

INTRODUCTION TO ELECTRICAL DC MACHINES

Learning Objectives

- Identify the parts of a DC machine and state the function of each part.
- Explain the principle of operation of a DC generator and a DC motor.
- Describe the various methods of speed control of a DC motor.
- Derive the EMF equation and the torque equation of a DC machine.

Introduction

A Direct Current (DC) machine is an electromechanical energy conversion device. When it converts mechanical energy into electrical energy, it is called a DC Generator; when it converts electrical energy into mechanical energy, it is called a DC Motor. Interestingly, the same physical machine can be made to work either as a generator or as a motor — the direction of energy flow alone decides its role. Because of this, a study of the construction, principle of operation, speed control and the governing equations of DC machines is fundamental to the study of electrical engineering. This chapter presents these topics in a systematic manner, beginning with the physical construction and proceeding to the underlying electromagnetic principles and mathematical relationships.

Construction of a DC Machine

Every DC machine, whether it is to function as a generator or as a motor, is built with the same basic mechanical structure. It consists of a stationary part called the stator and a rotating part called the armature or rotor. The stator produces the magnetic field required for the operation of the machine, while the armature is the part in which the electromechanical energy conversion actually takes place. The principal parts of a DC machine are the yoke, the poles, the field winding, the armature core, the armature winding, the commutator, the brushes, and the shaft with its bearings. Each of these is discussed below.

Yoke

The yoke is the outermost covering of the DC machine. It is usually made of cast iron in small machines and of cast steel or rolled steel in larger machines, since these materials offer greater mechanical strength and better magnetic permeability. The yoke serves two purposes: it provides

mechanical protection to the inner parts of the machine, and it forms a part of the magnetic circuit, providing a low-reluctance path for the magnetic flux produced by the poles.

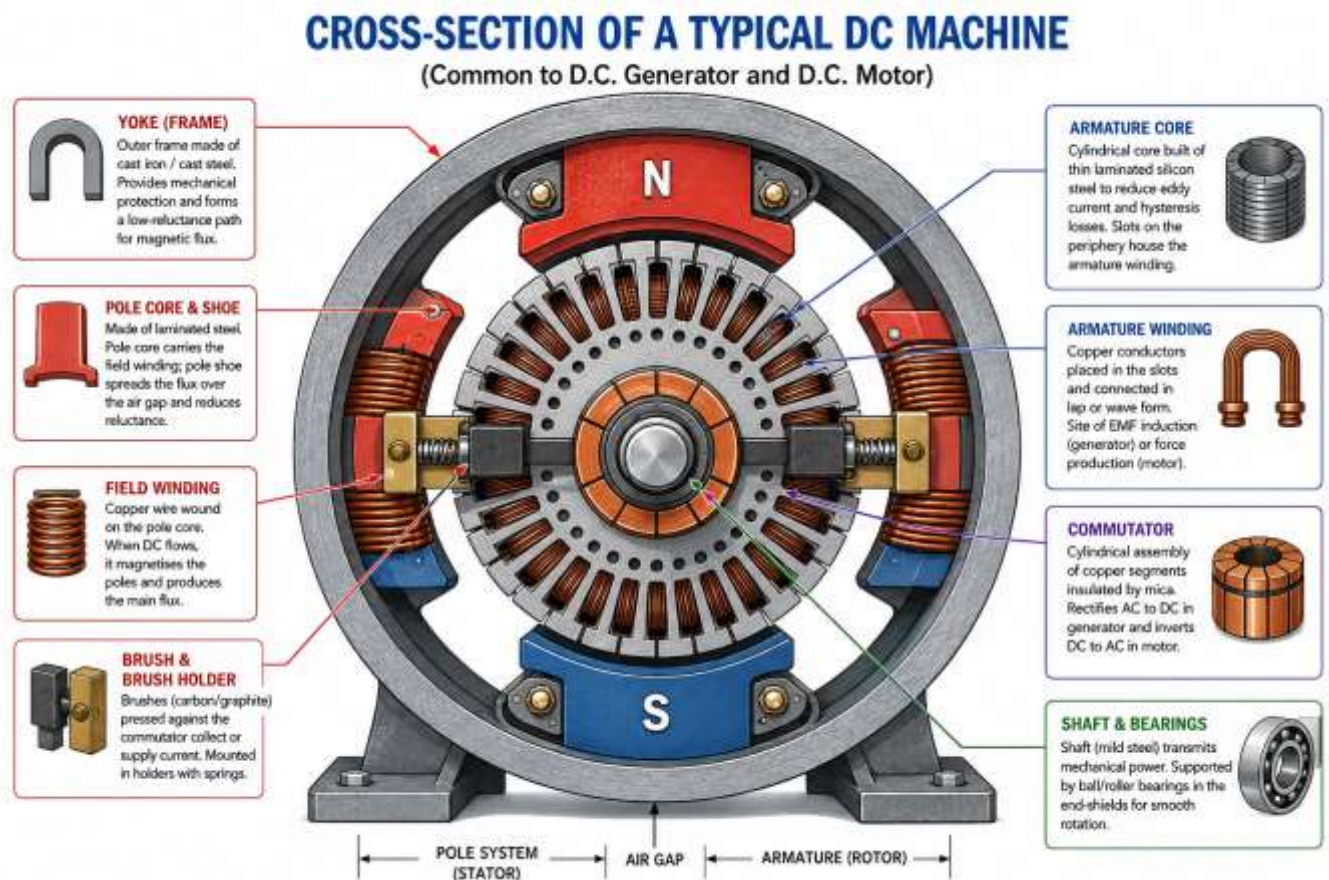
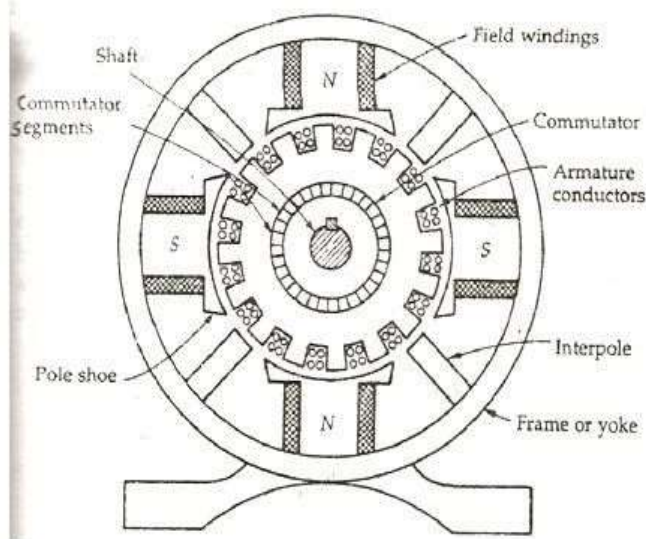
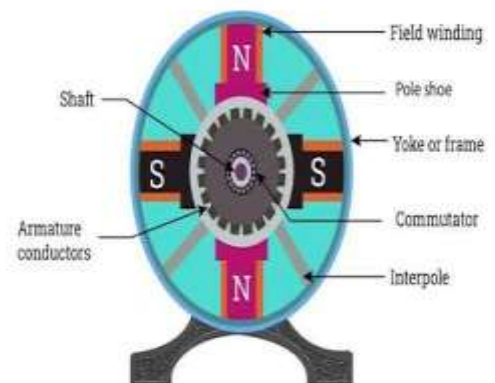


Fig. 3.1: Cross-section of a typical DC machine

DC GENERATOR



DC Motor Construction Parts



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Poles

The magnetic poles are fixed to the inside of the yoke by bolts. Each pole is made up of two parts — the pole core and the pole shoe. The pole core is the part around which the field winding is wound, while the pole shoe is the broader part at the end of the pole core; it spreads the flux over the air gap and reduces the reluctance of the magnetic path. Poles are usually built up of thin laminations of steel, insulated from one another, so as to reduce eddy current losses.

Field Winding

The field winding consists of copper wire wound around the pole cores. When direct current flows through this winding, it magnetises the poles and produces the main magnetic flux of the machine. The winding is arranged so that consecutive poles have alternate north and south polarities. The pole core together with its field winding forms an electromagnet, and this magnetic field is essential for the working of the machine, whether as a generator or as a motor.

Armature Core

The armature core is a cylindrical drum keyed to the shaft, built up of thin laminations of silicon steel, generally 0.4 mm to 0.6 mm thick, insulated from one another by a thin coat of varnish. Lamination is done to reduce the eddy current loss, and silicon steel is chosen to reduce the hysteresis loss. Slots are provided on the outer periphery of the core to house the armature winding.

Armature Winding

The armature winding consists of copper conductors housed in the armature slots, connected together in a systematic manner. Two types of armature windings are commonly employed: the lap winding, in which the number of parallel paths is equal to the number of poles ($A = P$), suitable for low-voltage, high-current machines; and the wave winding, in which there are only two parallel paths ($A = 2$), irrespective of the number of poles, suitable for high-voltage, low-current machines. In a generator, EMF is induced in this winding by electromagnetic induction; in a motor, this winding carries current and experiences a mechanical force.

Commutator

The commutator is a cylindrical device made up of a number of wedge-shaped copper segments, insulated from each other and from the shaft by means of mica. Each segment is connected to the armature conductors in a definite sequence. In a generator, the commutator converts the alternating EMF induced in the armature conductors into a unidirectional (DC) EMF at the brushes. In a motor, it performs the reverse function — it converts the direct current supplied from the brushes into an alternating current in the armature conductors, so that a continuous and unidirectional torque is produced on the armature. For this reason, the commutator is often described as a mechanical rectifier/inverter.

Brushes

Brushes are usually made of carbon or graphite and are mounted in brush holders, pressed against the surface of the commutator by means of springs. Their function is to collect current from the commutator, in the case of a generator, or to supply current to the commutator, in the case of a motor, thereby providing the electrical connection between the stationary external circuit and the rotating armature.

Shaft and Bearings

The shaft, made of mild steel, transmits the mechanical power to or from the armature. It is supported by ball or roller bearings housed in the end-covers of the machine, which allow the armature to rotate freely with minimum friction.

Summary of Parts

Part	Material	Function
Yoke	Cast iron / cast steel	Mechanical protection; part of the magnetic circuit
Pole core & shoe	Laminated steel	Carries field winding; spreads flux over air gap
Field winding	Copper wire	Produces the main magnetic field
Armature core	Laminated silicon steel	Houses armature winding; carries flux
Armature winding	Copper conductors	Site of EMF induction / force production
Commutator	Copper segments + mica	Rectifies (generator) or inverts (motor) the current
Brushes	Carbon / graphite	Electrical contact between rotor and external circuit
Shaft & bearings	Mild steel	Mechanical support and rotation

It should be noted that the construction described above is common to both DC generators and DC motors. This is precisely why a DC machine is said to be reversible — a machine built as a generator can, in principle, be run as a motor, and vice versa, simply by reversing the direction of energy flow.

Principle of Operation

Although a DC generator and a DC motor share the same construction, they work on two different, though related, electromagnetic principles. The generator works on the principle of electromagnetic induction, while the motor works on the principle of the motor effect (force on a current-carrying conductor placed in a magnetic field). Both principles are discussed below.

Principle of Operation of a DC Generator

A DC generator works on Faraday's Laws of Electromagnetic Induction, which state that whenever a conductor cuts across magnetic flux lines, a dynamically induced EMF is set up in that conductor. If the circuit of the conductor is closed, this EMF drives a current through the circuit.

$$e = N (d\phi / dt)$$

In practice, the field winding is excited so as to establish a magnetic field between the poles, and the armature is driven by a prime mover — such as a diesel engine, steam turbine, or water turbine — so that the armature conductors sweep through this magnetic field. As each conductor cuts the flux, an EMF is induced in it. Since a conductor passes alternately under a north pole and a south pole as the armature rotates, the EMF induced in it is alternating in nature. The direction of the induced EMF at any instant is given by Fleming's Right-Hand Rule: when the thumb, forefinger and middle finger of the right hand are held mutually perpendicular to one another, with the forefinger pointing in the direction of the field and the thumb in the direction of motion of the conductor, the middle finger indicates the direction of the induced EMF. The commutator and brush arrangement described in Section 3.2 then converts this alternating EMF into a unidirectional EMF, which appears across the brushes and is supplied to the external circuit.

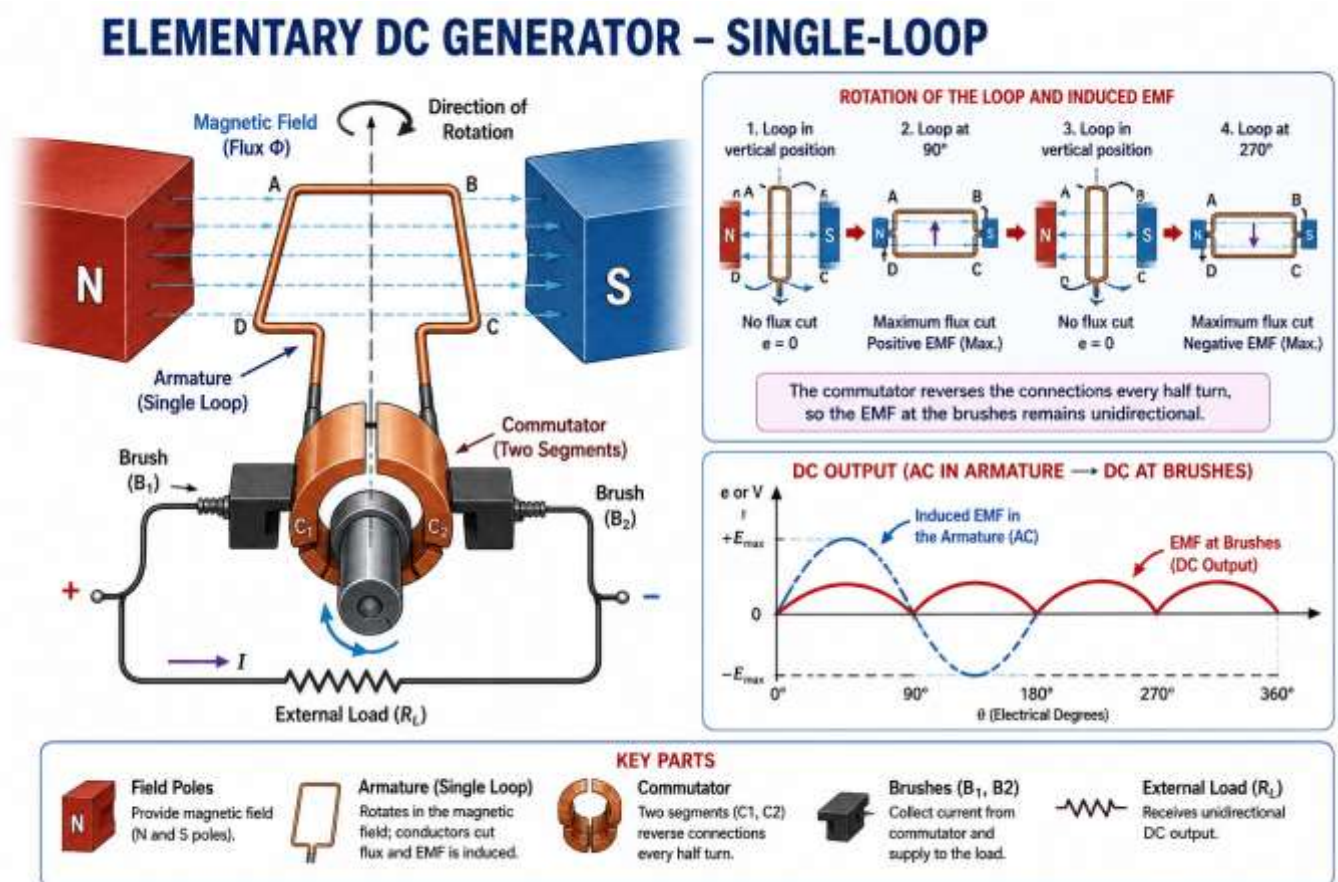


Fig. 3.2: Working of an elementary DC generator

For an EMF to be generated, three conditions must be satisfied simultaneously: there must exist a magnetic field; there must be relative motion between the conductor and the field; and the conductor must cut across the flux lines rather than move parallel to them.

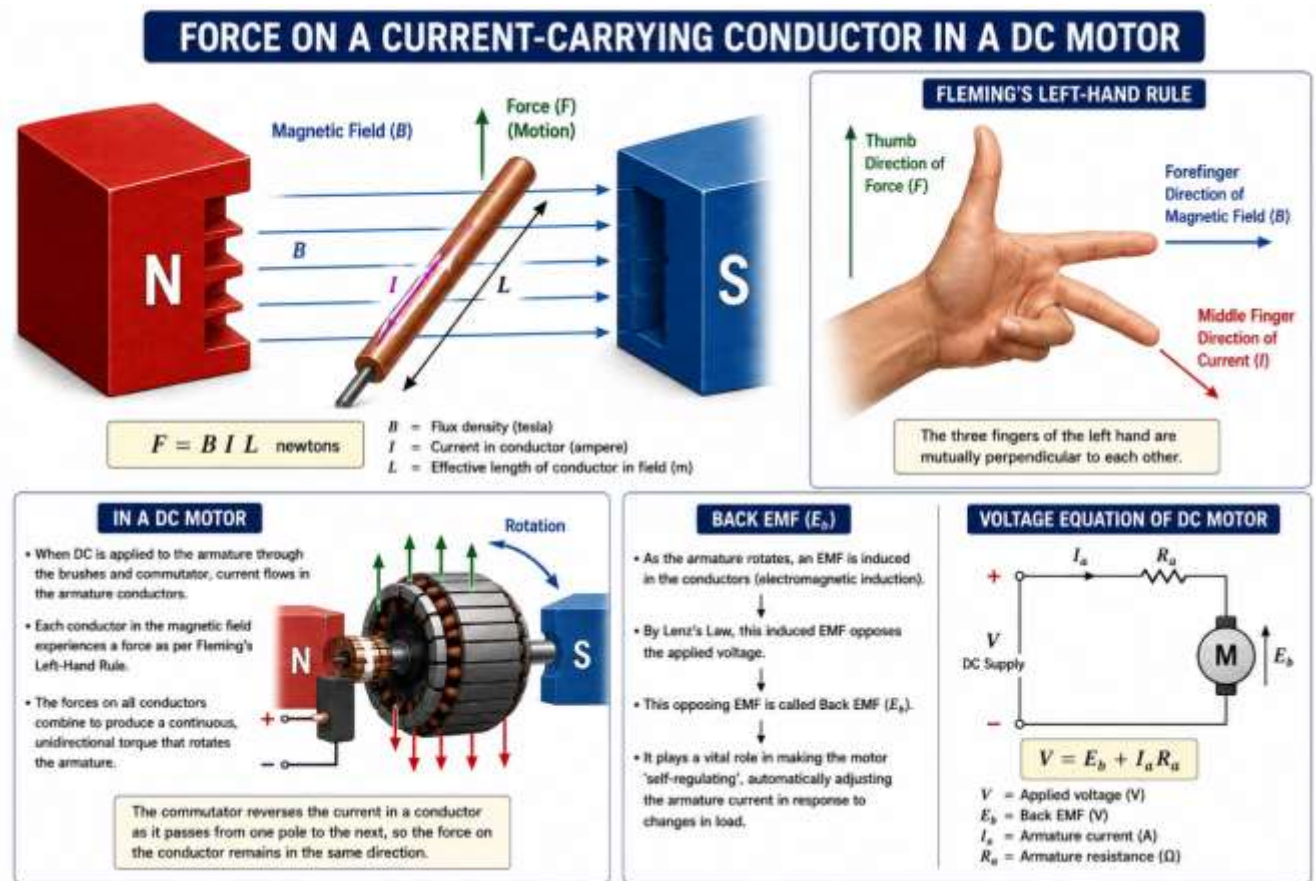
Principle of Operation of a DC Motor

A DC motor works on the principle that a current-carrying conductor, when placed in a magnetic field, experiences a mechanical force. The magnitude of this force is given by:

$$F = B I L \text{ newton's}$$

where B is the flux density in tesla, I is the current flowing through the conductor in amperes, and L is the effective length of the conductor in metres lying within the field.

When a DC supply is connected to the field winding, a magnetic field is set up between the poles. When the same or a separate DC supply is connected to the armature through the brushes and commutator, current flows through the armature conductors. Each current-carrying conductor lying within the magnetic field experiences a force as given above. The direction of this force is found using Fleming's Left-Hand Rule: when the thumb, forefinger and middle finger of the left hand are held mutually perpendicular, with the forefinger in the direction of the field and the middle finger in the direction of the current, the thumb indicates the direction of the force (and hence of motion). Because the commutator reverses the current in a conductor at the precise instant it passes from one pole to the next, the conductors under any given pole always carry current in the same direction relative to that pole, and the forces on all the conductors combine to produce a continuous, unidirectional torque that rotates the armature.



Force on a current-carrying conductor in a DC motor

As the armature rotates within the magnetic field, the same electromagnetic induction that governs the generator comes into play here as well: an EMF is induced in the rotating armature conductors. By Lenz's Law, this induced EMF opposes the applied voltage that is driving the current through the armature, and it is therefore called the back EMF, denoted E_b . The back EMF plays a crucial role in the working of a DC motor — it is what makes the motor 'self-regulating', automatically adjusting the armature current in response to changes in mechanical load, as expressed in the voltage equation $V = E_b + I_a R_a$.

Comparative Summary

Aspect	DC Generator	DC Motor
Energy conversion	Mechanical to electrical	Electrical to mechanical
Governing principle	Faraday's Law of electromagnetic induction	Motor effect — force on a current-carrying conductor
Rule applied	Fleming's Right-Hand Rule	Fleming's Left-Hand Rule
Role of induced EMF	Is the useful output, delivered to the load	Is a back EMF, opposing the applied voltage

