EEE/ETI3105
ELECTRICAL MACHINES I

LECTURE 6: DC MACHINES

FUNDAMENTALS

Introduction

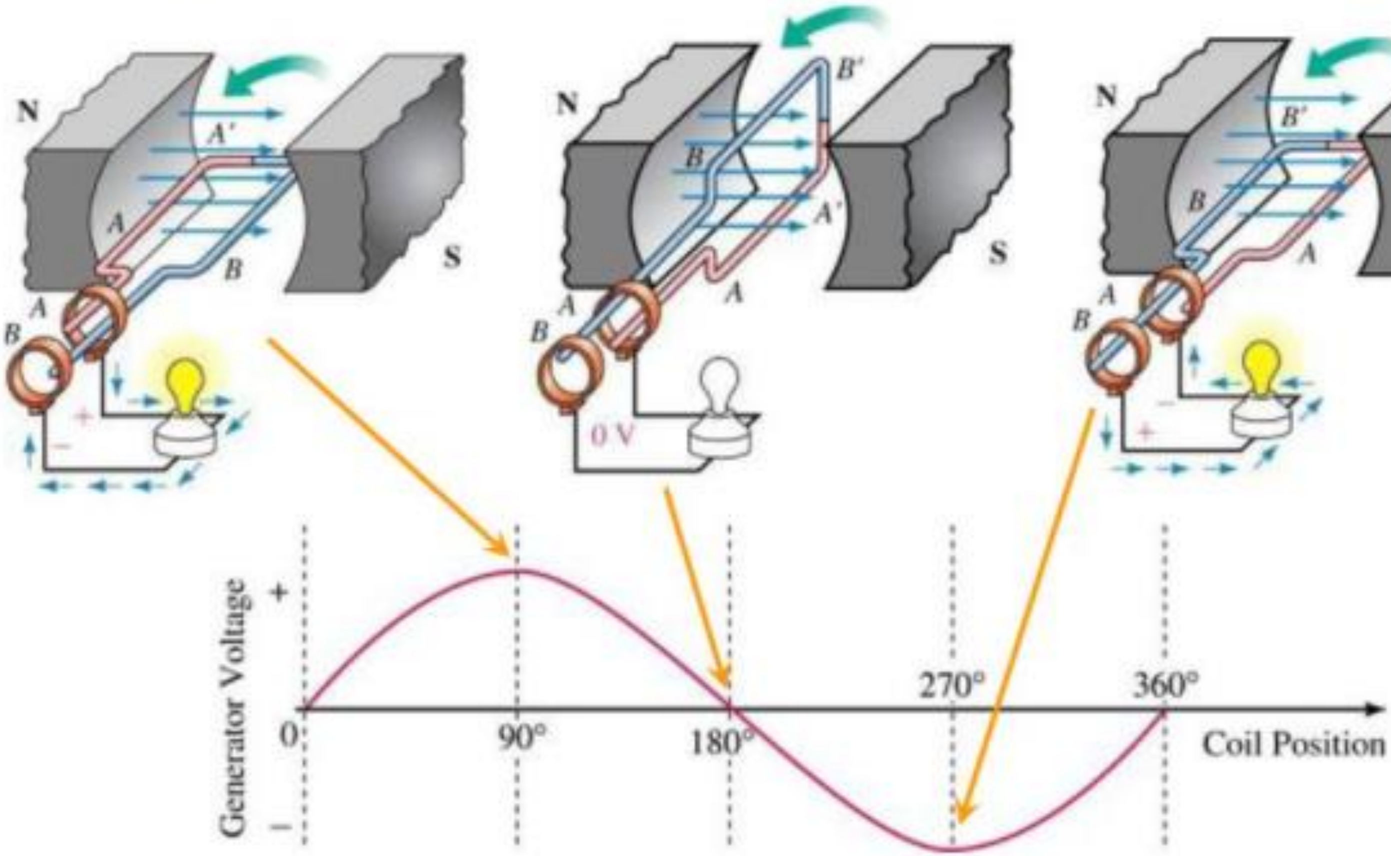
- DC Machines are an electro-mechanical energy conversion devices that uses DC power as input and/or DC output. (DC motor or DC generator)
- The greater percentage of the electrical machines in service are a.c. machines.
- The principal advantage of the d.c. machine, particularly the d.c. motor, is that it provides a fine control of speed. Such an advantage is not claimed by any a.c. motor.
- 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.

Introduction

- The DC generator converts mechanical energy to electrical energy while the DC motor converts electrical power to 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 Flemings right hand rule. Therefore, the essential components of a dc machine are:
  - a magnetic field
  - conductor or a group of conductors
  - motion of conductor w.r.t. magnetic field.

Simple Loop Generator

- Rotating a coil in fixed magnetic field generates sinusoidal voltage.



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.

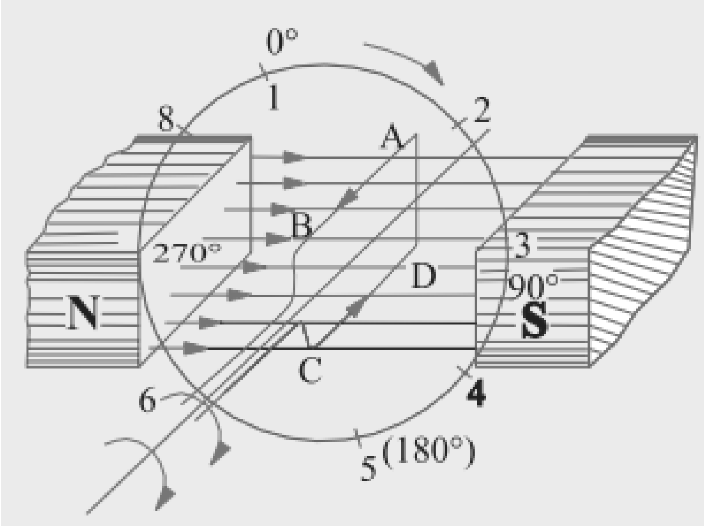


Fig. 1

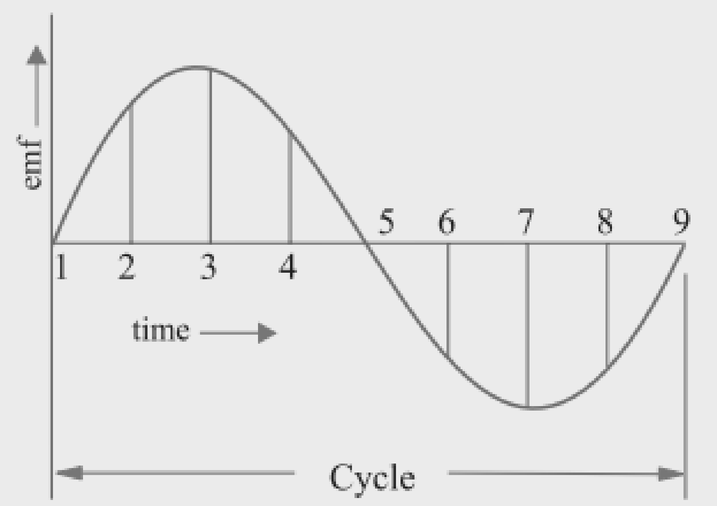


Fig. 2

- 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.

Single Loop Generator

- When the loop is in position no. 1 (Fig.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. (when the plane of the coil is at right angles to lines of flux, then flux linked with the coil is maximum but rate of change of flux linkages is minimum).
- 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. (2).
- 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. (2).

Single Loop Generator

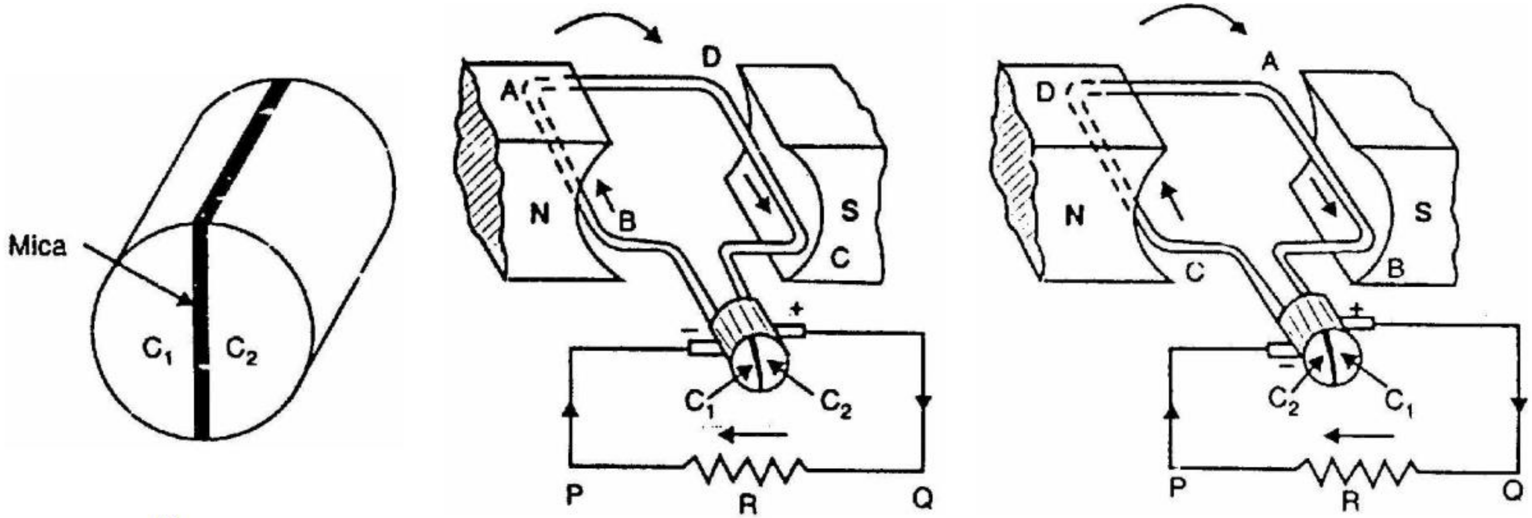
- At position 4, the generated e.m.f. is less because the coil sides are cutting the flux at an angle.
- At position 5, no magnetic lines are cut and hence induced e.m.f. is zero as indicated by point 5 in Fig. (2).
- At position 6, the coil sides move under a pole of opposite polarity and hence the direction of generated e.m.f. is reversed. The maximum e.m.f. in this direction (i.e., reverse direction, Fig. 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.

Single Loop Generator : Points to Note

- **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.

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.
- 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 Fig (i).
- The commutator is mounted on but insulated from the rotor shaft



(i) (ii) (iii)

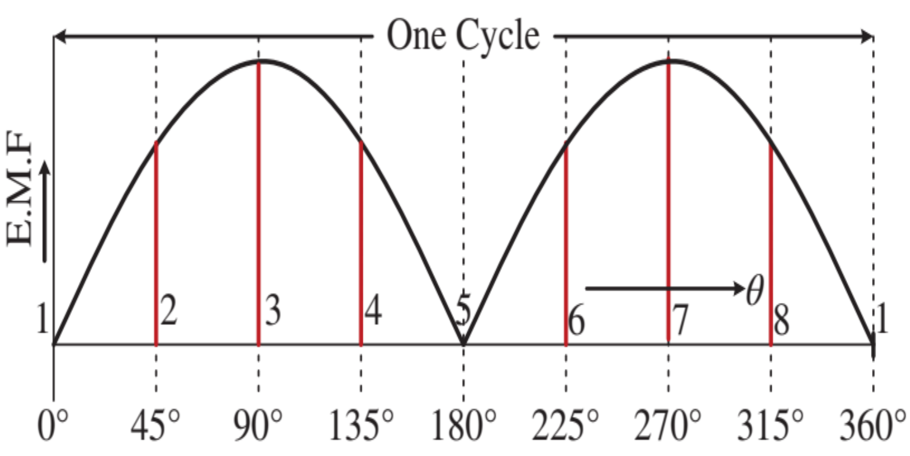
Action of a Commutator

- The ends of coil sides AB and CD are connected to the segments C_1 and C_2 respectively as shown in Fig. (ii).
- Two stationary carbon brushes rest on the commutator and lead current to the external load.
- With this arrangement, the commutator always connects the coil side under S-pole to the +ve brush and that under N-pole to the -ve brush.
- In Fig. (ii), 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.
- After half a revolution of the loop (i.e., 180o rotation), the coil side AB is under S-pole and the coil side CD under N-pole as shown in Fig. (iii).
- The currents in the coil sides now flow in the reverse direction but the segments C1 and C2 have also moved through 180o i.e., segment C1 is now in contact with +ve brush and segment C2 in contact with -ve brush.

Action of Commutator

- 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.
- Thus the alternating voltage generated in the loop will appear as direct voltage across the brushes.
- 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.

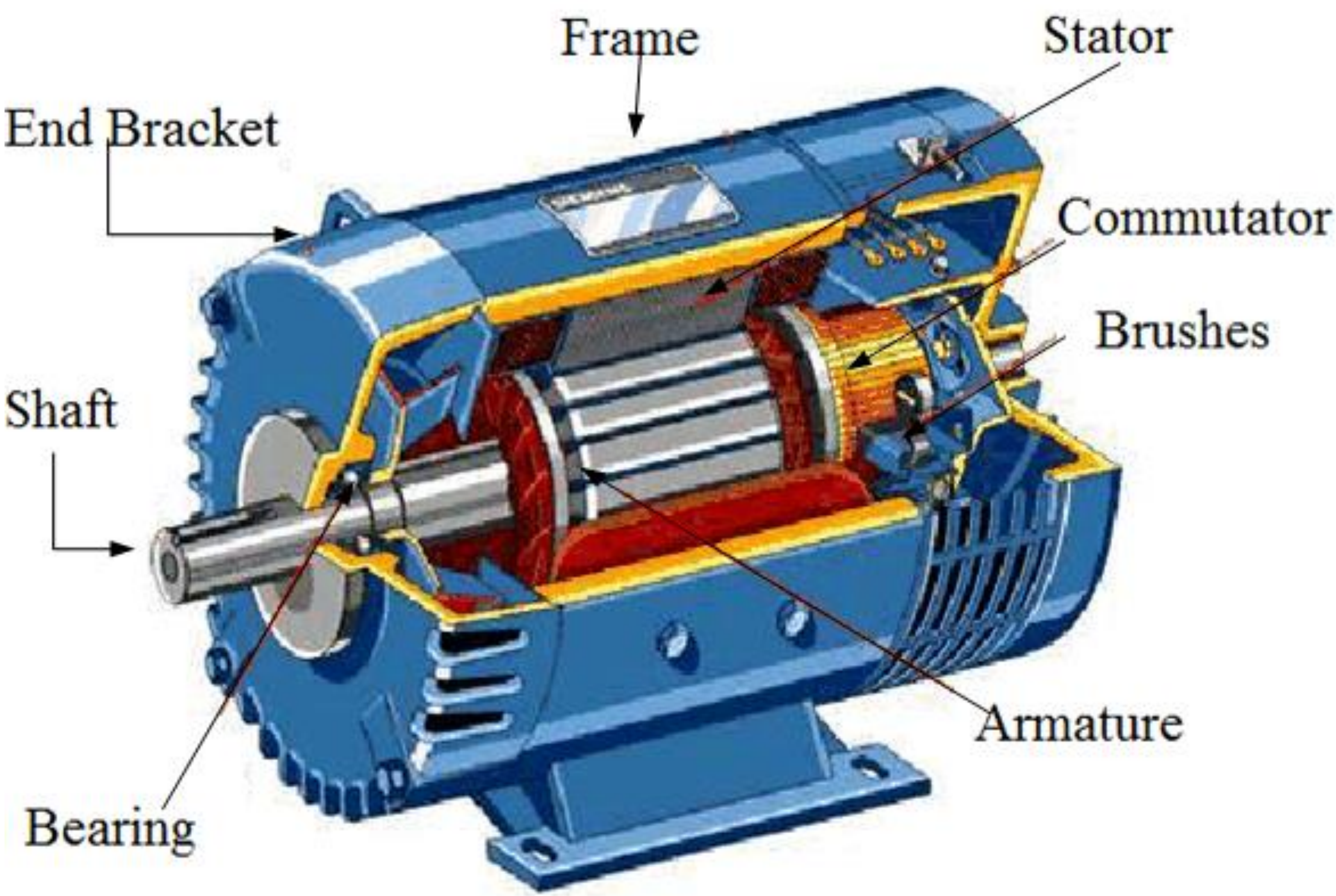
- Finally a pulsating direct voltage [See Fig] is produced by a single loop.
- However we require a steady direct voltage.
- This steady voltage can be achieved by using a large number of coils connected in series.
- The resulting arrangement is known as armature winding



Construction of DC Machines

- 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:
  - ✓ field system
  - ✓ armature core
  - ✓ armature winding
  - ✓ Commutator
  - ✓ brushes

Construction of d.c. Machine - longitudinal view



Construction of d.c. Machine - Cross-section view

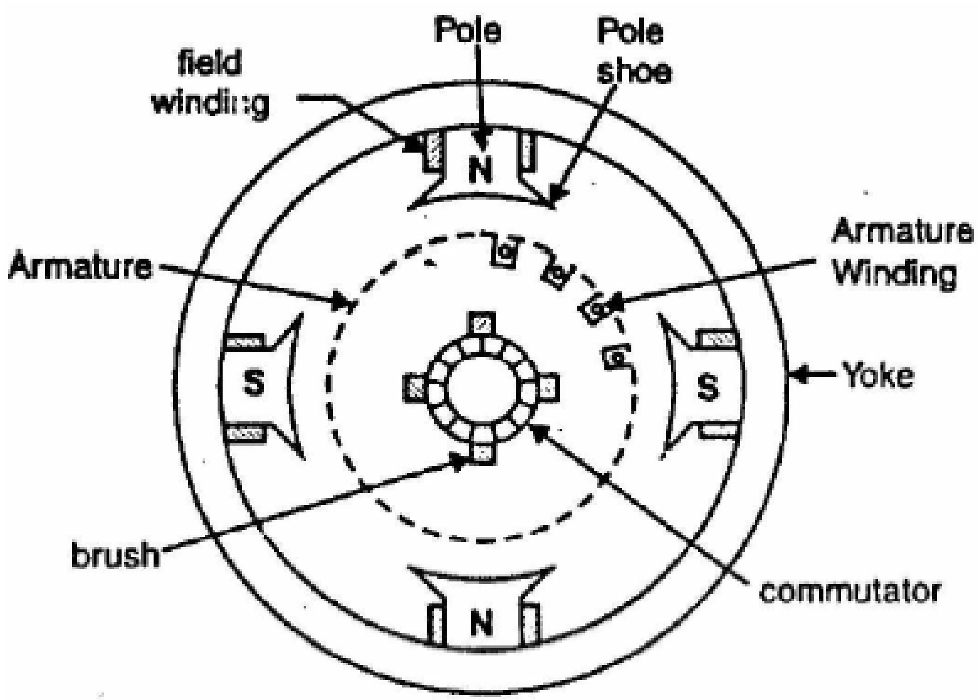


Fig. i

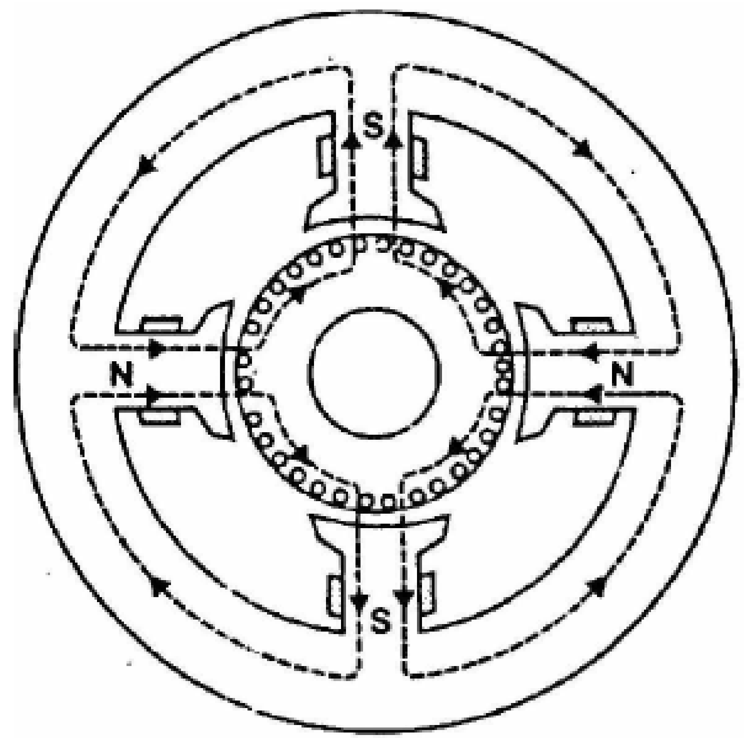
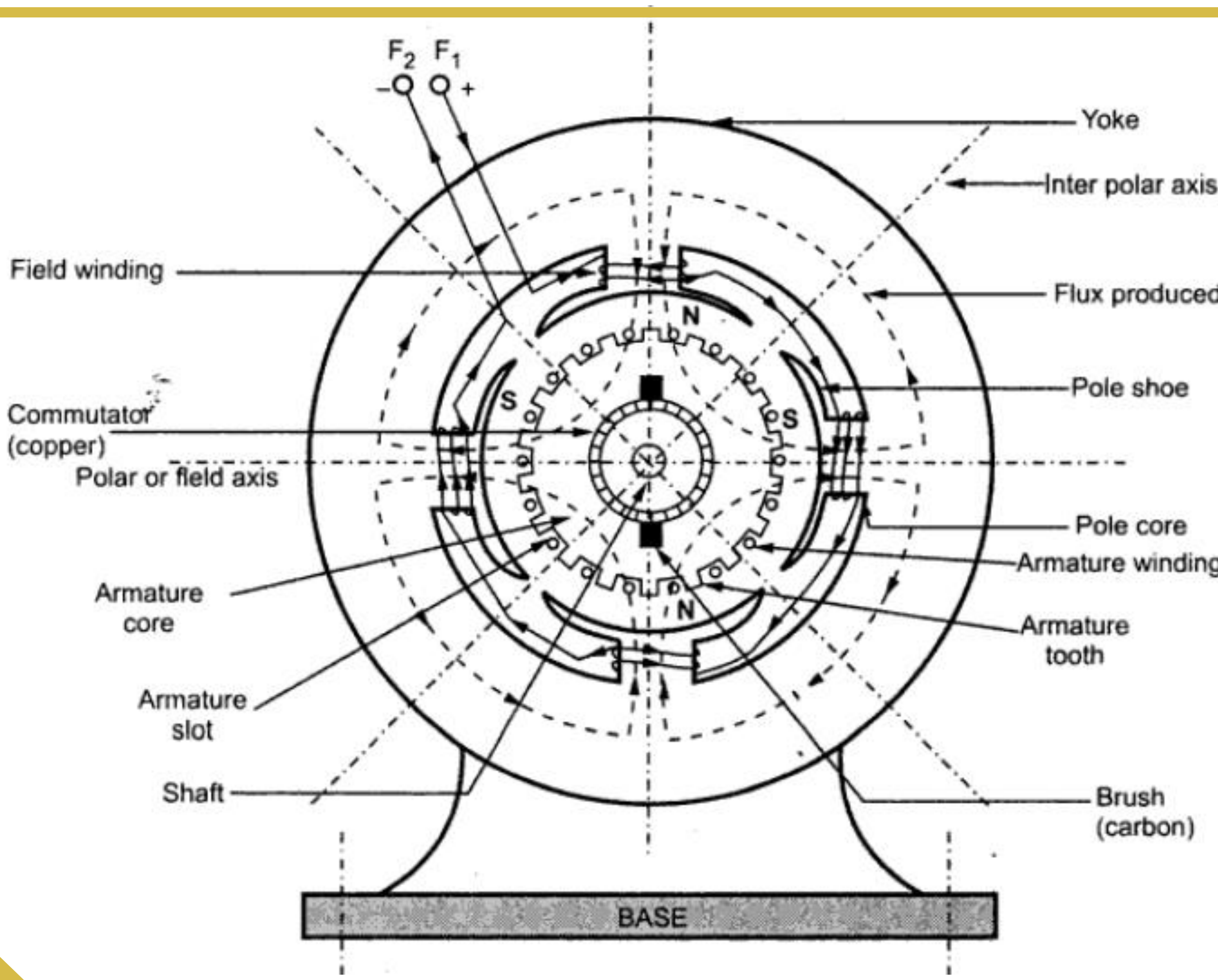


Fig. ii

Construction of d.c. Machine - Cross-section view

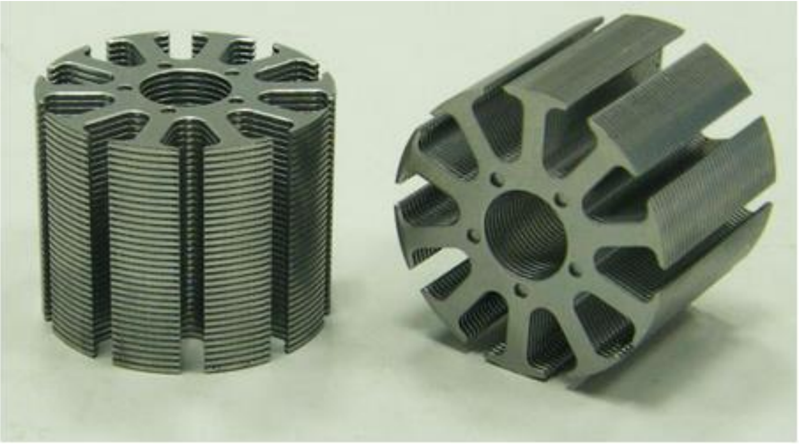


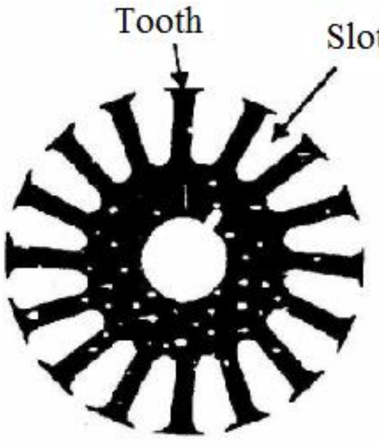
Field System

- 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 (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 (Fig. (ii).
- 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).

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.
- The laminations 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"





Armature winding

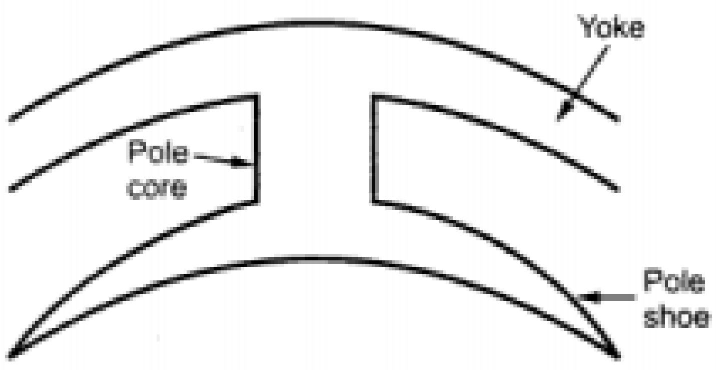
- This is the winding (conductors) in which the e.m.f. is induced.
- These insulated windings are held by armature core.
- The armature conductors are connected in series-parallel; the conductors being connected in series so as to increase the voltage and in parallel paths so as to increase the current.
- Generation of emf takes place in the armature winding in case of generators
- Carry the current supplied in case of d.c. motors

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.
- The armature conductors are soldered to the commutator segments in a suitable manner to give rise to the armature winding.

Poles

- Each pole is divided into two parts namely pole core and pole shoe as shown in Figure.
- Pole core basically carries a field winding which is necessary to produce the flux.
- It directs the flux produced through air gap to armature core then to the next pole
- Pole shoe enlarges the area of armature core to come across the flux, which is necessary to produce larger induced emf.
- Made up of magnetic material like iron or cast steel



Pole structure

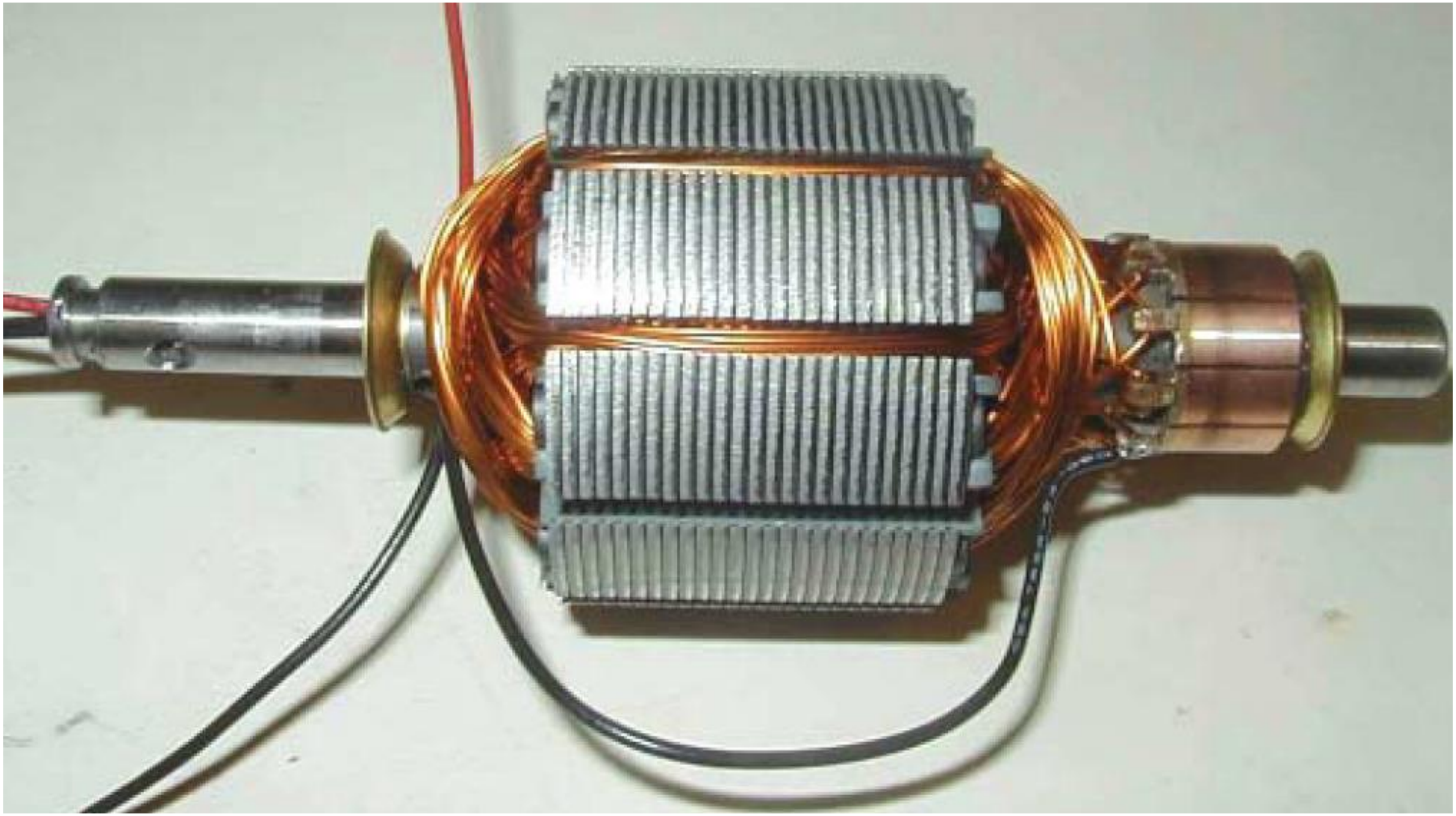
Brushes

- They 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.
- If the brush pressure is very large, the friction produces heating of the commutator and the brushes, if it is too weak, the imperfect contact with the commutator may produce sparking.
- Multipole machines have as many brushes as they have poles, e.g. a 4-pole machine has 4 brushes.

Yoke

- It serves the purpose of outermost cover of the d.c. machine. So the insulating materials get protected from harmful atmospheric elements.
- It provides mechanical support to the poles
- It forms a part of the magnetic circuit. It provides a path of low reluctance for magnetic flux.

Try Identify all the Components in this Picture



D.C. Armature Windings

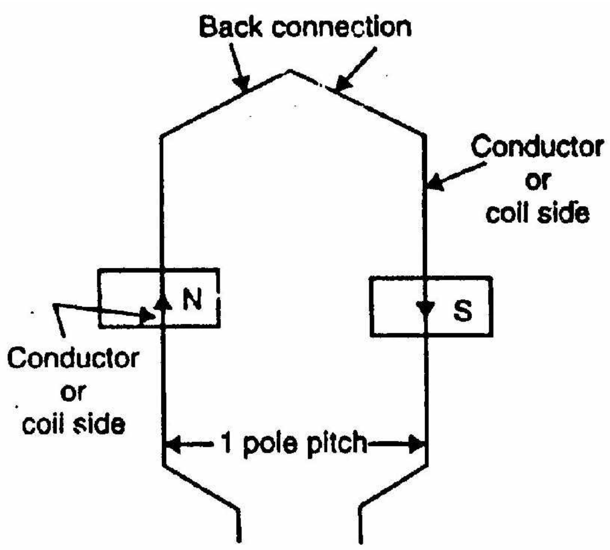
- A d.c. machine (generator or motor) generally employs windings distributed in slots over the circumference of the armature core.
- Each conductor lies at right angles to the magnetic flux and to the direction of its movement.
- Therefore, the induced e.m.f. in the conductor is given by;

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

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

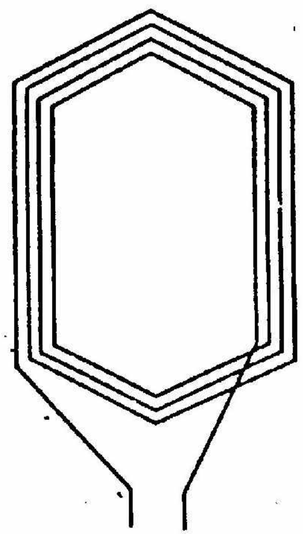
- The armature conductors are connected to form coils.

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



Single-turn coil

(i)

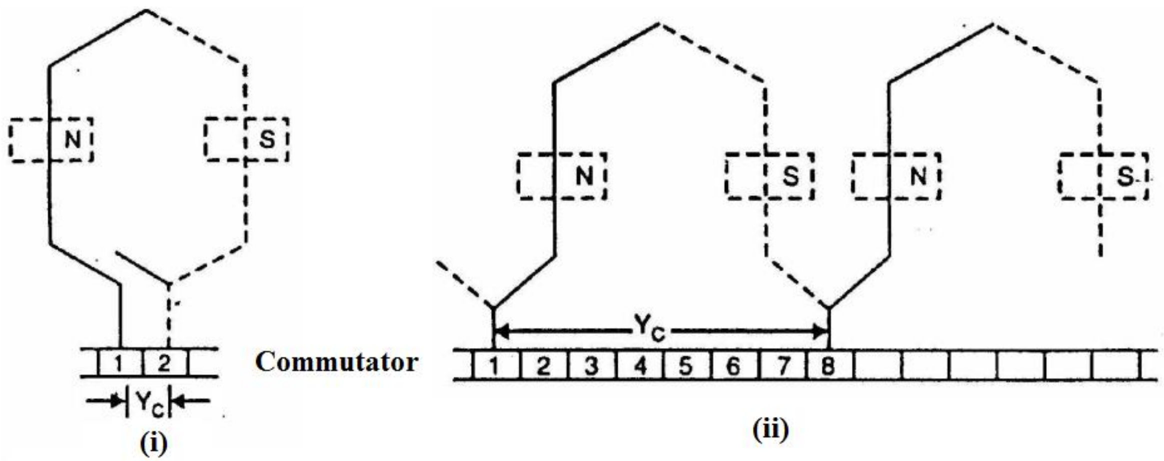

4-turn coil

(ii)

- 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.
- Consequently the e.m.f of the coil sides add together.
- If the e.m.f. induced in one conductor is 2.5V, then the e.m.f. of a single-turn coil will be = $2 \times 2.5 = 5$V. For the same flux and speed, the e.m.f. of a 4-turn coil will be = $8 \times 2.5 = 20$ 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.

Commutator Pitch (Y_C)

- The commutator pitch is the number of commutator segments spanned by each coil of the winding.
- It is always a whole number



- In Fig. (i), 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. (ii), $Y_c = 8 - 1 = 7$ segments i.e., $Y_c = 7$.
- Since each coil has two ends and as two coil connections are joined at each commutator segment,
- Number of coils = Number of commutator segments

Pole-Pitch

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

$$\therefore \text{Pole pitch} = \frac{\text{Number of Slots}}{\text{No of poles}} = \frac{16}{4} = 4 \text{ Slots}$$

$$\text{Also, Pole pitch} = \frac{\text{Number of conductors}}{\text{No of poles}} = \frac{16 \times 2}{4} = 8 \text{ Conductors}$$

Coil Span or Coil Pitch (Y_S)

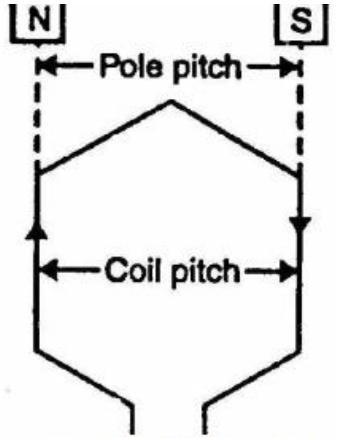
- It is the distance measured in terms of the number of armature slots (or armature conductors) spanned by a coil.
- Thus if the coil span is 9 slots, it means one side of the coil is in slot 1 and the other side in slot 10.

Full-Pitched Coil

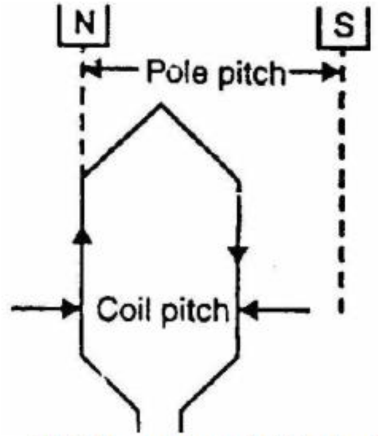
- If the coil-span or coil pitch is equal to pole pitch, it is called full-pitched coil.
- In this case, the e.m.f.s in the coil sides are additive and have a phase difference of 0°.
- Therefore, e.m.f. induced in the coil is maximum.
- Coil span should always be one pole pitch unless there is a good reason for making it shorter.

Fractional pitched coil

- Here coil span or coil pitch is less than the pole pitch.
- Fractional pitch winding requires less copper but if the pitch is too small, an appreciable reduction in the generated e.m.f. results.



(i) Full-Pitched Coil



(ii) Fractional Pitched

Short pitch vs Full Pitch

1) The length required for the end connections of coils is less thus less copper is required.
   - Hence it is economical.
2) Short pitching eliminates high frequency harmonics which distort the sinusoidal nature of e.m.f.
   - Hence waveform of an induced e.m.f. is more sinusoidal due to short pitching.
3) As high frequency harmonics get eliminated, eddy current and hysteresis losses which depend on frequency also get minimised.
   - This increases the efficiency.

Types of D.C. Armature Windings

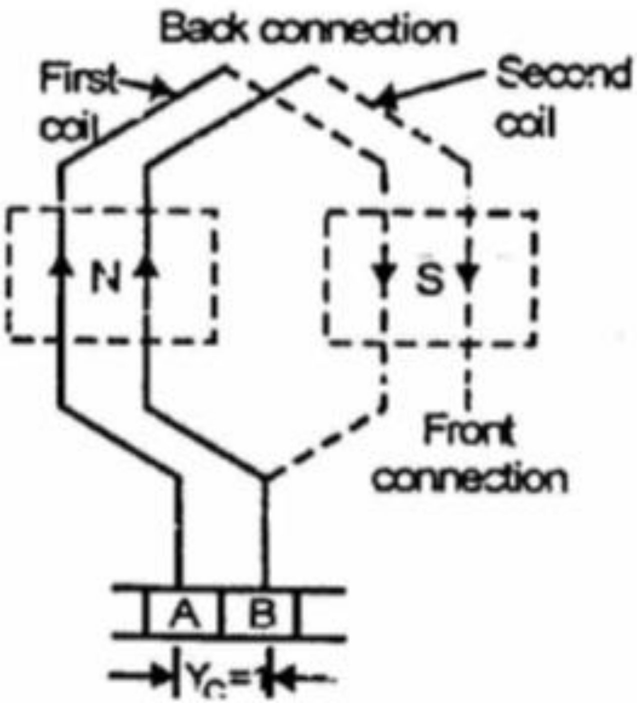
Simplex lap winding

- Here, the commutator pitch $Y_C = 1$ and coil span $Y_S \approx$ 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 are in sequence with the last coil connected to the first coil.
- Consequently, closed circuit winding results. where a part of the lap winding is shown.
- The name lap comes from the way in which successive coils overlap the proceeding one.

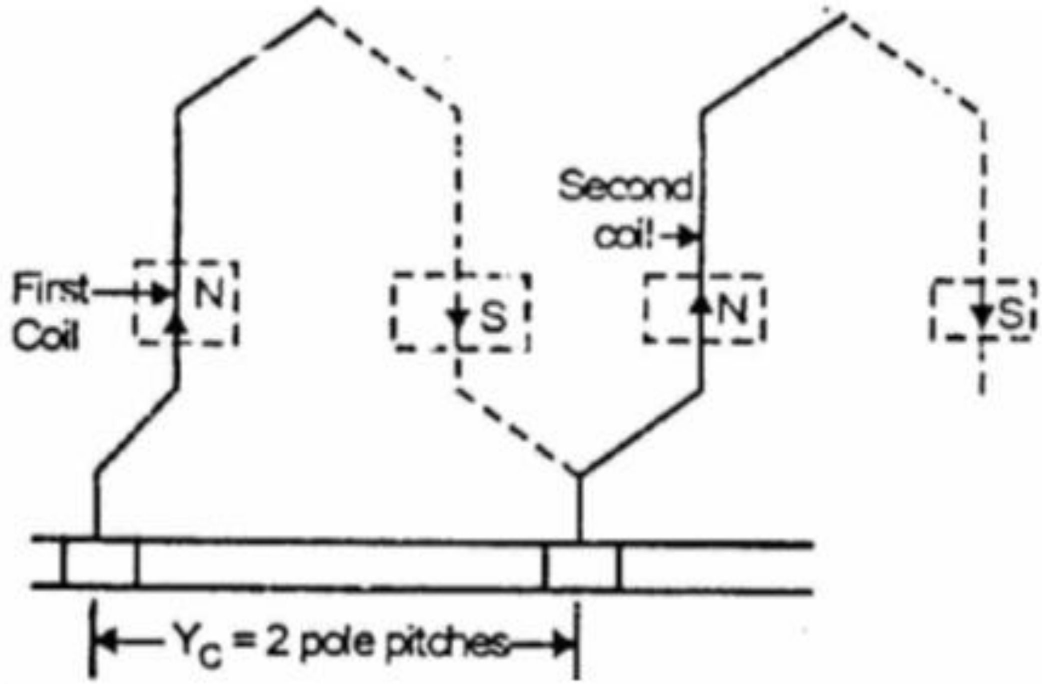
Simplex wave winding

- For a simplex wave winding, the commutator pitch $Y_C \sim 2$ 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.
- This winding is called wave winding from the appearance (wavy) of the end connections.

Lap vs Wave Windings



(i) Lap Winding



(ii) Wave Winding

Armature Winding Terminologies

Back Pitch (Y_B)

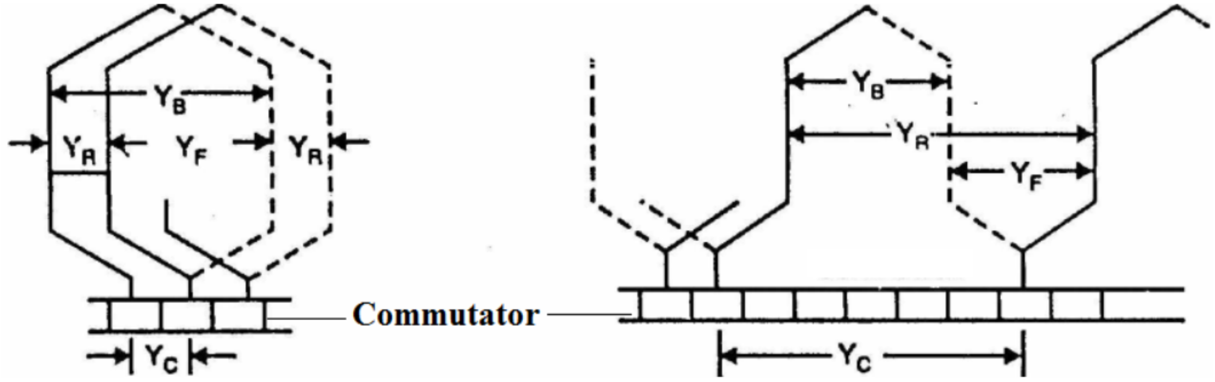
- It is the distance measured in terms of armature conductors between the two sides of a coil at the back of the armature.

Front Pitch (Y_F)

- It is the distance measured in terms of armature conductors between the coil sides attached to any one commutator segment.

Resultant Pitch (Y_R)

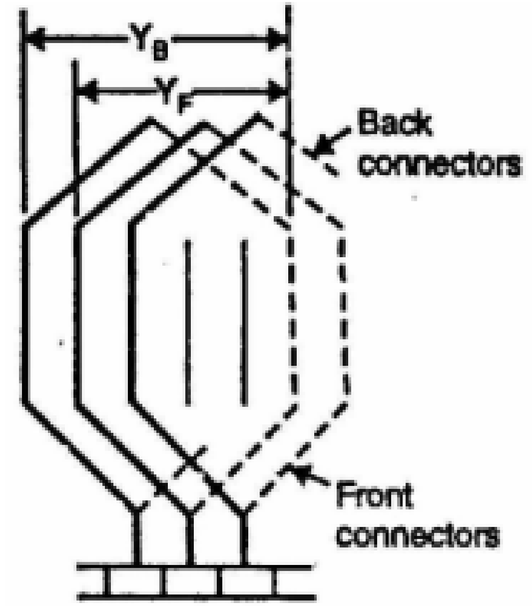
- It is the distance (measured in terms of armature conductors) between the beginning of one coil and the beginning of the next coil to which it is connected. Therefore, the resultant pitch is the algebraic sum of the back and front pitches.



Progressive and Retrogressive Armature Windings

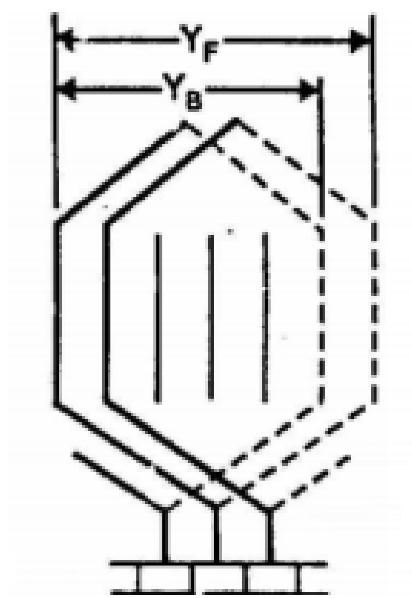
Progressive Winding

- It is a winding in which, as one traces through, 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.
- Note that $Y_B > Y_F$ and $Y_C = +1$.



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.
- Note that $Y_F > Y_B$ and $Y_C = 1$.
- A retrogressive winding is seldom used because it requires more copper.



General Rules in Design of D.C. Armature Windings

1. 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.
2. 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.
3. 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
4. The winding must close upon itself i.e. it should be a closed circuit winding.

Relations between Pitches for Simplex Lap Winding

1. The back and front pitches are odd and are of opposite signs. They differ numerically by 2; $Y_B = Y_F \pm 2$ i.e $Y_B = Y_F + 2$ for progressive and $Y_B = Y_F - 2$ for retrogressive winding.
2. If Z = number of armature conductors and P = number of poles, then;
   Pole pitch Z/ P
   Since both must be about one pole pitch and differ numerically by 2
   $Y_B = Z/P + 1$ $\quad$ $Y_F = Z/P - 1$ For Progressive winding.
   $Y_B = Z/P - 1$ $\quad$ $Y_F = Z/P + 1$ For Retrogressive winding.
3. Both Y_B and Y_F should be nearly equal to pole pitch.
4. Commutator pitch, $Y_C = \pm 1$
   $Y_C = +1$ for progressive $Y_C = -1$ for retrogressive winding
5. The resultant pitch (Y_R) is even, being the arithmetical sum of two odd numbers viz., Y_B and Y_F.
6. Average pitch $=(Y_B + Y_F)/2$. It equals pole pitch (= Z/P). It is clear that Z/P must be an even number to make the winding possible.

Lap vs 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.
- 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.
- 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.

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, $Y_C \sim 2$ pole pitches (segments)

- **Qn.** A 4-pole, simplex lap-wound armature contains 16 slots and has two coil sides per slot. Find:
  a) back pitch,
  b) front pitch and
  c) commutator pitch

for progressive and retrogressive winding

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

Let

$$\Phi = \text{flux/pole in Wb}$$
$$Z = \text{total number of armature conductors}$$
$$P = \text{number of poles}$$
$$A = \text{number of parallel paths}$$
$$= 2 \;\ldots\; \text{for wave winding}$$
$$= P \;\ldots\; \text{for lap winding}$$
$$N = \text{speed of armature in r.p.m.}$$
$$E_g = \text{e.m.f. of the generator} = \text{e.m.f./parallel path}$$

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

$$d\Phi = P\Phi \text{ Webers}$$

- Time taken to complete one revolution,

$$dt = \frac{60}{N} \text{ Seconds}$$

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

$$\text{E.M.F. generated/conductor} = \frac{d\Phi}{dt} = \frac{P\Phi}{60/N} = \frac{P\Phi N}{60} \text{ Volts}$$

- 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

$$E_g = \frac{P\Phi N}{60} \times \frac{Z}{A} = \frac{P\Phi ZN}{60A}$$

  Where A = 2 (for-wave winding); A= P (for lap winding)

- The induced E.M.F. is different from the terminal voltage V, at the generator terminals as a result of **armature resistance**.

Armature Resistance (R_a)

- The resistance offered by the armature circuit is known as armature resistance (R_a) and includes:
  - resistance of armature winding
  - resistance of brushes
- The armature resistance depends upon the construction of machine.
- Except for small machines, its value is generally less than 1Ω

Practice Question

- A 4 pole, lap wound, d.c. generator has a useful flux of 0.07Wb per pole. Calculate the generated e.m.f when it is rotated at a speed of 900 r.p.m with the help of prime mover. Armature consists of 440 number of conductors. Also calculate the generated e.m.f. if lap wound armature is replaced by wave wound armature

$P = 4 \quad Z = 440 \quad \phi = 0.07$ Wb and $N = 900$ r.p.m.

$$E = \frac{\phi P N Z}{60 A}$$

i) For lap wound, $A = P = 4$

$$E = \frac{\phi N Z}{60} = \frac{0.07 \times 900 \times 440}{60} = \mathbf{462\ V}$$

ii) For wave wound $A = 2$

$$E = \frac{\phi P N Z}{120} = \frac{0.07 \times 900 \times 4 \times 440}{120} = \mathbf{924\ V}$$

Practice Question

- A four-pole wave wound DC generator has 51 slots on its armature and each slot has 24 conductors. The flux per pole is 0.01Wb. 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.

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

where, $\phi = 0{\cdot}01$ Wb; $Z = 51 \times 24 = 1224$; $E = 220$ V; $P = 4$; $A = 2$ (wave winding).

$$\therefore \quad 220 = \frac{0 \cdot 01 \times 1224 \times N \times 4}{60 \times 2}$$

$$\text{or} \quad N = \frac{220 \times 60 \times 2}{0 \cdot 01 \times 1224 \times 4} = \mathbf{539{\cdot}21\ rpm}\ (Ans.)$$

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

$$E_g = \frac{0 \cdot 01 \times 1224 \times 539 \cdot 21 \times 4}{60 \times 4} = \mathbf{110\ V}\ (Ans.)$$

Self Assessment

- Why is commutator employed in DC machines?
- Define coil pitch and coil span.
- Define the factors and state benefits of short pitched coils.
- Why the armature of a DC machine is made of laminated silicon steel?
- Which are the different types of armature windings commonly used in DC machines ?
- 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?. [138.2V]
- A DC generator carries 600 conductors on its armature with lap connections. The generator has 8poles 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? [600V, 250rpm]