Principles of Electrical Machines

V.K. MEHTA
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ELECTRICAL MACHINES

[FOR DEGREE, A.M.I.E., DIPLOMA AND OTHER ENGINEERING EXAMINATIONS]

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- 291/1, Ganesh Gayatri Complex, 1st Floor, Somwarpeth, Near Jain Mandir, **Pune**-411011. Ph : 64017298, pune@schandgroup.com
- Flat No. 104, Sri Draupadi Smriti Apartment, East of Jaipal Singh Stadium, Neel Ratan Street, Upper Bazar, **Ranchi**-834001. Ph: 2208761, ranchi@schandgroup.com
- Kailash Residency, Plot No. 4B, Bottle House Road, Shankar Nagar, **Raipur.** Ph. 09981200834 raipur@schandgroup.com

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PREFACE TO THE SECOND EDITION

The general response to the first edition of the book was very encouraging. Authors feel that their work has been amply rewarded and wish to express their deep sense of gratitude, in common to the large number of readers who have used it, and in particular to those of them who have sent helpful suggestions from time to time for the improvement of the book.

In the present revised edition, we have made sincere efforts to make the book up-to-date. This edition has three notable features. First, three new chapters viz. ***Electromechanical Energy Conversion, Circle Diagrams*** and ***Special-purpose Electric Machines*** have been added. Secondly, a large number of solved examples have been added to enhance the utility of the book. Thirdly, the book has been made design oriented keeping in view the growing demand of the industry. It is hoped that these features will make the book more useful.

Authors wish to thank their colleagues and friends who have contributed many valuable suggestions regarding the scope and content-sequence of the book. Authors are also indebted to M/s S. Chand & Company Ltd., New Delhi for bringing out this revised edition in a short time and pricing the book moderately inspite of heavy cost of paper and printing.

Errors might have crept in despite utmost care to avoid them. Authors shall be grateful if these are pointed out along with other suggestions for the improvement of the book.

V.K. MEHTA
ROHIT MEHTA

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Electromechanical Energy Conversion

INTRODUCTION

We daily use many devices that convert one form of energy into another form. For example, a heater converts electrical energy into heat energy while an electric bulb converts electrical energy into light energy. However, electromechanical conversion devices (*i.e.,* devices that convert electrical energy into mechanical energy or vice – versa) find wide practical applications. For example, an electric motor converts electrical energy into mechanical energy. On the other hand, an electric generator converts mechanical energy into electrical energy. A major reason for the widespread use of electromechanical energy conversion devices is that they are relatively efficient and permit an easy control. In this chapter, we shall discuss the basic principles of electromechanical energy conversion.

1.1 ELECTROMECHANICAL ENERGY CONVERSION

The conversion of electrical energy into mechanical energy or vice versa is known as **electromechanical energy conversion**.

Electromechanical energy conversion involves the interchange of energy between an electrical system and a mechanical system through the medium of a coupling electric field or magnetic field. Therefore, an electromechanical conversion system has three essential parts *viz.*, *an electrical system*, *a mechanical system* and *a coupling field* (electric or magnetic). Fig. 1.1 shows the block diagram of an electromechanical energy conversion system. Note that from left to right, the system represents conversion from electrical to mechanical . However, from right to left, it will represent conversion from mechanical to electrical.

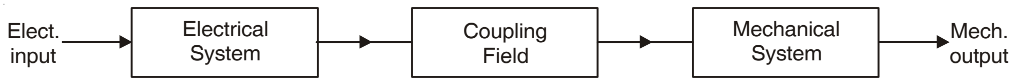


Fig. 1.1 Electromechanical Energy Conversion System

(*i*) **Electric field as coupling medium.** Electromechanical energy conversion can take place when electric field is used as the medium. Consider two oppositely charged plates of a capacitor which are separated by a dielectric medium. A force of attraction exists between the two plates that tends to move them together. If we allow one plate to move in the direction of the force, we are converting electrical energy into mechanical energy. On the other hand, if we apply an external force on one plate and try to increase the separation between them, we are then converting mechanical energy into electrical energy. Electrostatic microphones and electrostatic voltmeters use electrostatic fields for energy conversion.

(*ii*) **Magnetic field as coupling medium.** Electromechanical energy conversion can also take place more effectively when magnetic field is used as the medium. Consider the case of a current-carrying conductor placed in a magnetic field. The conductor experiences a force that tends to move it. If the conductor is free to move in the direction of the magnetic force, the magnetic field helps the conversion of electrical energy into mechanical energy. This is essentially the principle of operation of all electric motors. On the other hand, if an externally applied force moves the conductor in a direction opposite to the magnetic force, mechanical energy is converted into electrical energy. The generator action is based on this principle. Note that in both cases, the magnetic field acts as a medium for energy conversion.

It is important to note that the quantity of energy that can be converted by a device using electric field as a medium is relatively small. It is because the amount of force developed by an electric system is usually very small even when the applied voltage is high and the physical dimensions of the system are quite large. However, when magnetic field is used as a medium, a system with the same physical dimensions develops a much larger force than a system using an electric field as a medium. For this reason, the use of electric field as a medium for energy conversion has limited applications.

1.2 ELECTROMECHANICAL ENERGY CONVERSION DEVICES

Electromechanical energy conversion takes place through electric field or magnetic field as the medium. Although the various conversion devices operate on common set of physical principles, the structures of the devices depend on their function. Electromechanical energy conversion devices can be divided into the following three categories :

(*i*) **Transducers.** These conversion devices are used for measurement and control. They generally operate under linear input-output conditions and with relatively small signals. Examples include microphones, pick ups and loudspeakers.

(*ii*) **Force-producing devices.** These conversion devices are meant for producing force or torque with limited mechanical motion. Examples include relays, solenoid actuators and electromagnets.

(*iii*) **Continuous energy conversion devices.** These devices continuously convert electrical energy into mechanical energy or vice versa. They are used for bulk energy conversion and utilisation. Motors and generators are the examples of such conversion devices.

It may be noted that magnetic field is most suited as a medium for electromechanical energy conversion. *Therefore, in this book, we shall deal with magnetic field as the medium of energy conversion*.

1.3 FEATURES OF ELECTROMECHANICAL ENERGY CONVERSION

Electromechanical energy conversion takes place through the medium of magnetic field. The following salient features are worth noting in this energy conversion :

(*i*) As with any energy conversion system, the *principle of conservation of energy* holds good in case of electromechanical energy conversion. That is energy can neither be created nor destroyed; it can only be changed from one form to another.

(*ii*) During electromechanical energy conversion, various losses occur in the system. This is illustrated in Fig. 1.2 which shows the conversion of electrical energy into mechanical energy.

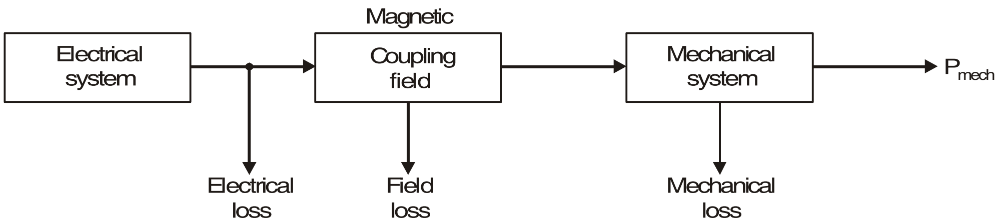


Fig. 1.2 Electromechanical Energy Conversion System

The electrical energy loss ($i^2 R$) is due to current (i) flowing in the winding (having resistance R) of the energy converter. 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 the motion of the moving components. All these losses are converted into heat and raise the temperature of the energy conversion system.

(*iii*) Electromechanical energy conversion is a reversible process except for the losses in the system. The term reversible means that the energy can be transferred back and forth between the electrical and the mechanical systems. However, each time we go through an energy conversion process, some of the energy is used up to meet the losses in the conversion process. These losses are converted into heat and are lost from the system forever.

(*iv*) Electromechanical conversion devices are built with air gaps in the magnetic circuit to separate the fixed and moving parts. Most of the m.m.f. of the windings is required to overcome the air-gap reluctance so that most of the energy is stored in the air gap and is returned to the electric source when the field is reduced.

(*v*) The electromechanical energy conversion system can be analysed by using principle of conservation of energy, laws of electric and magnetic field, electric circuits and Newtonian mechanics.

(*vi*) The rotating electrical machines (motors and generators) continuously convert electrical energy into mechanical energy or vice versa. Fig. 1.3 shows the block diagram of electromechanical energy conversion in an electrical machine. The primary quantities involved in the mechanical system are torque (T) and speed (ω_m) while the analogous quantities in the electrical system are voltage (e) and current (i) respectively.

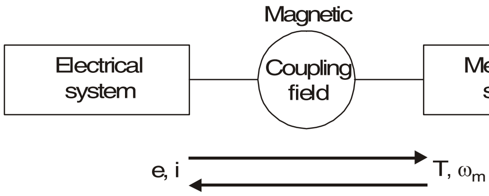


Fig. 1.3

1.4 ENERGY BALANCE EQUATION

An electromechanical energy conversion system has three essential parts *viz.,* an electrical system, a mechanical system and a coupling magnetic field as shown in Fig. 1.4. Since conversion of energy from one form into another form satisfies the principle of conservation of energy, the energy transfer equation is as under:

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

Eq. (*i*) is applicable to all conversion devices. For motor action, the electrical and mechanical energy terms have positive values. For generator action, the electrical and mechanical energy terms have negative values.

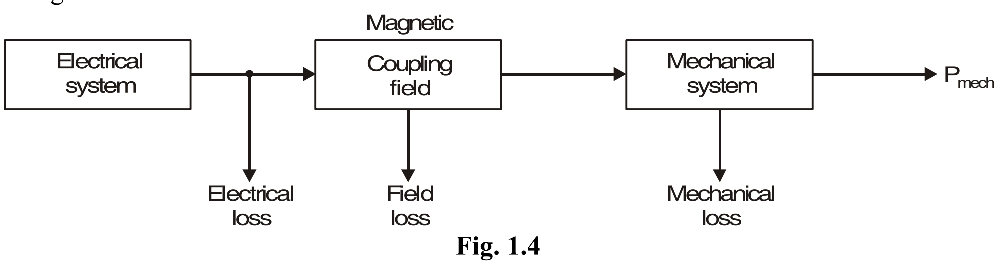


Fig. 1.4

During this energy conversion, energy loss occurs due to three causes *viz.,* (*i*) i^2R loss in the winding of the energy converter (*ii*) core or field loss due to changing magnetic field and (*iii*) mechanical loss is the friction and windage loss due to the motion of moving parts. All these losses are converted to heat. If the energy losses in the electrical system, the coupling magnetic field and the mechanical system are grouped with the corresponding terms in eq. (*i*) above, the energy balance equation can be written as under :

$$\begin{pmatrix}\text{Electrical energy}\\ \text{input } \textit{minus}\\ \text{resistance losses}\end{pmatrix} = \begin{pmatrix}\text{Mechanical energy}\\ \text{output } \textit{plus} \text{ friction}\\ \text{and windage losses}\end{pmatrix} + \begin{pmatrix}\text{Increase in stored}\\ \text{field energy } \textit{plus}\\ \text{core losses}\end{pmatrix} \quad ...(ii)$$

Now consider a differential time dt during which an increment of electrical energy dW_{elect} (excluding i^2R loss) flows to the system. During this time dt, let dW_{fld} be the energy supplied to the field (either stored or lost, or part stored and part lost) and dW_{mech} the energy converted to mechanical form (in useful form or as loss, or part useful and part as loss). In differential form, eq. (*ii*) can be expressed as

$$dW_{elect} = dW_{mech} + dW_{fld} \quad \text{...}(iii)$$

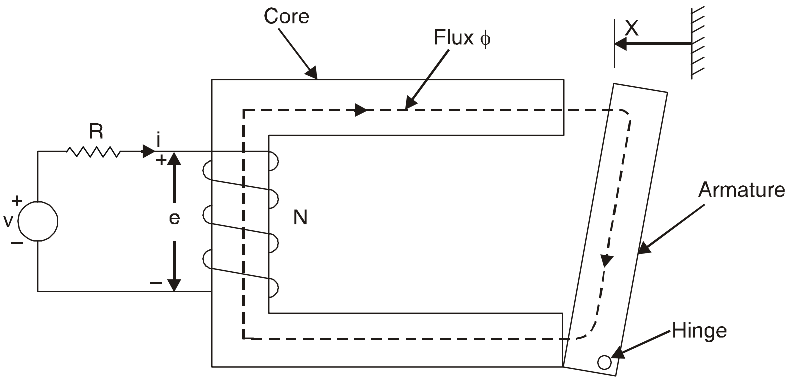
If no mechanical work is done [*i.e.* $dW_{mech} = 0$], then eq. (*iii*) becomes :

$$dW_{elect} = dW_{fld}$$

In this case, electrical energy input is stored in the magnetic field (neglecting core losses).

1.5 ENERGY IN MAGNETIC SYSTEM

Consider singly–excited magnetic system shown in Fig. 1.5. It is the magnetic system of an attracted armature relay. Here a coil of N turns wound on the magnetic core is connected to an electric source. Let us assume that the armature is held stationary at some air gap and the current is increased from zero to some value i. As a result, flux ϕ will be established in the magnetic system.



Attracted Armature Relay

Fig. 1.5

Total flux linkages, $\lambda = N\phi$

Induced e.m.f., $e = \dfrac{Nd\phi}{dt} = \dfrac{d}{dt}(N\phi) = \dfrac{d\lambda}{dt}$

For the coupling device to absorb energy from the electric circuit, the coupling field must produce a reaction in the circuit. This reaction is the e.m.f. e produced by the magnetic field.

The incremental electrical energy (dW_{elect}) due to the flow of current i in time dt is

$$dW_{elect} = e\, i\, dt$$

The energy balance equation in differential form is

$$dW_{elect} = dW_{mech} + dW_{fld}$$

Since we have assumed that the armature is held stationary, there is no mechanical output *i.e.*, $dW_{mech} = 0$. Therefore, *all the incremental electrical input energy is stored as incremental field energy *i.e.*

$$dW_{elect} = dW_{fld}$$

or $$e\, i\, dt = dW_{fld}$$

or $$\frac{d\lambda}{dt}\, i\, dt = dW_{fld}$$

∴ $$dW_{fld} = i\, d\lambda = N\, i\, d\phi \qquad (\because\ d\lambda = Nd\phi)$$

* Neglecting core loss.

The relationship between coil flux linkages λ and current i for a particuler air-gap length is shown in Fig. 1.6. The incremental field energy dW_{fld} is shown as crosshatched area in this figure. When the flux linkage is increased from zero to λ (or flux from zero to ϕ), the energy stored in the field is

$$W_{fld} = \int_0^{\lambda} i d\lambda = N\int_0^{\phi} i d\phi$$

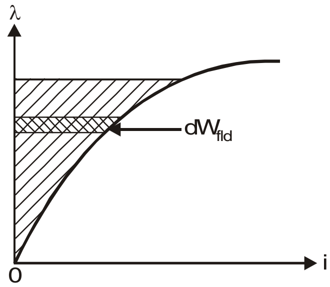


Fig. 1.6

The integral repesents the area between the λ axis and the λ-i characteristic and is equal to the entire shaded area shown in Fig. 1.6.

We can also derive another useful expression for the energy stored in the magnetic field. If l and A are the length and area of cross – section of the magnetic circuit respectively and B is the magnetic flux density, then,

$$Ni = Hl \text{ and } d\phi = A\, dB$$

Here H is the magnetic field intensity.

$$\therefore \qquad W_{fld} = N\int_0^{\phi} i d\phi = \int_0^{B} HlAdB = Al\int_0^{B} HdB$$

or

$$W_{fld} = Al\int_0^{B} HdB$$

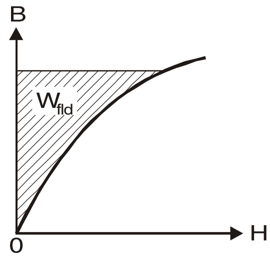


Fig. 1.7

Figure 1.7 shows B–H curve for the magnetic circuit.

Example 1.1. *Fig. 1.8 shows electromechanical system along with dimensions. The magnetic core is made of cast steel whose B–H characteristic is shown in Fig. 1.9. The coil has 250 turns and the coil resistance is 5Ω. For a fixed air gap length g = 5 mm, a d.c. source is connected to the coil to produce a flux density of 1 tesla in the air gap.*

(*i*) *Find the voltage of d.c. source.* (*ii*) *Find the stored field energy.*

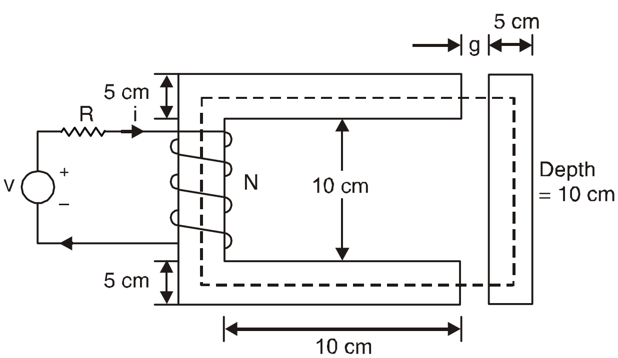


Fig. 1.8

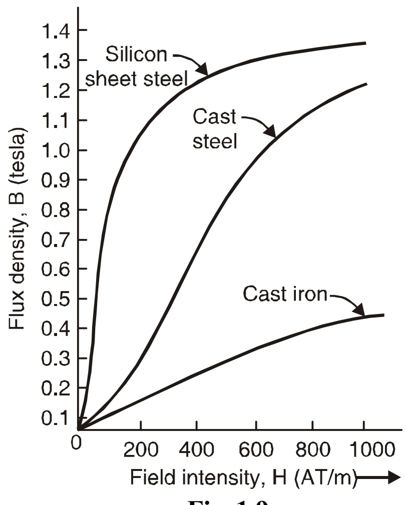


Fig. 1.9

Solution.

(*i*) From Fig. 1.9, the magnetic intensity H_c in the core material (cast steel) for a flux density of 1T is

$$H_c = 670\,\text{AT/m}$$

Length l_c of the flux path in the core is given by ;

$$l_c \simeq 2(10+5)+2(10+5) = 60\text{ cm} = 0.6\text{ m}$$

Magnetic intensity H_g in the air gap is given by ;

$$H_g = \frac{B_g}{\mu_0} = \frac{1}{4\pi\times 10^{-7}} = 795.8\times 10^3\text{ AT/m}$$

$$\text{Total m.m.f. required} = H_c l_c + H_g \times 2g$$
$$= (670\times 0.6)+(795.8\times 10^3\times 2\times 5\times 10^{-3})$$
$$= 402+7958 = 8360\text{ AT}$$

$$\therefore \quad Ni = 8360 \quad \text{or} \quad i = 8360/N = 8360/250 = 33.44\text{ A}$$

$$\therefore \quad \text{Voltage of dc source, } V = iR = 33.44\times 5 = \mathbf{167.2\ V}$$

(*ii*) Energy density in the core is given by ;

$$w_{fc} = \int_0^1 H dB$$

This energy density is given by the area enclosed between the B-axis and the B–H curve for cast steel in Fig. 1.9.

$$\therefore \quad w_{fc} = \frac{1}{2}\times B\times H = \frac{1}{2}\times 1\times 670 = 335\text{ J/m}^3$$

Volume of cast steel core is given by ;

$$V_c = 2(0.05\times 0.1\times 0.2)+2(0.05\times 0.1\times 0.1) = 0.003\text{ m}^3$$

$\therefore$ Field energy stored in the core is given by;

$$W_{fc} = w_{fc}\times V_c = 335\times 0.003 = 1\text{ J}$$

Energy density in the air gap is given by ;

$$w_{fg} = \frac{B^2}{2\mu_0} = \frac{(1)^2}{2\times 4\pi\times 10^{-7}} = 398\times 10^3\text{ J/m}^3$$

$$\text{Volume of air gaps, } V_g = 2(0.05\times 0.1\times 0.005) = 0.05\times 10^{-3}\text{ m}^3$$

$\therefore$ Field energy stored in the air gaps is given by ;

$$W_{fg} = w_{fg}\times V_g = 398\times 10^3\times 0.05\times 10^{-3} = 19.9\text{ J}$$

$\therefore$ Total stored field energy is given by ;

$$W_{fld} = W_{fc}+W_{fg} = 1+19.9 = \mathbf{20.9\ J}$$

Note that most of the field energy is stored in the air gap because the reluctance of air gap is very large as compared to the iron part.

Note. We know that B–H curve or λ–i curve for air gap is a straight line ($B = \mu_0\mu_r H = \mu_0 H$ or $B \propto H$). A practical magnetic circuit of electromagnetic devices (*e.g.*, relays, motors, generators etc.) consists of an iron part and an air gap. The reluctance of air gap is very large as compared to the reluctance of the iron part. Therefore, we can neglect the reluctance of iron part so that B–H or λ–i curve of a practical magnetic circuit may be considered linear. This assumption leads to reasonable accuracy.

Example 1.2. *The relation between the total flux linkages and the current in the coil for the magnetic circuit shown in Fig. 1.10 is given by ;*

$$\lambda = \frac{6i}{2i+1}\ \textit{weber-turns}$$

Determine the energy stored in the magnetic field for $0 \le \lambda \le 2$*Wb-turns.*