UNIT-1

Electromechanical Energy Conversion

Principle of Electromechanical Energy Conversion

Electromechanical energy conversion principle depends on the law of conservation. The law of conservation of energy takes place according to which “Energy neither created nor destroyed but it can be converted from one form to other form”.

Electromechanical Energy conversion device

It is a medium or device, which converts one form of energy into another form of energy, is known as electromechanical energy conversion device. It is also known as coupling field.

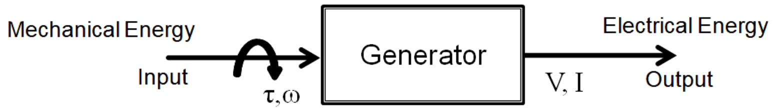
Applications of EMEC Devices

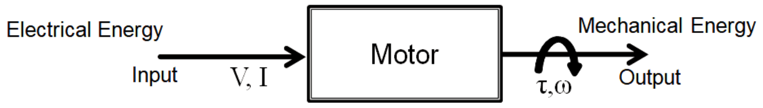
Electromechanical energy conversion device may categorized into three types

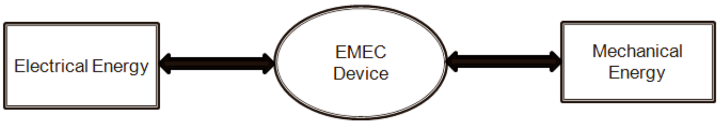
1. ***The first category devices:*** these are processing of only low energy signals from electrical to mechanical or vice versa.
   Ex: microphones, loud speakers and low signal transducers
2. ***The second category devices:*** these are producing force or torque with limited mechanical motion.
   Ex: Electromagnets, relays etc.
3. ***The third category devices:*** these are the continuous energy conversion devices.
   Ex: motors and generators.

A Dynamo is a best example for an electromechanical energy conversion process. Because which converts mechanical energy into electrical energy.

A generator is a machine which converts mechanical energy into electrical energy.







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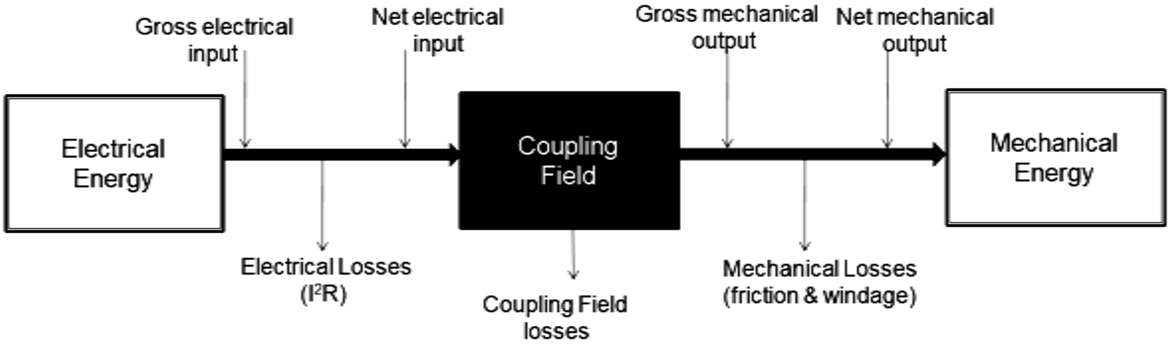
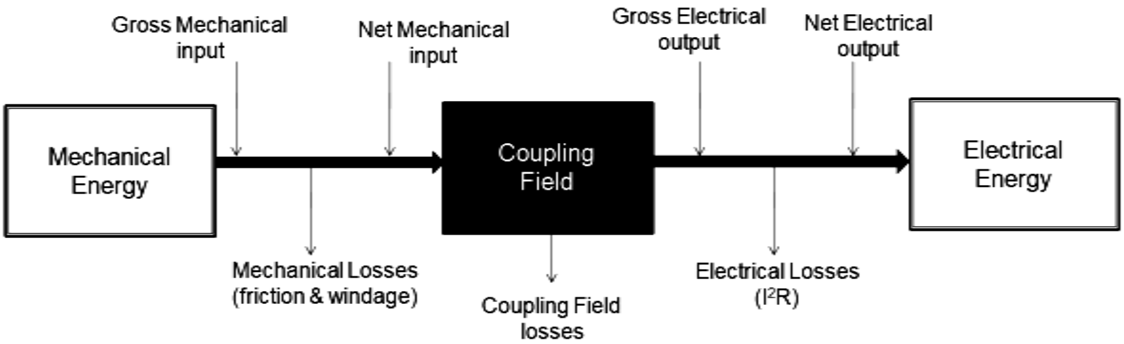
Energy flow diagram of Electro Mechanical Energy System:

Motor:



Generator:



Energy Balance Equation:

According to law of conservation, energy neither be created nor be destroyed but it can be transferred into one form of energy onto other form of energy.

But during this energy conversion process the entire energy is not converted but some amount of energy is lost in physical devices due to electrical and mechanical losses and as well as energy stored in storing elements (inductor L, capacitor C)

Total Losses = Electrical losses + Mechanical Losses

= [iron losses + Copper losses] + [friction losses + windage losses]

Input = Output + total losses + energy loss due to energy storing elements

Energy balance equation of motor and generator:

We know a motor converts electrical energy into mechanical energy. The energy balance equation is

$$\omega_{ele} = \omega_{mech} + \omega_{loss} + \omega_{fld}$$

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$$\omega_{mech} = \omega_{ele} + \omega_{loss} + \omega_{fld}$$

Faradays laws of Electromagnetic induction:

A Faradays law of electromagnetic induction explains how an EMF is induced across a conductor and the amount of EMF induced.

First Law:-

Whenever a variable magnetic flux linked with any conductor (or) whenever a rotating conductor cuts a magnetic flux an EMF is induced across the conductor.

Ex: Generators, motors, Transformers.

Second Law:-

This law states that the magnitude of induced EMF is directly proportional to the rate of change of flux linkages.

λ_1 = flux linkages with the coil at time t_1

λ_2 = flux linkages with the coil at time t_2

N = Number of turns in the coil

According to the faradays second law,

$$e \;\alpha\; \frac{change of\ \ flux linkages}{change of\ time}$$

Flux linkages, ψ = Number of turns x flux in the coil

$$\psi = N \times \phi$$

$$emf\ e = \frac{N(\phi_2 - \phi_1)}{t_2 - t_1}$$

$$e = \frac{Nd\phi}{dt}$$

$$e \;\alpha\; \frac{d\phi}{dt}$$

Lenz's law:-

- The induced EMF in the coil due to rate of change of flux causes a current flow in the coil, this current setups its own magnetic flux.
- The induced EMF in the coil opposes a very cause producing it (change in flux).
- From the faradays second law equation,

  $$e = \frac{Nd\phi}{dt}$$

  The induced emf 'e' and the flux 'ϕ' produced by the current due to supply voltage both are in reverse direction.
  Then

  $$e = -\frac{Nd\phi}{dt}$$

Ohm's law:-

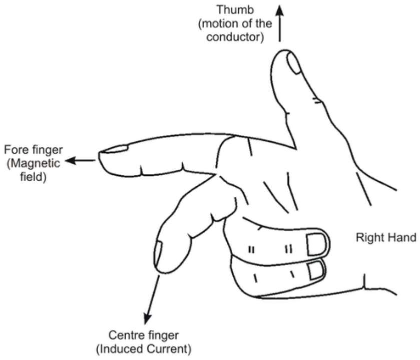
At constant temperature and physical dimensions remains unchanged then current flowing through an element is directly proportional to voltage applied across it.

$$V \alpha \ i$$

$$V = R \ i \qquad \text{[R = Resistance constant]}$$

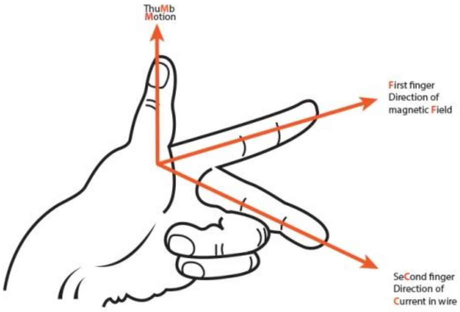
Flemings Right Hand Rule:

The direction of induced emf can be obtained by simple rule called Fleming right hand rule. This rule states that when the thumb, fore finger and middle finger of your right had will be placed or kept mutually perpendicular to each other. Then thumb indicates the direction of motion, fore finger points the direction of field, middle finger represents the direction of the induced emf.



Flemings Left Hand Rule:

Kept the thumb, fore finger and middle finger of left hand perpendicular to each other.
Thumb indicates the direction of force on the conductor
Middle finger points that the direction of current
Fore finger represents that the direction of field.



Induced EMF:-

It is classified into two types

1) Dynamically induced emf
2) Statically induced emf

Dynamically induced emf:

- If the conductor is moving or rotating and if it is cuts the constant flux, an emf is induced in the conductor called dynamically induced emf.

Statically induced emf:

- In this case usually the conductor or coil remains stationary and flux linked with it is changed by simply increasing or decreasing the magnitude of the current.

- This is again subdivided into two parts
  a) Self induced emf
  b) Mutual induced emf

Types of Magnetic Systems:

In a magnetic system, a coil is wound over a magnetic material by exciting this coil with a suitable electrical source. The energy can be stored or retrieved from a magnetic system.

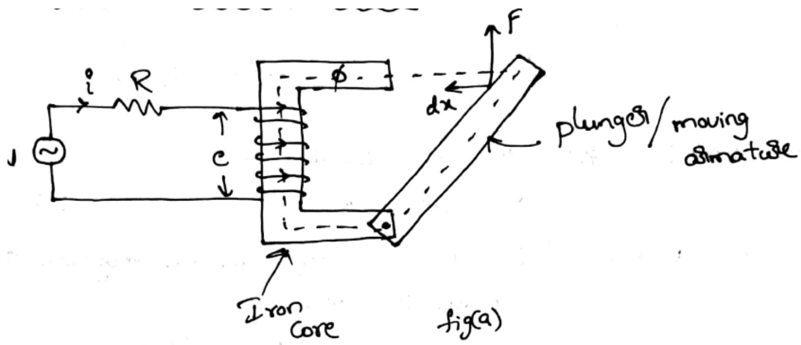
Depending on the number of excitations, the magnetic systems are classified into two types

1. Singly excited system
2. Multiple excited system

1. **Singly excited system**:

In singly exciting system, a single exciting coil is used to produce the magnetic field.

Ex: Electromagnets, Transformers, 1-ϕ induction motors, DC machines (Generators) etc.



fig(a)

The analysis of this singly excited magnetic system includes the derivations of expressions of electrical input energy, magnetically stored energy and mechanical force.

1. The resistance of the exciting coil is assumed to be present in lumped form, outside the coil. Thus coils are lossless and ideal.
2. Assume the leakage flux will be neglected. Total flux confined to the iron core and links with all the 'N' number of turns.

From the above figure it is clear that the electrical energy is converted into mechanical energy.

Whenever an electrical input is given, a change in flux links with the coil and produces a flux in the air gap and moves the armature a differential distance 'dx' in the direction of field.

By applying KVL to the above circuit

$$v = ir + e$$

$$v = ir + \frac{d\psi}{dt}$$

Where, $e = \frac{d\psi}{dt}$

Multiply both sides by 'i' then

$$vi = i^2 r + i\frac{d\psi}{dt}$$

$$vidt = i^2 rdt + id\psi$$

$$idt(v - ir) = id\psi$$

$$eidt = id\psi$$

So, input electrical energy

$$dw_{ele} = eidt = id\psi \text{ --------------- (1)}$$

The plunger has moved a distance ‘dx’ with the force ‘F’ on it.

$$dw_{mech} = Fdx \text{ -------------- (2)}$$

From the balance equation

$$dw_{ele} = dw_{mech} + dw_{fld} + dw_{loss}$$

$$dw_{ele} = dw_{mech} + dw_{fld}$$

$$dw_{fld} = dw_{ele} - dw_{mech} \text{ -------------- (3)}$$

By substituting equation (1) & (2) in equation (3)

$$dw_{fld} = id\psi - Fdx \text{ --------- (4)}$$

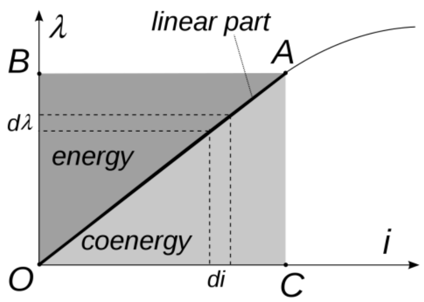
From the above equation it is clear that the field is in the function of flux linkage $d\lambda$ and differential distance *dx*. This can be mathematically written as

$$dw_{fld}(\psi, x) = \frac{\partial w_{fld}(\psi, x)}{\partial \psi} d\psi + \frac{\partial w_{fld}(\psi, x)}{\partial x} dx \text{ ------------ (5)}$$

By comparing the equations (4) and (5)

$$i = \frac{\partial w_{fld}(\psi, x)}{\partial \psi} \qquad F = -\frac{\partial w_{fld}(\psi, x)}{\partial x}$$

The curve between current and flux linkage is nearly linear shown below



The energy stored in the airgap or in magnetic field which is known as field energy. From the above graph the area of the portion above the magnetisation curve is known as **field energy**.

The energy converted from electrical to mechanical energy is called **co-energy**. The area of the portion under the magnetisation curve is known as co-energy.

From the graph

Field energy = area of OABO

$$w_{fld} = \int_0^{\psi} i d\psi$$

Co- energy = area of OACO

$$w_{fld}' = \int_0^{i} \psi di$$

Similarly the mathematical representation can be written as

$$dw_{fld}'(i,x) = \psi di - F dx \text{ ------------- (6)}$$

$$dw_{fld}'(i,x) = \frac{\partial w_{fld}'(i,x)}{\partial i} di + \frac{\partial w_{fld}'(i,x)}{\partial x} dx \text{ ------------- (7)}$$

Co-energy is the function of current *i*, distance *x*.

From equations (6) and (7)

$$\psi = \frac{\partial w_{fld}'(i,x)}{\partial i} \qquad F = -\frac{\partial w_{fld}'(i,x)}{\partial x}$$

$$w_{fld} = \frac{1}{2} L i^2$$

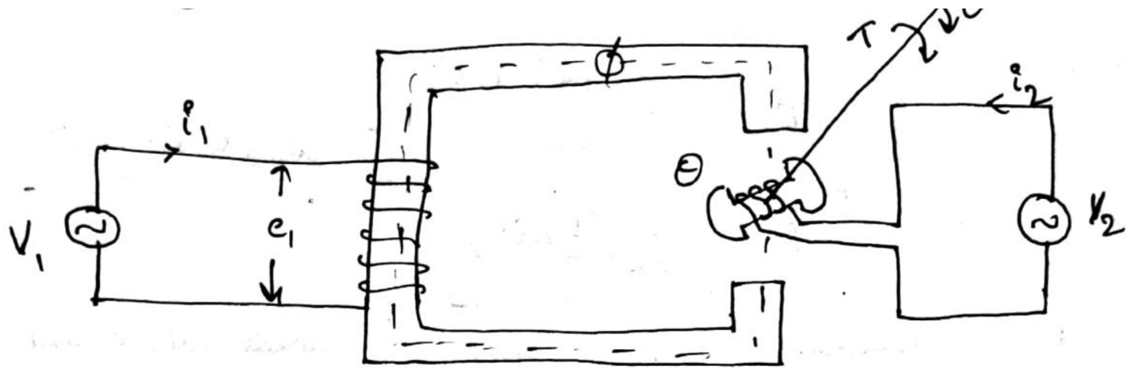
Now $F = -\dfrac{\partial w_{fld}(\psi,x)}{\partial x} = -\dfrac{1}{2} L_x i^2$

Single excited system with rotating actuator

$$dw_{fld} = i d\psi - \tau d\theta$$

$$dw_{fld}(\psi,\theta) = \frac{\partial w_{fld}(\psi,\theta)}{\partial \psi} d\psi + \frac{\partial w_{fld}(\psi,\theta)}{\partial \theta} d\theta$$

Doubly excited magnetic system:



A double excited magnetic system is one which has two independent sources of excitation. Block diagram of doubly excited system is shown below

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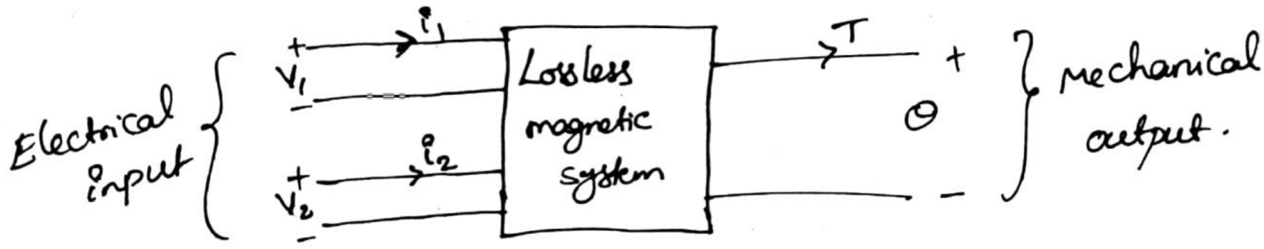

Most of the practical systems are of doubly excited systems. Like motors, generators, in which one group of winding is placed on a stationary part and other group of winding placed on a movable part.

The energy balance equation is

$$dw_{fld} = dw_{ele} - dw_{mech} \text{ --------------------- (1)}$$

Electrical energy is

$$dw_{ele} = i_1 d\psi_1 + i_2 d\psi_2 + M d\psi_1 d\psi_2 \text{ --------------- (2)}$$

Here we are using two sources; the mutual inductance M is also present in electrical energy form.

Mechanical energy is given by

$$dw_{mech} = \tau d\theta \text{ ----------------- (3)}$$

Substitute equation (2) & (3) in equation (1)

$$dw_{fld} = i_1 d\psi_1 + i_2 d\psi_2 + M d\psi_1 d\psi_2 - \tau d\theta \text{ ----------- (4)}$$

In double excited magnetic system, the field energy is a function of primary flux linkages (ψ_1), secondary flux linkages (ψ_2) & angular displacement (θ).

So the field energy can be expressed as function of ψ_1, ψ_2 & θ.

$$dw_{fld}(\psi_1,\psi_2,\theta) = \frac{\partial w_{fld}(\psi_1,\psi_2,\theta)}{\partial \psi_1} d\psi_1 + \frac{\partial w_{fld}(\psi_1,\psi_2,\theta)}{\partial \psi_2} d\psi_2 + \frac{\partial w_{fld}(\psi_1,\psi_2,\theta)}{\partial \theta} d\theta \text{ ------------ (5)}$$

By comparing equation (4) & (5)

$$i_1 = \frac{\partial w_{fld}(\psi_1,\psi_2,\theta)}{\partial \psi_1} \quad i_2 = \frac{\partial w_{fld}(\psi_1,\psi_2,\theta)}{\partial \psi_2} \quad \tau = -\frac{\partial w_{fld}(\psi_1,\psi_2,\theta)}{\partial \theta}$$

Let us assume the mechanical output is zero.

Then the field energy stored in doubly excited system is

$$dw_{fld} = i_1 d\psi_1 + i_2 d\psi_2$$

Integrating on both sides

$$w_{fld} = \int_0^{\psi_1} i_1 d\psi_1 + \int_0^{\psi_2} i_2 d\psi_2$$

Where, $i = \frac{\psi}{L}$

$$w_{fld} = \int_0^{\psi_1} \frac{\psi_1}{L_1} d\psi_1 + \int_0^{\psi_2} \frac{\psi_2}{L_2} d\psi_2$$

$$w_{fld} = \frac{1}{2}[L_1 i_1{}^2 + L_2 i_2{}^2]$$

It is a double excited system, so we have to consider the effect of mutual inductance. The field energy stored in magnetic system will be

$$w_{fld} = \frac{1}{2}[L_1 i_1{}^2 + L_2 i_2{}^2] + M i_1 i_2]$$

Torque $$\tau = -\frac{\partial w_{fld}(\psi_1, \psi_2, \theta)}{\partial \theta}$$

i_1 & i_2 are the constants so,

$$\tau = \frac{1}{2} i_1{}^2 \frac{\partial L_1}{\partial \theta} + \frac{1}{2} i_2{}^2 \frac{\partial L_2}{\partial \theta} + i_1 i_2 \frac{\partial M}{\partial \theta}$$