2 Principles of d.c. machines

D.C. machines are the electro mechanical energy converters which work from a d.c. source and generate mechanical power or convert mechanical power into a d.c. power. These machines can be broadly classified into two types, on the basis of their magnetic structure. They are,

1. Homopolar machines
2. Heteropolar machines.

These are discussed in sequence below.

2.1 Homopolar machines

Homopolar generators

Even though the magnetic poles occur in pairs, in a homopolar generator the conductors are arranged in such a manner that they always move under one polarity. Either north pole or south pole could be used for this purpose. Since the conductor encounters the magnetic flux of the same polarity every where it is called a homopolar generator. A cylindrically symmetric geometry is chosen. The conductor can be situated on the surface of the rotor with one slip-ring at each end of the conductor. A simple structure where there is only one cylindrical conductor with ring brushes situated at the ends is shown in Fig. 4. The excitation coil produces a field which enters the inner member from outside all along the periphery. The conductor thus sees only one pole polarity or the flux directed in one sense. A steady voltage now appears across the brushes at any given speed of rotation. The polarity of the induced voltage can be reversed by reversing either the excitation or the direction of

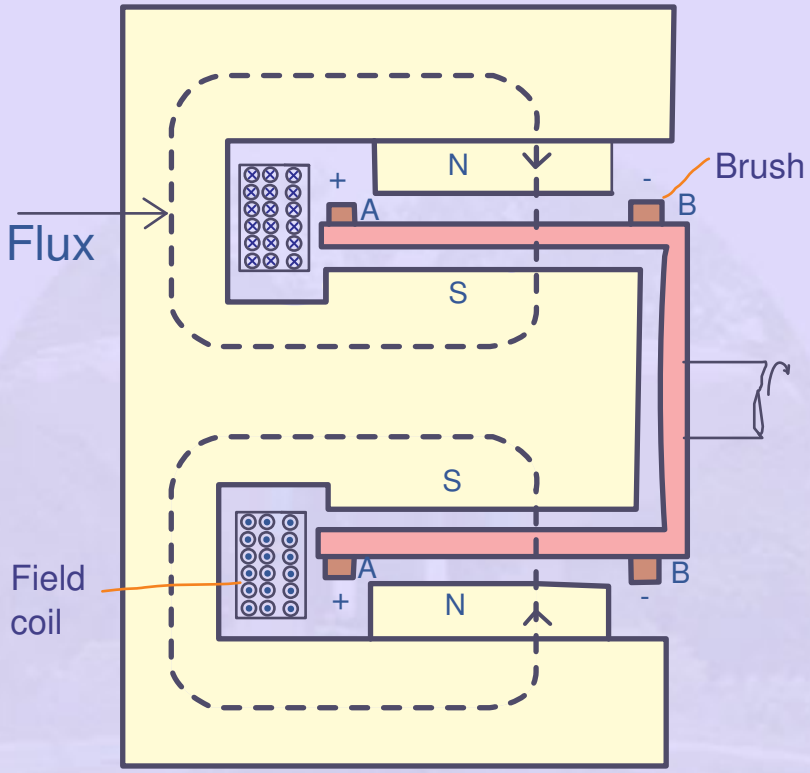


Figure 4: Homopolar Generator

rotation but not both. The voltage induced would be very low but the currents of very large amplitudes can be supplied by such machines. Such sources are used in some applications like pulse-current and MHD generators, liquid metal pumps or plasma rockets. The steady field can also be produced using a permanent magnet of ring shape which is radially magnetized. If higher voltages are required one is forced to connect many conductors in series. This series connection has to be done externally. Many conductors must be situated on the rotating structure each connected to a pair of slip rings. However, this modification introduces parasitic air-gaps and makes the mechanical structure very complex. The magnitude of the induced emf in a conductor 10 cm long kept on a rotor of 10 cm radius rotating at 3000 rpm, with the field flux density being 1 Tesla every where in the air gap, is given by

$$\begin{aligned} e &= BLv \\ &= 1 * 0.1 * 2\pi * 0.1 * \frac{3000}{60} = 3.14 \quad \text{volt} \end{aligned}$$

The voltage drops at the brushes become very significant at this level bringing down the efficiency of power conversion. Even though homopolar machines are d.c. generators in a strict sense that they 'generate' steady voltages, they are not quite useful for day to day use. A more practical converters can be found in the d.c. machine family called "hetero-polar" machines.

2.2 Hetero-polar d.c. generators

In the case of a hetero-polar generator the induced emf in a conductor goes through a cyclic change in voltage as it passes under north and south pole polarity alternately. The induced emf in the conductor therefore is not a constant but alternates in magnitude. For

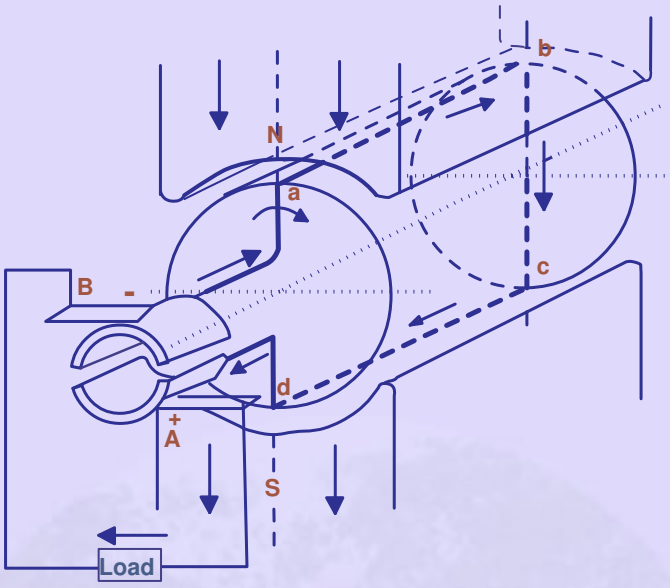


Figure 5: Elementary hetro-polar machine

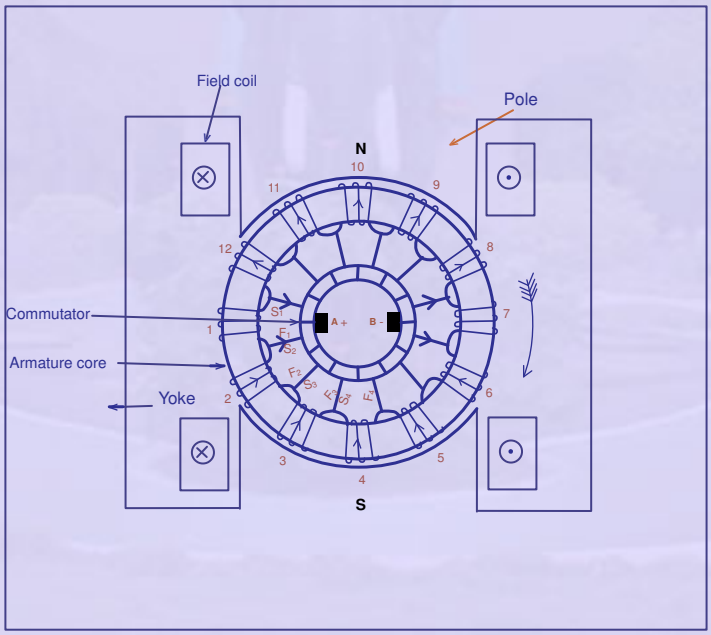


Figure 6: Two pole machine -With Gramme ring type armature

a constant velocity of sweep the induced emf is directly proportional to the flux density under which it is moving. If the flux density variation is sinusoidal in space, then a sine wave voltage is generated. This principle is used in the a.c generators. In the case of d.c. generators our aim is to get a steady d.c. voltage at the terminals of the winding and not the shape of the emf in the conductors. This is achieved by employing an external element, which is called a commutator, with the winding.

Fig. 5 shows an elementary hetero-polar, 2-pole machine and one-coil armature. The ends of the coil are connected to a split ring which acts like a commutator. As the polarity of the induced voltages changes the connection to the brush also gets switched so that the voltage seen at the brushes has a unidirectional polarity. This idea is further developed in the modern day machines with the use of commutators. The brushes are placed on the commutator. Connection to the winding is made through the commutator only. The idea of a commutator is an ingenious one. Even though the instantaneous value of the induced emf in each conductor varies as a function of the flux density under which it is moving, the value of this emf is a constant at any given position of the conductor as the field is stationary. Similarly the sum of a set of coils also remains a constant. This thought is the one which gave birth to the commutator. The coils connected between the two brushes must be "similarly located" with respect to the poles irrespective of the actual position of the rotor. This can be termed as the condition of symmetry. If a winding satisfies this condition then it is suitable for use as an armature winding of a d.c. machine. The ring winding due to Gramme is one such. It is easy to follow the action of the d.c. machine using a ring winding, hence it is taken up here for explanation.

Fig. 6 shows a 2-pole, 12 coil, ring wound armature of a machine. The 12 coils are placed at uniform spacing around the rotor. The junction of each coil with its neighbor is connected to a commutator segment. Each commutator segment is insulated from its neighbor by a mica separator. Two brushes A and B are placed on the commutator which looks like a cylinder. If one traces the connection from brush A to brush B one finds that there are two paths. In each path a set of voltages get added up. The sum of the emfs is constant(nearly). The constancy of this magnitude is altered by a small value corresponding to the coil short circuited by the brush. As we wish to have a maximum value for the output voltage, the choice of position for the brushes would be at the neutral axis of the field. If the armature is turned by a distance of one slot pitch the sum of emfs is seen to be constant even though a different set of coils participate in the addition. The coil which gets short circuited has nearly zero voltage induced in the same and hence the sum does not change substantially. This variation in the output voltage is called the 'ripple'. More the number of coils participating in the sum lesser would be the 'percentage' ripple.

Another important observation from the working principle of a heterogeneous generator is that the actual shape of the flux density curve does not matter as long as the integral of the flux entering the rotor is held constant; which means that for a given flux per pole the voltage will be constant even if the shape of this flux density curve changes (speed and other conditions remaining unaltered). This is one reason why an average flux density over the entire pole pitch is taken and flux density curve is assumed to be rectangular.

A rectangular flux density wave form has some advantages in the derivation of the voltage between the brushes. Due to this form of the flux density curve, the induced

emf in each turn of the armature becomes constant and equal to each other. With this back ground the emf induced between the brushes can be derived. The value of the induced in one conductor is given by

$$E_c = B_{av}.L.v \quad \text{Volt} \tag{7}$$

where

B_{av}- Average flux density over a pole pitch, Tesla.

L- Length of the 'active' conductor, m.

v- Velocity of sweep of conductor, $m/sec.$

If there are Z conductors on the armature and they form b pairs of parallel circuits between the brushes by virtue of their connections, then number of conductors in a series path is $Z/2b$.

The induced emf between the brushes is

$$E = E_c.\frac{Z}{2b} \tag{8}$$

$$E = B_{av}.L.v.\frac{Z}{2b} \quad \text{Volts} \tag{9}$$

But $v = (2p).Y.n$ where p is the pairs of poles Y is the pole pitch, in meters, and n is the number of revolutions made by the armature per second.

Also B_{av} can be written in terms of pole pitch Y, core length L, and flux per pole ϕ as

$$B_{av} = \frac{\phi}{(L.Y)} \quad \text{Tesla} \tag{10}$$

Substituting in equation Eqn. 9,

$$E = \frac{\phi}{(L.Y)}.L.(2p.Y.n).\frac{Z}{2b} = \frac{\phi pZn}{b} \quad \text{volts} \tag{11}$$

The number of pairs of parallel paths is a function of the type of the winding chosen. This

will be discussed later under the section on the armature windings.

2.2.1 Torque production

When the armature is loaded, the armature conductors carry currents. These current carrying conductors interact with the field and experience force acting on the same. This force is in such a direction as to oppose their cause which in the present case is the relative movement between the conductors and the field. Thus the force directly opposes the motion. Hence it absorbs mechanical energy. This absorbed mechanical power manifests itself as the converted electrical power. The electrical power generated by an armature delivering a current of I_a to the load at an induced emf of E is EI_a Watts. Equating the mechanical and electrical power we have

$$2\pi nT = EI_a \tag{12}$$

where T is the torque in Nm. Substituting for E from Eqn. 11, we get

$$2\pi nT = \frac{p.\phi.Z.n}{b}.I_a \tag{13}$$

which gives torque T as

$$T = \frac{1}{2\pi}.p.\phi.(\frac{I_a}{b})Z \ \text{ Nm} \tag{14}$$

This shows that the torque generated is not a function of the speed. Also, it is proportional to 'total flux' and 'Total ampere conductors' on the armature, knowing that $I_a/2b$ is I_c the conductor current on the armature. The expression for the torque generated can also be derived from the first principles by the application of the law of interaction. The law of interaction states that the force experienced by a conductor of length L kept in a

uniform field of flux density B carrying a current I_c is proportional to B,L and I_c.

Force on a single conductor F_c is given by,

$$F_c = B.L.I_c \quad \text{Newton} \tag{15}$$

The total work done by an armature with Z conductors in one revolution is given by,

$$W_a = B_{av}.L.I_c.Z.(2p.Y) \quad \text{Joules} \quad = \frac{\phi}{L.Y}.L.I_c.Z.2p.Y \quad \text{Joules} \tag{16}$$

The work done per second or the power converted by the armature is,

$$P_{conv} = \phi.2p.Z.I_c.n \quad \text{watts} \tag{17}$$

$$AsI_c = \frac{I_a}{2b} \tag{18}$$

$$= \phi.p.Z.n.\frac{I_a}{b} \tag{19}$$

which is nothing but EI_a.

The above principles can easily be extended to the case of motoring mode of operation also. This will be discussed next in the section on motoring operation of d.c. machines.

2.2.2 Motoring operation of a d.c. machine

In the motoring operation the d.c. machine is made to work from a d.c. source and absorb electrical power. This power is converted into the mechanical form. This is briefly discussed here. If the armature of the d.c. machine which is at rest is connected to a d.c. source then, a current flows into the armature conductors. If the field is already excited then

these current carrying conductors experience a force as per the law of interaction discussed above and the armature experiences a torque. If the restraining torque could be neglected the armature starts rotating in the direction of the force. The conductors now move under the field and cut the magnetic flux and hence an induced emf appears in them. The polarity of the induced emf is such as to oppose the cause of the current which in the present case is the applied voltage. Thus a 'back emf' appears and tries to reduce the current. As the induced emf and the current act in opposing sense the machine acts like a sink to the electrical power which the source supplies. This absorbed electrical power gets converted into mechanical form. Thus the same electrical machine works as a generator of electrical power or the absorber of electrical power depending upon the operating condition. The absorbed power gets converted into electrical or mechanical power. This is briefly explained earlier with the help of Figure 3(a) and 3(b). These aspects would be discussed in detail at a later stage.