Principles of Electromechanical Energy-Conversion and Direct Current Machines

8

8.1 INTRODUCTION

In this chapter we shall first discuss the electromechanical energy-conversion process, which takes place through the medium of the electric or magnetic fields of the conversion device and then the direct current machines.

The subject matter considered in this chapter is presented under two main parts; with Part I describing the basic principles underlying all electromechanical energy-conversion devices and Part II describing the working principles, constructional details and steady-state behaviour and other important aspects related to direct current Machines (generators and motors).

Part I : *PRINCIPLES OF ELECTROMECHANICAL ENERGY-CONVERSION*

Many electromechanical conversion devices operate on similar principles although their structure may be different depending upon their function such as transducers, force-producing devices like solenoids, relays, electromagnets etc., and *energy-conversion equipments* like motors and generators. Thus, there is a need to study first the basic concepts of electromechanical energy conversion.

This section is mainly devoted to the principle of electromechanical energy conversion and the analysis of the devices which accomplish this function. Emphasis will be placed upon the analysis of systems which use magnetic fields as the conversion medium since the many chapters of the book deal with such devices. The concepts and techniques presented in this chapter are quite powerful and can be applies to a wide range of engineering situations involving electromechanical energy conversion.

8.2 ENERGY-CONVERSION PROCESS

Although various techniques are available for calculating the forces or torque in an electromechanical energy conversion device, the method used here is based on the principle of conversion of energy and is known as energy method. This is quite powerful and can be applied to a wide range of engineering situations involving electromechanically energy conversion. The principle of conversion of energy states that energy can neither be created nor destroyed; it can only be changed from one from to another.

An electromechanical converter system has three essential parts as illustrated in Fig. 8.1.

(*i*) An electric system;

(*ii*) A mechanical system; and

(*iii*) A coupling field.

The energy transfer equation is

$$\begin{pmatrix}\text{Electrical}\\ \text{energy input}\\ \text{from source}\end{pmatrix} = \begin{pmatrix}\text{Mechanical}\\ \text{energy output}\end{pmatrix} + \begin{pmatrix}\text{Increase in stored}\\ \text{energy in coupling}\\ \text{field}\end{pmatrix} + \begin{pmatrix}\text{Energy}\\ \text{losses}\end{pmatrix} \qquad \text{...(8.1)}$$

The electrical energy loss is the heating loss due to current flowing in the winding of the energy converter. This loss is known as the i^2R loss in the resistance R of the winding. The field loss is the core loss due to changing magnetic field in the magnetic core. The mechanical loss is the friction and windage loss due to motion of the mechanical components. All these losses are converted to heat. In view of the losses, the energy balance Eqn. (8.1) can, therefore, be expressed as

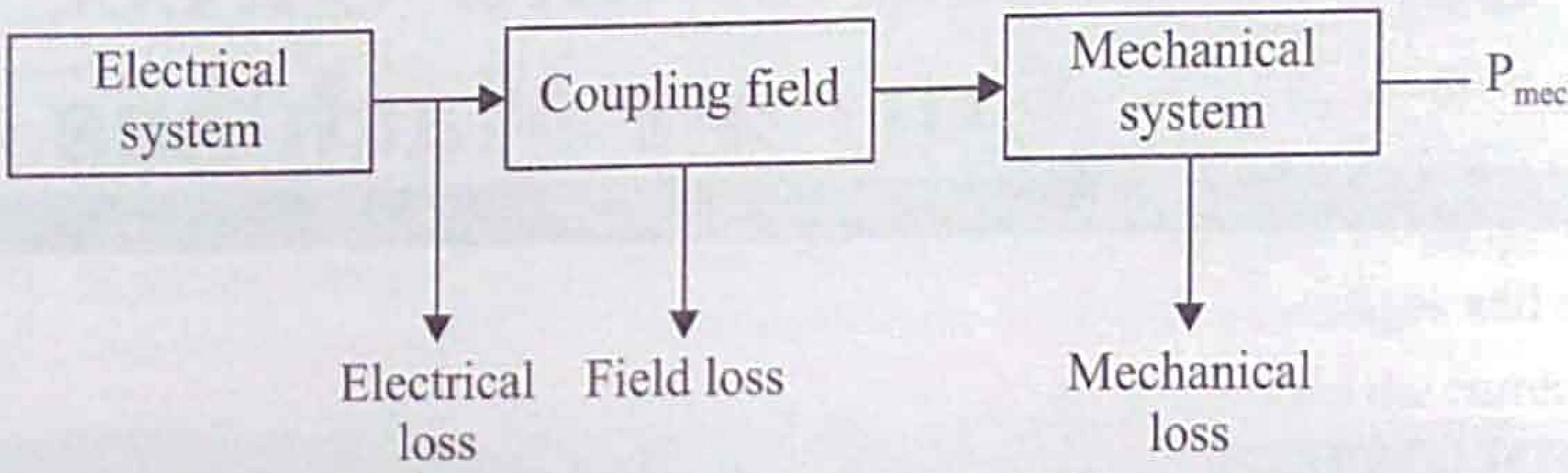

Fig. 8.1 *Electromechanical energy conversion system*

$$\begin{pmatrix}\text{Electrical energy}\\ \text{input from source}\\ \text{resistance loss}\end{pmatrix} = \begin{pmatrix}\text{Mechanical energy}\\ \text{output + friction}\\ \text{and windage loss}\end{pmatrix} + \begin{pmatrix}\text{Increase in stored}\\ \text{field energy + core}\\ \text{loss}\end{pmatrix} \qquad \text{...(8.2)}$$

Let us now consider a differential time interval dt during which an increment of electrical energy dW_e (excluding the i^2R loss) flows to the system. During this time dt, let dW_f be the energy supplied to the field (either stored or lost, or part stored and part lost) and dW_m the energy converted to mechanical form (in useful form or as loss, or part useful and part as loss).

For the lossless magnetic energy-storage system, Eqn. (8.2) in differential form (for small energy changes) becomes

$$dW_e = dW_m + dW_f \qquad \text{...(8.3)}$$

where dW_e = Differential electric-energy input

dW_m = Differential mechanical-energy output

dW_f = Differential change in magnetic stored energy

The core losses are usually small, and if they are neglected, dW_f will represent the change in the stored field energy. Similarly, if friction and windage losses can be neglected, then all of dW_m will be available as useful mechanical energy output. Note that the losses do not contribute to the energy conversion process.

system respectively.

Part II : *DIRECT CURRENT MACHINES*

8.8 GENERAL CONSIDERATIONS OF ELECTRIC MACHINES

- Energy converters that are used to continuously translate electrical input to mechanical output or vice versa are called *electric machines and the process of translation is known as electromechanical energy conversion.*
- Rotating electromechanical energy-conversion devices are popularly known as *rotating machines.* They are classified as *direct-current machines* if their outputs are direct currents of if the energy input to the machines is from a source of direct current. They are called *alternating current* if their outputs are periodic of if their primary energy input comes from a source of alternating current.
- A rotating machine is called a *generator* if it converts mechanical energy into electrical energy, and is called a *motor* if it converts electrical energy into a mechanical energy. In principle the same machine can be use both as a generator and as a motor, but practical design considerations may favor its use either as a generator or a motor. However, both generator and motor actions are present in a machine irrespective of whether it is being used as a generator or motor. In other words, in case of a motor which produces mechanical torque, electromotive forces are generated in certain parts of the device due to motion. Similarly, while the generation of electromotive force is the function of a generator, a mechanical torque which opposes motion is produced in certain parts of the machine.
- There are three types of applications of rotating machines: (*i*) As *generators,* they *are used to supply electrical energy to homes and industries.* (*ii*) As *motors* they *are used to drive or turn mechanical devise such as fans, pumps,* etc. and (*iii*) As *servomechanism devices they used to control system;* here machines are used as positioning devices and/or conveying information from one part of the system to another.

8.8A Electromagnetic Conversion

As mentioned above, energy converters that are used to continuously translate electrical input to mechanical output or vice versa are called *electric machines* and the process of translation is known as *electromechanical energy conversion.* An electric machine is, therefore, a link between an electrical system and a mechanical system, as shown in Fig. 8.14. In these machines the conversion is reversible. If the conversion is from electrical to mechanical, the machine is said to be motor. Hence the same machine can be made to operate as a generator as well as a motor.

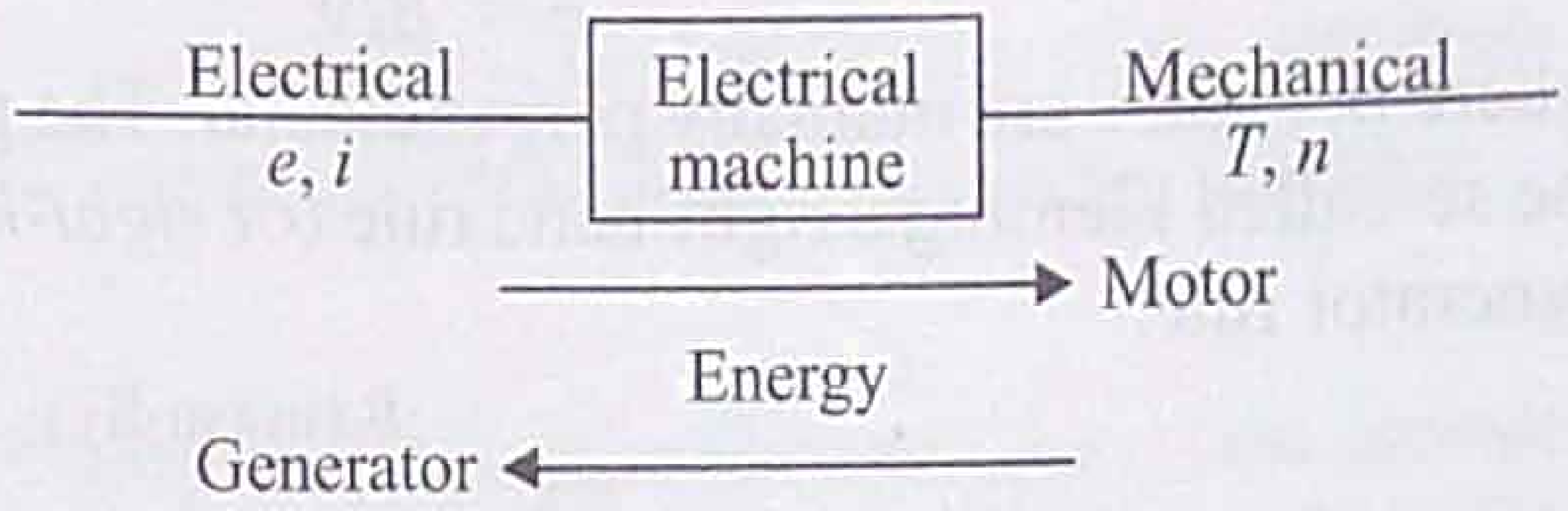

Fig. 8.14 *Electrical energy conversion*

As shown in Fig. 8.14 the two systems, electrical and mechanical, are different in nature. In the electrical system, the primary quantities involved are voltage and current, while the analogous quantities in the mechanical system are torque and speed. The coupling medium between these different systems is the field, as illustrated in Fig. 8.15.

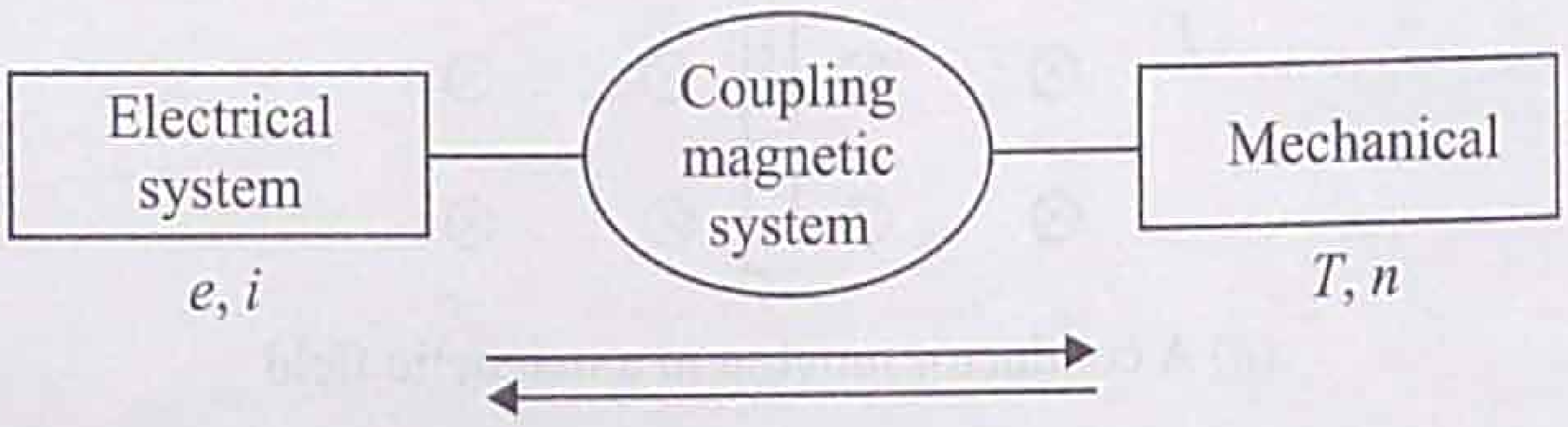

Fig. 8.15 *Coupling field between electrical and mechanical systems*

Electrical machines such as direct current, induction, and synchronous are used extensively for electromechanical energy conversion. In these machines, conversion of energy from electrical to mechanical or vice versa results from the following two electromagnetic phenomena:

1. When a conductor moves in a magnetic field, voltage is induced in the conductor.
2. When a current-carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force.

These two effects occur simultaneously whenever energy conversion takes place from electrical to mechanical or vice versa.

(*a*) In *motoring action*, the electrical system makes the current flow through conductors that are placed in the magnetic field and a force is produced on each conductor. If the conductors are placed on a structure free to rotate, and electromagnetic torque will be produced which will tend to rotate the rotating structure at some speed. If the conductors rotate in a magnetic field, a voltage will also be induced in each conductor.

(*b*) In *generating action*, the process is reversed. In this case, the rotating structure, the rotor, is driven by a prime mover (such as turbine or diesel engine). A voltage will be induced in the conductors that are rotating with the rotor. If an electrical load is connected to the winding formed by these conductors, a current i will flow, delivering electrical power to the load. Moreover, the current flowing through the conductor will interact with the magnetic field to produce a reaction torque, which will tend to oppose the torque applied by the prime mover.

Note that in both the motoring and generating actions, the coupling magnetic field is involved in producing a torque and an induced voltage. The basic electric machines (direct current, induction and synchronous), which depend on electromagnetic energy conversion, are extensively used in various power ratings.