Chapter (1)

D.C. Generators

Introduction

Although a far greater percentage of the electrical machines in service are a.c. machines, the d.c. machines are of considerable industrial importance. The principal advantage of the d.c. machine, particularly the d.c. motor, is that it provides a fine control of speed. Such an advantage is not claimed by any a.c. motor. However, d.c. generators are not as common as they used to be, because direct current, when required, is mainly obtained from an a.c. supply by the use of rectifiers. Nevertheless, an understanding of d.c. generator is important because it represents a logical introduction to the behaviour of d.c. motors. Indeed many d.c. motors in industry actually operate as d.c. generators for a brief period. In this chapter, we shall deal with various aspects of d.c. generators.

1.1 Generator Principle

An electric generator is a machine that converts mechanical energy into electrical energy. An electric generator is based on the principle that whenever flux is cut by a conductor, an e.m.f. is induced which will cause a current to flow if the conductor circuit is closed. The direction of induced e.m.f. (and hence current) is given by Fleming's right hand rule. Therefore, the essential components of a generator are:
 (a)   a magnetic field
  (b)   conductor or a group of conductors
  (c)   motion of conductor w.r.t. magnetic field.

1.2 Simple Loop Generator

Consider a single turn loop ABCD rotating clockwise in a uniform magnetic field with a constant speed as shown in Fig.(1.1). As the loop rotates, the flux linking the coil sides AB and CD changes continuously. Hence the e.m.f. induced in these coil sides also changes but the e.m.f. induced in one coil side adds to that induced in the other.
  (i)   When the loop is in position no. 1 [See Fig. 1.1], the generated e.m.f. is zero because the coil sides (AB and CD) are cutting no flux but are moving parallel to it

(ii) When the loop is in position no. 2, the coil sides are moving at an angle to the flux and, therefore, a low e.m.f. is generated as indicated by point 2 in Fig. (1.2).

(iii) When the loop is in position no. 3, the coil sides (AB and CD) are at right angle to the flux and are, therefore, cutting the flux at a maximum rate. Hence at this instant, the generated e.m.f. is maximum as indicated by point 3 in Fig. (1.2).

(iv) At position 4, the generated e.m.f. is less because the coil sides are cutting the flux at an angle.

(v) At position 5, no magnetic lines are cut and hence induced e.m.f. is zero as indicated by point 5 in Fig. (1.2).

(vi) At position 6, the coil sides move under a pole of opposite polarity and hence the direction of generated e.m.f. is reversed. The maximum e.m.f. in this direction (i.e., reverse direction, See Fig. 1.2) will be when the loop is at position 7 and zero when at position 1. This cycle repeats with each revolution of the coil.
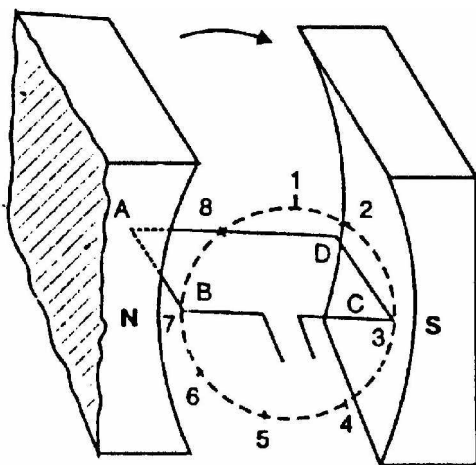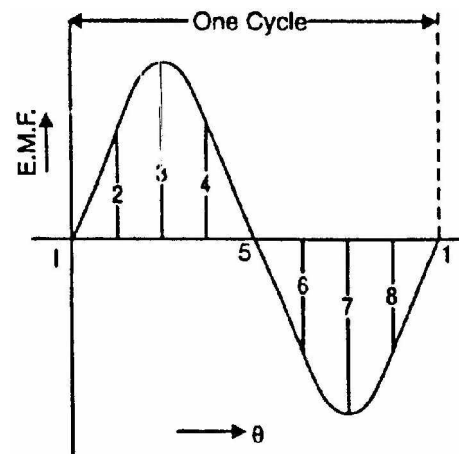
**Fig. (1.1)**   **Fig. (1.2)**

Note that e.m.f. generated in the loop is alternating one. It is because any coil side, say AB has e.m.f. in one direction when under the influence of N-pole and in the other direction when under the influence of S-pole. If a load is connected across the ends of the loop, then alternating current will flow through the load. The alternating voltage generated in the loop can be converted into direct voltage by a device called commutator. We then have the d.c. generator. In fact, a commutator is a mechanical rectifier.

1.3 Action Of Commutator

If, somehow, connection of the coil side to the external load is reversed at the same instant the current in the coil side reverses, the current through the load

will be direct current. This is what a commutator does. Fig. (1.3) shows a commutator having two segments C_1 and C_2. It consists of a cylindrical metal ring cut into two halves or segments C_1 and C_2 respectively separated by a thin sheet of mica. The commutator is mounted on but insulated from the rotor shaft. The ends of coil sides AB and CD are connected to the segments C_1 and C_2 respectively as shown in Fig. (1.4). Two stationary carbon brushes rest on the commutator and lead current to the external load. With this arrangement, the commutator at all times connects the coil side under S-pole to the +ve brush and that under N-pole to the −ve brush.

(i)   In Fig. (1.4), the coil sides AB and CD are under N-pole and S-pole respectively. Note that segment C_1 connects the coil side AB to point P of the load resistance R and the segment C_2 connects the coil side CD to point Q of the load. Also note the direction of current through load. It is from Q to P.

(ii)   After half a revolution of the loop (i.e., 180° rotation), the coil side AB is under S-pole and the coil side CD under N-pole as shown in Fig. (1.5). The currents in the coil sides now flow in the reverse direction but the segments C_1 and C_2 have also moved through 180° i.e., segment C_1 is now in contact with +ve brush and segment C_2 in contact with −ve brush. Note that commutator has reversed the coil connections to the load i.e., coil side AB is now connected to point Q of the load and coil side CD to the point P of the load. Also note the direction of current through the load. It is again from Q to P.
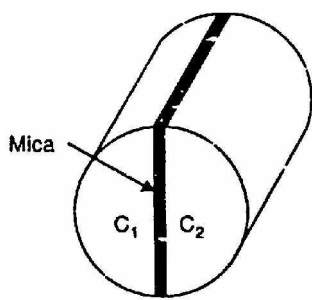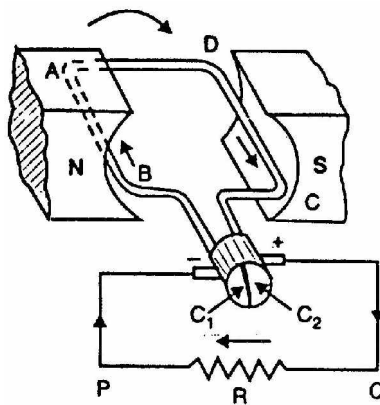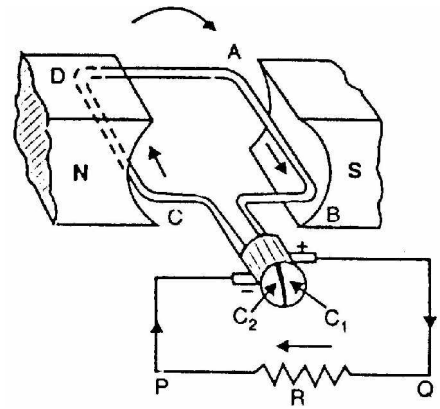

| Fig.(1.3) | Fig.(1.4) | Fig.(1.5) |

Thus the alternating voltage generated in the loop will appear as direct voltage across the brushes. The reader may note that e.m.f. generated in the armature winding of a d.c. generator is alternating one. It is by the use of commutator that we convert the generated alternating e.m.f. into direct voltage. The purpose of brushes is simply to lead current from the rotating loop or winding to the external stationary load.

The variation of voltage across the brushes with the angular displacement of the loop will be as shown in Fig. (1.6). This is not a steady direct voltage but has a pulsating character. It is because the voltage appearing across the brushes varies from zero to maximum value and back to zero twice for each revolution of the loop. A pulsating direct voltage such as is produced by a single loop is not suitable for many commercial uses. What we require is the steady direct voltage. This can be achieved by using a large number of coils connected in series. The resulting arrangement is known as armature winding.
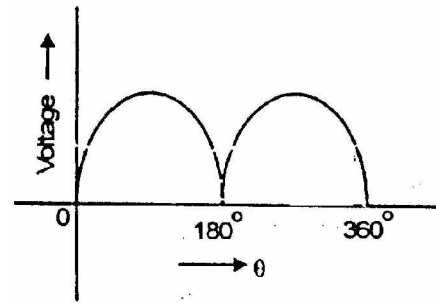

Fig. (1.6)

1.4 Construction of d.c. Generator

The d.c. generators and d.c. motors have the same general construction. In fact, when the machine is being assembled, the workmen usually do not know whether it is a d.c. generator or motor. Any d.c. generator can be run as a d.c. motor and vice-versa. All d.c. machines have five principal components viz., (i) field system (ii) armature core (iii) armature winding (iv) commutator (v) brushes [See Fig. 1.7].
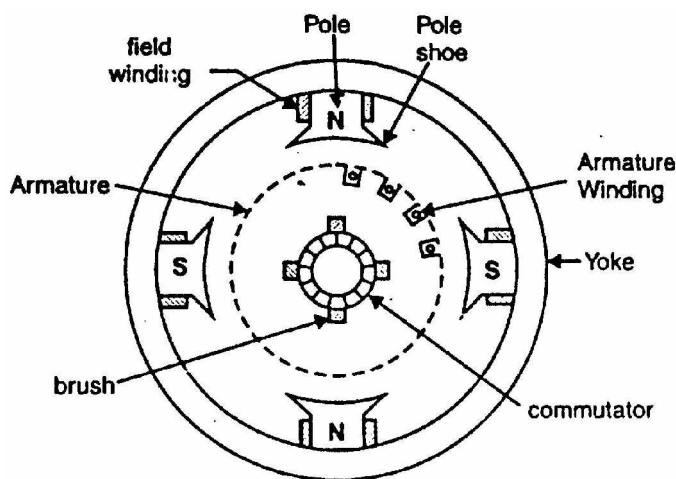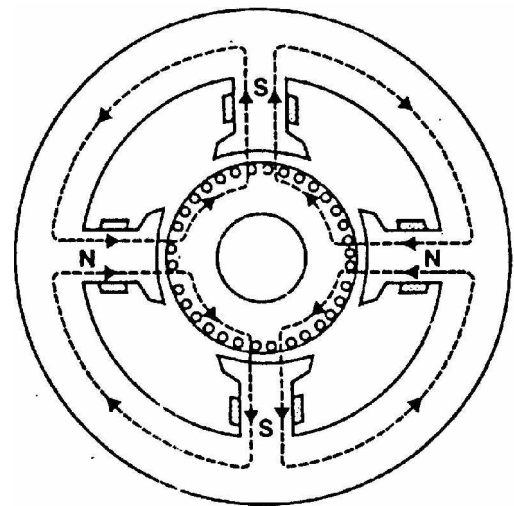
Fig. (1.7)   **Fig. (1.8)**

(i)   Field system

The function of the field system is to produce uniform magnetic field within which the armature rotates. It consists of a number of salient poles (of course, even number) bolted to the inside of circular frame (generally called yoke). The

yoke is usually made of solid cast steel whereas the pole pieces are composed of stacked laminations. Field coils are mounted on the poles and carry the d.c. exciting current. The field coils are connected in such a way that adjacent poles have opposite polarity.

The m.m.f. developed by the field coils produces a magnetic flux that passes through the pole pieces, the air gap, the armature and the frame (See Fig. 1.8). Practical d.c. machines have air gaps ranging from 0.5 mm to 1.5 mm. Since armature and field systems are composed of materials that have high permeability, most of the m.m.f. of field coils is required to set up flux in the air gap. By reducing the length of air gap, we can reduce the size of field coils (i.e. number of turns).

(ii) Armature core

The armature core is keyed to the machine shaft and rotates between the field poles. It consists of slotted soft-iron laminations (about 0.4 to 0.6 mm thick) that are stacked to form a cylindrical core as shown in Fig (1.9). The laminations (See Fig. 1.10) are individually coated with a thin insulating film so that they do not come in electrical contact with each other. The purpose of laminating the core is to reduce the eddy current loss. The laminations are slotted to accommodate and provide mechanical security to the armature winding and to give shorter air gap for the flux to cross between the pole face and the armature "teeth".
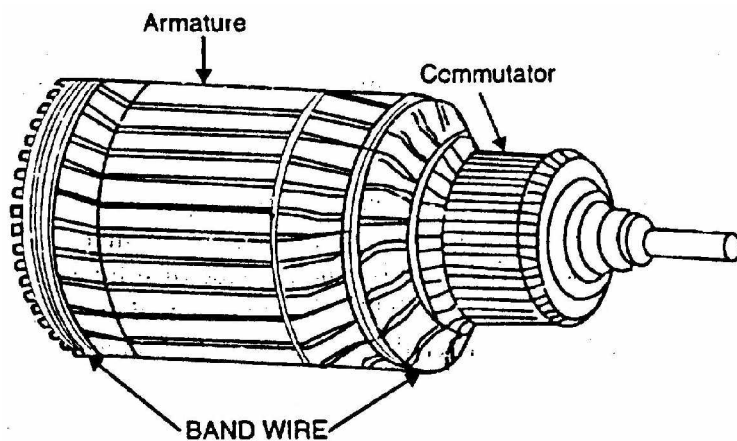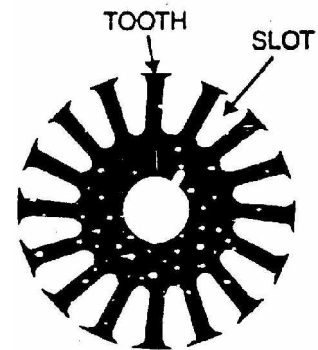

Fig. (1.9)   **Fig. (1.10)**

(iii) Armature winding

The slots of the armature core hold insulated conductors that are connected in a suitable manner. This is known as armature winding. This is the winding in which "working" e.m.f. is induced. The armature conductors are connected in series-parallel; the conductors being connected in series so as to increase the

voltage and in parallel paths so as to increase the current. The armature winding of a d.c. machine is a closed-circuit winding; the conductors being connected in a symmetrical manner forming a closed loop or series of closed loops.

(iv) Commutator

A commutator is a mechanical rectifier which converts the alternating voltage generated in the armature winding into direct voltage across the brushes. The commutator is made of copper segments insulated from each other by mica sheets and mounted on the shaft of the machine (See Fig 1.11). The armature conductors are soldered to the commutator segments in a suitable manner to give rise to the armature winding. Depending upon the manner in which the armature conductors are connected to the commutator segments, there are two types of armature winding in a d.c. machine viz., (a) lap winding (b) wave winding.

Great care is taken in building the commutator because any eccentricity will cause the brushes to bounce, producing unacceptable sparking. The sparks may bum the brushes and overheat and carbonise the commutator.

(v) Brushes

The purpose of brushes is to ensure electrical connections between the rotating commutator and stationary external load circuit. The brushes are made of carbon and rest on the commutator. The brush pressure is adjusted by means of adjustable springs (See Fig. 1.12). If the brush pressure is very large, the friction produces heating of the commutator and the brushes. On the other hand, if it is too weak, the imperfect contact with the commutator may produce sparking.
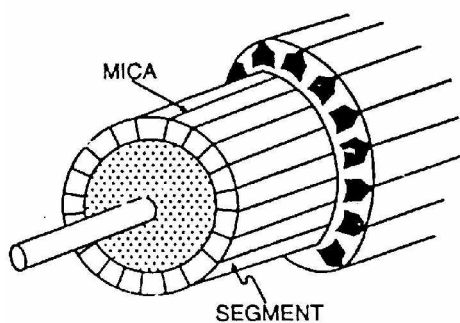

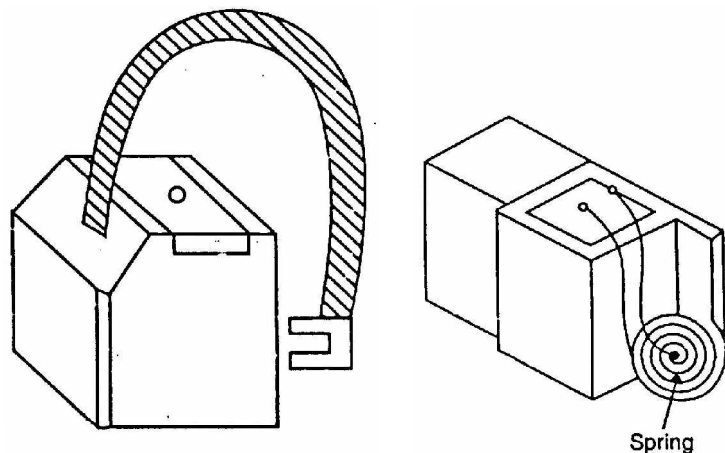**Fig. (1.11)**   **Fig. (1.12)**

Multipole machines have as many brushes as they have poles. For example, a 4-pole machine has 4 brushes. As we go round the commutator, the successive brushes have positive and negative polarities. Brushes having the same polarity

are connected together so that we have two terminals viz., the +ve terminal and the −ve terminal.

1.5 General Features OF D.C. Armature Windings

(i) A d.c. machine (generator or motor) generally employs windings distributed in slots over the circumference of the armature core. Each conductor lies at right angles to the magnetic flux and to the direction of its movement Therefore, the induced e.m.f. in the conductor is given by;

$$e = B \} v \qquad \text{volts}$$

where   B = magnetic flux density in Wb/m^2
            } = length of the conductor in metres
            v = velocity (in m/s) of the conductor

(ii) The armature conductors are connected to form coils. The basic component of all types of armature windings is the armature coil. Fig. (1.13) (i) shows a single-turn coil. It has two conductors or coil sides connected at the back of the armature. Fig. 1.13 (ii) shows a 4-turn coil which has 8 conductors or coil sides.
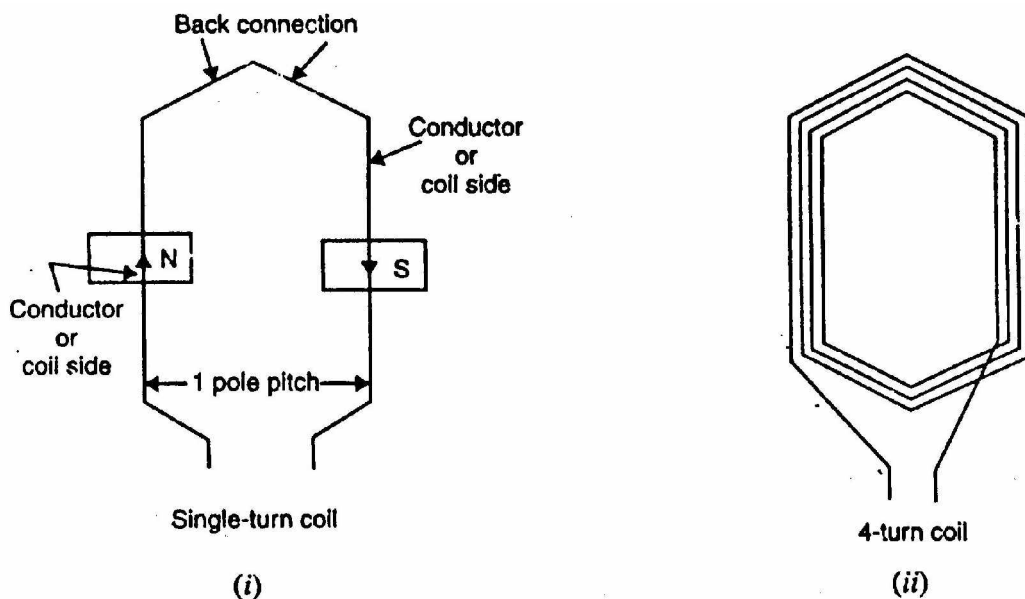
Fig. (1.13)

The coil sides of a coil are placed a pole span apart i.e., one coil side of the coil is under N-pole and the other coil side is under the next S-pole at the corresponding position as shown in Fig. 1.13 (i). Consequently the e.m.f.s of the coil sides add together. If the e.m.f. induced in one conductor is 2.5 volts, then the e.m.f. of a single-turn coil will be = 2 × 2.5 = 5 volts. For the same flux and speed, the e.m.f. of a 4-turn coil will be = 8 × 2.5 = 20 V.

(iii) Most of d.c. armature windings are double layer windings i.e., there are two coil sides per slot as shown in Fig. (1.14). One coil side of a coil lies at the top of a slot and the other coil side lies at the bottom of some other slot. The coil ends will then lie side by side. In two-layer winding, it is desirable to number the coil sides rather than the slots. The coil sides are numbered as indicated in Fig. (1.14). The coil sides at the top of slots are given odd numbers and those at the bottom are given even numbers. The coil sides are numbered in order round the armature.
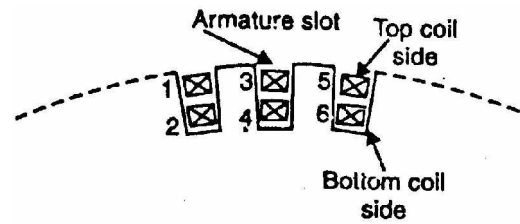
Fig. (1.14)

As discussed above, each coil has one side at the top of a slot and the other side at the bottom of another slot; the coil sides are nearly a pole pitch apart. In connecting the coils, it is ensured that top coil side is joined to the bottom coil side and vice-versa. This is illustrated in Fig. (1.15). The coil side 1 at the top of a slot is joined to coil side 10 at the bottom of another slot about a pole pitch apart. The coil side 12 at the bottom of a slot is joined to coil side 3 at the top of another slot. How coils are connected at the back of the armature and at the front (commutator end) will be discussed in later sections. It may be noted that as far as connecting the coils is concerned, the number of turns per coil is immaterial. For simplicity, then, the coils in winding diagrams will be represented as having only one turn (i.e., two conductors).

Fig. (1.15)

Fig. (1.16)

Λ
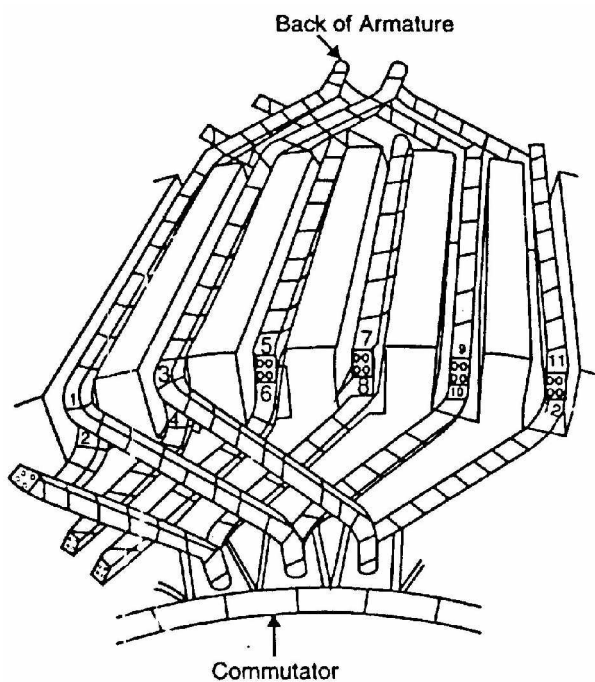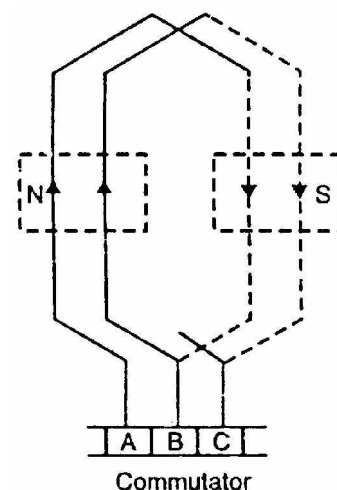
(iv) The coil sides are connected through commutator segments in such a manner as to form a series-parallel system; a number of conductors are connected in series so as to increase the voltage and two or more such series-connected paths in parallel to share the current. Fig. (1.16) shows how the two coils connected through commutator segments (A, R, C etc) have their e.m.f.s added together. If voltage induced in each conductor is 2-5 V, then voltage between segments A and C = 4 × 2.5 = 10 V. It may be noted here that in the conventional way of representing a developed armature winding, full lines represent top coil sides (i.e., coil sides lying at the top of a slot) and dotted lines represent the bottom coil sides (i.e., coil sides lying at the bottom of a slot).

(v) The d.c. armature winding is a closed circuit winding. In such a winding, if one starts at some point in the winding and traces through the winding, one will come back to the starting point without passing through any external connection. D.C. armature windings must be of the closed type in order to provide for the commutation of the coils.

1.6 Commutator Pitch (Y_C)

The commutator pitch is the number of commutator segments spanned by each coil of the winding. It is denoted by Y_C.

In Fig. (1.17), one side of the coil is connected to commutator segment 1 and the other side connected to commutator segment 2. Therefore, the number of commutator segments spanned by the coil is 1 i.e., $Y_C = 1$. In Fig. (1.18), one side of the coil is connected to commutator segment 1 and the other side to commutator segment 8. Therefore, the number of commutator segments spanned by the coil = 8 − 1 = 7 segments i.e., $Y_C = 7$. The commutator pitch of a winding is always a whole number. Since each coil has two ends and as two coil connections are joined at each commutator segment,
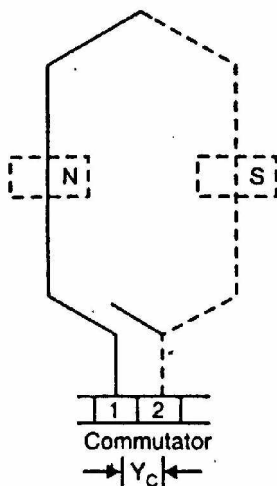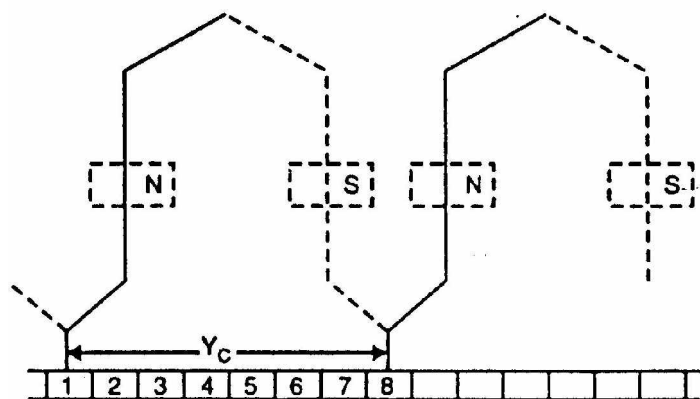

Fig. (1.17)

Fig. (1.18)

$$\therefore \qquad \text{Number of coils} = \text{Number of commutator segments}$$

For example, if an armature has 30 conductors, the number of coils will be 30/2 = 15. Therefore, number of commutator segments is also 15. Note that commutator pitch is the most important factor in determining the type of d.c. armature winding.

1.7 Pole-Pitch

It is the distance measured in terms of number of armature slots (or armature conductors) per pole. Thus if a 4-pole generator has 16 coils, then number of slots = 16.

$$\therefore \qquad \text{Pole pitch} = \frac{16}{4} = 4 \text{ slots}$$

$$\text{Also} \qquad \text{Pole pitch} = \frac{\text{No. of conductors}}{\text{No. of poles}} = \frac{16 \times 2}{4} = 8 \text{ conductors}$$

1.8 Coil Span or Coil Pitch (Y_S)

It is the distance measured in terms of the number of armature slots (or armature conductors) spanned by a coil. Thus if the coil span is 9 slots, it means one side of the coil is in slot 1 and the other side in slot 10.

1.9 Full-Pitched Coil

If the coil-span or coil pitch is equal to pole pitch, it is called full-pitched coil (See Fig. 1.19). In this case, the e.m.f.s in the coil sides are additive and have a phase difference of 0°. Therefore, e.m.f. induced in the coil is maximum. If e.m.f. induced in one coil side is 2-5 V, then e.m.f. across the coil terminals = 2 × 2.5 = 5 V. Therefore, coil span should always be one pole pitch unless there is a good reason for making it shorter.

Fractional pitched coil. If the coil span or coil pitch is less than the pole pitch, then it is called fractional pitched coil (See Fig. 1.20). In this case, the phase difference between the e.m.f.s in the two coil sides will not be zero so that the e.m.f. of the coil will be less compared to full-pitched coil. Fractional pitch winding requires less copper but if the pitch is too small, an appreciable reduction in the generated e.m.f. results.
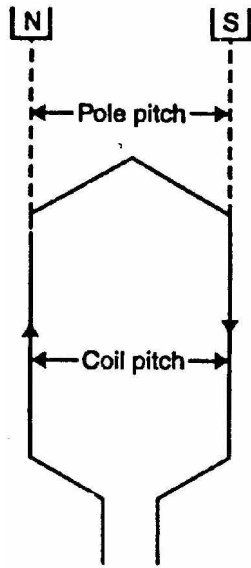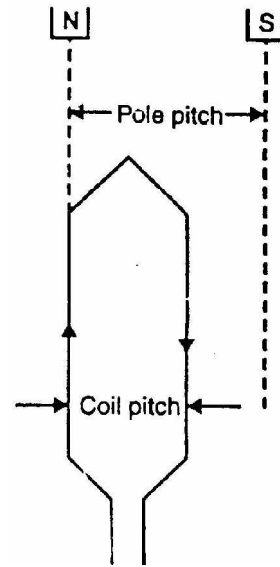
Fig. (1.19)   **Fig. (1.20)**

1.10 Types of D.C. Armature Windings

The different armature coils in a d.c. armature Winding must be connected in series with each other by means of end connections (back connection and front connection) in a manner so that the generated voltages of the respective coils will aid each other in the production of the terminal e.m.f. of the winding. Two basic methods of making these end connections are:

    1.   Simplex lap winding
    2.   Simplex wave winding

1.   Simplex lap winding.

For a simplex lap winding, the commutator pitch $Y_C = 1$ and coil span $Y_S \simeq$ pole pitch. Thus the ends of any coil are brought out to adjacent commutator segments and the result of this method of connection is that all the coils of the armature .ire in sequence with the last coil connected to the first coil. Consequently, closed circuit winding results. This is illustrated in Fig. (1.21) where a part of the lap winding is shown. Only two coils are shown for simplicity. The name lap comes from the way in which successive coils overlap the preceding one.

2.   Simplex wave winding

For a simplex wave winding, the commutator pitch $Y_C \simeq 2$ pole pitches and coil span = pole pitch. The result is that the coils under consecutive pole pairs will be joined together in series thereby adding together their e.m.f.s [See Fig. 1.22]. After passing once around the armature, the winding falls in a slot to the left or

right of the starting point and thus connecting up another circuit. Continuing in this way, all the conductors will be connected in a single closed winding. This winding is called wave winding from the appearance (wavy) of the end connections.
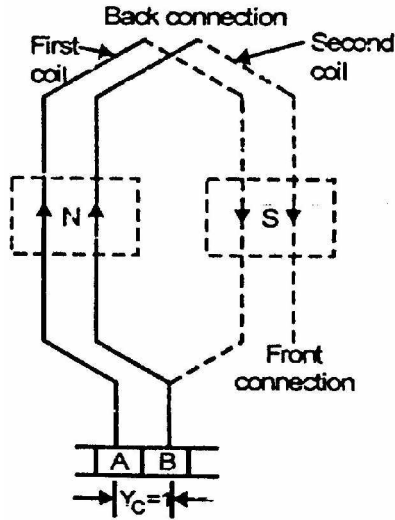
Fig. (1.21)
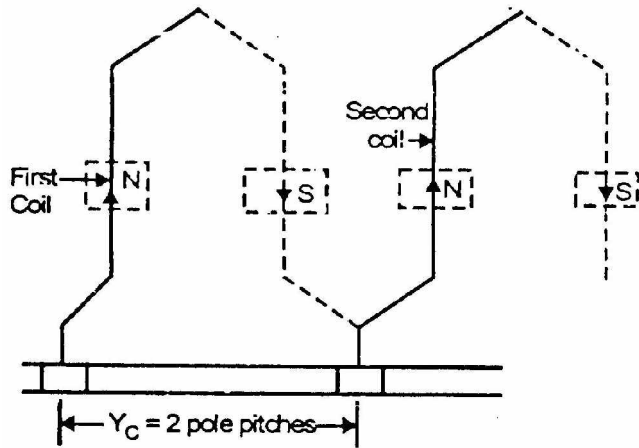
Fig. (1.22)

1.11 Further Armature Winding Terminology

Apart from the terms discussed earlier, the following terminology requires discussion:

(i) Back Pitch (Y_B)

It is the distance measured in terms of armature conductors between the two sides of a coil at the back of the armature (See Fig. 1.23). It is denoted by Y_B For example, if a coil is formed by connecting conductor 1 (upper conductor in a slot) to conductor 12 (bottom conductor in another slot) at the back of the armature, then back pitch is $Y_B = 12 - 1 = 11$ conductors.

Lap winding
(*i*)

Wave winding
(*ii*)

Fig. (1.23)

(ii) Front Pitch (Y_F)

It is the distance measured in terms of armature conductors between the coil sides attached to any one commutator segment [See Fig. 1.23]. It is denoted by Y_F For example, if coil side 12 and coil side 3 are connected to the same commutator segment, then front pitch is $Y_F = 12 - 3 = 9$ conductors.

(iii) Resultant Pitch (YR)

It is the distance (measured in terms of armature conductors) between the beginning of one coil and the beginning of the next coil to which it is connected (See Fig. 1.23). It is denoted by Y_R. Therefore, the resultant pitch is the algebraic sum of the back and front pitches.
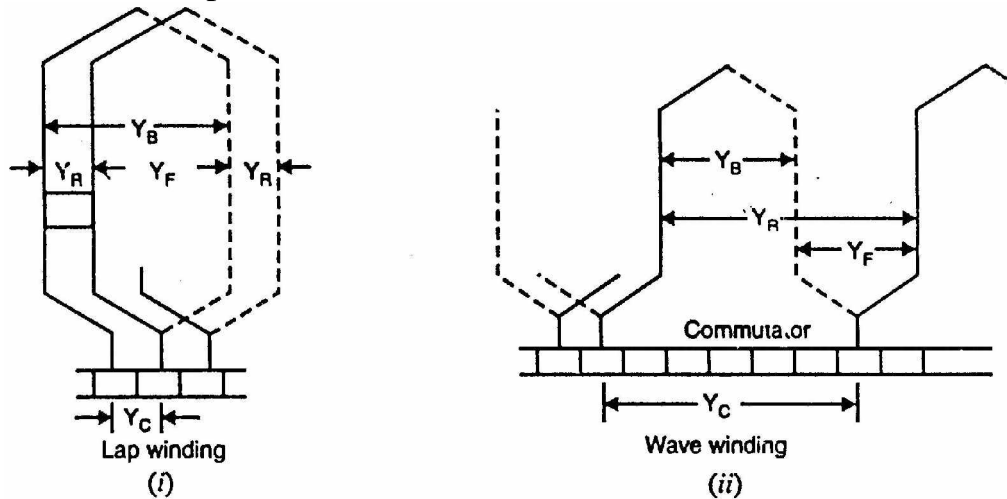
(iv) Commutator Pitch (Y_C)

It is the number of commutator segments spanned by each coil of the armature winding.

For simplex lap winding, $Y_C = 1$

For simplex wave winding, $Y_C \simeq 2$ pole pitches (segments)

(v) Progressive Winding

A progressive winding is one in which, as one traces through the winding, the connections to the commutator will progress around the machine in the same direction as is being traced along the path of each individual coil. Fig. (1.24) (i) shows progressive lap winding. Note that $Y_B > Y_F$ and $Y_C = +1$.

(vi) Retrogressive Winding

A retrogressive winding is one in which, as one traces through the winding, the connections to the commutator will progress around the machine in the opposite direction to that which is being traced along the path of each individual coil. Fig. (1.24) (ii) shows retrogressive lap winding. Note that $Y_F > Y_B$ and $Y_C = -1$. A retrogressive winding is seldom used because it requires more copper.
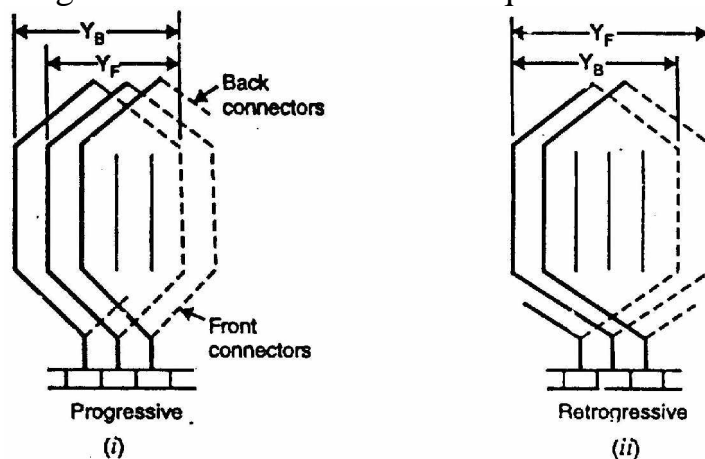
Fig. (1.24)

1.12 General Rules For D.C. Armature Windings

In the design of d.c. armature winding (lap or wave), the following rules may be followed:

(i) The back pitch (Y_B) as well as front pitch (Y_F) should be nearly equal to pole pitch. This will result in increased e.m.f. in the coils.

(ii) Both pitches (Y_B and Y_F) should be odd. This will permit all end connections (back as well as front connection) between a conductor at the top of a slot and one at the bottom of a slot.

(iii) The number of commutator segments is equal to the number of slots or coils (or half the number of conductors).

No. of commutator segments = No. of slots = No. of coils

It is because each coil has two ends and two coil connections are joined at each commutator segment

(iv) The winding must close upon itself i.e. it should be a closed circuit winding.

1.13 Relations between Pitches for Simplex Lap Winding

In a simplex lap winding, the various pitches should have the following relation:

(i) The back and front pitches are odd and are of opposite signs. They differ numerically by 2,

$$\therefore \quad Y_B = Y_B = Y_F \pm 2$$
$$Y_B = Y_F + 2 \qquad \text{for progressive winding}$$
$$Y_B = Y_F - 2 \qquad \text{for retrogressive winding}$$

(ii) Both Y_B and Y_F should be nearly equal to pole pitch.

(iii) Average pitch $= (Y_B + Y_F)/2$. It equals pole pitch ($= Z/P$).

(iv) Commutator pitch, $Y_C = \pm 1$

$Y_C = +1$ for progressive winding

$Y_C = -1$ for retrogressive winding

(v) The resultant pitch (Y_B) is even, being the arithmetical difference of two odd numbers viz., Y_B and Y_F.

(vi) If Z = number of armature conductors and P = number of poles, then,

$$\text{Polr - pitch} = \frac{Z}{P}$$

Since Y_B and Y_F both must be. about one pole pitch and differ numerically by 2,

$$\left. \begin{array}{l} Y_B = \dfrac{Z}{P} + 1 \\[2mm] Y_F = \dfrac{Z}{P} - 1 \end{array} \right\} \quad \text{For progressive winding}$$

$$Y_B = \dfrac{Z}{P} - 1 \left.\vphantom{\dfrac{\dfrac{Z}{P}}{\dfrac{Z}{P}}}\right\}$$
$$Y_F = \dfrac{Z}{P} + 1$$

For retrogressive winding

It is clear that Z/P must be an even number to make the winding possible.

Developed diagram

Developed diagram is obtained by imagining the cylindrical surface of the armature to be cut by an axial plane and then flattened out. Fig. (1.25) (i) shows the developed diagram of the winding. Note that full lines represent the top coil sides (or conductors) and dotted lines represent the bottom coil sides (or conductors).

The winding goes from commutator segment 1 by conductor 1 across the back to conductor 12 and at the front to commutator segment 2, thus forming a coil. Then from commutator segment 2, through conductors 3 and 14 back to commutator segment 3 and so on till the winding returns to commutator segment 1 after using all the 40 conductors.

Position and number of brushes

We now turn to find the position and the number of brushes required. The brushes, like field poles, remain fixed in space as the commutator and winding revolve. It is very important that brushes are in correct position relative to the field poles. The arrowhead marked "rotation" in Fig. (1.25) (i) shows the direction of motion of the conductors. By right-hand rule, the direction of e.m.f. in each conductor will be as shown.

In order to find the position of brushes, the ring diagram shown in Fig. (1.25) (ii) is quite helpful. A positive brush will be placed on that commutator segment where the currents in the coils are meeting to flow out of the segment. A negative brush will be placed on that commutator segment where the currents in the coils are meeting to flow in. Referring to Fig. (1.25) (i), there are four brushes—two positive and two negative. Therefore, we arrive at a very important conclusion that in a simplex lap winding, the number of brushes is equal to the number of poles. If the brushes of the same polarity are connected together, then all the armature conductors are connected in four parallel paths; each path containing an equal number of conductors in series. This is illustrated in Fig. (1.26).

Since segments 6 and 16 are connected together through positive brushes and segments 11 and 1 are connected together through negative brushes, there are four parallel paths, each containing 10 conductors in series. Therefore, in a simplex lap winding, the number of parallel paths is equal to the number of poles.
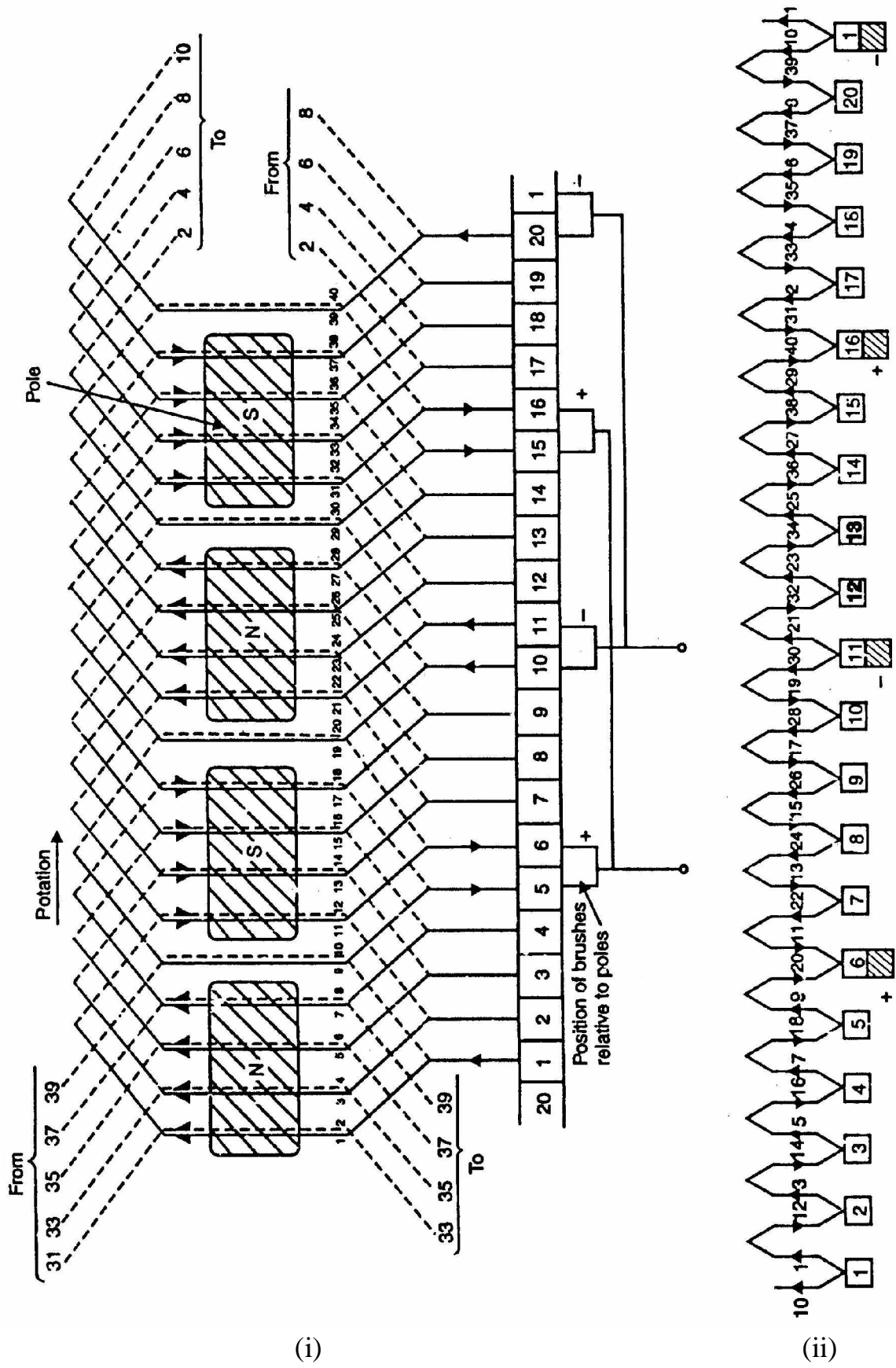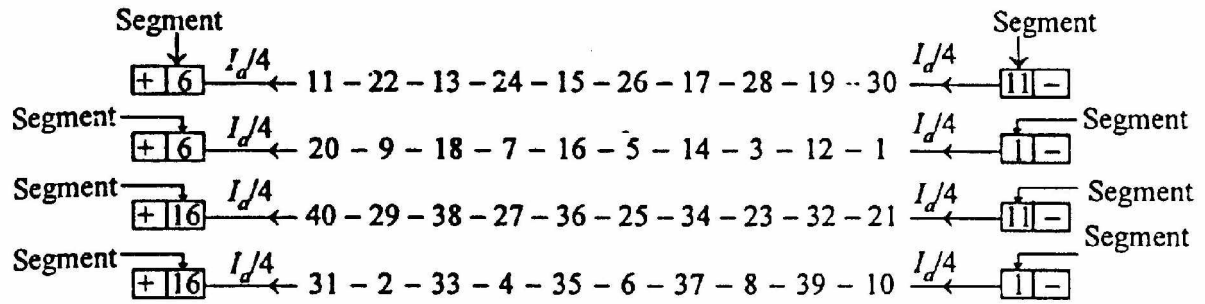
Fig. (1.25)

Fig. (1.26)

Conclusions

From the above discussion, the following conclusions can be drawn:

   (i)   The total number of brushes is equal to the number of poles.

   (ii) The armature winding is divided into as many parallel paths as the number of poles. If the total number of armature conductors is Z and P is the number of poles, then,

$$\text{Number of conductors/path} = Z/P$$

In the present case, there are 40 armature conductors and 4 poles. Therefore, the armature winding has 4 parallel paths, each consisting of 10 conductors in series.

  (iii)   E.M.F. generated = E.M.F. per parallel path

$$= \text{average e.m.f. per conductor} \times \frac{Z}{P}$$

  (iv) Total armature current, $I_a = P \times$ current per parallel path

  (v) The armature resistance can be found as under:

Let $\}$ = length of each conductor; a = cross-sectional area

A = number of parallel paths = P   for simplex lap winding

$$\text{Resistance of whole winding, } R = \frac{\rho\}}{a} \times Z$$

$$\text{Resistance per parallel path} = \frac{R}{A} = \frac{\rho\}Z}{a \times A}$$

Since there are A (= P) parallel paths, armature resistance R_a is given by:

$$R_a = \frac{\text{Resistance per parallel path}}{A} = \frac{1}{A}\left(\frac{\rho\}Z}{a \times A}\right)$$

$$\therefore \quad R_a = \frac{\rho\}Z}{aA^2}$$

1.14 Simplex Wave Winding

The essential difference between a lap winding and a wave winding is in the commutator connections. In a simplex lap winding, the coils approximately pole pitch apart are connected in series and the commutator pitch $Y_C = \pm 1$ segment. As a result, the coil voltages add. This is illustrated in Fig. (1.27). In a simplex wave winding, the coils approximately pole pitch apart are connected in series and the commutator pitch $Y_C \simeq 2$ pole pitches (segments). Thus in a wave winding, successive coils "wave" forward under successive poles instead of "lapping" back on themselves as in the lap winding. This is illustrated in Fig. (1.28).

The simplex wave winding must not close after it passes once around the armature but it must connect to a commutator segment adjacent to the first and the next coil must be adjacent to the first as indicated in Fig. (1.28). This is repeated each time around until connections are made to all the commutator segments and all the slots are occupied after which the winding automatically returns to the starting point. If, after passing once around the armature, the winding connects to a segment to the left of the starting point, the winding is retrogressive [See Fig. 1.28 (i)]. If it connects to a segment to the right of the starting point, it is progressive [See Fig. 1.28 (ii)]. This type of winding is called wave winding because it passes around the armature in a wave-like form.

Lap winding

Fig. (1.27)

Retrogressive
(i)

Wave winding

Progressive
(ii)
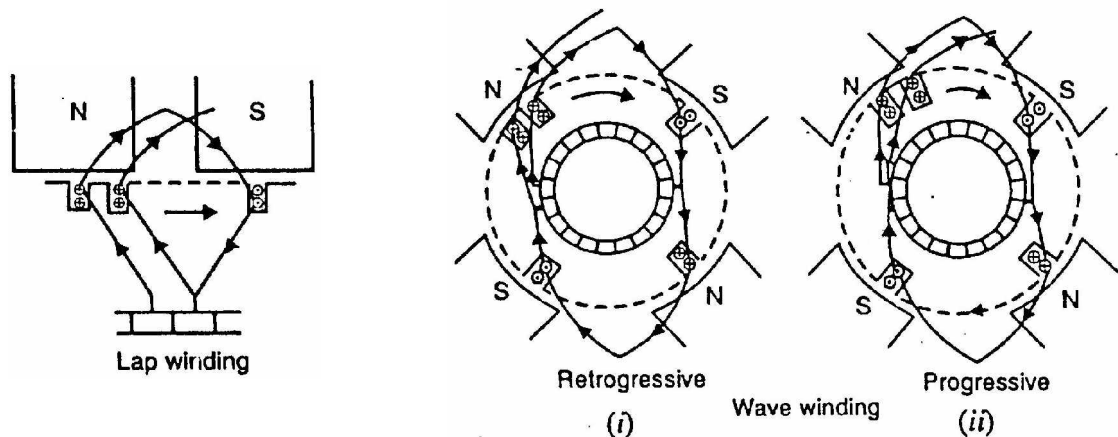
Fig. (1.28)

Various pitches

The various pitches in a wave winding are defined in a manner similar to lap winding.

(i) The distance measured in terms of armature conductors between the two sides of a coil at the back of the armature is called back pitch Y_B (See Fig. 1.29). The Y_B must be an odd integer so that a top conductor and a bottom conductor will be joined.

(ii) The distance measured in terms of armature conductors between the coil sides attached to any one commutator segment is called front pitch Y_B (See Fig. 1.29). The Y_B must be an odd integer so that a top conductor and a bottom conductor will be joined.
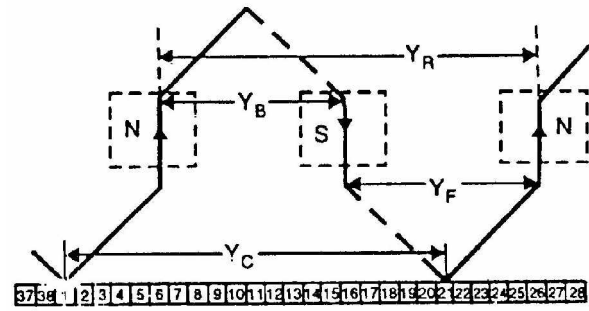

Fig. (1.29))

(iii) Resultant pitch, $Y_R = Y_B + Y_F$ (See Fig. 1.29)

The resultant pitch must be an even integer since Y_B and Y_F are odd. Further Y_R is approximately two pole pitches because Y_B as well as Y_F is approximately one pole pitch.

(iv) Average pitch, $Y_A = \dfrac{Y_B + Y_F}{2}$. When one tour of armature has been completed, the winding should connect to the next top conductor (progressive) or to the preceding top conductor (retrogressive). In either case, the difference will be of 2 conductors or one slot. If P is the number of poles and Z is the total number of armature conductors, then,

$$P \times Y_A = Z \pm 2$$

or $Y_A = \dfrac{Z + 2}{P}$ (i)

Since P is always even and $Z = PY_A \pm 2$, Z must be even. It means that $Z \pm 2/P$ must be an integer. In Eq.(i), plus sign will give progressive winding and the negative sign retrogressive winding.

(v) The number of commutator segments spanned by a coil is called commutator pitch (Y_C) (See Fig. 1.29). Suppose in a simplex wave winding,

P = Number of poles; N_C = Number of commutator segments;

Y_C = Commutator pitch.

∴   Number of pair of poles = P/2

If $Y_C \times P/2 = N_C$, then the winding will close on itself in passing once around the armature. In order to connect to the adjacent conductor and permit the winding to proceed,

$$Y_C \times \frac{P}{2} = N_C \pm 1$$

or $Y_C = \dfrac{2N_C \pm 2}{P} = \dfrac{N_C \pm 1}{P/2} = \dfrac{\text{No. of commutator seg.} \pm 1}{\text{Number of pair of poles}}$

Now $\qquad Y_C = \dfrac{2N_C \pm 2}{P} = \dfrac{Z \pm 2}{P} = Y_A \qquad\qquad (\because\ 2N_C = Z)$

$\therefore \qquad$ Commutator pitch, $\ Y_C = Y_A = \dfrac{Y_B + Y_F}{2}$

In a simplex wave winding Y_B, Y_F and Y_C may be equal. Note that Y_B, Y_F and Y_B are in terms of armature conductors whereas Y_C is in terms of commutator segments.

1.15 Design of Simplex Wave Winding

In the design of simplex wave winding, the following points may be kept in mind:

   (i)   Both pitches Y_B and Y_F are odd and are of the same sign.

   (ii)   Average pitch, $Y_A = \dfrac{Z \pm 2}{P}$ (i)

   (iii)   Both Y_B and Y_F are nearly equal to pole pitch and may be equal or differ by 2. If they differ by 2, they are one more and one less than Y_A.

   (iv)   Commutator pitch is given by;

$$Y_C = Y_A = \dfrac{\text{Number of commutator segments} \pm 1}{\text{Number of pair of poles}}$$

The plus sign for progressive winding and negative for retrogressive winding.

   (v) $Y_A = \dfrac{Z \pm 2}{P}$

Since Y_A must be a whole number, there is a restriction on the value of Z. With Z = 180, this winding is impossible for a 4-pole machine because Y_A is not a whole number.

   (vi) $Z = P Y_A \pm 2$

$\therefore \qquad$ Numnber of coils $= \dfrac{Z}{2} = \dfrac{P Y_A \pm 2}{2}$

Developed diagram

Fig. (1.30) (i) shows the developed diagram for the winding. Note that full lines represent the top coil sides (or conductors) and dotted lines represent the bottom coil sides (or conductors). The two conductors which lie in the same slot are drawn nearer to each other than to those in the other slots.
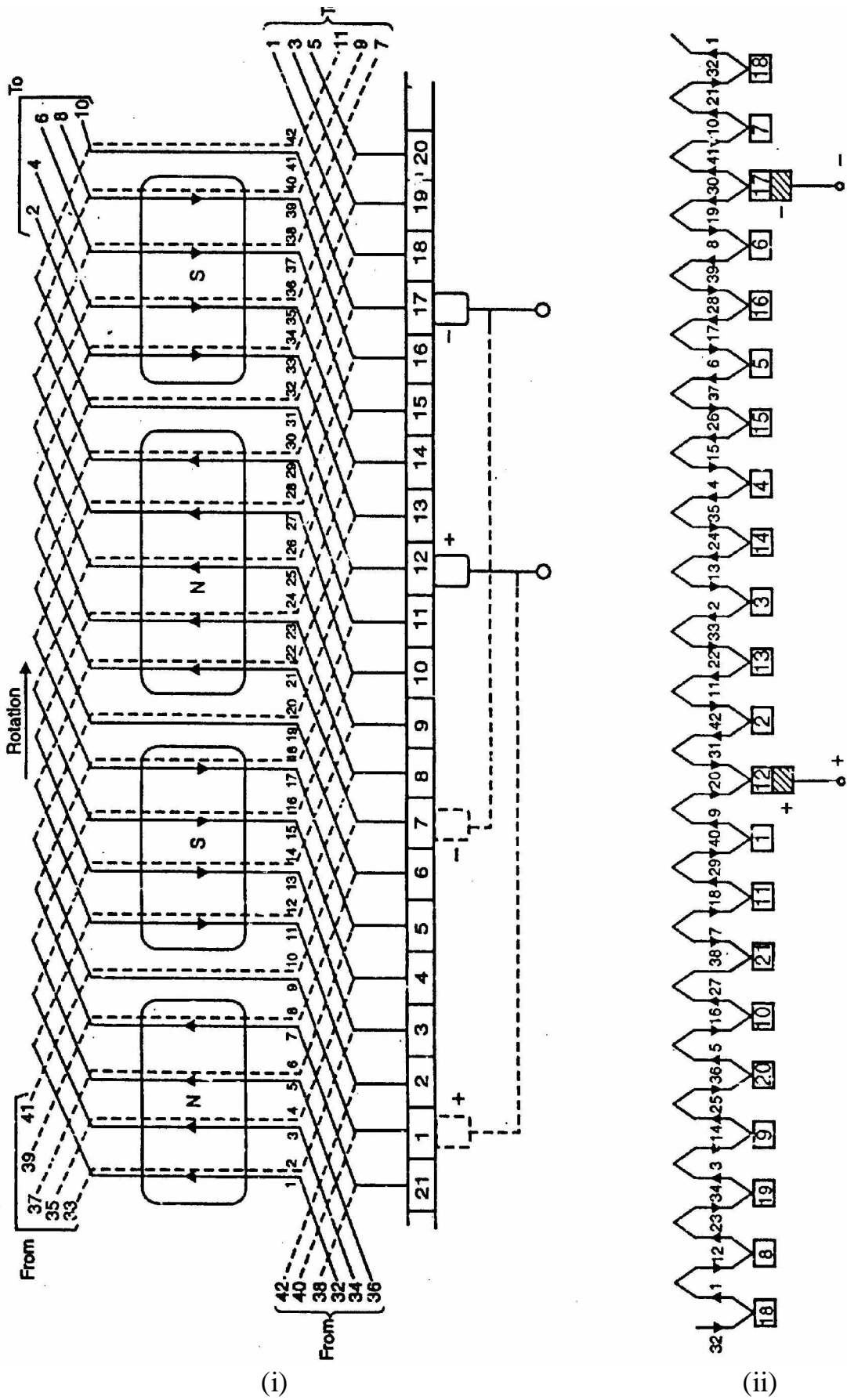
Fig. (1.30)

(i)

(ii)

Referring to Fig. (1.30) (i), conductor 1 connects at the back to conductor 12(1 + 11) which in turn connects at the front to conductor 23 (12 + 11) and so on round the armature until the winding is complete. Note that the commutator pitch $Y_C = 11$ segments. This means that the number of commutator segments spanned between the start end and finish end of any coil is 11 segments.

Position and number of brushes

We now turn to find the position and the number of brushes. The arrowhead marked "rotation" in Fig. (1.30) (i) shows the direction of motion of the conductors. By right hand rule, the direction of e.m.f. in each conductor will be as shown.

In order to find the position of brushes, the ring diagram shown in Fig. (1.30) (ii) is quite helpful. It is clear that only two brushes—one positive and one negative—are required (though two positive and two negative brushes can also be used). We find that there are two parallel paths between the positive brush and the negative brush. Thus is illustrated in Fig. (1.31).

Therefore, we arrive at a very important conclusion that in a simplex wave winding, the number of parallel paths is two irrespective of the number of poles. Note that the first parallel path has 11 coils (or 22 conductors) while the second parallel path has 10 coils (or 20 conductors). This fact is not important as it may appear at first glance. The coils m the smaller group should supply less current to the external circuit. But the identity of the coils in either parallel path is rapidly changing from moment to moment. Therefore, the average value of current through any particular coil is the same.

First Path
20 – 9 – 40 – 29 – 18 – 7 – 38 – 27 – 16 – 5 – 36 – 25 – 14 – 3 – 34 – 23 – 12 – 1 – 32 – 21 – 10 – 41

Second Path
31 – 42 – 11 – 22 – 33 – 2 – 13 – 24 – 35 – 4 – 15 – 26 – 37 – 6 – 17 – 28 – 39 – 8 – 19 – 30

Segment $I_a/2$ — I_a — [+ 12] — [17 –] — I_a — $I_a/2$ — Segment

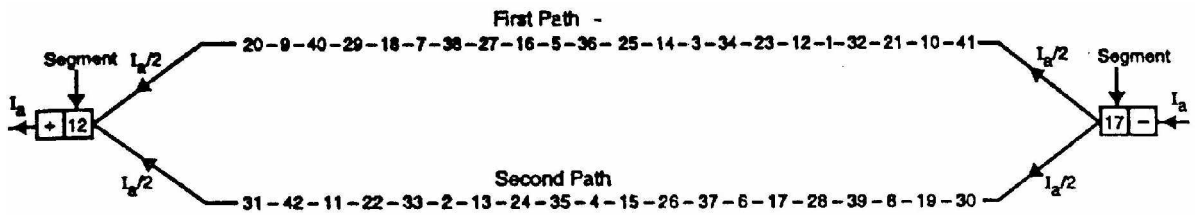**Fig. (1.31)**

Conclusions

From the above discussion, the following conclusions can be drawn:
  (i)   Only two brushes are necessary but as many brushes as there are poles may be used.
  (ii) The armature winding is divided into two parallel paths irrespective of the number of poles. If the total number of armature conductors is Z and P is the number of poles, then,

$$\text{Number of conductors/path} = \frac{Z}{2}$$

(iii) E.M.F. generated = E.M.F. per parallel path

$$= \text{Average e.m.f. per conductor x ---}$$

(iv) Total armature current, $I_a = 2 \times$ current per parallel path

(v) The armature can be wave-wound if Y_A or Y_C is a whole number.

1.16 Dummy Coils

In a simplex wave winding, the average pitch Y_A (or commutator pitch Y_C) should be a whole number. Sometimes the standard armature punchings available in the market have slots that do not satisfy the above requirement so that more coils (usually only one more) are provided than can be utilized. These extra coils are called dummy or dead coils. The dummy coil is inserted into the slots in the same way as the others to make the armature dynamically balanced but it is not a part of the armature winding.

Let us illustrate the use of dummy coils with a numerical example. Suppose the number of slots is 22 and each slot contains 2 conductors. The number of poles is 4. For simplex wave wound armature,

$$Y_A = \frac{Z \pm 2}{P} = \frac{2 \times 22 \pm 2}{4} = \frac{44 \pm 2}{4} = 11\frac{1}{2} \ \text{ or } \ 10\frac{1}{2}$$

Since the results are not whole numbers, the number of coils (and hence segments) must be reduced. If we make one coil dummy, we have 42 conductors and

$$Y_A = \frac{42 \pm 2}{4} = 11 \ \text{ or } \ 10$$

This means that armature can be wound only if we use 21 coils and 21 segments. The extra coil or dummy coil is put in the slot. One end of this coil is taped and the other end connected to the unused commutator segment (segment 22) for the sake of appearance. Since only 21 segments are required, the two (21 and 22 segments) are connected together and considered as one.

1.17 Applications of Lap and Wave Windings

In multipolar machines, for a given number of poles (P) and armature conductors (Z), a wave winding has a higher terminal voltage than a lap winding because it has more conductors in series. On the other hand, the lap winding carries more current than a wave winding because it has more parallel paths.

In small machines, the current-carrying capacity of the armature conductors is not critical and in order to achieve suitable voltages, wave windings are used. On the other hand, in large machines suitable voltages are easily obtained because of the availability of large number of armature conductors and the current carrying capacity is more critical. Hence in large machines, lap windings are used.

Note: In general, a high-current armature is lap-wound to provide a large number of parallel paths and a low-current armature is wave-wound to provide a small number of parallel paths.

1.18 Multiplex Windings

A simplex lap-wound armature has as many parallel paths as the number of poles. A simplex wave-wound armature has two parallel paths irrespective of the number of poles. In case of a 10-pole machine, using simplex windings, the designer is restricted to either two parallel circuits (wave) or ten parallel circuits (lap). Sometimes it is desirable to increase the number of parallel paths. For this purpose, multiplex windings are used. The sole purpose of multiplex windings is to increase the number of parallel paths enabling the armature to carry a large total current. The degree of multiplicity or plex determines the number of parallel paths in the following manner:

(i)   A lap winding has pole times the degree of plex parallel paths.

$$\text{Number of parallel paths, } A = P \times \text{plex}$$

Thus a duplex lap winding has 2P parallel paths, triplex lap winding has 3P parallel paths and so on. If an armature is changed from simplex lap to duplex lap without making any other change, the number of parallel paths is doubled and each path has half as many coils. The armature will then supply twice as much current at half the voltage.

(ii) A wave winding has two times the degree of plex parallel paths.

$$\text{Number of parallel paths, } A = 2 \times \text{plex}$$

Note that the number of parallel paths in a multiplex wave winding depends upon the degree of plex and not on the number of poles. Thus a duplex wave winding has 4 parallel paths, triplex wave winding has 6 parallel paths and so on.

1.19 Function of Commutator and Brushes

The e.m.f. generated in the armature winding of a d.c. generator is alternating one. The commutator and brushes cause the alternating e.m.f. of the armature conductors to produce a p.d. always in the same direction between the terminals of the generator. In lap as well as wave winding, it will be observed that currents

in the coils to a brush are either all directed towards the brush (positive brush) or all directed away from the brush (negative brush). Further, the direction of current in coil reverses as it passes the brush. Thus when the coil approaches the contact with the brush, the current through the coil is in one direction; when the coil leaves the contact with the brush, the current has been reversed. This reversal of current in the coil as the coil passes a brush is called commutation and fakes place while the coil is short-circuited by the brush. These changes occur in every coil in turn. If, at the instant when the brush breaks contact with the commutator segment connected to the coil undergoing commutation, the current in the coil has not been reversed, the result will be sparking between the commutator segments and the brush.

The criterion of good commutation is that it should be sparkless. In order to have sparkless commutation, the brushes on the commutator should be placed at points known as neutral point where no voltage exists between adjacent segments. The conductors connected to these segments lie between the poles in position of zero magnetic flux which is termed as magnetic neutral axis (M.N.A)

1.20 E.M.F. Equation of a D.C. Generator

We shall now derive an expression for the e.m.f. generated in a d.c. generator.

Let ϕ = flux/pole in Wb

Z = total number of armature conductors

P = number of poles

A = number of parallel paths = 2 ... for wave winding

$= P$ ... for lap winding

N = speed of armature in r.p.m.

E_g = e.m.f. of the generator = e.m.f./parallel path

Flux cut by one conductor in one revolution of the armature,

$$d\phi = P\phi \text{ webers}$$

Time taken to complete one revolution,

$$dt = 60/N \text{ second}$$

e.m.f generated/conductor $= \dfrac{d\phi}{dt} = \dfrac{P\phi}{60/N} = \dfrac{P\phi N}{60}$ volts

e.m.f. of generator,

E_g = e.m.f. per parallel path

= (e.m.f/conductor) × No. of conductors in series per parallel path

$= \dfrac{P\phi N}{60} \times \dfrac{Z}{A}$

$\therefore \quad E_g = \dfrac{P\phi ZN}{60 A}$

where $A = 2$ for-wave winding

$$= P \qquad\qquad \text{for lap winding}$$

1.21 Armature Resistance (R$_a$)

The resistance offered by the armature circuit is known as armature resistance (R_a) and includes:

      (i)   resistance of armature winding

      (ii)   resistance of brushes

The armature resistance depends upon the construction of machine. Except for small machines, its value is generally less than 1Ω.

1.22 Types of D.C. Generators

The magnetic field in a d.c. generator is normally produced by electromagnets rather than permanent magnets. Generators are generally classified according to their methods of field excitation. On this basis, d.c. generators are divided into the following two classes:

      (i)   Separately excited d.c. generators

      (ii)   Self-excited d.c. generators

The behaviour of a d.c. generator on load depends upon the method of field excitation adopted.

1.23 Separately Excited D.C. Generators

A d.c. generator whose field magnet winding is supplied from an independent external d.c. source (e.g., a battery etc.) is called a separately excited generator. Fig. (1.32) shows the connections of a separately excited generator. The voltage output depends upon the speed of rotation of armature and the field current ($E_g = P\phi$ ZN/60 A). The greater the speed and field current, greater is the generated e.m.f. It may be noted that separately excited d.c. generators are rarely used in practice. The d.c. generators are normally of self-excited type.
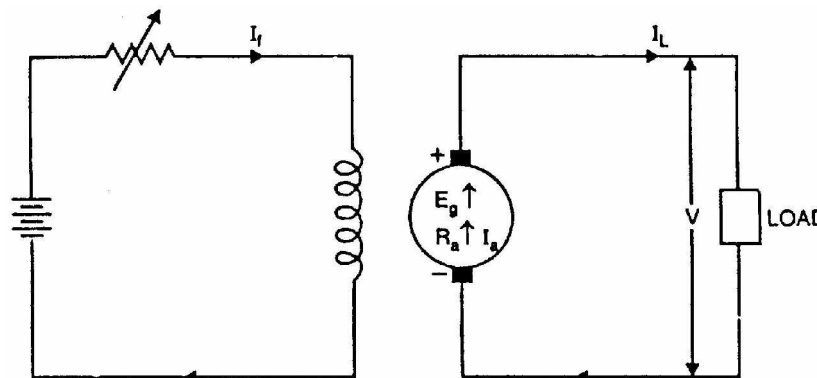

Fig. (1.32)

Armature current, $I_a = I_L$

Terminal voltage, $V = E_g - I_a R_a$

Electric power developed $= E_g I_a$

Power delivered to load $= E_g I_a - I_a^2 R_a = I_a \left(E_g - I_a R_a \right) = V I_a$

1.24 Self-Excited D.C. Generators

A d.c. generator whose field magnet winding is supplied current from the output of the generator itself is called a self-excited generator. There are three types of self-excited generators depending upon the manner in which the field winding is connected to the armature, namely;

  (i)   Series generator;
  (ii)   Shunt generator;
  (iii)   Compound generator

(i)   Series generator

In a series wound generator, the field winding is connected in series with armature winding so that whole armature current flows through the field winding as well as the load. Fig. (1.33) shows the connections of a series wound generator. Since the field winding carries the whole of load current, it has a few turns of thick wire having low resistance. Series generators are rarely used except for special purposes e.g., as boosters.

Armature current, $I_a = I_{se} = I_L = I(say)$

Terminal voltage, $V = E_G - I(R_a + R_{se})$

Power developed in armature $= E_g I_a$

Power delivered to load

$$= E_g I_a - I_a^2 (R_a + R_{se}) = I_a \left[E_g - I_a (R_a - R_{se}) \right] = V I_a \text{ or } V I_L$$

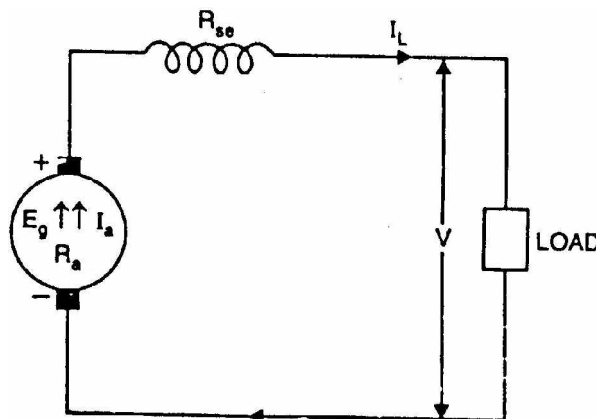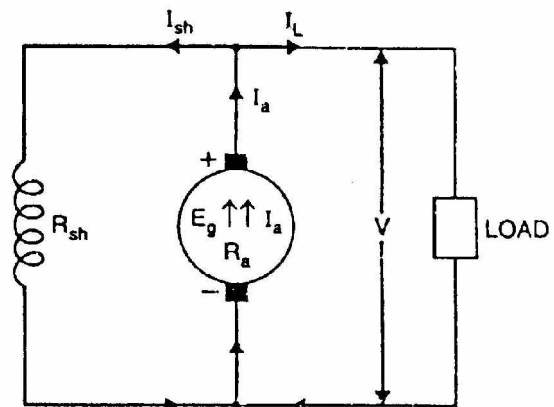
Fig. (1.33)   Fig. (1.34)

(ii)   Shunt generator

In a shunt generator, the field winding is connected in parallel with the armature winding so that terminal voltage of the generator is applied across it. The shunt field winding has many turns of fine wire having high resistance. Therefore, only a part of armature current flows through shunt field winding and the rest flows through the load. Fig. (1.34) shows the connections of a shunt-wound generator.

Shunt field current, $I_{sh} = V/R_{sh}$
Armature current, $I_a = I_L + I_{sh}$
Terminal voltage, $V = E_g - I_aR_a$
Power developed in armature $= E_gI_a$
Power delivered to load $= VI_L$

(iii)   Compound generator

In a compound-wound generator, there are two sets of field windings on each pole—one is in series and the other in parallel with the armature. A compound wound generator may be:

(a)   Short Shunt in which only shunt field winding is in parallel with the armature winding [See Fig. 1.35 (i)].
(b)   Long Shunt in which shunt field winding is in parallel with both series field and armature winding [See Fig. 1.35 (ii)].
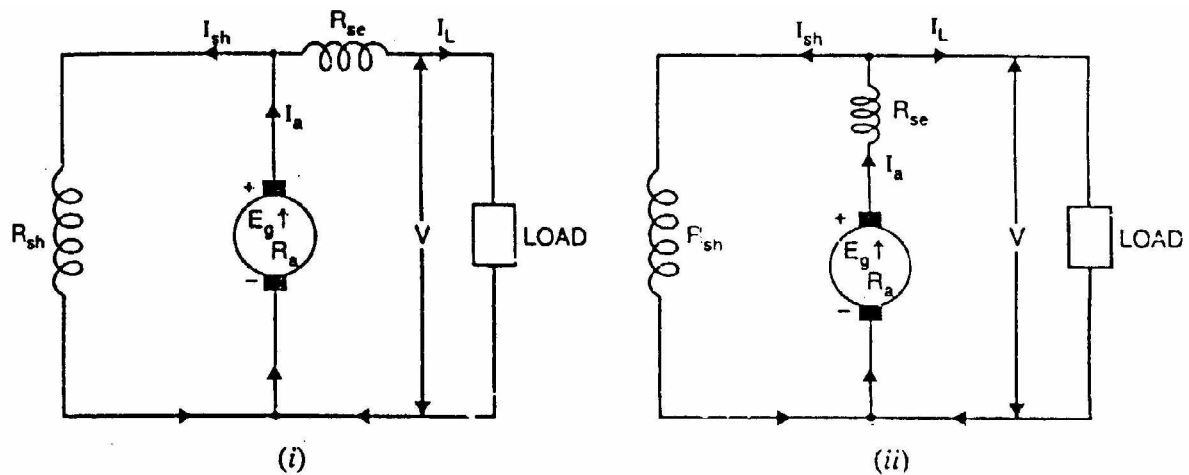

(*i*)   (*ii*)

Fig. (1.35)

Short shunt

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

Shunt field current, $I_{sh} = \dfrac{V + I_{se}R_{se}}{R_{sh}}$

Terminal voltage, $V = E_g - I_aR_a - I_{se}R_{se}$
Power developed in armature $= E_gI_a$
Power delivered to load $= VI_L$

Long shunt
      Series field current, $I_{se} = I_a = I_L + I_{sh}$
      Shunt field current, $I_{sh} = V/R_{sh}$
      Terminal voltage, $V = E_g - I_a(R_a + R_{se})$
   Power developed in armature $= E_g I_a$
      Power delivered to load $= VI_L$

1.25 Brush Contact Drop

It is the voltage drop over the brush contact resistance when current flows. Obviously, its value will depend upon the amount of current flowing and the value of contact resistance. This drop is generally small.

1.26 Losses in a D.C. Machine

The losses in a d.c. machine (generator or motor) may be divided into three classes viz (i) copper losses (ii) iron or core losses and (iii) mechanical losses. All these losses appear as heat and thus raise the temperature of the machine. They also lower the efficiency of the machine.
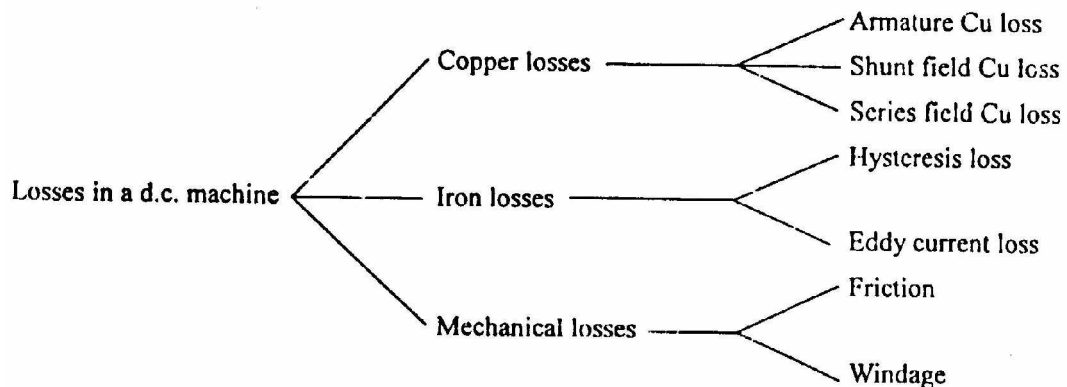
1. Copper losses

These losses occur due to currents in the various windings of the machine.
      (i)   Armature copper loss $= I_a^2 R_a$
      (ii)   Shunt field copper loss $= I_{sh}^2 R_{sh}$
      (iii) Series field copper loss $= I_{se}^2 R_{se}$

Note. There is also brush contact loss due to brush contact resistance (i.e., resistance between the surface of brush and surface of commutator). This loss is generally included in armature copper loss.

2. Iron or Core losses

These losses occur in the armature of a d.c. machine and are due to the rotation of armature in the magnetic field of the poles. They are of two types viz., (i) hysteresis loss (ii) eddy current loss.

(i) Hysteresis loss

Hysteresis loss occurs in the armature of the d.c. machine since any given part of the armature is subjected to magnetic field reversals as it passes under successive poles. Fig. (1.36) shows an armature
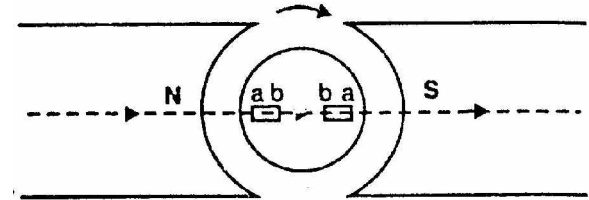
Fig. (1.36)

rotating in two-pole machine. Consider a small piece ab of the armature. When the piece ab is under N-pole, the magnetic lines pass from a to b. Half a revolution later, the same piece of iron is under S-pole and magnetic lines pass from b to a so that magnetism in the iron is reversed. In order to reverse continuously the molecular magnets in the armature core, some amount of power has to be spent which is called hysteresis loss. It is given by Steinmetz formula. This formula is

$$\text{Hysteresis loss, } P_h = \eta B_{max}^{16} f V \quad \text{watts}$$

where B_{max} = Maximum flux density in armature
f = Frequency of magnetic reversals
= NP/120 where N is in r.p.m.
V = Volume of armature in m^3
η = Steinmetz hysteresis co-efficient

In order to reduce this loss in a d.c. machine, armature core is made of such materials which have a low value of Steinmetz hysteresis co-efficient e.g., silicon steel.
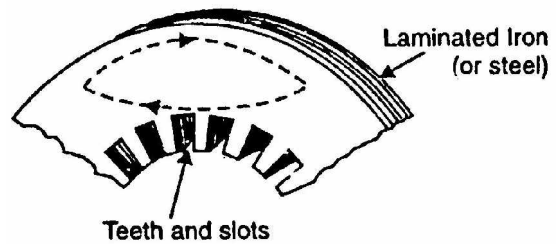
(ii) Eddy current loss

In addition to the voltages induced in the armature conductors, there are also voltages induced in the armature core. These voltages produce circulating currents in the armature core as shown in Fig. (1.37). These are called eddy currents and power loss due to their flow is called eddy current loss. The eddy current loss appears as heat which raises the temperature of the machine and lowers its efficiency.

If a continuous solid iron core is used, the resistance to eddy current path will be small due to large cross-sectional area of the core. Consequently, the magnitude of eddy current and hence eddy current loss will be large. The magnitude of eddy current can be reduced by making core resistance as high as practical. The

core resistance can be greatly increased by constructing the core of thin, round iron sheets called laminations [See Fig. 1.38]. The laminations are insulated from each other with a coating of varnish. The insulating coating has a high resistance, so very little current flows from one lamination to the other. Also, because each lamination is very thin, the resistance to current flowing through the width of a lamination is also quite large. Thus laminating a core increases the core resistance which decreases the eddy current and hence the eddy current loss.
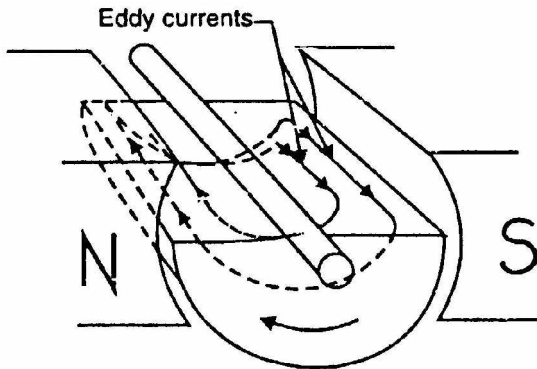
Fig. (1.37)   **Fig. (1.38)**

$$\text{Eddy current loss, } P_e = K_e B_{max}^2 f^2 t^2 V \quad \text{watts}$$

where K_e = Constant depending upon the electrical resistance of core and system of units used

B_{max} = Maximum flux density in Wb/m2

f = Frequency of magnetic reversals in Hz

t = Thickness of lamination in m

V = Volume of core in m^3

It may be noted that eddy current loss depends upon the square of lamination thickness. For this reason, lamination thickness should be kept as small as possible.

3.   Mechanical losses

These losses are due to friction and windage.
  (i)   friction loss e.g., bearing friction, brush friction etc.
  (ii)   windage loss i.e., air friction of rotating armature.

These losses depend upon the speed of the machine. But for a given speed, they are practically constant.

Note. Iron losses and mechanical losses together are called stray losses.

1.27 Constant and Variable Losses

The losses in a d.c. generator (or d.c. motor) may be sub-divided into (i) constant losses (ii) variable losses.

(i) Constant losses
Those losses in a d.c. generator which remain constant at all loads are known as constant losses. The constant losses in a d.c. generator are:

   (a) iron losses
   (b) mechanical losses
   (c) shunt field losses

(ii) Variable losses
Those losses in a d.c. generator which vary with load are called variable losses. The variable losses in a d.c. generator are:

(a)   Copper loss in armature winding ($I_a^2 R_a$)

(b)   Copper loss in series field winding ($I_{se}^2 R_{se}$)

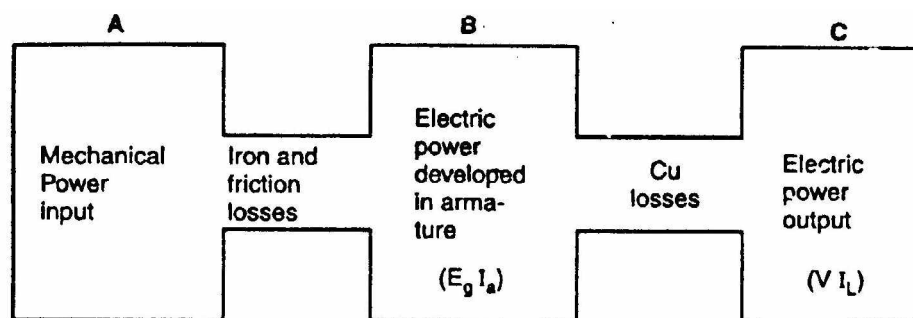$$\text{Total losses} = \text{Constant losses} + \text{Variable losses}$$

Note. Field Cu loss is constant for shunt and compound generators.

1.28 Power Stages

The various power stages in a d.c. generator are represented diagrammatically in Fig. (1.39).

$$A - B = \text{Iron and friction losses}$$

$$B - C = \text{Copper losses}$$

Fig. (1.39)

(i)   Mechanical efficiency

$$\eta_m = \frac{B}{A} = \frac{E_g I_a}{\text{Mechanical power input}}$$

(ii)   Electrical efficiency

$$\eta_e = \frac{C}{B} = \frac{V\,I_L}{E_g\,I_a}$$

(iii)   Commercial or overall efficiency

$$\eta_c = \frac{C}{A} = \frac{V\,I_L}{\text{Mechanical power input}}$$

Clearly $\eta_c = \eta_m \times \eta_e$

Unless otherwise stated, commercial efficiency is always understood.

Now,   commercial efficiency, $\eta_c = \dfrac{C}{A} = \dfrac{\text{output}}{\text{input}} = \dfrac{\text{input} - \text{losses}}{\text{input}}$

1.29 Condition for Maximum Efficiency

The efficiency of a d.c. generator is not constant but varies with load. Consider a shunt generator delivering a load current I_L at a terminal voltage V.

Generator output $= V\,I_L$

Generator input $=$ Output + Losses

$\qquad\qquad = V\,I_L +$ Variable losses $+$ Constant losses

$\qquad\qquad = VI_L + I_a^2 R_a + W_C$

$\qquad\qquad = VI_L + (I_L + I_{sh})^2 R_a + W_C \qquad\qquad [\because\ I_a + I_L + I_{sh}]$

The shunt field current I_{sh} is generally small as compared to I_L and, therefore, can be neglected.

$\therefore$ Generator input $= VI_L + I_L^2 R_a + W_C$

Now $\eta = \dfrac{\text{output}}{\text{input}} = \dfrac{VI_L}{VI_L + I_L^2 R_a + W_C}$

$$= \frac{1}{1 + \left(\dfrac{I_L R_a}{V} + \dfrac{W_C}{VI_L} \right)} \qquad\qquad \text{(i)}$$

The efficiency will be maximum when the denominator of Eq.(i) is minimum i.e.,

$$\frac{d}{dI_L}\left(\frac{I_L R_a}{V} + \frac{W_C}{VI_L} \right) = 0$$
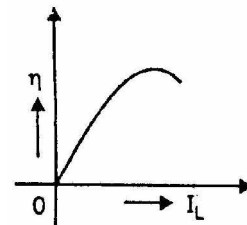
or $\dfrac{R_a}{V} - \dfrac{W_C}{VI_L^2} = 0$

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Fig. (1.40)

or $\qquad \dfrac{R_a}{V} = \dfrac{W_C}{VI_L^2}$

or $\qquad I_L^2 R_a = W_C$

i.e. $\qquad$ Variable loss = Constant loss $\quad \left(b\ I_L \simeq I_a \right)$

The load current corresponding to maximum efficiency is given by;

$$I_L = \sqrt{\dfrac{W_C}{R_a}}$$

Hence, the efficiency of a d.c. generator will be maximum when the load current is such that variable loss is equal to the constant loss. Fig (1.40) shows the variation of η with load current.