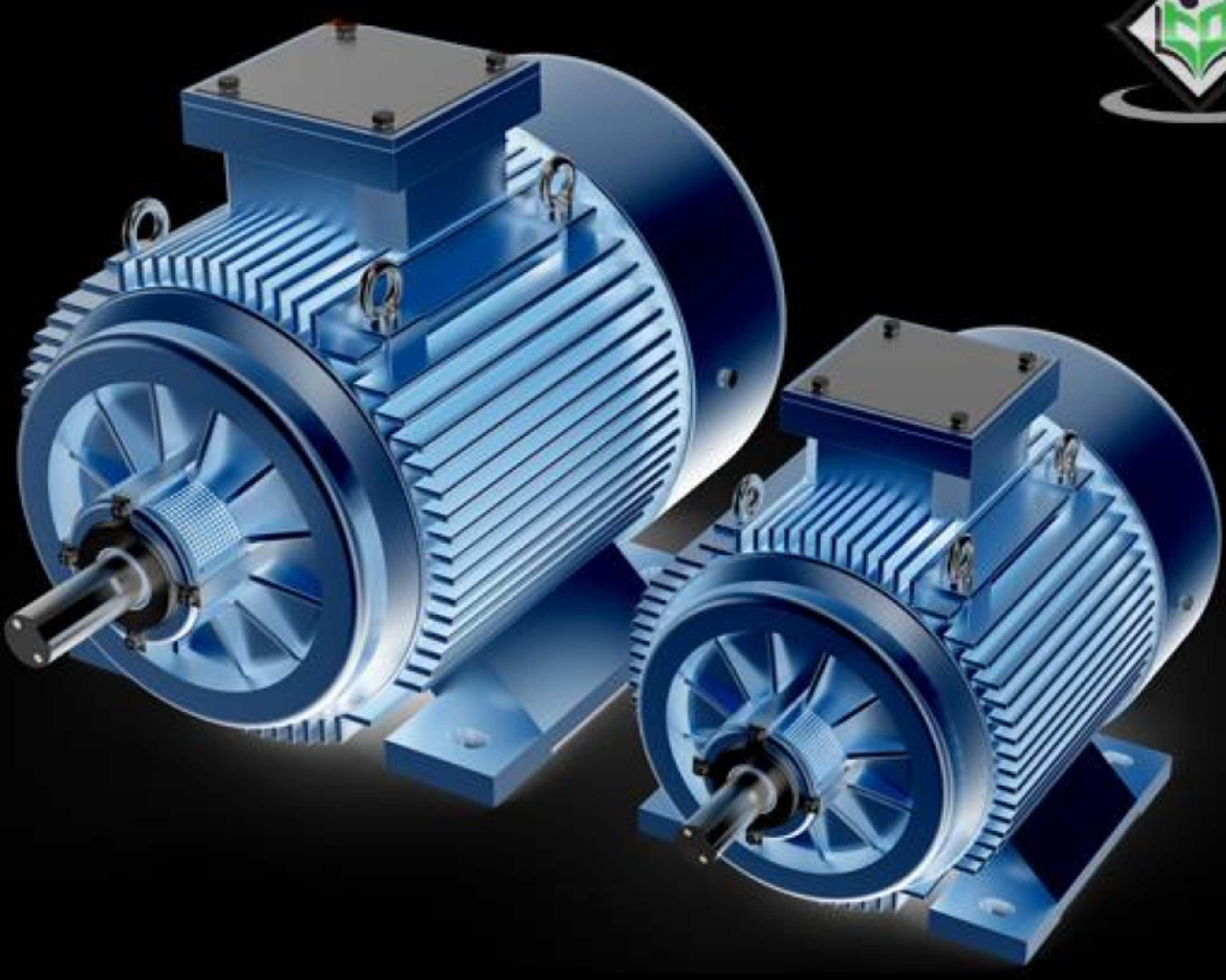

Electrical Machines

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About the Tutorial

Electrical Machines is a core subject within electrical engineering discipline that deals with the design, operation and applications of energy conversion devices. A system that converts electrical energy into other forms of energy is known as an **Electrical Machine**.

The purpose of the tutorial is to introduce and explain the fundamental concepts in Electrical Machines, which include Basic Concepts of Electromechanical Energy Conversion Devices, Transformers, DC Machines (Motor and Generator), Induction Motors, and Synchronous Machines (Alternator and Motor).

Audience

The target of this tutorial is electrical engineering students. It is good resource to help them gain knowledge on fundamentals of electrical machines.

Prerequisites

This tutorial is meant for novice readers. Almost anyone with a basic knowledge of elementary physics and electric circuits can make the most of this tutorial. It is difficult to avoid complex mathematics at some places, although we have tried to keep it at a minimum level. Therefore, it is expected that the readers are comfortable with mathematical equations.

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Part 1: Basic Concepts

1. Electromechanical Energy Conversion

Today, **electrical energy** is the most widely used form of energy for performing several industrial, commercial and domestic functions such as pumping water, fans, coolers, air conditioning, refrigeration, etc. Since, most of processes require the conversion of electrical energy into mechanical energy. Also, the mechanical energy is converted into electrical energy. Hence, this clears that we need a mechanism to convert the electrical energy into mechanical energy and mechanical energy into electrical energy and such a mechanism is known as electromechanical energy conversion device.

Electromechanical Energy Conversion Device

Thus, a device which can convert electrical energy into mechanical energy or mechanical energy into electrical energy is known as **electromechanical energy conversion device**. The electric generators and electric motors are the examples of electromechanical energy conversion device.

In any electromechanical energy conversion device, the conversion of electrical energy into mechanical energy and vice-versa takes place through the medium of an electric field or a magnetic field. Though, in most of the practical electromechanical energy conversion devices, magnetic field is used as the coupling medium between electrical and mechanical systems.

The electromechanical energy conversion devices can be classified into two types:

- **Gross motion devices** (like motors and generators)
- **Incremental motion devices** (such as electromagnetic relays, measuring instruments, loudspeakers, etc.)

The device which converts electrical energy into mechanical energy is known as **electric motor**. The device which converts mechanical energy into electrical energy is known as **electric generator**.

In an electric motor, when a current carrying conductor is placed in a changing (or rotating) magnetic field, the conductor experiences a mechanical force. In case of a generator, when a conductor moves in a magnetic field, an EMF is induced in the conductor. Although, these two electromagnetic effects occur simultaneously, when the energy conversion takes place from electrical to mechanical and vice-versa in all the electromechanical energy conversion devices.

Energy Balance Equation

The **energy balance equation** is an expression which shows the complete process of energy conversion. In an electromechanical energy conversion device, the total input energy is equal to the sum of three components-

- Energy dissipated or lost
- Energy stored
- Useful output energy

Therefore, for an electric motor, the energy balance equation can be written as,

Electrical energy input = Energy dissipated + Energy stored + Mechanical energy output

Where,

- The electrical energy input is the electricity supplied from the main supply.
- Energy stored is equal to sum of the energy stored in the magnetic field and in the mechanical system in the form of potential and kinetic energies.
- The energy dissipated is equal to sum of energy loss in electric resistance, energy loss in magnetic core (hysteresis loss + eddy current loss) and mechanical losses (windage and friction losses).

For an electric generator, the energy balance equation can be written as,

Mechanical energy input = Electrical energy output + Energy stored + Energy dissipated

Where, the mechanical energy input is the mechanical energy obtained from a turbine, engine, etc. to turn the shaft of the generator.

2. Energy Stored in a Magnetic Field

In the previous chapter, we discussed that in an **electromechanical energy conversion device**, there is a medium of coupling between electrical and mechanical systems. In most of practical devices, magnetic field is used as the coupling medium. Therefore, an electromechanical energy conversion device comprises an **electromagnetic system**. Consequently, the energy stored in the coupling medium is in the form of the magnetic field. We can calculate the energy stored in the magnetic field of an electromechanical energy conversion system as described below.

Consider a coil having *N* turns of conductor wire wound around a magnetic core as shown in Figure-1. This coil is energized from a voltage source of *v* volts.

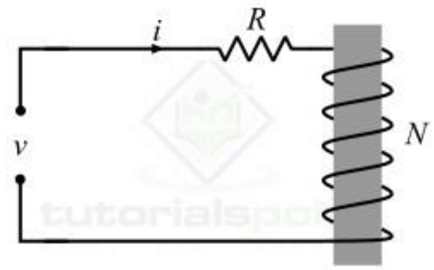

Figure 1 - Electromagnetic Circuit

By applying KVL, the applied voltage to the coil to given by,

$$v = e + iR \quad ...(1)$$

Where,

- $\boldsymbol{e}$ is induced EMF in the coil due to electromagnetic induction
- $\boldsymbol{R}$ is the resistance of the coil circuit
- $\boldsymbol{i}$ is the current flowing the coil

The instantaneous power input to the electromagnetic system is given by,

$$p = vi = i(e + iR)$$

$$\Rightarrow p = ie + i^2R \quad ...(2)$$

Now, let a direct voltage is applied to the circuit at time $t = 0$ and that at end of $t = t_1$ seconds, and the current in the circuit has attained a value of I amperes. Then, during this time interval, the energy input the system is given by,

$$W_{in} = \int_0^{t_1} p\, dt$$

$$\Rightarrow W_{in} = \int_0^{t_1} ie\, dt + \int_0^{t_1} i^2R\, dt \quad ...(3)$$

From Equation-3, it is clear that the total input energy consists of two parts:

- The first part is the energy stored in the magnetic field.
- The second part is the energy dissipated due to electrical resistance of the coil.

Thus, the energy stored in the magnetic field of the system is,

$$W_f = \int_0^{t_1} ie\, dt \quad \ldots (4)$$

According to Faraday's law of electromagnetic induction, we have,

$$e = \frac{d\psi}{dt} = \frac{d}{dt}(N\phi) = N\frac{d\phi}{dt} \quad \ldots (5)$$

Where, $\boldsymbol{\psi}$ is the magnetic flux linkage and it is equal to $\psi = N\phi$.

$$\therefore W_f = \int_0^{t_1} \frac{d\psi}{dt} i\, dt$$

$$\Rightarrow W_f = \int_0^{\psi_1} i\, d\psi \quad \ldots (6)$$

Therefore, the equation (6) shows that the energy stored in the magnetic field is equal to the area between the (ψ-i) curve (i.e., magnetization curve) for the electromagnetic system and the flux linkage (ψ) axis as shown in Figure-2.

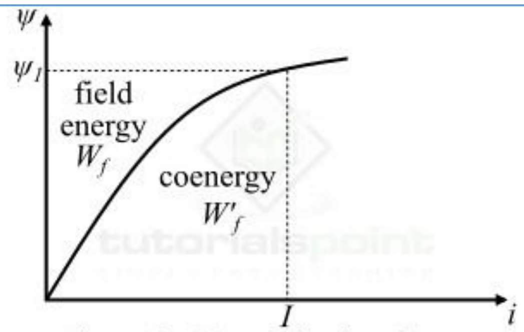

Figure 2 - Magnetization Curve

For a **linear electromagnetic system**, the energy stored in the magnetic field is given by,

$$W_f = \int_0^{\psi_1} i\, d\psi = \int_0^{\psi_1} \frac{\psi}{L} d\psi$$

Where, $\psi = N\phi = Li,$ and L is the self-inductance of the coil.

$$\therefore W_f = \frac{\psi^2}{2L} = \frac{1}{2}Li^2 \quad \ldots (7)$$

Concept of Coenergy

Coenergy is an imaginary concept used to derive expressions for torque developed in an electromagnetic system. Thus, the coenergy has no physical significance in the system.

Basically, the coenergy is the area between the ψ-i curve and the current axis and is denoted by W_f' as shown above in Figure-2.

Mathematically, the coenergy is given by,

$$W_f' = \int_0^i \psi \, di = \int_0^i Li \, di$$

$$\Rightarrow W_f' = \frac{1}{2} Li^2 \quad \dots (8)$$

From equations (7) and (8), it is clear that for a linear magnetic system, the energy stored in the magnetic field and the coenergy are equal.

3. Singly-Excited and Doubly Excited Systems

Excitation means providing electrical input to an electromechanical energy conversion device such as electric motors. The excitation produces working magnetic field in the electrical machine. Some electrical machines require single electrical input whereas some others require two electrical inputs.

Therefore, depending on the number of electrical inputs to electromechanical energy conversion systems, they can be classified into two types-

- Singly-Excited System
- Doubly-Excited System

Singly-Excited System

As its name implies, a **singly-excited system** is one which consists of only one electrically energized coil to produce working magnetic field in the machine or any other electromechanical energy conversion device. Hence, the singly-excited system requires only one electrical input.

A singly excited system consists of coil wound around a magnetic core and is connected to a voltage source so that it produces a magnetic field. Due to this magnetic field, the rotor (or moving part) which is made up of ferromagnetic material experiences a torque which move it towards a region where the magnetic field is stronger, i.e., the torque exerted on the rotor tries to position it such that it shows minimum reluctance in the path of magnetic flux. The reluctance depends upon the rotor angle. This torque is known as **reluctance torque** or **saliency torque** because it is caused due to saliency of the rotor.

Analysis of Singly-Excited System

We made following assumption to analyze the singly-excited system-

- For any rotor position, the relationship between flux linkage (ψ) and current (i) is linear.
- The coil has negligible leakage flux, which means all the magnetic flux flows through the main magnetic path.
- Hysteresis loss and eddy-current loss are neglected.
- All the electric fields are neglected and the magnetic field is predominating.

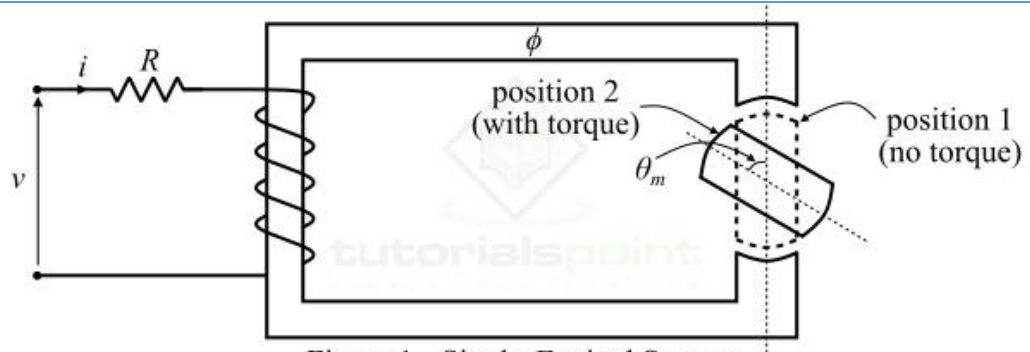

Figure 1 - Singly-Excited System

Consider the singly-excited system as shown in Figure-1. If *R* is the resistance of the coil circuit, the by applying KVL, we can write the voltage equation as,

$$v = iR + \frac{d\psi}{dt} \quad \dots(1)$$

On multiplying equation (1) by current $\boldsymbol{i}$, we have,

$$vi = i^2 R + i\frac{d\psi}{dt} \quad \dots(2)$$

We are assuming initial conditions of the system zero and integrating the equation (2) on both side with respect to time, we obtain,

$$\int_0^T vi\, dt = \int_0^T \left(i^2 R + i\frac{d\psi}{dt}\right) dt$$

$$\Rightarrow \int_0^T vi\, dt = \int_0^T i^2 R\, dt + \int_0^\psi i\, d\psi \quad \dots(3)$$

Equation-3 gives the total electrical energy input the singly-excited system and it is equal to two parts namely,

- First part is the electrical loss (W_{el}).
- Second part is the useful electrical energy which is the sum of field energy (W_f) and output mechanical energy (W_m).

Therefore, symbolically we may express the Equation-3 as,

$$W_{in} = W_{el} + (W_f + W_m) \quad \dots(4)$$

The **energy stored in the magnetic field** of a singly-excited system is given by,

$$W_f = \int_0^\psi i\, d\psi = \int_0^\psi \frac{\psi}{L} d\psi = \frac{\psi^2}{2L} \quad \dots(5)$$

For a rotor movement, where the rotor angle is θ_m, the **electromagnetic torque** developed in the singly-excited system is given by,

$$\tau_e = \frac{i^2}{2}\frac{\partial L}{\partial \theta_m} \quad \dots(6)$$

The most common examples of singly-excited system are induction motors, PMMC instruments, etc.

Doubly-Excited System

An electromagnetic system is one which has two independent coils to produce magnetic field is known as **doubly-excited system**. Therefore, a doubly-excited system requires two separate electrical inputs.

Analysis of Doubly-Excited System

A doubly-excited system consists of two main parts namely a stator and a rotor as shown in Figure-2. Here, the stator is wound with a coil having a resistance R_1 and the rotor is wound with a coil of resistance R_2. Therefore, there are two separated windings which are excited by two independent voltage sources.

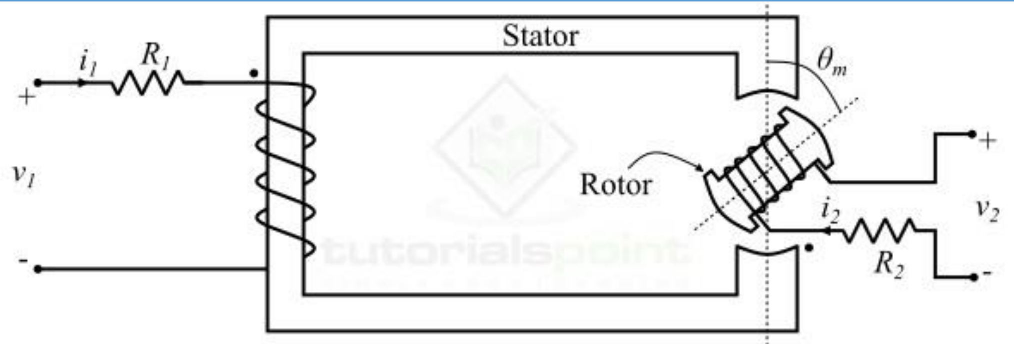

Figure 2 - Doubly-Excited System

In order to analyze the double-excited system, the following assumption are made-

- For any rotor position the relationship between flux-linkage (ψ) and current is linear.
- Hysteresis and eddy current losses are neglected.
- The coils have negligible leakage flux.
- The electric fields are neglected and the magnetic fields are predominating.

The magnetic flux linkages to two windings are given by,

$$\psi_1 = L_1 i_1 + M i_2 \quad \ldots (7)$$

$$\psi_2 = L_2 i_2 + M i_1 \quad \ldots (8)$$

Where, *M* is the mutual inductance between two windings.

By applying KVL, we can write the equations of instantaneous voltage for two coils as,

$$v_1 = i_1 R_1 + \frac{d\psi_1}{dt} \quad \dots(9)$$

$$v_2 = i_2 R_2 + \frac{d\psi_2}{dt} \quad \dots(10)$$

In case of doubly-excited system, the **energy stored in the magnetic field** is given by,

$$W_f = \frac{1}{2} L_1 i_1^2 + \frac{1}{2} L_2 i_2^2 + M i_1 i_2 \quad \dots(11)$$

And, the **electromagnetic torque** developed in the doubly excited system is given by,

$$\tau_e = \frac{i_1^2}{2} \frac{dL_1}{d\theta_m} + \frac{i_2^2}{2} \frac{dL_2}{d\theta_m} + i_1 i_2 \frac{dM}{d\theta_m} \quad \dots(12)$$

In Equation-12, the first two terms are the reluctance torque and the last term gives the co-alignment torque due to interaction of two fields.

The practical examples of doubly-excited system are synchronous machines, tachometer, separately-excited DC machines, etc.

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