D.C Machines

1 Introduction

The steam age signalled the beginning of an industrial revolution. The advantages of machines and gadgets in helping mass production and in improving the services spurred the industrial research. Thus a search for new sources of energy and novel gadgets received great attention. By the end of the 18th century the research on electric charges received a great boost with the invention of storage batteries. This enabled the research work on moving charges or currents. It was soon discovered (in 1820) that, these electric currents are also associated with magnetic field like a load stone. This led to the invention of an electromagnet. Hardly a year later the force exerted on a current carrying conductor placed in the magnetic field was invented. This can be termed as the birth of a motor. A better understanding of the inter relationship between electric and magnetic circuits was obtained with the enumeration of laws of induction by Faraday in 1831. Parallel research was contemporarily being done to invent a source of energy to recharge the batteries in the form of a d.c. source of constant amplitude (or d.c. generator). For about three decades the research on d.c. motors and d.c. generators proceeded on independent paths. During the second half of the 19th century these two paths merged. The invention of a commutator paved the way for the birth of d.c. generators and motors. These inventions generated great interest in the generation and use of electrical energy. Other useful machines like alternators, transformers and induction motors came into existence almost contemporarily. The evolution of these machines was very quick. They rapidly attained the physical configurations that are being used even today. The d.c. power system was poised for a predominant place as a preferred system for use, with the availability of batteries for storage, d.c. generators for conversion of mechanical energy into electrical form and d.c. motors for getting mechanical outputs from electrical energy.

The limitations of the d.c. system however became more and more apparent as the power demand increased. In the case of d.c. systems the generating stations and the load centers have to be near to each other for efficient transmission of energy. The invention of induction machines in the 1880s tilted the scale in favor of a.c. systems mainly due to the advantage offered by transformers, which could step up or step down the a.c.voltage levels at constant power at extremely high efficiency. Thus a.c. system took over as the preferred system for the generation transmission and utilization of electrical energy. The d.c. system, however could not be obliterated due to the able support of batteries. Further, d.c. motors have excellent control characteristics. Even today the d.c. motor remains an industry standard as far as the control aspects are concerned. In the lower power levels and also in regenerative systems the d.c. machines still have a major say.

In spite of the apparent diversity in the characteristics, the underlying principles of both a.c. and d.c. machines are the same. They use the electromagnetic principles which can be further simplified at the low frequency levels at which these machines are used. These basic principles are discussed at first.

1.1 Basic principles

Electric machines can be broadly classified into electrostatic machines and electromagnetic machines. The electrostatic principles do not yield practical machines for commercial electric power generation. The present day machines are based on the electro-magnetic principles. Though one sees a variety of electrical machines in the market, the basic underlying principles of all these are the same. To understand, design and use these machines the following laws must be studied.

1. Electric circuit laws - $Kirchoff's\ \ Laws$
2. Magnetic circuit law - $Ampere's\ \ Law$
3. Law of electromagnetic induction - $Faraday's\ \ Law$
4. Law of electromagnetic interaction -$BiotSavart's\ \ Law$

Most of the present day machines have one or two electric circuits linking a common magnetic circuit. In subsequent discussions the knowledge of electric and magnetic circuit laws is assumed. The attention is focused on the Faraday's law and Biot Savart's law in the present study of the electrical machines.

1.1.1 Law of electro magnetic induction

Faraday proposed this law of Induction in 1831. It states that if the magnetic flux lines linking a closed electric coil changes, then an emf is induced in the coil. This emf is proportional to the rate of change of these flux linkages. This can be expressed mathematically,

$$e \propto \frac{d\psi}{dt} \tag{1}$$

where ψ is the flux linkages given by the product of flux lines in weber that are linked and N the number of turns of the coil. This can be expressed as,

$$e \propto N\frac{d\Phi}{dt} \tag{2}$$

Here N is the number of turns of the coil, and Φ is the flux lines in weber linking all these turns. The direction of the induced emf can be determined by the application of Lenz's law. Lenz's law states that the direction of the induced emf is such as to produce an effect to oppose this change in flux linkages. It is analogous to the inertia in the mechanical systems.

The changes in the flux linkages associated with a turn can be brought about by

(i) changing the magnitude of the flux linking a static coil

(ii) moving the turn outside the region of a steady field

(iii) moving the turn and changing the flux simultaneously

These may be termed as Case(i), Case(ii), and Case(iii) respectively.

This is now explained with the help of a simple geometry. Fig. 1 shows a rectangular loop of one turn (or N=1). Conductor 1 is placed over a region with a uniform flux density of B Tesla. The flux lines, the conductor and the motion are in mutually perpendicular directions. The flux linkages of the loop is BLN weber turns. If the flux is unchanging and conductor stationary, no emf will be seen at the terminals of the loop. If now the flux alone changes with time such that $B = B_m.\cos\omega t$, as in Case(i), an emf given by

$$\begin{aligned} e = \frac{d}{dt}(B_m.L.N\cos\omega t) = -(B_m.L.N\omega).\sin\omega t. \\ = -jB_m.L.N\omega.\cos\omega t \quad \text{volt} \end{aligned} \tag{3}$$

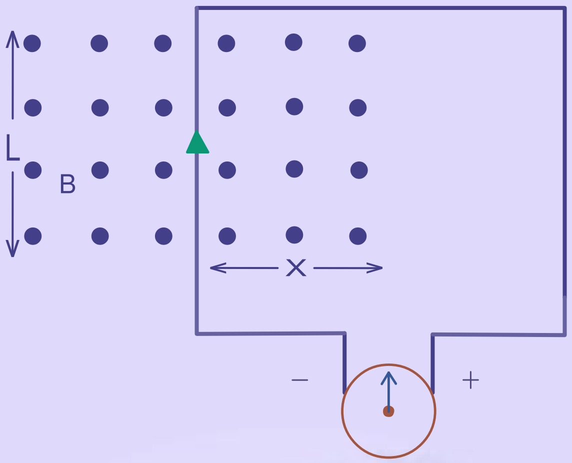

Figure 1: Faraday's law of Induction

appears across the terminals. This is termed as a "transformer" emf.

If flux remains constant at B_m but the conductor moves with a velocity v, as in Case(ii), then the induced emf is

$$e = \frac{d\psi}{dt} = \frac{d(B_m.L.N)}{dt} = B_m.L.N\frac{dX}{dt} \quad \text{volts} \tag{4}$$

but

$$\frac{dX}{dt} = v \quad \therefore e = B_m.L.N.v \quad \text{volts} \tag{5}$$

The emf induced in the loop is directly proportional to the uniform flux density under which it is moving with a velocity v. This type of voltage is called speed emf (or rotational emf). The Case(iii) refers to the situation where B is changing with time and so also is X. Then the change in flux linkage and hence the value of e is given by

$$e = \frac{d\psi}{dt} = \frac{d(B_m.L.X.N.\cos\omega t)}{dt} = B_m.\cos\omega t.L.N.\frac{dX}{dt} - B_m.L.X.N.\omega.\sin\omega t. \tag{6}$$

In this case both transformer emf and speed emf are present.

The Case(i) has no mechanical energy associated with it. This is the principle used in transformers. One coil carrying time varying current produces the time varying field and a second coil kept in the vicinity of the same has an emf induced in it. The induced emf of this variety is often termed as the transformer emf.

The Case(ii) is the one which is employed in d.c. machines and alternators. A static magnetic field is produced by a permanent magnet or by a coil carrying a d.c. current. A coil is moved under this field to produce the change in the flux linkages and induce an emf in the same. In order to produce the emf on a continuous manner a cylindrical geometry is chosen for the machines. The direction of the field, the direction of the conductor of the coil and the direction of movement are mutually perpendicular as mentioned above in the example taken.

In the example shown above, only one conductor is taken and the flux 'cut' by the same in the normal direction is used for the computation of the emf. The second conductor of the turn may be assumed to be far away or unmoving. This greatly simplifies the computation of the induced voltage as the determination of flux linkages and finding its rate of change are dispensed with. For a conductor moving at a constant velocity v the induced emf becomes just proportional to the uniform flux density of the magnetic field where the conductor is situated. If the conductor, field and motion are not normal to each other then the mutually normal components are to be taken for the computation of the voltage. The induced emf of this type is usually referred to as a rotational emf (due to the geometry).

Application of Faradays law according to Case(iii) above for electro mechanical energy conversion results in the generation of both transformer and rotational emf to be present in the coil moving under a changing field. This principle is utilized in the induction machines and a.c. commutator machines. The direction of the induced emf is decided next. This can be obtained by the application of the Lenz's law and the law of interaction. This is illustrated in Fig. 3.

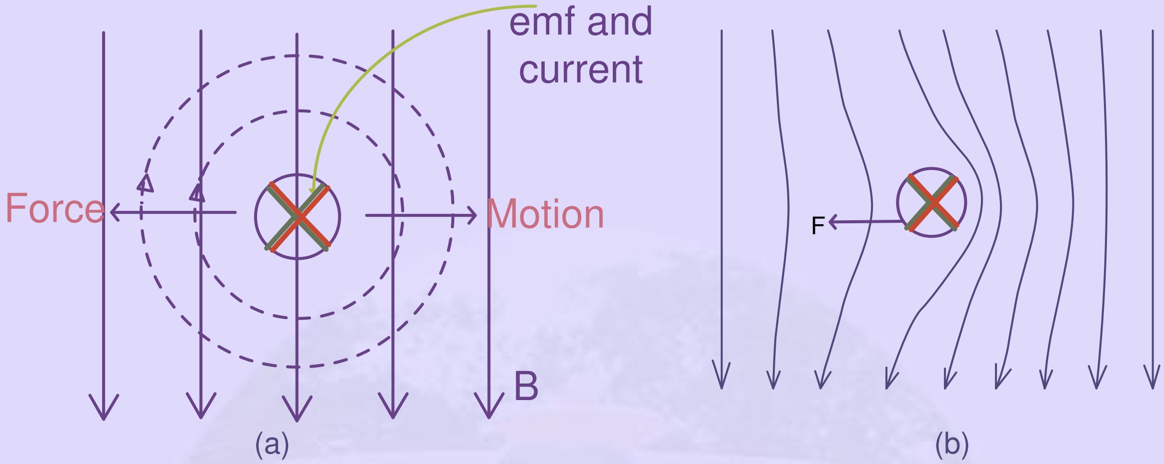

Figure 2: Law of induction-Generator action

In Case(i), the induced emf will be in such a direction as to cause a opposing mmf if the circuit is closed. Thus, it opposes the cause of the emf which is change in ψ and hence ϕ. Also the coil experiences a compressive force when the flux tries to increase and a tensile force when the flux decays. If the coil is rigid, these forces are absorbed by the supporting structure.

In Case(ii), the direction of the induced emf is as shown. Here again one could derive the same from the application of the Lenz's law. The changes in the flux linkages is