ELECTRICAL MACHINES(EE 554)

Chapter-3 (DC Generator)

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3.1 Introduction

DC machine is a rotating electrical machine which converts mechanical energy into electrical energy and vice versa. It generates electrical energy in DC system or it converts the electrical energy in DC system into the mechanical energy in the form of rotation. A dc machine can be used as generator as well as motor.

3.2 Basic constructional details of DC machine

Fig.3.1 shows a cut-way view of a dc machine. The various parts of the machine are described below:

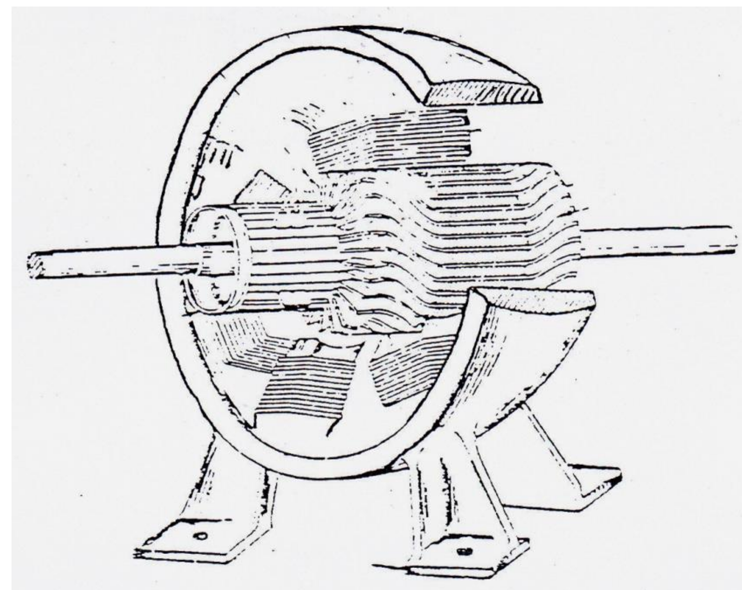


Fig.3.1 Cut-way view of a dc machine.

Yoke: It is the outermost frame of the machine. It provides mechanical support to the field pole and also acts as protecting cover for the whole machine. It also carries the magnetic flux produced by the field poles. For small machines, cheapness is more important than the efficiency of the machine. Hence, for the sake of cheapness, yoke is usually made of cast iron in small machine. Whereas, in case of large machine, efficiency is more concerns. Hence, yoke of the large machine is made of cast steel or rolled steel having higher value of permeability.

Field poles: Field poles are the iron core projected from the yoke as shown in Fig.3.2. The upper part of the pole, which is connected to the yoke, is known as pole-core. The lower and wider part is known as pole-shoe. The combination of many pole shoes surface forms a circular gap at the centre of the machine. The field poles are generally made of laminated annealed steel sheet.

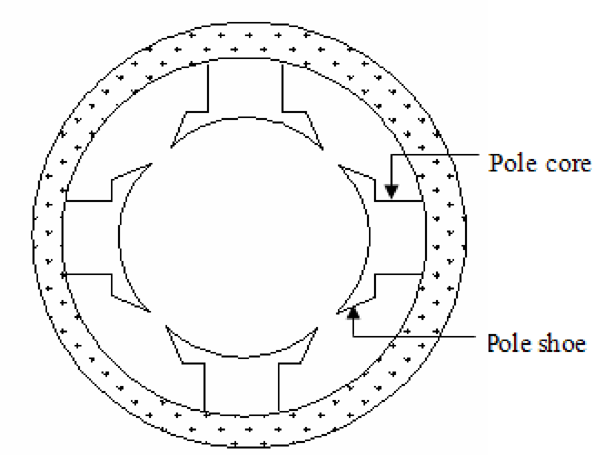


Fig.3.2 Cross-sectional view of field poles of DC machine

Field windings: It is the copper wire wound on the field pole as shown in Fig.3.3. The windings are insulated from the core and each turns of windings are also insulated from each other to protect from turn to turn short circuit. Enamel insulated copper wire is used for this purpose. When DC current is passed through these windings, the pole core gets magnetized and produces magnetic flux in the central space of the machine.

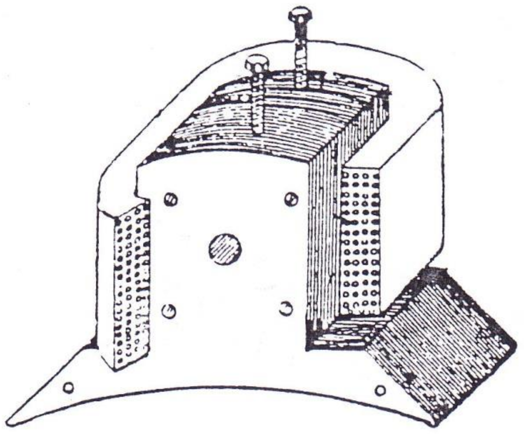


Fig.3.3 Detail of field pole

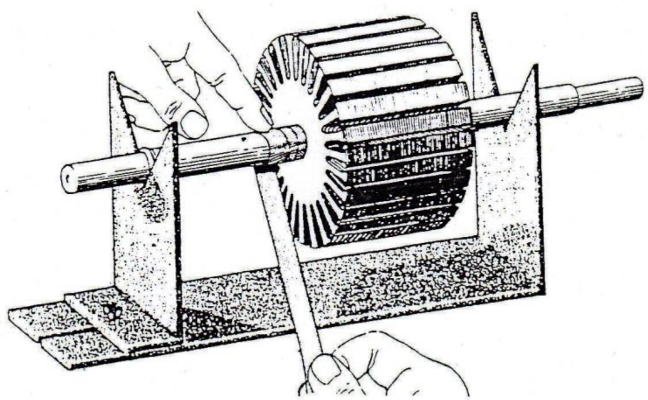


Fig.3.4 Armature core

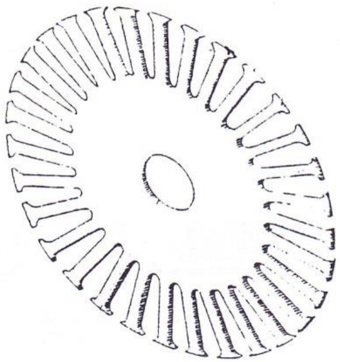


Fig.3.5 A typical lamination of armature core

Armature: It is the rotating part of the machine. The various parts of an armature are shaft, armature core, armature winding and commutator. Fig.3.4 shows an armature core with shaft. The bearings at both ends hold the shaft on the central empty space of the machine. The armature core is made of laminated silicon steel sheet insulated with varnish. A typical lamination of armature core is shown in Fig.3.5.

Commutator: It is another cylinder fitted on the shaft little away from the armature core. It is made of many numbers of copper segments (Known as commutator segments) insulated from each other and from the shaft. A cross-sectional view of a commutator is shown in Fig.3.6. The slots of the armature core are provided with armature winding with many numbers of turns. The armature windings are made of enamel insulated copper wire. The coil ends of the armature windings are connected to each segments through the riser. Fig.3.7 shows a complete armature of DC machine.

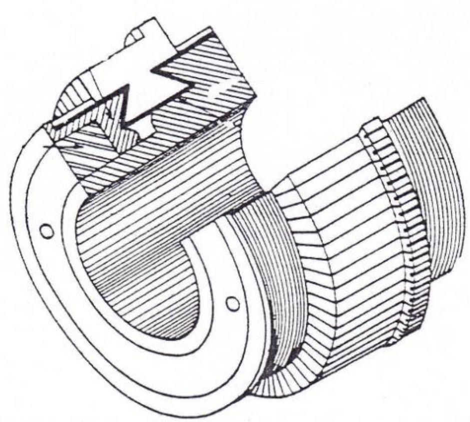


Fig.3.6 Detail of commutator

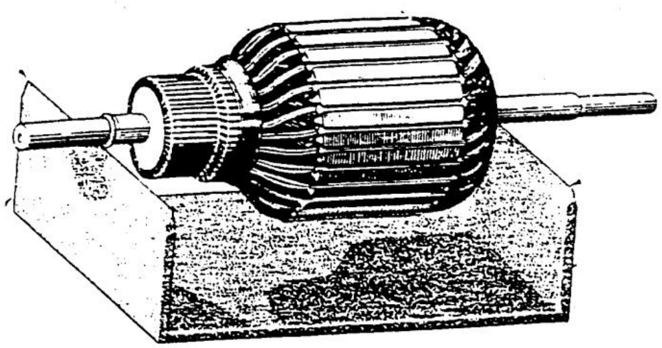
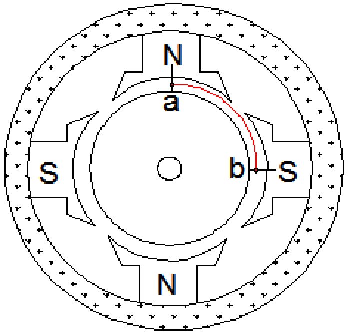


Fig.3.7 A complete armature of DC machine.

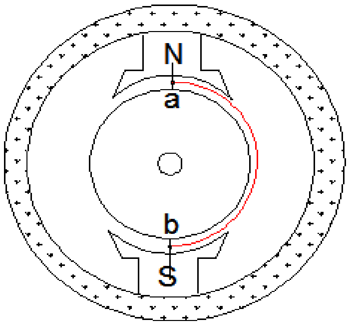
Armature Winding:

It is enamel insulated copper wire wound on the slots of the armature core. There are definite rules and methods for armature winding. Followings are some technical terms related to armature winding.

i) Pole pitch : It is defined as the peripheral distance of armature core divided by number of poles OR it the distance between adjacent poles. Fig.3.8 shows the illustration of definition of pole pitch for 4-pole machine and 2-pole machine. The arc length a-b is the pole pitch.



(a) Four pole machine



(b) Two pole machine

Fig.3.8 Illustration of pole pitch

ii) Conductor: The length of the armature winding conductor lying within the magnetic field is known as the conductor. Fig.3.9 shows a coil ABCD. The length AB and CD are known as conductor. The length BC is not considered as a conductor because emf will not induce in this part of the coil.

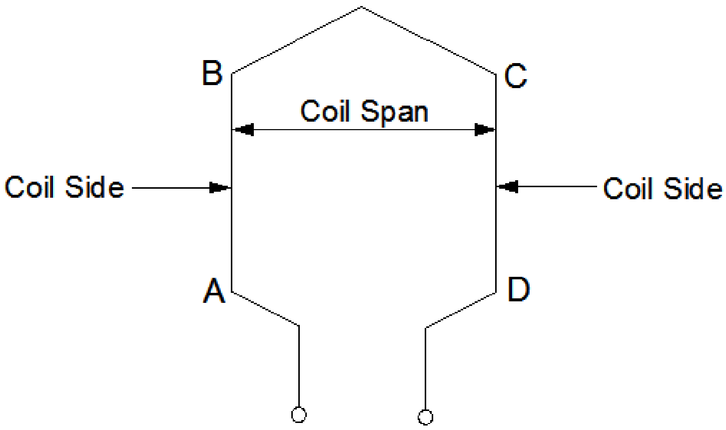


Fig.3.9 Illustration of a coil

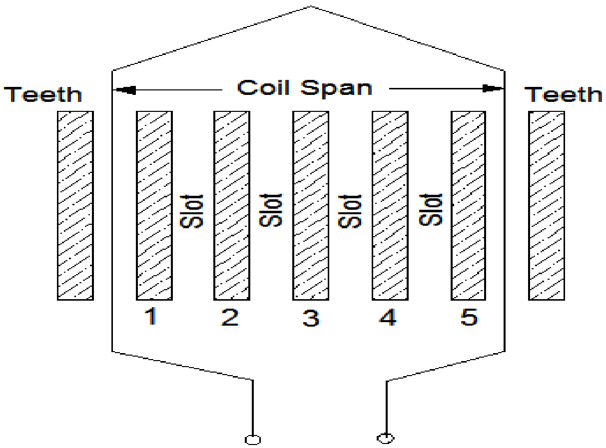


Fig.3.10 Illustration of a coil span

iii) Coil Span: It defined as the distance (in terms of number of teeth) between two sides of a coil. Coil span is 5 in the Fig.3.10.

iv) <u>Types of armature winding</u>:
- Lap winding
- Wave winding

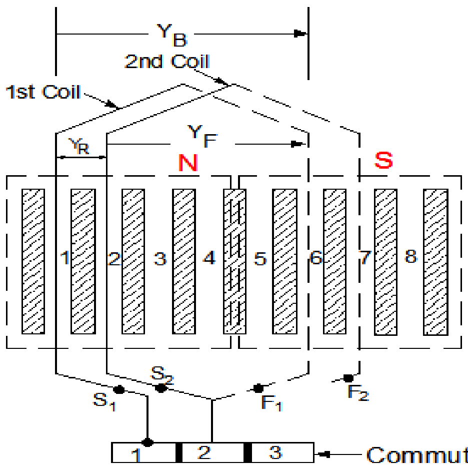


Fig.3.10(a)

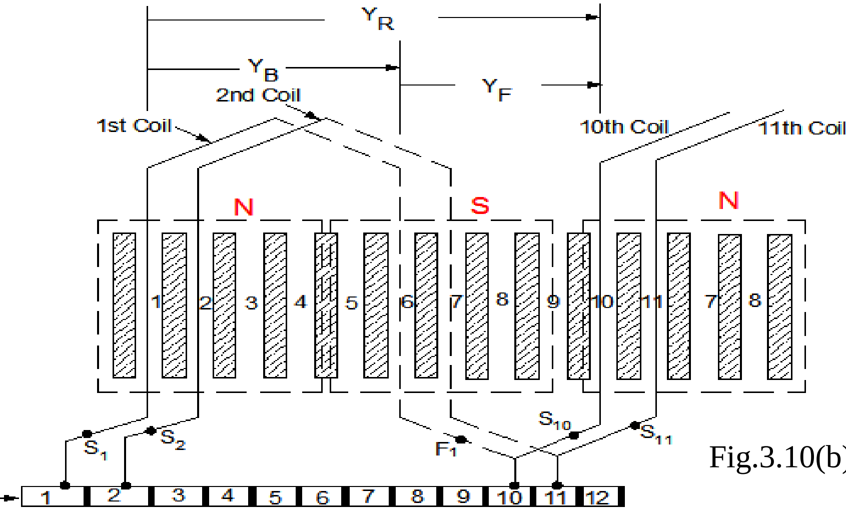


Fig.3.10(b)

Fig.3.10(a) shows an example of lap winding. Here, the finishing end of first coil (F_1) is connected to the starting end of the second coil (S_2) under the same pole as that of the starting end S_1 of the first coil. The common joint point of F_1 and S_2 is connected to the commutator segment-2.

Fig.3.10(b) shows an example of wave winding. Here, the finishing end of first coil (F_1) is connected to the starting end of the 10th coil (S_{10} in this particular example) under the similar pole, but one pole away. The common joint point of F_1 and S_{10} is connected to the commutator segment-10.

<u>Back Pitch (Y_B)</u> : It is the distance (in terms of no of armature slots) by which a coil advances on the back and it is denoted by Y_B.

<u>Front Pitch (Y_F)</u> : It is the distance (in terms of no of armature slots) by which a coil spans on the back and it is denoted by Y_Y.

<u>Resultant Pitch (Y_R)</u> : It is the distance (in terms of no of armature slots) between the starting end of a coil and starting end of the next coil to which it is connected. and it is denoted by Y_Y.

$Y_R = Y_B - Y_F$ for lap winding

$Y_R = Y_B + Y_F$ for wave winding

An Example of Lap Winding:

Number of slots = 12, Number of poles = 2, Number of commutator segments=12

$$\text{Coil Span} = \frac{\text{No of slots}}{\text{No of poles}} = \frac{12}{2} = 6$$

That means number of teeth between two sides of a coil = 6. Therefore, a coil started from slot no-1 shall come back through the slot no-7. The winding diagram is shown in Fig.3.11.

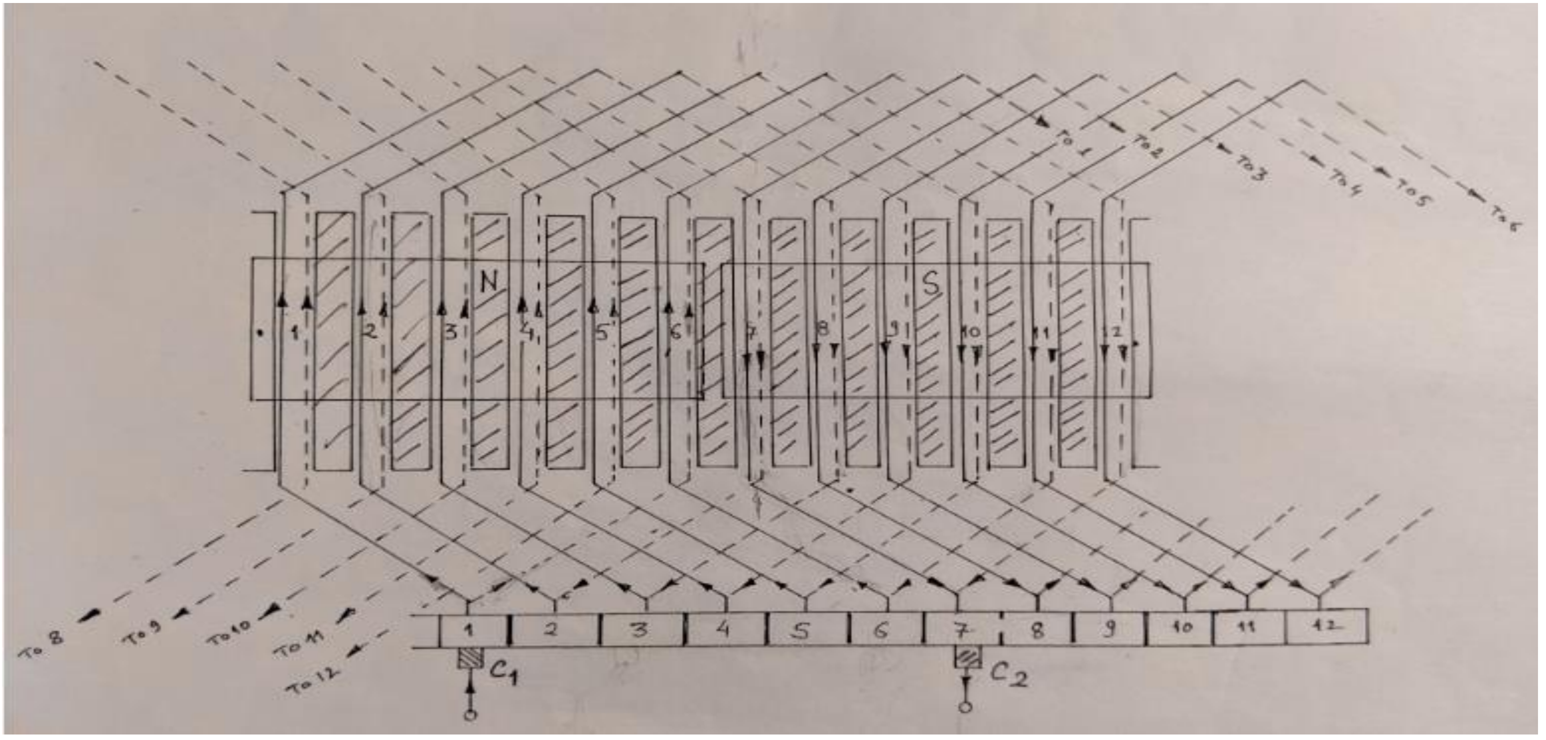


Fig.3.11 Winding diagram of Lap winding

Note that: No of parallel path in the armature winding =2

Incase of Lap winding, the number of parallel path = Number of field poles.

Incase of Wave winding, , the number of parallel path = 2 (irrespective of no of poles)

3.3 Operating principle of DC generator

The operating principle of DC generator is based on Faraday's law of electromagnetic induction. Let us consider a 2-pole elementary DC machine as shown in Fig.3.12.

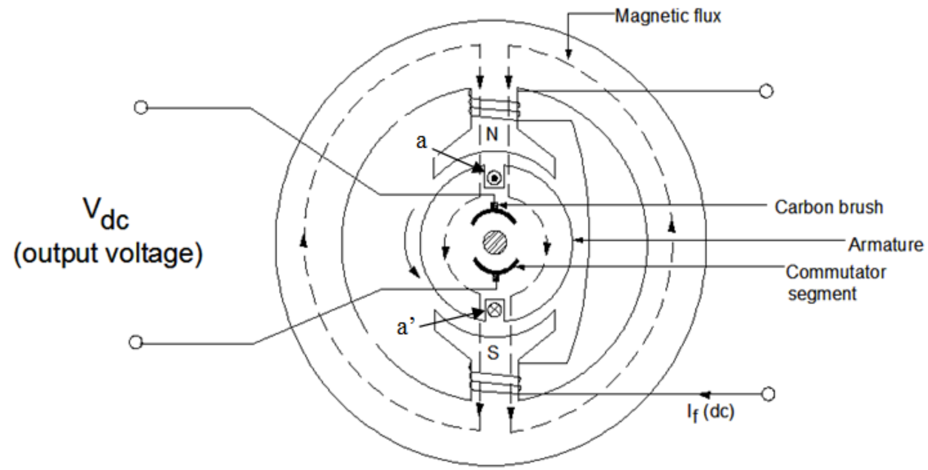


Fig.3.12 Elementary 2-pole DC machine

When the field winding is excited by DC current (I_f), the field poles get magnetized and magnetic flux flows as shown in Fig.3.8. If the armature is rotated continuously by some prime mover, then the armature conductors a and a' continuously cut the magnetic flux. Hence, according to Faraday's law of electromagnetic induction emf will induce in the armature conductors. The nature of emf induced in the armature conductors can be studied with the help of Fig.3.13

Fig.3.13(a) shows a particular position of armature coil, the direction of velocity of conductor 'a' is same as direction of magnetic flux density 'B'. That means: angle between direction of v and the direction of B is zero. The magnitude of emf induced in a conductor is given by:

$$e = B.l.v \sin\theta \qquad (3.1)$$

Where, B = Magnetic flux density in the air gap
l = Length of the conductor lying within the magnetic field.
v = Velocity of the conductor
θ = *Angle between directions of B* and v

At this particular instant shown in Fig.3.13(a), the angle $\theta = 0^0$. Therefore, emf induce is zero. Let us assume this position as reference position to compare the magnitude and direction of emf induced at various positions of the armature.

After 30^0 rotation from this reference position, the situation will be as shown in Fig.3.13(b). The magnitude of emf induced across the armature coil a-a' is given by:

$$e = 2B.l.v \sin\theta = 2B.l.v \sin 30^0 = (0.5)\, 2B.l.v = 0.5\, E_m$$

Where, $E_m = 2B.l.v$

Here, the total emf induce across the armature coil is sum of the emf induced in conductor a and conductor a'. Hence, number '2' appears in the above emf equation. The direction of emf induce in this position can be determined by Fleming's right hand rule and it is shown in Fig.3.13(b). The cross mark (×) indicates the current flowing into the plane of paper and the dot (•) indicates the current coming out from the plane of paper.

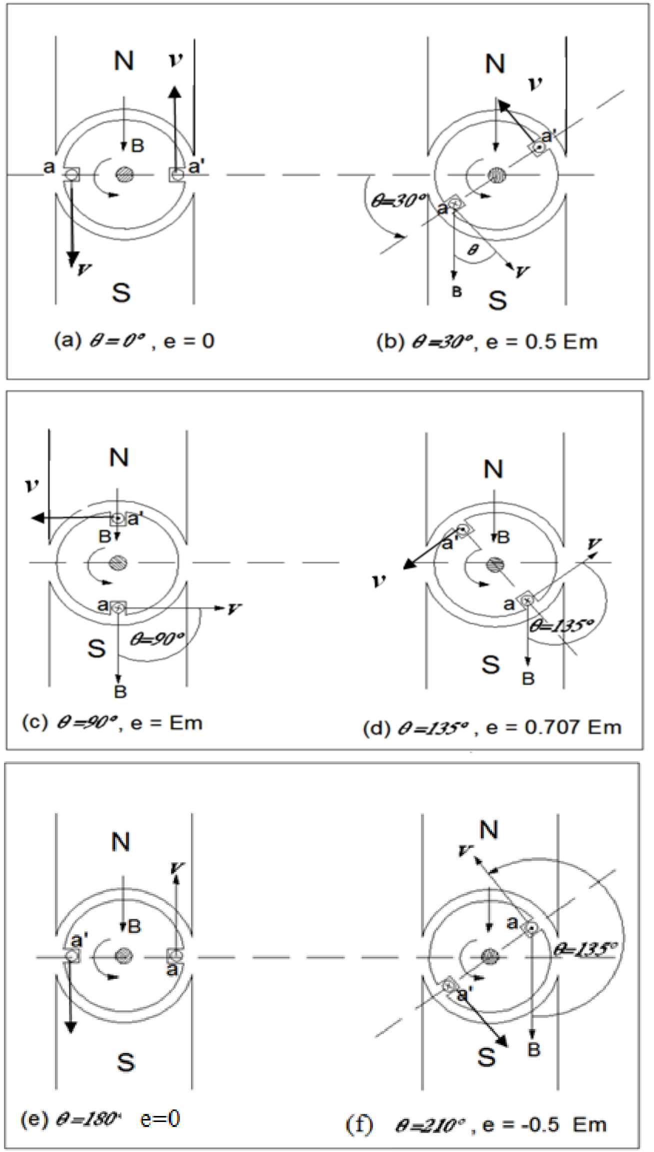
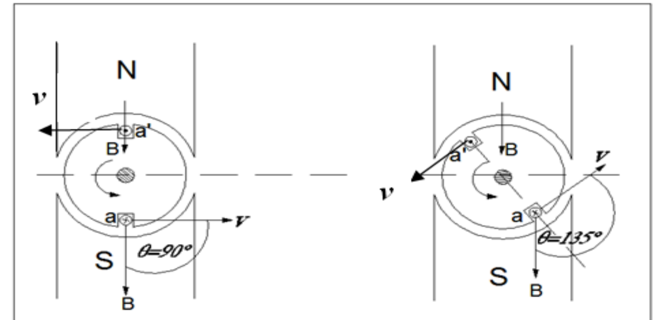


Fig.3.13 Magnitude and direction of emf at various positions of armature.

After 90^0 rotation from this reference position, the situation will be as shown in Fig.3.13(c). The magnitude of emf induced across the armature coil a-a' is given by:

$$e = 2B.l.v\ \sin\theta = 2B.l.v\ \sin 90^0 = 2B.l.v = E_m$$

The direction of induced emf is shown in Fig.3.13(c), which is same as in case of $\theta = 30^0$.

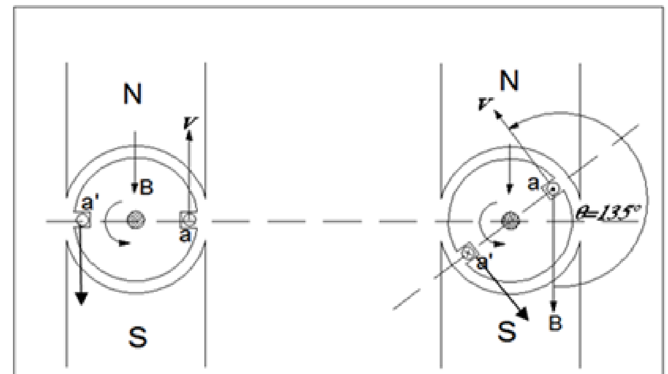


(c) $\theta=90°$, e = Em

(d) $\theta=135°$, e = 0.707 Em

Fig.3.13(d) shows the situation for $\theta = 135^0$. The magnitude of emf induced across the coil a-a' is given by:

$$e = 2B.l.v\ \sin\theta = 2B.l.v\ \sin 135^0 = 0.707E_m$$



(e) $\theta=180°$ e=0

(f) $\theta=210°$, e = -0.5 Em

Fig.3.13(e) shows the situation for $\theta = 180^0$. The magnitude of emf induced across the coil a-a' is given by:

$$e = 2B.l.v\ \sin\theta = 2B.l.v\ \sin 180^0 = 0$$

Fig.3.13(f) shows the situation for $\theta = 210^0$. The magnitude of emf induced across the coil a-a' is given by:

$$e = 2B.l.v\ \sin\theta = 2B.l.v\ \sin 210^0 = -0.5E_m$$

Here, the direction of emf induced has reversed as determined by Fleming's Right Hand Rule.
Here, it shall be noted that the direction of emf induce reverses after 180^0 rotation.

Similarly, the magnitude and direction of emf induced at various positions of armature can be evaluated and the results are tabulated in Table3.1.

Table 3.1 Magnitude and direction of emf at various positions of armature.

Position of armature (θ)	Magnitude of emf (e)	Direction of emf
0^0	0	
30^0	$0.5\ E_m$	positive
90^0	E_m	positive
135^0	$0.707\ E_m$	
180^0	0	
210^0	$-0.5\ E_m$	Negative
270^0	$-\ E_m$	Negative
360^0	0	

If these data are plotted in a graph paper, it will be a sine-wave as shown in Fig.3.14.

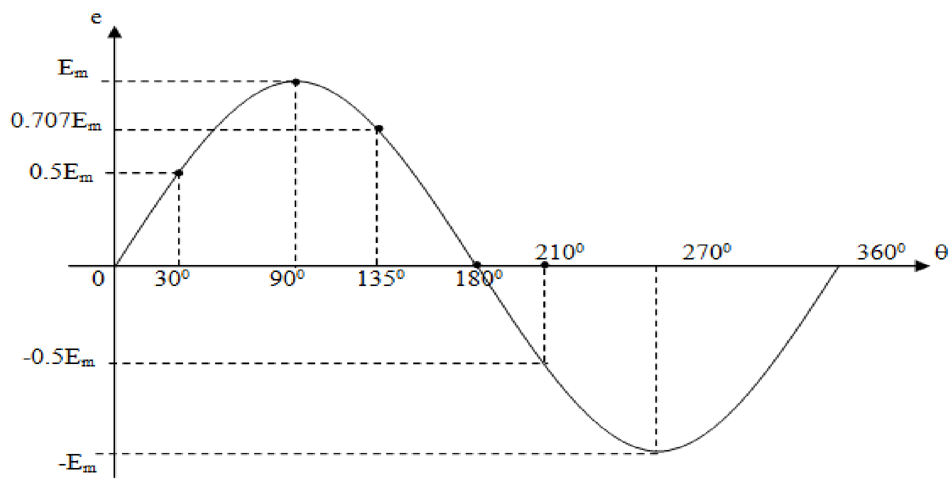


Fig.3.14 Waveform of emf induced in the armature coil.

From the above analysis, it is clear that the nature of emf induced in the armature coil is alternating in nature. However, the generator is supposed to supply DC voltage across the external load. The commutator segments and the carbon brushes helps to convert the AC voltage generated in the armature coil into the unidirectional DC voltage across the load. The commutator segments and the carbon brushes also helps to connect the stationary external load and the rotating armature coil. How the commutator segments and the carbon brushes perform these two actions can be explained with the help of Fig.3.15.

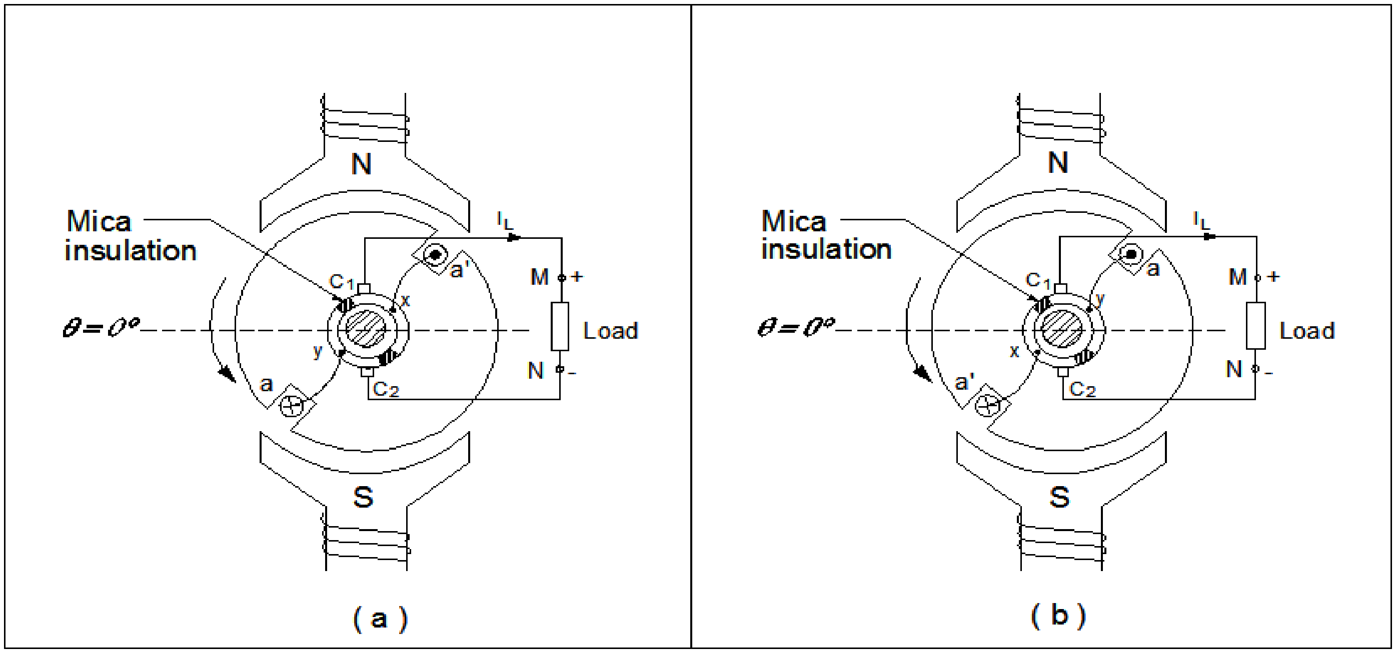


Fig.3.15 DC machine with commutator segments and carbon brushes

Fig.3.15 shows the DC generator with commutator segments and carbon brushes. The conductor-a is connected to the commutator segment-y and the conductor-a' is connected to the commutator segment-x. The commutator segments rotates along with the armature coil. Whereas, the carbon brushes C_1 and C_2 are fixed touching over the commutator segments surface.

Fig.3.15(a) shows an instant at which emf induced in the coil is positive. Here, the current comes out from the conductor-a' which is connected to the commutator segment-x and delivers current to the load through the carbon brush-C_1. The current comes back to the commutator segment-y through the carbon brush-C_2. Hence, the direction of current through the load is M to N for positive half cycle of emf in the coil.

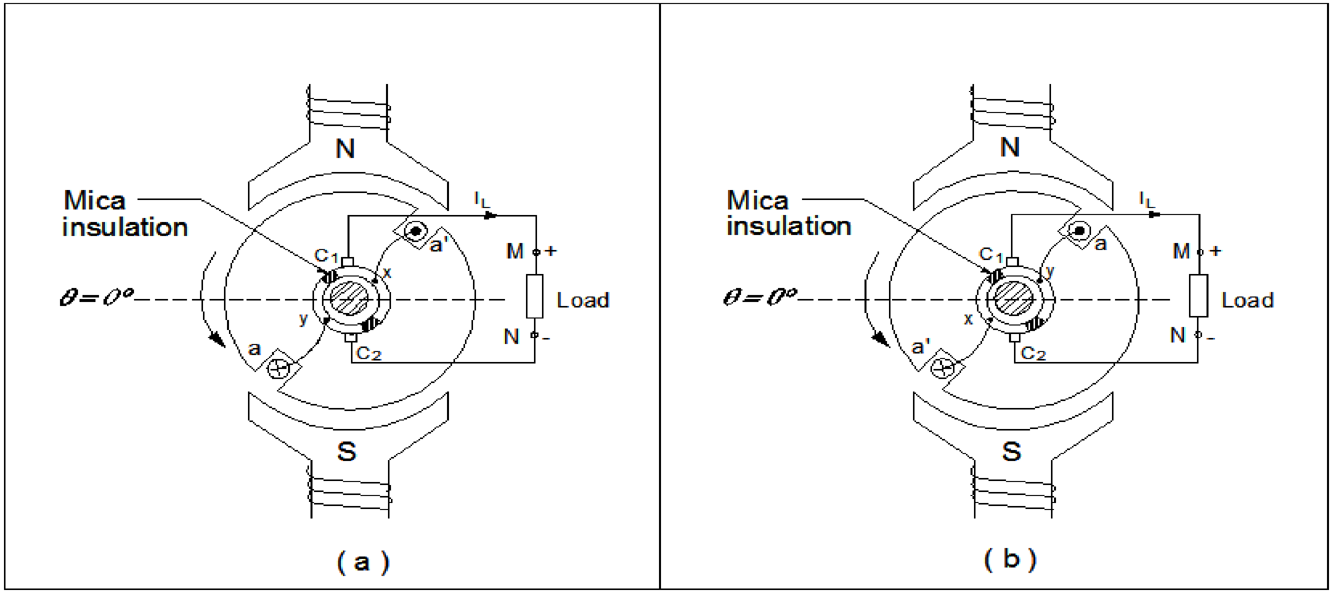


Fig.3.15(b) shows an instant at which emf induced in the coil is negative. Here, the current comes out from the conductor-a, which is connected to the commutator segment-y and delivers current to the load through the carbon brush-C_2. The current comes back to the commutator segment-x through the carbon brush-C_1. Hence, the direction of current through the load is again M to N for negative half cycle of emf in the coil. Therefore, emf across the external load in one revolution of armature will be as shown in Fig.3.16.

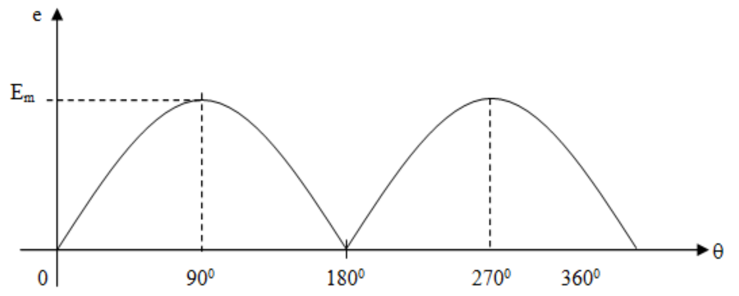


Fig.3.16 Waveform of emf across the external load

If two number of armature coils spaced 90^0 apart are used as shown in Fig.3.17(a), then two cycles of emf will be generated across the each armature coil and emf across the external load will be as shown in Fig.3.17(b) which is more smooth than that in case of DC machine with single armature coil. In fact, there will be many numbers of armature coils in a real DC generator and the nature of emf across the external load will be almost a horizontal line.

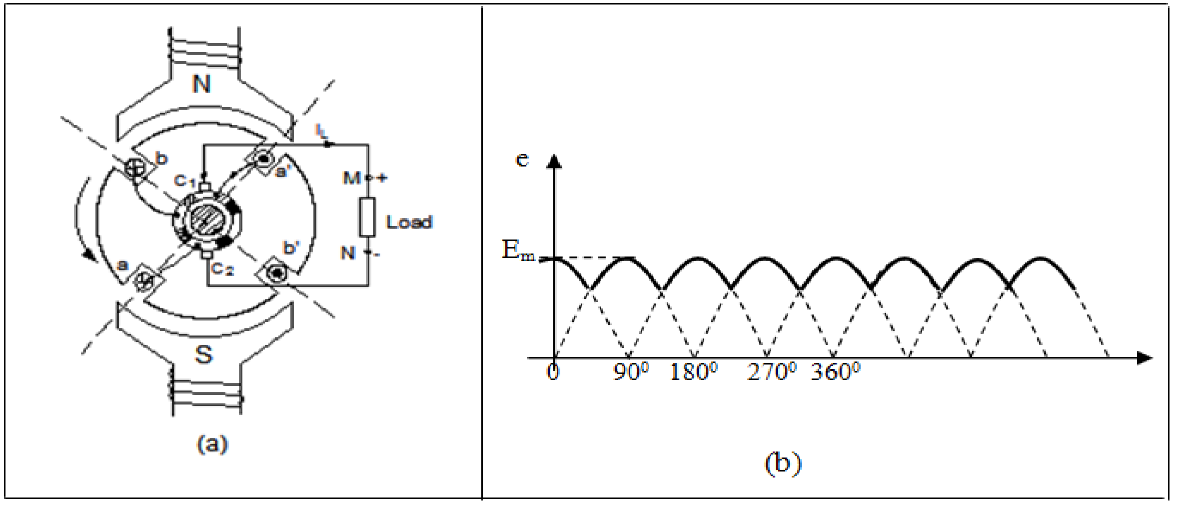
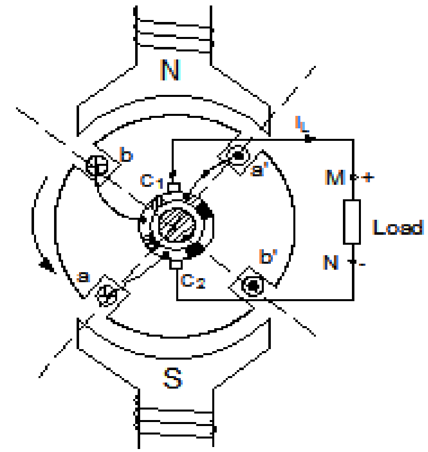


Fig.3.17 DC generator with 2 numbers of armature coils

EMF Equation:

Let ϕ = Magnetic flux per pole (Wb)
P = Number of magnetic pole
Z = Total number of armature conductor
N = Speed of the armature (RPM)



(a)

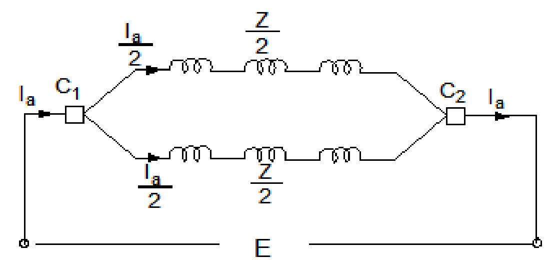
$$\text{Average value of emf induced in a conductor} = \frac{d\phi}{dt}$$

Magnetic flux cut by each conductor in one revolution $d\phi = P.\phi$

$$\text{Time for one revolution} = dt = \frac{60}{N}\ \text{Sec}$$

$$\therefore \text{Average value of emf induced in a conductor} = \frac{d\phi}{dt} = \frac{P.\phi.N}{60}\ \text{Volt}$$

Let A = number of parallel paths in the armature winding.



$$\text{Therefore, Total emf across the carbon brushes} = E = \frac{P.\phi.N}{60} \times \frac{Z}{A}$$

$$\text{OR} \quad E = \frac{Z\phi.N}{60} \times \frac{P}{A}\ \text{(Volts)} \qquad (3.2)$$