output}}{\text{Full-load efficiency}} = \frac{48750}{0.88} = 55398 \text{ W}$$

$$\text{Total losses} = \text{Power input} - \text{power output} = 55398 - 48750 = 6648 \text{ W}$$

$$\text{Shunt field current, } I_{sh} = \frac{V}{R_{sh}} = \frac{250}{50} = 5 \text{ A}$$

$$\text{Shunt field copper loss} = I_{sh}^2 R_{sh} = (5)^2 \times 50 = 1250 \text{ W}$$

$$\text{Stray loss} = 720 \text{ W}$$

$$\text{Armature current, } I_a = I_L + I_{sh} = 195 + 5 = 200 \text{ A}$$

$$\begin{aligned} \text{Armature copper loss, } I_a^2 R_a &= \text{Total losses} - \text{stray loss} - \text{shunt field copper loss} \\ &= 6648 - 720 - 1250 = 4678 \text{ W} \end{aligned}$$

or

$$\text{Armature resistance, } P_C = \frac{4678}{I_a^2} = \frac{4678}{(200)^2} = 0.11695 \Omega \text{ (Ans.)}$$

$$\text{Constant losses, } P_C = \text{Shunt field loss} + \text{Stray loss} = 1250 + 720 = 1970 \text{ W}$$

Armature current at which the efficiency will be maximum (say I'_a),

$$I'_a = \sqrt{\frac{P_C}{R_a}} = \sqrt{\frac{1970}{0.11695}} = 130 \text{ A}$$

Load current at which the efficiency will be maximum (say I'_L),

$$I'_L = I'_a - I_{sh} = 130 - 4 = \mathbf{126 \text{ A}} \text{ (Ans.)}$$

Example 5.48

A 400 V shunt generator has full-load current of 200 A. Its armature resistance is 0.06 ohm, field resistance is 100 ohm and the stray losses are 2000 watt. Find the h.p. of prime-mover when it is delivering full load, and find the load for which the efficiency of the generator is maximum.

Solution:

Here, $V = 400 \text{ V}$; $I_L = 200 \text{ A}$; $R_a = 0.06 \Omega$; $R_{sh} = 100 \Omega$

$$\text{Stray losses} = 2000 \text{ W}$$

$$\text{Shunt field current, } I_{sh} = \frac{V}{R_{sh}} = \frac{400}{100} = 4 \text{ A}$$

$$\text{Armature current, } I_a = I_L + I_{sh} = 200 + 4 = 204 \text{ A}$$

$$\text{Armature copper loss} = I_a^2 R_a = (204)^2 \times 0.06 = 2497 \text{ W}$$

$$\text{Shunt field copper loss} = I_{sh}^2 R_{sh} = (4)^2 \times 100 = 1600 \text{ W}$$

$$\begin{aligned} \text{Total losses} &= \text{Armature copper loss} + \text{shunt field copper loss} + \text{stray loss} \\ &= 2497 + 1600 + 2000 = 6097 \text{ W} \end{aligned}$$

$$\text{Output power} = VI_L = 400 \times 200 = 80000 \text{ W}$$

$$\text{Input power} = \text{Output power} + \text{losses} = 80000 + 6097 = 86097 \text{ W}$$

$$\text{Horse power of prime mover} = \frac{\text{Input power}}{735.5} = \frac{86097}{735.5} = \mathbf{117.06 \text{ H.P. (Ans.)}}$$

$$\begin{aligned}\text{Constant losses, } P_c &= \text{stray losses} + \text{shunt field copper loss} \\ &= 2000 + 1600 = 3600 \text{ W}\end{aligned}$$

Condition for maximum efficiency is,

$$\text{Variable losses} = \text{Constant losses}$$

Let, I_L' be the load current at which the efficiency is maximum and armature current is I_a' .

$$I_a' = \sqrt{\frac{P_c}{R_a}} = \sqrt{\frac{3600}{0.06}} = 245 \text{ A}$$

$$\text{Load current, } I_L' = I_a' - I_{sh} = 245 - 4 = 241 \text{ A}$$

$$\text{Load for which the efficiency is maximum} = I_L' V = 241 \times 400 = 96.4 \times 10^3 \text{ W} = \mathbf{96.4 \text{ kW (Ans.)}}$$

Example 5.49

A 250 V, 20 kW shunt motor running at 1500 rpm has a maximum efficiency of 85% when delivering 80% of its rated output. The resistance of the shunt field winding is 125 Ω . Determine the efficiency and speed of the motor when it draws 100 A from the mains.

Solution:

$$\text{Rated output} = 20 \text{ kW} = 20000 \text{ W}$$

$$\text{Actual output} = \text{Operating } \eta \times \text{rated output} = 0.8 \times 20000 \text{ W}$$

$$\text{Maximum efficiency, } \eta_{\max} = 85\%$$

$$\text{Efficiency of machine, } \eta = \frac{\text{Output}}{\text{Output} + \text{losses}}$$

$$\begin{aligned}\text{or} \quad \text{Total losses} &= \frac{1 - \eta_{\max} \text{ output}}{\eta_{\max}} = \left(\frac{1}{\eta_{\max}} - 1 \right) \times \text{actual output} \\ &= \left(\frac{1}{0.85} - 1 \right) \times 0.8 \times 20000 = 2824 \text{ W}\end{aligned}$$

At maximum efficiency, constant losses (rotational losses + shunt field loss)

$$= \text{Variable armature circuit losses, } I_a^2 R_a$$

$$= \frac{\text{Total losses}}{2} = \frac{2824}{2} = 1412 \text{ W}$$

$$\text{Input to motor, } P_{in} = \text{Motor output, } P_{out} + \text{total losses}$$

$$= 20000 \times 0.8 + 2824 = 18824 \text{ W}$$

$$\text{Input line current, } I_{L1} = \frac{P_{in}}{V} = \frac{18824}{250} = 75.3 \text{ A}$$

$$\text{Shunt field current, } I_{sh} = \frac{V}{R_{sh}} = \frac{250}{125} = 2 \text{ A}$$

$$\text{Armature, } I_{a1} = I_{L1} - I_{sh} = 75.3 - 2 = 73.3 \text{ A}$$

$$\text{Armature copper loss, } I_{a1}^2 R_a = 1412 \text{ W}$$

or $\text{Armature circuit resistance, } R_a = \frac{1412}{I_{a1}^2} = \frac{1412}{73.3^2} = 0.263 \Omega$

$$\text{Now input of motor, } I_{L2} = 100 \text{ A}$$

$$\text{Armature current, } I_{a2} = I_{L2} - I_{sh} = 100 - 2 = 98 \text{ A}$$

$$\text{Armature copper loss} = I_{a2}^2 R_a = 98^2 \times 0.263 = 2,525 \text{ W}$$

$$\text{Motor input} = VI = 250 \times 100 = 25000 \text{ W}$$

$$\begin{aligned} \text{Motor output} &= \text{Motor input} - \text{constant losses} - \text{armature copper losses} \\ &= 25000 - 1412 - 2525 = 21063 \text{ W} \end{aligned}$$

$$\text{Motor efficiency, } \eta = \frac{\text{Output}}{\text{Input}} \times 100 = \frac{21063}{25000} \times 100 = \mathbf{84.25\% (Ans.)}$$

Assuming flux remaining the same, the speed of the motor,

$$\begin{aligned} N_2 &= N_1 \times \frac{E_{b2}}{E_{b1}} = N_1 \times \frac{V - I_{a2}R_a}{V - I_{a1}R_a} \\ &= 1500 \times \frac{250 - 98 \times 0.263}{250 - 73.3 \times 0.263} = \mathbf{1458 \text{ rpm (Ans.)}} \end{aligned}$$

5.33 Test Performed to Determine Efficiency of DC Machines

To determine the efficiency of a DC machine namely, three methods can be used direct method, indirect method and regenerative method.

- 1. Direct Method.** In this method, full load is applied to the machine and output is directly measured. Although, this method looks to be very simple but it is very difficult and inconvenient to apply full load to large size machines. Therefore, this method is restricted only to determine the efficiency of small sized machines. *Brake test* comes under this category.
- 2. Indirect Method.** In this method, the losses are determined without actually loading the machine. The power is required to supply the losses only, therefore, large machines can be tested by applying this method. Accordingly, this method is usually employed to determine the efficiency of large DC shunt and compound wound machines. The major drawback of this method is that the temperature rise of the winding on load and commutating qualities cannot be *assessed* since the machine is operated at light loads. *Swinburne's test* falls in this category.
- 3. Regenerative Method.** In this method, two identical, mechanically coupled machines are used. One acts as a motor drawing power from the supply and the other acts as a generator which

feeds the generated power back to the supply. Thus motor draws power equal to the total losses of the two machines at rated speed and load. Very large machines can be tested by this method. Moreover, the machines can be operated (or tested) for long duration and their performance regarding commutation, temperature rise, etc., can be studied conveniently. *Hopkinson's test* falls in this category.

5.34 Brake Test

It is a direct method of determining the efficiency of a DC motor. This test is performed only with small motors. The brake is applied to a pulley (either air cooled or water cooled) mounted on the motor shaft as shown in Fig. 5.57. The load on the motor is increased by tightening the belt mounted on the pulley. The electrical connections are made as shown in the circuit diagram.

Let, spring balance reading on tight side = W_1 kg

Spring balance reading on loose side = W_2 kg

Motor speed = N rpm (reading taken by tachometer)

Radius of pulley = r metre

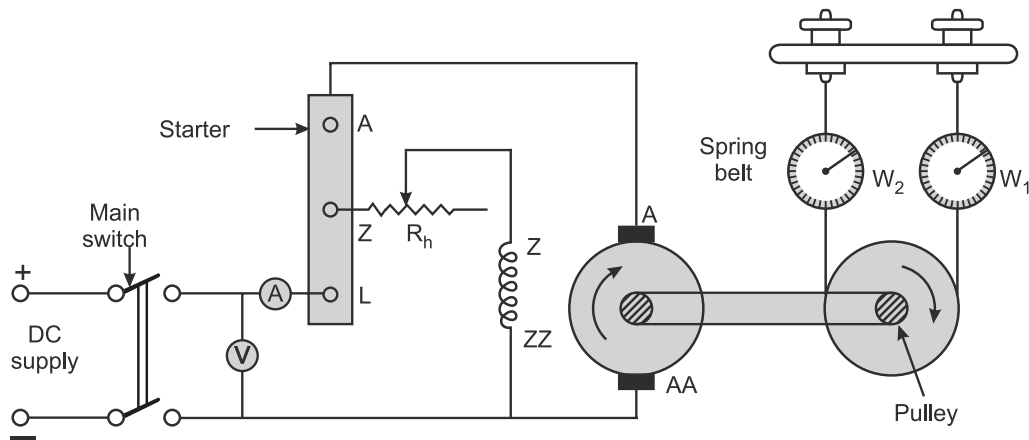


Fig. 5.57 Circuit arrangement for brake test

Thickness of belt = t metre

$$\text{Motor output} = T \times \frac{2\pi N}{60} = (W_1 - W_2) \left(r + \frac{t}{2} \right) \frac{2\pi N}{60}$$

(since T = effective pull $\times$ effective radius)

$$= (W_1 - W_2) r \times \frac{2\pi N}{60} \text{ kg m/s (neglect } t \text{ being small)}$$

$$= (W_1 - W) r \times \frac{2\pi N}{60} \times 9.81 \text{ Nm/s or watt} \quad \dots(5.27)$$

If voltmeter reading = V volt

Armature reading = I ampere

$$\text{Motor input} = VI \text{ watt} \quad \dots(5.28)$$

$$\therefore \text{Efficiency of motor, } \eta = \frac{\text{output}}{\text{input}} = \frac{(W_1 - W_2) r \times \frac{2\pi N}{60} \times 9.81}{VI} \quad \dots(5.29)$$

This method of measuring efficiency has the following drawbacks:

- (i) We cannot determine the efficiency of large machines because such facilities of loading are not available.
- (ii) The output measured by this method is not accurate because belt is not offering a constant load (usually belt slips over the pulley)

A special precaution is to be observed while performing this test on a series motor. If the brakes applied fails, the motor may obtain a dangerously high speed; therefore, this test is usually applied only on shunt and compound machines.

Example 5.50

In a brake test, the DC motor took 38.5 A from a 240 V supply mains. The brake pulley of radius 35 cm had an effective load of 30 kg and the speed was 720 rpm. Find the bhp (metric) and the efficiency at the above load.

Solution:

Torque exerted, $T = \text{Effective load} \times \text{radius of brake pulley}$

$$= (W_1 - W_2) r = 30 \times 0.35 = 10.5 \text{ kg-m or } 10.5 \times 9.81 \text{ Nm}$$

$$\text{Output of motor} = T \times \frac{2\pi N}{60} = 10.5 \times 9.81 \times 2 \times \pi \times \frac{720}{60} = 7766.4 \text{ watt}$$

$$\text{BHP of motor} = \frac{\text{Output in watts}}{735.5} = \frac{7766.4}{735.5} = \mathbf{10.56 \text{ (Ans.)}}$$

$$\text{Input to motor} = V \times I = 240 \times 38.5 = 9240 \text{ watt}$$

$$\text{Efficiency of motor, } \eta = \frac{\text{Output}}{\text{Input}} \times 100 = \frac{7766.4}{9240} \times 100 = \mathbf{84.05\% \text{ (Ans.)}}$$

Example 5.51

In a brake test on a DC shunt motor, the load on tight side of the brake band was 32 kg and the other side 2 kg. The motor was running at 1200 rpm; its input being 65 A at 400 V DC. The pulley diameter is 1 m. Determine the torque, output of the motor and efficiency of the motor.

Solution:

$$\text{Effective force, } F = 32 - 2 = 30 \text{ kg}$$

$$\text{Pulley radius, } r = \frac{1.0}{2} = 0.5 \text{ m}$$

$$\text{Torque exerted, } T = F \times r = 30 \times 0.5 = 15 \text{ kg-m or } 15 \times 9.81 = \mathbf{147.15 \text{ Nm (Ans.)}}$$

$$\text{Motor output} = T \times \frac{2\pi N}{60} = \frac{147.15 \times 2\pi \times 1200}{60} = \mathbf{18499 \text{ W (Ans.)}}$$

$$\text{Input power to motor} = V \times I = 400 \times 65 = 26000$$

$$\text{Motor efficiency, } \eta = \frac{\text{Output}}{\text{Input}} \times 100 = 71.15\% \text{ (Ans.)}$$

Example 5.52

In a break test on DC motor, the effective load on the brake drum was 23 kgf, the effective diameter of the drum 45 cm and the speed 960 rpm. The input of the motor was 28A at 230 V. Calculate the efficiency of the motor.

Solution:

$$\text{Here, load } (W_1 - W_2) = 23 \text{ kg f; } d_m = 45 \text{ cm} = 0.45 \text{ m;}$$

$$N = 960 \text{ rpm; } I_L = 28 \text{ A; } V = 230 \text{ V}$$

$$\begin{aligned} \text{Torque developed, } T &= (W_1 - W_2) \times \frac{dm}{2} = 23 \times \frac{0.45}{2} = 5.175 \text{ kg m} \\ &= 5.175 \times 9.81 = 50.77 \text{ Nm} \end{aligned}$$

$$\text{Motor output} = \frac{2\pi NT}{60} = \frac{2\pi \times 960 \times 50.77}{60} \text{ Nm/s or watt} = 5106 \text{ W}$$

$$\text{Motor input} = V \times I_L = 230 \times 28 = 6440 \text{ W}$$

$$\text{Motor efficiency, } \eta = \frac{\text{output}}{\text{input}} \times 100 = \frac{5106}{6440} \times 100 = \mathbf{79.28\% \text{ (Ans.)}}$$

5.35 Swinburne's Test

Swinburne's test is performed to determine the constant losses in a DC shunt machine. In this test, the machine is operated as a motor on no-load. This no-load test is also known as Swinburne's test. A voltmeter and two ammeters A_1 and A_2 are connected in the circuit as shown in Fig. 5.58. The normal rated voltage V is applied to the motor terminals. The ammeter A_1 and A_2 measure the no-load line current I_{L0} and shunt field current I_{sh} respectively. The voltmeter measures the applied voltage. As there is no output at no-load, all the power supplied to the motor, given by the product of current I_{L0} and voltage V , is being utilised to meet with losses only. The following are the losses at no-load:

- (i) Iron losses in the core
- (ii) Windage and friction losses at bearing and commutator.
- (iii) Shunt field copper losses.
- (iv) Armature copper losses at no-load (very small)

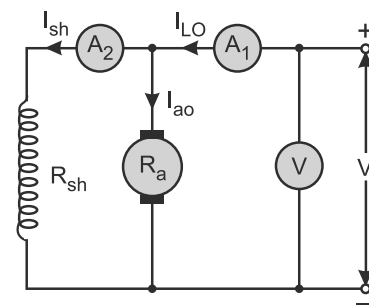


Fig. 5.58 Circuit arrangement for Swinburne's Test

Except the armature copper loss all other losses are the constant losses.

$$\text{No-load input power to the machine} = V I_{L0} \text{ watt} \quad \dots(5.30)$$

$$\text{No-load armature current, } I_{a0} = I_{L0} - I_{sh}$$

The resistance of armature circuit including the inter pole winding, etc., is determined (measured) by disconnecting one end of the shunt field circuit. Let its value be R_a .

$$\text{Then, variable losses} = I_a^2 R_a \text{ watt}$$

$$\therefore \text{Constant losses } P_c = (V I_{L0} - I_{a0}^2 R_a) \text{ watt} \quad \dots(5.31)$$

Note: For all practical purposes the copper losses in the armature at no-load may be neglected being very small.

After determining the constant losses, the efficiency of the machine, when it is working as a motor or generator can be calculated at any load, as discussed below:

Let I_L be the line current at which efficiency is to be calculated.

(i) *When the machine is working as a motor:*

$$\text{Armature current, } I_a = I_L - I_{sh} \quad \dots(5.32)$$

$$\text{Variable or armature copper loss at load} = I_a^2 R_a$$

$$\therefore \text{Total losses} = P_c + I_a^2 R_a \quad \dots(5.33)$$

$$\text{Input power} = V I_L$$

$$\text{Output power} = \text{input power} - \text{total losses}$$

$$= V I_L - (P_c + I_a^2 R_a) \quad \dots(5.34)$$

$$\therefore \text{Efficiency, } \eta = \frac{\text{output}}{\text{input}} = \frac{V I_L - (P_c + I_a^2 R_a)}{V I_L} \quad \dots(5.35)$$

(ii) *When the machine is working as a generator;*

$$\text{Armature current, } I_a = I_L + I_{sh} \quad \dots(5.36)$$

$$\text{Variable or armature copper loss at load} = I_a^2 R_a$$

$$\text{Total losses} = P_c + I_a^2 R_a$$

$$\text{Output power} = V I_L$$

$$\text{Input power} = \text{output power} + \text{total losses}$$

$$= V I_L + (P_c + I_a^2 R_a) \quad \dots(5.37)$$

$$\therefore \text{Efficiency, } \eta = \frac{V I_L}{V I_L + (P_c + I_a^2 R_a)} \quad \dots(5.38)$$

Advantages

1. Very convenient and economical method since power required is very small.
2. Stray or constant losses are determined, therefore, efficiency at any desired value of load can be determined.

Disadvantages

1. Since the test is performed at no-load, the effect of temperature rise and performance of commutator cannot be assessed properly.
2. This test cannot be performed with DC series motors because at no-load series motors obtain dangerously high speeds.
3. The change in iron losses from no-load to full-load are not accounted for, although this change is prominent due to armature reaction.

Example 5.53

A 250 V shunt motor takes 4A at no-load and resistance of armature is 0.4Ω and that of shunt field is 125Ω calculate: (i) output in kW (ii) Efficiency of motor when motor current is 102A.

Solution:

Here, $I_{a0} = 4 \text{ A}$; $R_a = 0.4 \Omega$; $R_{sh} = 125 \Omega$;

$$I_{sh} = \frac{V}{R_{sh}} = \frac{250}{125} = 2 \text{ A}$$

$$I_{a0} = I_{L0} - I_{sh} = 4 - 2 = 2 \text{ A}$$

$$\text{Copper losses at no-load} = I_{a0}^2 R_a = (2)^2 \times 0.4 = 1.6 \text{ W}$$

$$\text{Power input at no-load} = V I_{L0} = 250 \times 4 = 1000 \text{ W}$$

$$\text{Constant losses} = 1000 - 1.6 = 998.4 \text{ W}$$

$$\text{Armature full load current, } I_a = I_{L(f)} - I_{sh} = 102 - 2 = 100 \text{ A}$$

$$\text{Armature Cu loss at full-load} = I_a^2 R_a = (100)^2 \times 0.4 = 4000 \text{ W}$$

$$\text{Total losses at full-loaded} = 4000 + 998.4 = 4998.4 \text{ W}$$

$$\text{Input at full-load} = V I_{L(f)} = 250 \times 102 = 25500 \text{ W}$$

$$\begin{aligned} \text{Output} &= \text{Input} - \text{losses} = 25500 - 4998.4 = 20501.6 \text{ W} \\ &= \mathbf{20.5016 \text{ kW}} \text{ (Ans.)} \end{aligned}$$

$$\text{Efficiency of the motor, } \eta = \frac{\text{output}}{\text{input}} \times 100$$

$$= \frac{20501.6}{25500} \times 100 = \mathbf{80.4\%} \text{ (Ans.)}$$

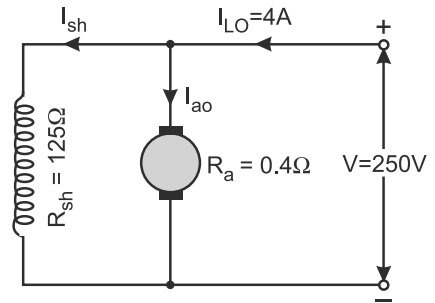


Fig. 5.59 Circuit diagram

Example 5.54

A 50 kW, 250 V compound motor takes a current of 9A while running on no-load at rated voltage and speed. The shunt field current is 5A. The resistances of the windings when hot are :

Armature $0.1\ \Omega$, series field $0.07\ \Omega$ and interpole $0.03\ \Omega$. The brush drop is 2V . Determine motor output and the efficiency when the motor intake is 155 A .

Solution:

At No-load; $I_{L0} = 9\text{A}$; $I_{sh} = 5\text{A}$

$$\text{Input at no-load} = I_{L0} \times V = 9 \times 250 = 2250\text{ W}$$

$$\text{Armature current, } I_{a0} = I_{L0} - I_{sh} = 9 - 5 = 4\text{A}$$

Considering the machine as long-shunt;

Variable losses = Copper losses in armature circuit and at brushes

$$= I_{a0}^2 (R_a + R_{se} + R_i) + I_{a0} \times \text{brush drop}$$

$$= 4^2 (0.1 + 0.07 + 0.03) + 4 \times 2 = 11.2\text{ W}$$

Constant losses, P_C = Input at no-load – variable losses

$$= 2250 - 11.2 = 2238.8\text{ W}$$

At full-load; Line current, $I_{Lf} = 155\text{ A}$

$$\text{Power input} = I_{Lf} \times V = 155 \times 250 = 38750\text{ W}$$

$$\text{Armature current, } I_{af} = I_{Lf} - I_{sh} = 155 - 5 = 150\text{ A}$$

$$\text{Variable losses} = I_{af}^2 (R_a + R_{se} + R_i) + I_{af} \times \text{brush drop}$$

$$= 150^2 (0.1 + 0.07 + 0.03) + 150 \times 2 = 4800\text{ W}$$

$$\text{Total losses} = P_C + \text{variable losses} = 2238.8 + 4800 = 7038.8\text{ W}$$

Motor output, $P_{out} = P_{in} - \text{total losses}$

$$= 38750 - 7038.8 = 31711.2\text{ W or } \mathbf{31.7\text{ kW}} \text{ (Ans.)}$$

$$\text{Motor efficiency, } \eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{31711.2}{38750} \times 100 = \mathbf{81.84\%} \text{ (Ans.)}$$

Example 5.55

A 100 kW , 500 V shunt generator was run as a motor on no-load at its rated voltage and speed. The total current taken was 9.8 A including a shunt current of 2.7 A . The resistance of the armature circuit (including interpoles) at normal working temperature was 0.11 ohm . Calculate the efficiency at half full-load.

Solution:

Terminal voltage, $V = 500\text{ V}$

Armature resistance, $R_a = 0.11\text{ ohm}$

No-load line current, $I_{L0} = 9.8\text{ A}$

Shunt field current, $I_{sh} = 2.7\text{ A}$

When machine is operated at no-load as a motor as shown in Fig. 5.60.

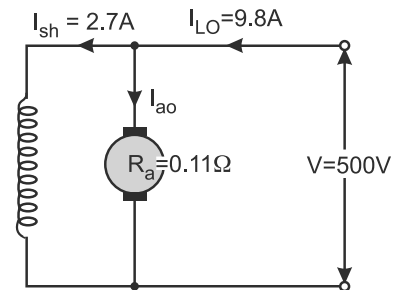


Fig. 5.60 Circuit diagram

$$\text{Input at no-load} = VI_{L0} = 500 \times 9.8 = 4900 \text{ W}$$

$$\text{No-load armature current, } I_{a0} = I_{L0} - I_{sh} = 9.8 - 2.7 = 7.1 \text{ A}$$

Variable or armature copper losses at no-load

$$= I_{a0}^2 R_a = (7.1)^2 \times 0.11 = 5.55 \text{ W}$$

$$\text{Constant losses} = 4900 - 5.55 = 4894.45 \text{ W}$$

When the machine is operated at half full-load as a generator.

$$\text{Output power} = \frac{100}{2} = 20 \text{ kW} = 50 \times 10^3 \text{ W}$$

$$\text{Line current, } I_L = \frac{50 \times 10^3}{500} = 100 \text{ A}$$

$$\text{Armature current at half full-load, } I_a = I_L + I_{sh} = 100 + 2.7 = 102.7 \text{ A}$$

Variable or armature copper losses, at half full-load

$$= I_a^2 R_a = (102.7)^2 \times 0.11 = 1160.2 \text{ W}$$

$$\text{Total losses at half full load} = \text{constant losses} + \text{variable losses}$$

$$= 4894.45 + 1160.2 = 6054.65 \text{ W}$$

$$\text{Input power} = \text{output power} + \text{total losses}$$

$$= 50000 + 6054.65 = 56054.65 \text{ W}$$

$$\text{Efficiency, } \eta = \frac{\text{output power}}{\text{input power}} \times 100 = \frac{50000}{56054.65} \times 100$$

$$= \mathbf{89.2\% \text{ (Ans.)}}$$

Example 5.56

A 500 V, 25 hp, DC shunt motor takes 2.4 A while running light. The field and armature resistances are 650 Ω and 0.57 Ω respectively. Calculate full-load efficiency, assuming a brush drop of 2V.

Solution:

$$\text{At No-load; } I_{L0} = 2.4 \text{ A; } V = 500 \text{ V}$$

$$\text{Power input, } P_{in0} = VI_{L0} = 500 \times 2.4 = 1200 \text{ W}$$

$$\text{Shunt field current, } I_{sh} = \frac{V}{R_{sh}} = \frac{500}{650} = 0.77 \text{ A}$$

$$\text{Armature current, } I_{a0} = I_{L0} - I_{sh} = 2.4 - 0.77 = 1.63 \text{ A}$$

$$\text{Armature copper loss} = I_{a0}^2 R_a + I_{a0} \times \text{brush drop}$$

$$= (1.63)^2 \times 0.57 + 1.63 \times 2 = 4.77 \text{ W}$$

$$\text{Constant losses, } P_C = P_{in0} - \text{no-load armature copper loss}$$

$$= 1200 - 4.77 = 1195.23 \text{ W}$$

$$\begin{aligned}\text{At full-load; Power output } P_{out} &= 25 \times 735.5 \\ &= 18387.5 \text{ W}\end{aligned}$$

At full-load, let the armature current be I_a ampere

$$\text{Power input, } P_{in} = V \times (I_a + I_{sh}) = 500 (I_a + 0.77)$$

$$\text{Armature copper loss} = I_a^2 R_a + I_a \times v_b = 0.57 I_a^2 + 2 I_a$$

$$\text{Also power input, } P_{in} = P_{out} + \text{armature copper loss} + \text{constant losses}$$

$$\text{or } 500 (I_a + 0.77) = 18387.5 + 0.57 I_a^2 + 2 I_a + 1195.3 \text{ W}$$

$$\text{or } 0.57 I_a^2 - 498 I_a + 19197.8 = 0$$

$$\begin{aligned}\text{or } I_a &= \frac{498 \pm \sqrt{(498)^2 - 4 \times 0.57 \times 19197.8}}{2 \times 0.57} \\ &= 833.26 \text{ A or } 41.05 \text{ A}\end{aligned}$$

Since the value of current 833.26 A is impracticable

$$\text{Full-load armature current, } I_a = 41.05 \text{ A}$$

$$\text{Motor input} = VI_L = 500 \times (41.05 + 0.77) = 20910 \text{ W}$$

$$\begin{aligned}\text{Motor efficiency, } \eta &= \frac{\text{Motor output}}{\text{Motor input}} \times 100 \\ &= \frac{18387.5}{20910} \times 100 = \mathbf{87.94\% (Ans.)}\end{aligned}$$

5.36 Hopkinson's Test

Hopkinson's test is basically a regenerative test. It is also known as *back-to-back* test. To perform this test, two identical machines are required. These machines are mechanically coupled to each other. One of them works as a motor which acts as a prime-mover for the other machine which works as a generator.

The electrical power or energy supplied to the motor is converted into mechanical energy which is further converted into electrical energy by the second machine coupled to it, and fed back to the motor through supply system. In the process, in fact, the two machines draw electrical power or energy to meet with the losses of the two machines. Since the mechanics are identical, the losses in each machine are determined by dividing the input into two equal parts. Usually, this test is performed on large size machines at full-load for longer duration.

Circuit Arrangements and Procedure of Performing the Test

The electrical circuit arrangement is shown in Fig. 5.61.

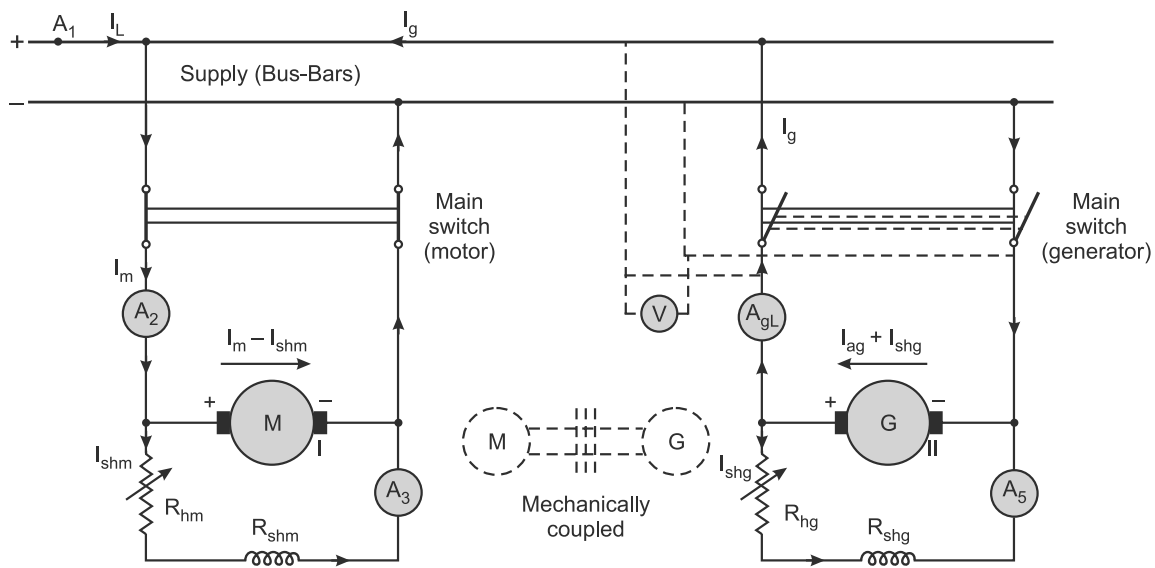


Fig. 5.61 Circuit arrangement for Hopkinson's test

Connect machine-I to the supply through its main switch (motor) and starter keeping main switch of the other machine-II open. Operate machine-I to its rated speed and adjust the field current I_{shg} of second machine such that the voltage developed by this machine (working as a generator) is 1 to 2V more than the mains voltage having same polarity as that of bus-bars. The voltage and polarity can be checked with the help of a paralleling voltmeter V. Now, connect the second machine (generator) to the mains through its main switch.

It may be noted that a machine with smaller excitation acts as a motor and a machine with larger excitation acts as a generator.

To increase the load, the excitation of machine-I (i.e., motor) is decreased gradually. With the decrease in excitation its back emf decreases due to which motor draws more current from the mains. This process goes on till the machine draws its full-load current as per the rating. During this process, the supply voltage must be maintained at its rated value.

The value of the resistances involved in the armature circuit such as armature winding resistance including brush contact, interpole winding resistance, compensating winding resistance of the two machines are measured by passing full-load current through them after the completion of whole procedure when these windings attain their final temperature at full-load.

Let various ammeters A_1, A_2, A_3, A_4 and A_5 connected in the circuit shown in Fig. 5.61 measure line current I_L , motor current I_m , motor shunt field current I_{shm} , generator current I_g and generator shunt field current I_{shg} respectively.

$$\text{Where, motor current, } I_m = I_L + I_g \quad (\text{as per Kirchhoff's current law}) \dots(5.39)$$

$$\text{Motor input} = VI_m \dots(5.40)$$

$$\text{and generator output} = VI_g \dots(5.41)$$

where V is bus = bar voltage.

If η_m and η_g are the efficiencies of motor and generator respectively,

then $\text{motor output} = VI_m \eta_m$... (5.42)

and $\text{generator input} = \frac{VI_g}{\eta_g}$... (5.43)

But $\text{motor output} = \text{Generator input}$

or $VI_m \eta_m = \frac{VI_g}{\eta_g}$ or $\eta_m \eta_g = \frac{I_g}{I_m}$... (5.44)

Since armature, field and stray power losses in both of the machines are considered to be equal then $\eta_m = \eta_g$

Thus, $\eta_m = \eta_g = \sqrt{\frac{I_g}{I_m}} = \sqrt{\frac{I_g}{I_g + I_L}} = \sqrt{\frac{I_m - I_L}{I_m}}$... (5.45)

This assumption is true for large machines since there is very slight difference in their armature and excitation current, but in case of small machines, the difference between the armature currents and shunt field currents is large. To obtain accurate results, armature and shunt field losses are determined separately and stray losses are assumed to be equal in both the machines.

Current supplied by the mains, $I_L = I_m - I_g$... (5.46)

Current drawn by motor = I_m

Motor shunt field current = I_{shm}

Motor armature current, $I_{am} = (I_m - I_{shm})$... (5.47)

Current supplied by generator = I_g

Generator shunt field current = I_{shg}

Generator armature current, $I_{ag} = (I_g + I_{shg})$... (5.48)

Terminal voltage = V

Total losses of both machines = Power supplied by the mains = VI_L

Armature copper loss in motor = $(I_m - I_{shm})^2 R_{am}$... (5.49)

Armature copper loss in generator = $(I_g + I_{shg})^2 R_{ag}$... (5.50)

Shunt field copper loss in motor = VI_{shm}

Shunt field copper loss in generator = VI_{shg}

Total copper losses = $(I_m - I_{shm})^2 R_{am} + (I_g + I_{shg})^2 R_{ag} + VI_{shm} + VI_{shg}$

Stray losses of both the machines, $P_S = VI_L - [(I_m - I_{shm})^2 R_{am} + (I_g + I_{shg})^2 R_{ag} + V(I_{shm} + I_{shg})]$... (5.51)

Stray loss of each machine = $\frac{P_S}{2}$... (5.52)

For efficiency of motor (machine-I)

Motor input = VI_m ... (5.53)

Total losses in the motor = Armature loss + field loss + stray loss

$$= (I_m - I_{shm})^2 R_{am} + VI_{shm} + \frac{P_s}{2} \quad \dots(5.54)$$

$$\text{Motor output} = VI_m - \left[(I_m - I_{shm})^2 R_{am} + VI_{shm} + \frac{P_s}{2} \right] \quad \dots(5.55)$$

$$\text{Motor efficiency} = \frac{\text{Output}}{\text{Input}} \times 100 \quad \dots(5.56)$$

For efficiency of generator (machine-II)

$$\text{Generator output} = VI_g \quad \dots(5.57)$$

Total losses in the generator = Armature loss + field loss + stray loss

$$= (I_g + I_{shg})^2 R_{ag} + VI_{shg} + \frac{P_s}{2} \quad \dots(5.58)$$

$$\text{Generator input} = VI_g + (I_g + I_{shg})^2 R_{ag} + VI_{shg} + \frac{P_s}{2} \quad \dots(5.59)$$

$$\text{Generator efficiency, } \eta_g = \frac{\text{Output}}{\text{Input}} \times 100 \quad \dots(5.60)$$

Thus, the efficiency of motor and generator can be determined from the data available from the test.

Advantages

- (i) It is economical since small power is required.
- (ii) The performance of the machines regarding commutation and temperature rise, etc., can be conveniently studied as the machines are tested at full-load, that too for long duration.
- (iii) Accurate results are obtained since the efficiency is determined under load conditions and the stray load loss are being taken into account.

Disadvantage

The main disadvantage of this test is that there is necessity of two identical machines which are rarely available.

Example 5.57

The results of Hopkinson's test on two similar DC machines are as follows:

Line voltage 250 V, Motor armature current 23A, Generator armature current 20A, Generator field current 0.4 A. Motor armature current 0.3 A. Armature resistance of each machine 0.5 Ω . Calculate the efficiency of each machine.

Solution:

Supply voltage, $V = 250 \text{ V}$

Generator armature current, $I_{og} = 20 \text{ A}$

Generator shunt field current, $I_{shg} = 0.4 \text{ A}$

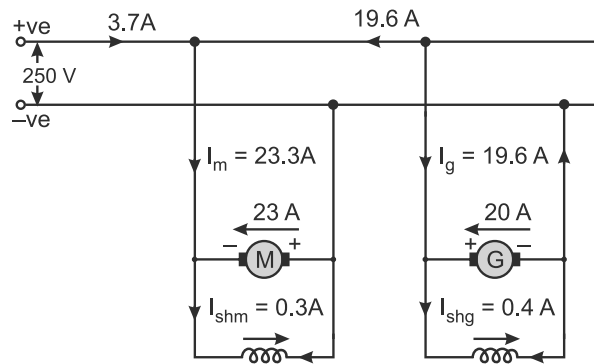


Fig. 5.62 Circuit diagram

Generator output current, $I_g = I_{ag} - I_{shg} = 20 - 0.4 = 19.6 \text{ A}$

Motor armature current, $I_{am} = 23 \text{ A}$

Motor shunt field current, $I_{shm} = 0.3 \text{ A}$

Motor input current, $I_m = 23.3 \text{ A}$

Input line current, $I_L = \text{Motor input current} - \text{generator output current}$
 $= 23.3 - 19.6 = 3.7 \text{ A}$

Input power to set = $VI_L = 250 \times 3.7 = 925 \text{ W}$

Motor armature copper loss = $(I_{am})^2 R_{am} = (23)^2 \times 0.5 = 264.5 \text{ W}$

Generator armature copper loss = $(I_{ag})^2 R_{ag} = (20)^2 \times 0.5 = 200 \text{ W}$

Motor shunt field copper loss = $VI_{shm} = 250 \times 0.3 = 75 \text{ W}$

Generator shunt field copper loss = $VI_{shg} = 250 \times 0.4 = 100 \text{ W}$

Total copper loss = $264.5 + 200 + 75 + 100 = 639.5 \text{ W}$

Total stray power loss, $P_s = \text{Input to machines} - \text{total copper loss}$
 $= 925 - 639.5 = 285.5 \text{ W}$

Stray power loss per machine = $\frac{P_s}{2} = \frac{285.5}{2} = 142.75 \text{ W}$

Input to motor = $VI_m = 250 \times 23.3 = 5825 \text{ W}$

Total losses in motor = Armature loss + field loss + stray power loss
 $= 264.5 + 75 + 142.75 = 482.25 \text{ W}$

Motor efficiency, $\eta_m = \frac{\text{Input} - \text{Total losses}}{\text{Input}} \times 100 = \frac{5825 - 482.25}{5825} \times 100$
 $= 91.72\% \text{ (Ans.)}$

Generator output = $VI_g = 250 \times 19.6 = 4900 \text{ W}$

Total losses in generator = Armature loss + field loss + stray power loss
 $= 200 + 100 + 142.75 = 442.75 \text{ W}$

$$\begin{aligned}\text{Generator efficiency, } \eta_g &= \frac{\text{Output}}{\text{Output} + \text{Total losses}} \times 100 \\ &= \frac{4900}{4900 + 442.75} \times 100 = 91.72\% \text{ (Ans.)}\end{aligned}$$

Example 5.58

The Hopkinson test on two shunt machines gave the following results for full load:

Line voltage, 250 V; line current excluding field currents, 50 A; motor armature current 380 A; field currents, 5 A and 4.2 A. Calculate the efficiency of each machine. Armature resistance of each machine is 0.02 ohm.

Solution.

Here, $V = 250 \text{ V}$; $I_{am} = 380 \text{ A}$; $I_L = 50 \text{ A}$; $R_a = 0.2 \Omega$

In Hopkinson's test, the machine working as a generator must have field current more than the machine working as a motor.

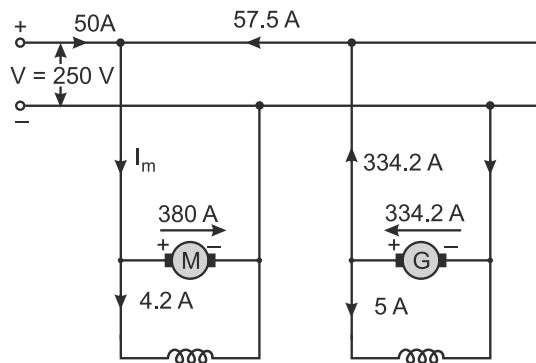


Fig. 5.63 Circuit diagram

Therefore,

$$I_{shg} = 5\text{A}; I_{shm} = 4.2 \text{ A}$$

Current drawn by the motor, $I_m = I_{am} + I_{shm}$

$$= 380 + 4.2 = 384.2 \text{ A}$$

Current delivered by the generator,

$$\begin{aligned}I_g &= I_m - I_L \\ &= 384.2 - 50 = 334.2 \text{ A}\end{aligned}$$

$$\begin{aligned}I_{ag} &= I_g - I_{shg} \\ &= 334.2 - 5 = 329.2 \text{ A}\end{aligned}$$

$$\text{Armature copper loss in motor} = (I_{am})^2 R_a = (380)^2 \times 0.02 = 2888 \text{ W}$$

$$\text{Armature copper loss in generator} = (I_{ag})^2 R_a = (329.2)^2 \times 0.02 = 2168 \text{ W}$$

$$\text{Field copper loss in motor} = VI_{shm} = 250 \times 5 = 1250 \text{ W}$$

$$\text{Field copper loss in generator} = VI_{shg} = 250 \times 4.2 = 1050 \text{ W}$$

$$\text{Power supplied to the set} = VI_L = 250 \times 50 = 12500 \text{ W}$$

$$\begin{aligned} \text{Total stray losses} &= \text{Power input to set} - \text{copper losses in both the machines} \\ &= 12500 - (2888 + 2168 + 1250 + 1050) \\ &= 12500 - 7357 = 5144 \text{ W} \end{aligned}$$

$$\text{Stray losses for each machine, } P_s = \frac{5144}{2} = 2572 \text{ W}$$

$$\text{Motor input} = VI_m = 250 \times 384.2 = 96050 \text{ W}$$

$$\begin{aligned} \text{Motor output} &= \text{motor input} - \text{copper losses} - \text{stray losses} \\ &= 96050 - (2888 + 1250) - 2572 = 89340 \text{ W} \end{aligned}$$

$$\text{Efficiency, } \eta_m = \frac{\text{output}}{\text{input}} \times 100 = \frac{89340}{96050} \times 100 = 93.01\% \text{ (Ans.)}$$

$$\text{Generator output} = VI_g = 250 \times 334.2 = 83550 \text{ W}$$

$$\begin{aligned} \text{Generator input} &= \text{generator output} + \text{copper loss} + \text{stray loss} \\ &= 83550 + (2169 + 1050) + 2572 = 89341 \text{ W} \end{aligned}$$

$$\text{Generator efficiency, } \eta_g = \frac{\text{output}}{\text{input}} \times 100 = \frac{83550}{89341} \times 100 = \mathbf{93.52\% \text{ (Ans.)}}$$

Example 5.59

The following test results were obtained while Hopkinson's test was performed on two similar DC shunt machines:

Supply voltage = 250 V, Field current of motor = 2A, Field current of generator = 2.5 A, Armature current of generator = 60A, Current taken by the two armatures from supply = 15A, Resistance of each armature circuit = 0.2 ohm.

Calculate the efficiency of the motor and generator under these conditions of load.

Solution.

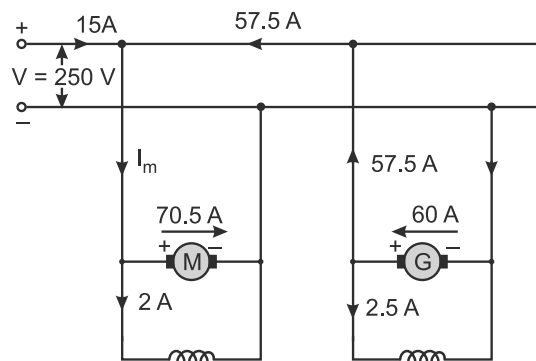


Fig. 5.64 Circuit diagram

Here, $V = 250 \text{ V}$; $I_{shm} = 2 \text{ A}$; $I_{shg} = 2.5 \text{ A}$; $I_{ag} = 60 \text{ A}$

$$I_L = 15 \text{ A}; R_{am} = R_{ag} = 0.2 \Omega$$

$$\text{Generator current, } I_g = I_{ag} - I_{shg} = 60 - 2.5 = 57.5 \text{ A}$$

$$\begin{aligned}\text{Motor current, } I_m &= I_g + I_L \\ &= 57.5 + 15 = 72.5 \text{ A}\end{aligned}$$

$$\begin{aligned}\text{Motor armature current, } I_{am} &= I_m - I_{shm} \\ &= 72.5 - 2 = 70.5 \text{ A}\end{aligned}$$

$$\begin{aligned}\text{Motor armature copper loss} &= I_{am}^2 R_{am} \\ &= (70.5)^2 \times 0.2 = 994.05 \text{ W}\end{aligned}$$

$$\text{Motor shunt field Cu loss} = I_{shm} V = 2 \times 250 = 500 \text{ W}$$

$$\text{Generator armature Cu loss} = I_{ag}^2 R_{ag} = (60)^2 \times 0.2 = 720 \text{ W}$$

$$\text{Generator shunt field Cu loss} = I_{shg} V = 2.5 \times 250 = 625 \text{ W}$$

$$\text{Copper losses of motor} = 994.05 + 500 = 1494.05 \text{ W}$$

$$\text{Copper losses of generator} = 720 + 625 = 1345 \text{ W}$$

$$\text{Total copper losses} = 1494.05 + 1345 \cong 2839.05 \text{ W (say 2839 W)}$$

$$\begin{aligned}\text{Input to the set of two machines} &= VI_L = 250 \times 15 \\ &= 3750 \text{ W}\end{aligned}$$

$$\begin{aligned}\text{Total stray losses} &= 3750 - 2839 \\ &= 911 \text{ W}\end{aligned}$$

$$\text{Stray losses of each machine} = \frac{911}{2} = 455.5 \text{ W}$$

$$\begin{aligned}\text{Total losses of motor} &= \text{Cu loss} + \text{stray loss} \\ &= 1494.05 + 455.5 = 1949.55 \text{ W}\end{aligned}$$

$$\text{Motor input} = I_m \times V = 72.5 \times 250 = 18125 \text{ W}$$

$$\begin{aligned}\text{Motor efficiency, } \eta &= \frac{\text{motor input} - \text{losses}}{\text{motor input}} \times 100 \\ &= \frac{18125 - 1949.55}{1812.5} \times 100 = \mathbf{89.24\% (Ans.)}\end{aligned}$$

$$\text{Generator output} = I_g \times V = 60 \times 250 = 15000 \text{ W}$$

$$\begin{aligned}\text{Generator efficiency, } \eta &= \frac{\text{generator output}}{\text{output} + \text{losses}} \times 100 \\ &= \frac{15000}{15000 + 1345 + 455.5} \times 100 \\ &= \mathbf{89.28\% (Ans.)}\end{aligned}$$

5.37 Testing of DC Series Machines

(Field test)

Small DC series machines can be tested by brake test but large DC series machines cannot be tested by brake test because neither it is convenient nor possible to develop a mechanism to apply load on such large machines directly.

Moreover, DC series machines cannot be tested by Swinburne's test, because at no-load these machines obtain dangerously high speeds. In view of this*, *field test* is considered to be most suitable for determining efficiency of these machines.

Field Test

To determine efficiency of large DC series machines usually field test is employed. To perform this test, two** identical DC series machines are coupled mechanically, as shown in Fig. 5.65, and their fields are connected in series so that the iron losses of both the machines be made equal. One of the machine-I to which supply is given, operates as a motor and drives the other machine-II. This other machine operates as a separately excited generator. A variable load R_L is connected directly across its terminals without any switch.

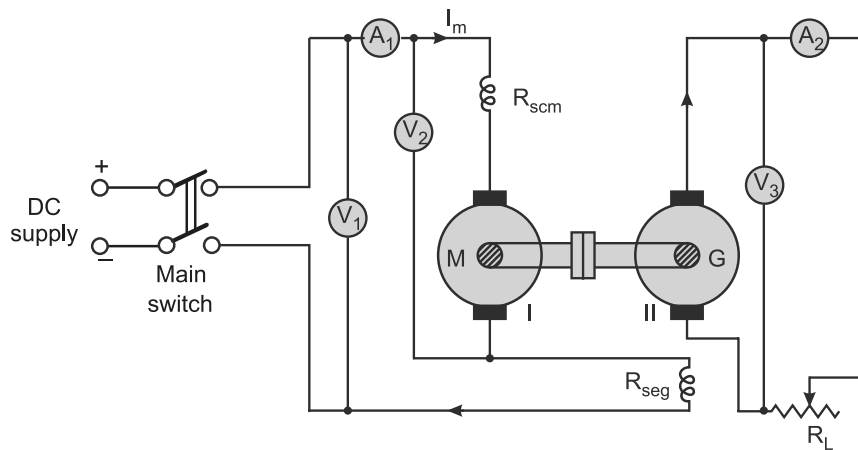


Fig. 5.65 Circuit arrangement for field test of DC series motors

Performance

The machine-I (motor) is switched-ON to the supply in a usual manner and the output of the other machine-II, working as a generator, is dissipated in the variable load resistor R_L . The voltage across the motor terminals V_2 is kept equal to its rated value. It is obvious that the supply voltage V_1 will be more than V_2 i.e., $V_1 = V_2 + I_m R_{seg}$. The load resistor R_L is varied till the ammeter A_1 , shows full-

*Field test looks to be similar to regenerative test but it is not so because in this case the output of the generator is not feedback to the motor rather it is dissipated in a load resistor. This will be confirmed after going through the test.

**It is not difficult to have two identical DC series machines because in electric traction DC series motors are used in pairs.

load motor current. The hot resistances of various windings are measured by voltmeter-ammeter (or other suitable) method after performing the test. Note down the readings of various measuring instruments as mentioned below:

Precautions

Every effort is to be made to get accurate measurements since the accuracy of the test depends upon the accuracy of these measurements.

Let, Supply voltage = Reading of voltmeter $V_1 = V_1$ volt

Motor input current = Reading of ammeter $A_1 = I_m$

Terminal voltage of generator = Reading of voltmeter $V_3 = V_3$

Load current or generator current = Reading of ammeter $A_2 = I_g$

Armature resistance of each machine = R_a

Series field resistance of each machine = R_{se}

$$\text{Input to the whole set} = V_1 I_m \quad \dots(5.61)$$

$$\text{Output} = V_3 I_g \quad \dots(5.62)$$

$$\text{Total losses of the set, } P_T = V_1 I_m - V_3 I_g \quad \dots(5.63)$$

$$\text{Series field and armature copper losses of motor} = I_m^2 (R_a + R_{se}) \quad \dots(5.64)$$

$$\text{Series field and armature copper losses of generator} = I_g^2 R_{se} + I_g^2 R_a \quad \dots(5.65)$$

$$\text{Total copper losses of the set, } P_{cu} = I_m^2 (R_a + 2R_{se}) + I_g^2 R_a \quad \dots(5.66)$$

$$\text{Stray power losses for the set} = P_T - P_{cu}$$

$$\text{Stray power losses per machine, } P_s = \frac{P_T - P_{cu}}{2} \quad \dots(5.67)$$

$$\textbf{Motor efficiency} \quad \text{Motor input} = V_2 I_m \quad \dots(5.68)$$

$$\text{Motor losses} = I_m^2 (R_a + R_{se}) + P_s \quad \dots(5.69)$$

$$\text{Motor output} = V_2 I_m - I_m^2 (R_a + R_{se}) - P_s \quad \dots(5.70)$$

$$\text{Motor efficiency, } \eta_m = \frac{V_2 I_m - I_m^2 (R_a + R_{se}) - P_s}{V_2 I_m} \quad \dots(5.71)$$

$$\textbf{Generator efficiency} \quad \text{Generator output} = V_3 I_g \quad \dots(5.72)$$

$$\text{Generator losses} = I_g^2 R_a + I_m^2 R_{se} + P_s \quad \dots(5.73)$$

$$\text{Generator input} = V_3 I_g + I_g^2 R_a + I_m^2 R_{se} + P_s \quad \dots(5.74)$$

$$\text{Generator efficiency, } \eta_g = \frac{V_3 I_g}{V_3 I_g + I_g^2 R_a + I_m^2 R_{se} + P_s} \quad \dots(5.75)$$

Disadvantages of Field Test Method

1. Even for a small error in the measurement of the input to motor or output of generator may cause a relatively large error in computed the efficiency.
2. Whole of the power supplied to the set is wasted.

Example 5.60

The following test data is obtained after performing a field test on two identical, mechanically coupled DC series motors (with their field windings connected in series):

Motor: Armature current-50 A, Armature voltage-500 V; Field winding voltage drop 35 V

Generator: Armature current-38 A; Armature voltage-400 V; Field winding voltage drop-32 V; Resistance of each armature is 0.2 Ω .

Calculate the efficiency of each machine at this load.

Solution.

Voltage across motor armature = 500 V

Voltage across motor, $V_2 = 500 + 35 = 535$ V

Supply voltage, $V_1 = V_2 + \text{voltage drop across generator field winding}$
 $= 535 + 32 = 567$ V

Terminal voltage of generator, $V_3 = 400$ V

Generator armature current, $I_g = 38$ A

Motor armature current, $I_m = 50$ A

Total power input = $V_1 I_m = 567 \times 50 = 28350$ W

Generator output = $V_3 I_g = 400 \times 38 = 15200$ W

Total copper losses = $I_m^2 \times 0.2 + I_g^2 \times 0.2 + I_m (35 + 32)$ watt
 $= (50)^2 \times 0.2 + (38)^2 \times 0.2 + 50 \times 67 = 4149.8$ W

Stray losses of the set = total power input – power output – total copper losses
 $= 28350 - 15200 - 4149.8 = 9000.2$ W $\cong 9000$ W

Stray losses per machine, $P_s = \frac{9000}{2} = 4500$ W

Motor Efficiency

Input power to motor = $V_2 I_m = 535 \times 50 = 26750$ W

Total losses in motor = $50^2 \times 0.2 + 50 \times 35 + 4500$ W = 6750 W

Motor output = Input – total losses = $26750 - 6750 = 20000$ W

Motor efficiency, $\eta_m = \frac{\text{Motor output}}{\text{Motor input}} \times 100 = \frac{20000}{26750} \times 100 = 74.77\%$ (Ans.)

Generator Efficiency

Generator output = $V_3 I_g = 400 \times 38 = 15200$ W

$$\text{Total losses in generator} = (38)^2 \times 0.2 + 50 \times 32 + 4500 = 6388.8 \text{ W}$$

$$\text{Generator input} = \text{Output} + \text{total losses} = 15200 + 6388.8 = 21588.8 \text{ W}$$

$$\begin{aligned} \text{Generator efficiency, } \eta_g &= \frac{\text{Generator output}}{\text{Generator input}} \times 100 \\ &= \frac{15200}{21588.8} \times 100 = \mathbf{70.4\% \text{ (Ans.)}} \end{aligned}$$

Example 5.61

The field windings of the two similar tramway motors are connected in series and the motors are coupled to perform a test. The following test results were obtained while one machine acts as a motor and the other acts as a generator.

Motor: Armature Current: 56A, Armature Voltage: 590 V,

Voltage drop a cross field winding: 40V

Generator: Armature Current: 44A, Armature Voltage: 400V, Field Voltage drop: 40V, Resistance of each armature: 0.3 ohm.

Calculate the efficiency of motor and generator.

Solution:

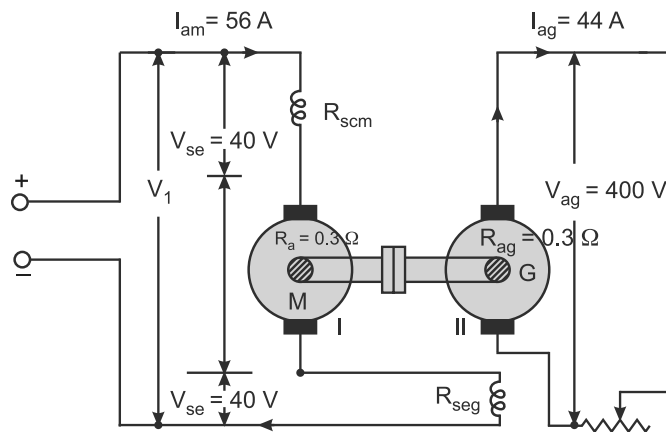


Fig. 5.66 Circuit diagram

Here,

$$I_{am} = 56 \text{ A}; V_{am} = 590 \text{ V}; V_{se} = 40 \text{ V}$$

$$I_{ag} = 44 \text{ A}; V_{ag} = 400 \text{ V}; V_{se} = 40 \text{ V}$$

$$R_{am} = R_{ag} = 0.3 \Omega$$

$$\text{Input to the whole set} = V_1 I_{am} = (40 + 590 + 40) \times 56 = 37520 \text{ W}$$

$$\text{Output of the set} = V_{ag} I_{ag} = 400 \times 44 = 17600 \text{ W}$$

$$\text{Total losses of the set} = \text{Input} - \text{Output} = 37520 - 17600 = 19920 \text{ W}$$

Series field and armature Cu loss of motor

$$= V_{sem} \times I_{am} + I_{am}^2 R_{am}$$

$$= 40 \times 56 + (56)^2 \times 0.3 = 3180.8 \text{ W}$$

Series field and armature Cu loss of generator

$$\begin{aligned} &= V_{seg} \times I_{am} + I_{ag}^2 R_{ag} \\ &= 40 \times 56 + (44)^2 \times 0.3 = 2820.8 \text{ W} \end{aligned}$$

$$\text{Total Cu losses of the set} = 3180.8 + 2820.8 = 6001.6 \text{ W}$$

$$\text{Stray losses of the set} = 19920 - 6001.6 = 13918.4 \text{ W}$$

$$\text{Stray losses of each machine} = \frac{13918.4}{2} = 6959.2 \text{ W}$$

For motor efficiency

$$\text{Motor input} = (V_{am} + V_{sem}) \times I_{am} = (590 + 40) \times 56 = 35280 \text{ W}$$

$$\text{Motor losses} = 3180.8 + 6959.2 = 10140 \text{ W}$$

$$\begin{aligned} \text{Motor efficiency, } \eta_m &= \frac{\text{motor input} - \text{losses}}{\text{motor input}} \times 100 \\ &= \frac{35280 - 10140}{35280} \times 100 = \mathbf{71.26\% (Ans.)} \end{aligned}$$

For generator efficiency:

$$\text{Generator output} = V_{ag} I_{ag} = 400 \times 44 = 17600 \text{ W}$$

$$\text{Generator losses} = 2820.8 + 6959.2 = 9780 \text{ W}$$

$$\begin{aligned} \text{Generator efficiency, } \eta_g &= \frac{\text{Generator output}}{\text{Generator output} + \text{losses}} \times 100 \\ &= \frac{17600}{17600 + 9780} \times 100 = \mathbf{64.28\% (Ans.)} \end{aligned}$$

5.38 Inspection/maintenance of DC Machines

The basic purpose of inspection/maintenance is to ensure uninterrupted and efficient service from the machine. The frequency of routine inspection/maintenance depends upon conditions under which a machine is operating. The normal routine inspection/maintenance tasks are discussed below :

1. Mechanical maintenance

(i) *Bearings*: Check sound and excessive play if any. Check for proper lubrication-avoid excessive lubrication.

(ii) *General*: Check all the fixing fixtures – tight them if required.

Check that all the cover-plates and enclosures are clean and correctly in place – if not fix them.

2. Electrical maintenance

Always keep the insulation dry and in good condition for better reliability.

(i) *Commutator*: Trouble may be caused due to dirt deposits deposit, of carbon dust in the grooves between segments, rough surface or eccentricity. Check for these and clean the commutator surface with a dry soft fluff free cloth if required.

(ii) *Brushes*: Trouble may be caused due to less spring tension, wrong brush positioning, insufficient contact surface or too short a brush. Check for there and do the adjustments or changes as per the need.

- (iii) *Winding*: Trouble may be caused due to deterioration of insulation. Check the insulation resistance of armature winding and field winding periodically – if faulty, it should be repaired.
- (iv) *Insulation resistance*: The insulation resistance of the whole machine be checked periodically which should not be less than $1\text{ M}\Omega$. If its value is found to be less than this then the machine should be cleaned and dried.
- (v) *Earthing*: Outer frame of the motor must be properly earth, the earth resistance should be checked, if found more pour water in earthing pit.
- (vi) *Starter*: Check the functioning of the starter, its relay must be sensitive enough to protect the machine.

5.39 Faults in DC Machines

In DC machines faults may occur in field windings or in armature winding.

1. *Faults in field winding*: The faults in field winding may be
 - (a) *Open circuit fault*: Check the winding for open circuit, if found faulty, check the opening at the terminals if so tight-up the terminals otherwise replace the field winding.
 - (b) *Earth fault*: Check for the earth fault, if found remove it or replace the coil.
 - (c) *Short circuit fault*: Check for the voltage drop in each turn and locate the fault and replace the turn or repair the field winding.
2. *Faults in armature winding*: In armature winding, following faults may develop:
 - (i) *Short-circuit in coils*: The turns placed in the same slot of the armature may get short circuited due to insulation failure between the turns. Heavy local current flows and heat is produced. This may lead to open circuit. The heavy current is purely local and it does not over-load the brushes.
 - (ii) *Open-circuit in coils*: Due to open circuiting of armature coil, half of the armature which carries sound coils carries double the normal current and the other portion carries no current. This produces heavy sparking at the brushes which may damage it. Therefore machine has to be stopped and repaired immediately.
 - (iii) *Earthed coil*: When a coil in the armature comes in direct contact with armature stampings due to insulation rupturing, the fault is called earth fault. If this fault occurs at one place, the effect is not that serious but if this fault occurs at two places, the two coils are being short circuited causing a serious short circuit fault which produces heavy sparking due to unbalancing of armature currents.

5.40 Trouble Shooting in a DC Motor

For trouble shooting of a DC motor, the following steps are taken:

1. Check the fuses.
2. Check the electrical connections at the terminals
3. Check the wear and tear of the brushes.

4. Check the continuity of field winding.
5. Check the armature winding.

Section Practice Problems

Numerical Problems

1. The field and armature resistance of a 250 V DC shunt generator is 50 ohm and 0.02 ohm respectively. It delivers 195 A at rated voltage. The iron and friction losses equal 1050 W. Find (a) emf generated (b) copper losses (c) output of the prime-mover (d) commercial, mechanical and electrical efficiencies.
(Ans. 254 V; 2050 W; 51.85 kW; 94.11%, 97.975%, 95.96%)
2. A four-pole DC shunt motor draws a current of 36 A when connected to 230 V mains and delivering 10 hp. If armature and field circuit resistances are 0.1 Ω and 300 Ω respectively, find the motor current when load is 5 hp. Neglect armature reaction effect.
(Ans. 19627 A)
3. A 6-pole, 250 V series motor is wave-connected. There are 240 slots and each slot has four conductors. The flux per pole in 1.75×10^{-2} Wb when the motor is taking 80 A. The field resistance is 0.05 Ω , the armature resistance is 0.1 Ω and the iron and frictional loss is 0.1 kW. Calculate (a) speed (b) bhp (c) shaft torque (d) the pull in newton at the rim of the pulley of diameter 30 cm.
(Ans. 283.3 rpm; 25.75; 638.34 Nm; 4255.6 N)
4. In a brake test, a DC shunt motor draws 40 A from a 231 V supply mains. The brake pulley of radius 30 cm had an effective load of 35 kg and the speed was 720 rpm. Find the bhp (metric) and the efficiency at the above load.
(Ans. 10.56; 84.05%)
5. The field resistance and armature resistance of a 400 V DC shunt motor is 200 ohm and 0.5 ohm respectively. It draws 5 A at no-load. What will be its output and efficiency when it draws 50 A from the mains. Also find the percentage change in speed from no-load to full-load. (Ans. 16.852 kW; 84.26%,; 5.65%)
6. A DC machine is rated at 5 kW, 250 V, 2000 rpm. Its armature resistance R_a is 1 Ω . Driven from the electrical end at 2000 rpm the no-load power input to the armature is $I_a = 1.2$ A at 250 V with the field winding ($R_f = 250 \Omega$) excited by $I_f = 1$ A. Estimate the efficiency of the machine as a 5 kW generator.
(Ans. 83.48%)
7. The following test results we obtained when Hopkinson test was performed on two identical DC shunt machines at full load:
Line voltage 250 V, line current excluding field currents 50 A;
Motor armature current 380 A; Field currents 5 A and 4.2 A.
Calculate the efficiency of each machine. The armature resistance of each machine = 0.02 ohm.
(Ans. $\eta_m = 92.03\%$; $\eta_g = 91.9\%$)

Short Answer Type Questions

Q.1. What do you mean by “energy loss” in a machine?

- Ans.** Whole of the input energy supplied to the electrical machine is not converted into useful output energy but a part of it is lost in the form of heat while doing useful work. The energy converted into heat is called the energy loss.

Q.2. What are the different losses which occur in a DC machine.

Ans. The following losses occur in a DC machine:

1. Copper losses: These may be

(i) Armature copper loss ($I_a^2 R_a$)

(ii) Series field copper loss ($I_{se}^2 R_{se}$)

(iii) Interpole winding copper loss ($I_a^2 R_i$)

(iv) Compensating winding copper loss ($I_a^2 R_c$)

(v) Brush contact loss ($I_a v_b$)

(vi) Shunt field copper loss ($I_{sh}^2 R_{sh}$)

2. Iron-loss: (i) Hysteresis loss ($K_b V f B_m^{1.6}$) (ii) Eddy current loss ($K_e V f^2 t^2 B_m^2$).

3. Mechanical loss: (i) Friction loss (ii) Windage loss

Q.3. How do the various losses occurring in a DC machine vary with the load?

Ans. The copper losses occurring in armature windings i.e., series field winding, compensating winding and interpole winding, vary as the square of the load current whereas copper losses occurring in DC shunt field winding is constant. Iron and mechanical losses are independent of load and remain constant.

Q.4. What are the components of iron loss in DC machine and in which part of the machine it occurs?

Ans. The components of iron loss are hysteresis and eddy-current losses obviously these losses occur in the iron parts of the machine such as armature core, pole shoe, etc.

Q.5. How does eddy current losses change if the thickness of laminations is increased?

Ans. Eddy current loss will increase as the square of the thickness of magnetic material laminations.

Q.6. What type of tests are performed to determine efficiency of DC motors?

Ans. Basically, direct, indirect and regenerative tests are performed to determine the efficiency of DC machines.

Q.7. Can a Swinburne's test be applied to a DC series motor? Justify.

Ans. No, Swinburne's test is performed at no-load and at no-load series motors obtain dangerously high speed and gets damaged. Therefore, Swinburne's test cannot be applied for determining efficiency of DC series motors.

Q.8. What is the main drawback of brake test?

Ans. The output of the motor cannot be measured accurately.

Q.9. Why constant losses can be considered equal to input to a machine at no-load?

Ans. Because at no-load variable losses (armature copper losses and losses in series field winding, interpole winding and compensating winding, if any) are negligible owing to very small armature current.

Q.10. State the advantages of Swinburne's test.

Ans. Advantages of Swinburne's test are:

1. Very convenient and economical method since power required is very small.

2. Stray or constant losses are determined, therefore, efficiency at any desired value of load can be determined.

Q.11. Why Hopkinson's test is also called the regenerative or back-to-back test?

Ans. The motor supplies mechanical power which is used to drive the generator while generator develops electrical power which is sent back to the system and is utilised in driving the DC motor in addition to electrical power drawn from the supply mains.

Q.12. What are the possible causes of sparking at brushes?

Ans. Sparking at brushes may occur due to

- (i) trouble in brushes,
- (ii) commutation difficulties
- (iii) excessive load current.

Review Questions

1. Explain the principle of operation of a DC motor.
2. Explain with suitable diagram the working of a DC motor.
3. Explain the function of commutator in a DC motor.
4. What is back emf? Give its significance.
5. On what factors does the torque developed by a DC motor depends?
6. What is back emf? Is the back emf greater or lesser than the applied voltage? Why? By what amount do the two voltages differ. Write voltage equation of a motor.
7. A DC shunt motor operating from a constant voltage supply is running steadily on no-load. Explain how the motor will adjust itself on application of load.
8. Derive an expression for the speed of a DC motor in terms of back emf and flux per pole.
9. Explain back emf in a DC motor. Explain the effect of field current on the speed of a DC motor.
10. How may the direction of rotation of a DC shunt motor be reversed? What is the effect of reversing the line terminals?
11. Derive the torque equation of a DC machine.
12. Define an expression for the torque developed by a DC motor in terms of ϕ , Z , P , A , L_a where the symbols have their usual meaning.
13. Differentiate between the motoring and generating action of a DC machine.
14. Mention the various types of DC motors and their uses.
15. Show that a shunt motor is almost constant speed motor. Draw its speed-armature current characteristics.
16. Sketch the speed-torque curve of a DC series motor and discuss its nature. What are the applications for DC series motors?
17. A DC series motor should not be started without load why?
18. Show that a series motor develops high starting torque.
19. Using characteristics, explain why a DC series motor
 - (i) Is suitable for electric traction
 - (ii) Should never be started without a load on it.

20. Sketch the speed-load and torque-load characteristics of DC cumulatively-compound motor and comment on the shape of the characteristics. Indicate where such a motor can be ideally used.
21. Some of the applications given below need suitable motors. Motors available are series, shunt, cumulatively compound, differential compound DC motors. Mention the motor used for the following applications; give reasons for your answer.
- Blower, shearing machines, diesel electric locomotives, cranes, hoists centrifugal pumps, elevators and rolling mills.
22. Describe the factors for the selection of DC motors for specific application.
23. List applications of DC shunt, DC series and DC compound motors.
24. How will you determine the value of resistance of each step of a DC shunt motor starter when the maximum and minimum value of current varies between I_1 and I_2 ?
25. Explain the function of no-volt and over load release coil in a two-point series motor starter?
26. While starting a DC motor, why does a resistor connected in series with the armature? Describe a suitable starter for starting a DC shunt motor having No-volt and overload protections.
27. Name various starters used for DC motor and explain working of any one of them with a suitable diagram.
28. Write a short note on DC motor starters.
29. Explain why a starter is required for starting a DC motor. Describe a three-point starter having no-volt and over-load protections for starting a DC shunt motor. What modification is made in a 4 point starter?
30. Explain the working principle of a 3 point starter of a DC shunt motor.
31. What may happen to a DC shunt motor connected to a three-point starter if the field excitation is kept minimum at the time of starting?
32. A DC shunt motor is connected to a three-point starter. Explain what would happen if:
- (i) The starter handle is moved rapidly from OFF to the ON position.
 - (ii) The field circuit is open and an attempt is made to start the motor.
 - (iii) The field circuit becomes open-circuited with the motor running at no-load, with the assumption that the starter is not provided with the no-volt release and the spring.
 - (iv) The field excitation is minimum at the time of starting.
33. Why is starting current high in a DC motor? Explain the working of a four-point starter for a DC machine.
34. Write a general expression for the speed of a DC motor in terms of supply voltage and flux per pole.
35. Describe the speed control methods of DC shunt motors.
36. Describe briefly the methods of speed control used for DC series motors.
37. Explain with neat sketch how speed control of a DC shunt motor is obtained by Ward Leonard control system. How the direction of rotation of the motor is usually reversed in this method of speed control?
38. Identify the factors that predominantly affect the speed of a DC motor. Discuss two methods for varying the speed of a DC series motor for constant load torque. List one application of each of these methods.
39. Define speed regulation and percentage speed regulation of a DC motor.
40. Which of the following three motors has the poorest speed regulation: Shunt motor, series motor or cumulative compound motor? Explain.

41. Explain the series-parallel control of two identical series motors. How many speeds are possible? Are the motors run faster in series combination or parallel combination?
42. Explain the speed control of DC series motor by (i) field divertors (ii) variable resistance in series with motor.
43. With relevant circuit diagrams, describe different methods of speed control of DC series motor.
44. Explain four methods by which flux is varied to control the speed of a DC series motor, with neat sketches.
45. What is meant by braking of DC motors? Describe, briefly, the various methods of braking of DC shunt motors.
46. Why is electric braking of electric motors superior to mechanical braking? How is dynamic braking of DC shunt motor done?
47. What is regenerative braking? Why it cannot be accomplished with a series wound DC motor without modifications in the circuit diagram? Give merits and demerits?
48. What are the various losses occurring in rotating machines? Mention the method to reduce them.
49. Give an account of the losses which occur in a DC machine and explain how these losses vary with load and speed.
50. Mention the factors on which the hysteresis loss (W_b) and eddy current loss (W_e) in a DC machine depend. How these losses are reduced?
51. Draw a power flow diagram of a DC motor and define commercial, mechanical and electrical efficiency of a motor.
52. Derive condition for maximum efficiency of a DC motor.
53. What are the various tests performed on a DC Machine? Explain any two.
54. To determine no-load losses, Swinburne's test is performed. Explain it and mention its limitations.
55. Describe the Hopkinson's test for obtaining the efficiency of two similar shunt machines.
56. What is Hopkinson test? Draw a diagram and explain the procedure of Hopkinson test.
57. Classify various losses in a DC machine and indicate the factors on which these depend. Explain the regenerative method of determining the efficiency of a DC machine. List the merits and demerits of the method.
58. Explain a suitable method for determining the efficiency of a series motor.
59. With a neat circuit diagram discuss how the efficiency of DC series motors can be determined, by conducting field's test.

Multiple Choice Questions

1. Usually, the normal value of the armature resistance of a DC motor is

(a) $100\ \Omega$	(b) $0.5\ \Omega$
(c) $10\ \Omega$	(d) $0.005\ \Omega$
2. The ratio E_b/V of a DC motor represents its

(a) efficiency	(b) speed regulation
(c) starting torque	(d) Running Torque

3. The power developed in the armature of a DC motor is equal to
 - (a) armature current multiplied by back emf
 - (b) power input minus losses
 - (c) power output plus iron losses
 - (d) power output multiplied by efficiency
4. If load on a DC shunt motor is increased, its speed is decreased due primarily to
 - (a) increase in its flux
 - (b) decrease in back emf
 - (c) increase in armature current
 - (d) increase in brush drop
5. If the voltage applied across the armature of a DC shunt motor is increased by 5% keeping its load current and field constant, what will be the effect on its speed?
 - (a) decrease by about 5 per cent
 - (b) remain unchanged
 - (c) increase by about 5 per cent
 - (d) increase by 10 per cent
6. The torque available at the shaft of a DC motor is less than the torque developed in the armature because of.....losses.
 - (a) copper
 - (b) mechanical
 - (c) iron
 - (d) rotational
7. Neglecting saturation, if current taken by series motor is increased from 10 A to 13A, the percentage increase in its torque is..... percent
 - (a) 80
 - (b) 69
 - (c) 44
 - (d) 39
8. The armature resistance of a 110 V DC motor is 0.5 ohm. What will be its armature current if the back emf is 100 V.
 - (a) 20 A
 - (b) 200 A
 - (c) 220 A
 - (d) 60 A
9. With the increase in load, the speed of a DC shunt motor
 - (a) reduces slightly
 - (b) remains constant
 - (c) increases slightly
 - (d) increases proportionately
10. For drives requiring high starting torque but only fairly constant speed such as crushers, the most suitable DC motor would be
 - (a) shunt
 - (b) series
 - (c) compound
 - (d) permanent magnet
11. DC shunt motors are most suitable to drive fans because they require
 - (a) small torque at start
 - (b) large torque at high speeds
 - (c) practically constant voltage
 - (d) both (a) and (b)
12. When a 220 V DC shunt motor draws an armature current of 10 A, it develops a torque of 50 Nm. What will be the torque developed when armature current reduces to 20 A.
 - (a) 54 N-m
 - (b) 81 N-m
 - (c) 108 N-m
 - (d) None of the above
13. One can change the speed of a DC motor by varying
 - (a) its flux per pole
 - (b) resistance of armature circuit
 - (c) applied voltage
 - (d) all of above
14. The most efficient method of increasing the speed of a 5 kW DC shunt motor would be
 - (a) armature control method
 - (b) flux control method
 - (c) Ward-Leonard method
 - (d) tapped-field control method

15. Usually, ... test is performed to determine the efficiency of a traction motor
 (a) Field's (b) brake
 (c) Hopkinson's (d) Swinburne's
16. The Swinburne's test is considered to be the best one because it
 (a) is applicable both to shunt and compound motors
 (b) needs one running test
 (c) is very economical and convenient
 (d) ignores any change in iron loss
17. The major disadvantage of Hopkinson's test for finding efficiency of DC shunt motors is that it
 (a) requires full-load power (b) ignores any change in iron loss
 (c) needs one motor and one generator (d) requires two identical shunt machines

Keys to Multiple Choice Questions

1. b	2. a	3. a	4. b	5. c	6. b	7. b	8. a	9. a	10. c
11. d	12. c	13. d	14. b	15. a	16. c	17. d			

Synchronous Generators or Alternators

CHAPTER

6

Chapter Objectives

After the completion of this unit, students/readers will be able to understand:

- ✓ What are the basic principles on which working of synchronous machine depends?
- ✓ How emf is induced in a synchronous generator.
- ✓ Why stationary armature and revolving field system is preferred for large synchronous generators?
- ✓ What is the function and material of different parts of a synchronous machine?
- ✓ Where and why synchronous generators of salient or non-salient pole type construction are preferred.
- ✓ How magnetic poles of synchronous machines are excited.
- ✓ What are various types of windings used in synchronous machines, viz. single-phase and three-phase, concentrated and distributed, single-layer and double-layer, full-pitched and short-pitched, concentric, lap and wave winding?
- ✓ What is the meaning of different terms used while preparing different winding schemes viz. coil, coil pitch, pole pitch, electrical and mechanical angle, slot pitch, phase spread etc.
- ✓ What are coil span and distribution factors and their significance.
- ✓ Various factors on which induced emf in an alternator depends.
- ✓ How revolving field is set-up in the stator core of a 3-phase wound machine
- ✓ What is Ferraris's principle and its importance?
- ✓ Why the alternators are rated in kVA?
- ✓ What is armature resistance and leakage reactance?
- ✓ What is armature reaction and how it is affected by the type of load (resistive, inductive or capacitive)?
- ✓ What is the effect of armature reaction on the terminal voltage or induced emf of an alternator?
- ✓ How to draw a simplified equivalent circuit of an alternator?
- ✓ What is voltage regulation and how it is affected by the power factor of the load?
- ✓ How to perform open-circuit and short-circuit test on a synchronous generator?
- ✓ What is ampere-turn (or mmf) method for determining voltage regulation of a synchronous generator?
- ✓ What is zero power factor (or Potier method) of determining voltage regulation of a synchronous generator?
- ✓ What power is developed by a cylindrical synchronous generator?

- ✓ What is two-reactance concept for salient pole synchronous machines?
- ✓ How to determine direct axis synchronous reactance (X_d) and quadrature axis synchronous reactance (X_q)?
- ✓ What are transients in alternators?
- ✓ What is the meaning of sub-transient, transient and direct reactance?
- ✓ What are the various losses in an alternator?
- ✓ Why alternator are heated-up during working and how these are cooled down?

Introduction

In an AC system voltage level can be increased or decreased (as per requirement) very easily with the help of a transformer, therefore, this system is exclusively used for generation, transmission and distribution of electric power. The mechanical power or energy is converted into electrical power or energy with the help of an AC machine called *alternator* or *synchronous generator*. However, when the same machine can be used to convert electrical power or energy into mechanical power or energy, then it is known as a *synchronous motor*. Thus, the same machine can be operated as a generator or as a motor and in general, it is called as a *synchronous machine*. In fact, it is a machine which rotates only at synchronous speed ($N_s = 120 f/P$) under all conditions. To understand the construction, working and performance of the machine its study is divided into number of main topics as chapters, to be followed.

In this chapter, the readers will go through various topics related to this machine when working as a *synchronous generator or alternator*.

6.1 General Aspects of Synchronous Machines

A machine in which the following relation is maintained for its satisfactory operation is called a *synchronous machine* (The machine may work as a generator or motor):

$$N_s = \frac{120f}{P} \quad \text{or} \quad f = \frac{PN_s}{120}$$

where N_s is the synchronous speed in rpm; f is the supply frequency and P is the number of poles of the machine.

When the machine is to work as a generator, it has to run at synchronous speed (N_s) to generate power at certain frequency (f), called power frequency. In India its value is 50 Hz, whereas in the USA it is kept at 60 Hz.

When the machine works as a motor, it can rotate only at synchronous speed (N_s) since the magnetic poles are locked with the revolving field. If the machine fails to rotate at synchronous speed, it is pulled out of step and stops.

Hence, synchronous machine (generator or motor) is a machine which only runs at synchronous speed and maintains the relation;

$$N_s = 120 f / P \text{ rpm}$$