ELECTROMECHANICAL ENERGY CONVERSION AND CONCEPTS IN ROTATING MACHINES

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Recap

- Connections of three phase transformer and its application
- Necessary and desirable conditions of the transformer
- Scott-T connections and phase conversions
- Phase conversion
- Harmonics

Lecture-10 Objectives

- Electromechanical energy conversion
- Energy balance
- Types of magnetic systems
- Magnetic Field Energy Stored
- Concept of Co-energy
- Magnetic force

Electro Mechanical Energy Conversion

- Electrical energy can be transmitted to long distances with ease and it is highly efficient.
- It acts as a transmitting link for transporting other forms of energy.
- Devices for EMEC are,
  - Transducers which are used for low energy conversion.
  - Relays, solenoids and actuators which produce mechanical force or torque.
  - Motors and generators which are used for continuous energy conversion.

Electro Mechanical Energy Conversion

- EMEC takes place via magnetic field because of its higher energy storing capacity.
- The fields involved with such electromechanical devices must be slowly varying due to inertia in the mechanical parts.
- Such fields are called quasi static fields.

Energy Balance

- Principle of conservation of energy – Energy can neither be created nor destroyed. But it can be transformed from one form to other.
- Not the entire energy be transformed to other form.
- There are some energy loss.
- Some part of the energy is stored in the form of magnetic field.
- Thus the input energy has three parts.
  - ✓ Transformed energy
  - ✓ Energy loss
  - ✓ Stored energy

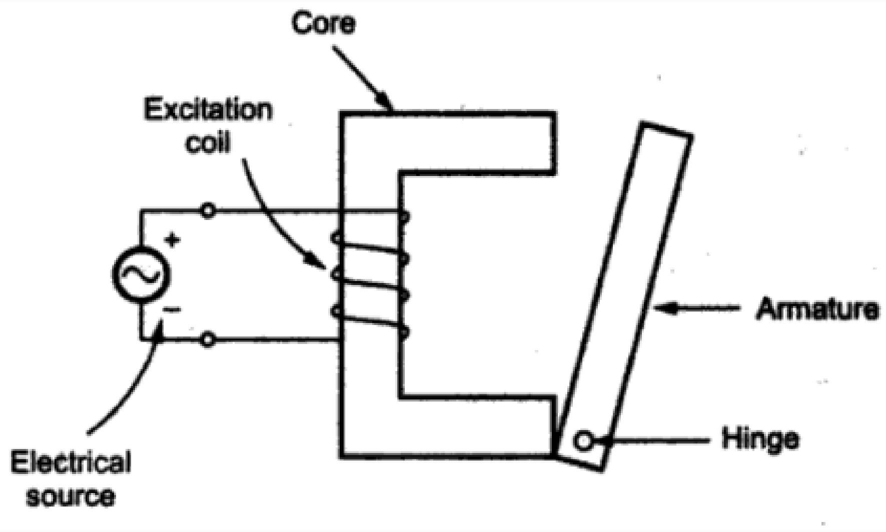
Energy Balance In Motor and Generator

Electrical Energy input from source = Mech Energy Output + Change in stored energy + Energy losses

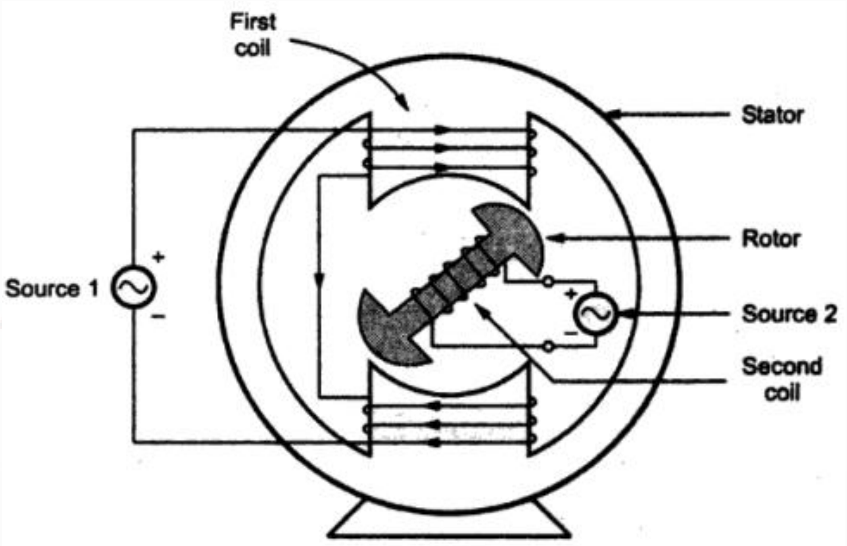
Mech Energy Input = Electrical Energy Output + Change in stored energy + Energy losses

Types of Magnetic Systems

- **Singly Excited System**
  - ✓ A single exciting coil is used to produce the magnetic field.
  - ✓ Ex: Electromagnetic relay, solenoid coil etc…

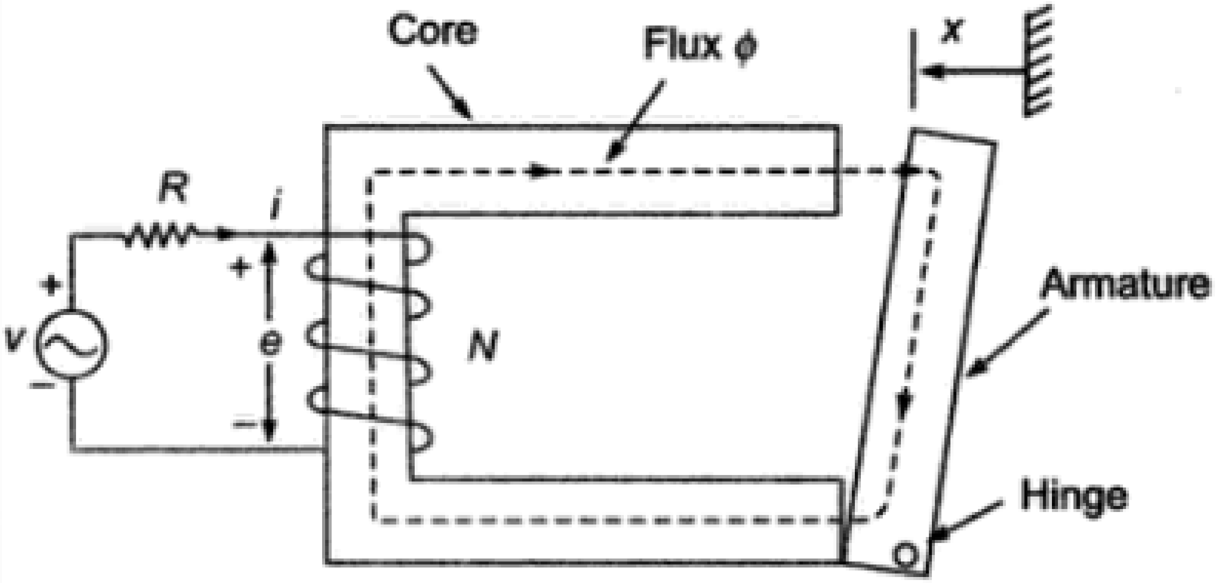


- **Multiply Excited System**
  - ✓ More than one coils are used to produce magnetic field.
  - ✓ Ex: Motors, alternators etc…



Singly Excited Magnetic System

- Derivations of expressions of electrical input, stored energy and the mechanical force.
- Consider an attracted armature relay.



Assumptions

- Exciting coil is lossless.
- No leakage flux. All the flux links with all N turns.

Electrical Energy Input

- Energy can be stored or retrieved from a magnetic system by means of an exciting coil connected to an electric source.
- When a voltage *V* is applied to the coil having *N* turns, a current of *i* will flow to produce a flux of φwebers.
- This flux will link with all N turns and create the flux linkages of,

$$\lambda = N\phi$$

- The EMF induced in the coil is given by,

$$e = N\frac{d\phi}{dt} = \frac{d\lambda}{dt}$$

Electrical Energy Input

- Applying KVL to the coil circuit,

$$V - i.R - e = 0$$

$$V = i.R + e$$

$$V = i.R + \frac{d\lambda}{dt}$$

- The energy input to the coil due to the flow of current i in time dt is,

$$dW_e = e.i\,dt$$

$$dW_e = \frac{d\lambda}{dt}.i\,dt = i.d\lambda = i.d(N.\phi) = N.i.d\phi = \mathcal{F}.d\phi \;\; ---- -1$$

Magnetic Field Energy Stored

- Consider that the armature is fixed at position x. Hence mechanical work done is zero.
- Hence the entire electrical energy input gets stored in the magnetic field.

$$dW_f = dW_e = i.d\lambda = \mathcal{F}.d\phi$$

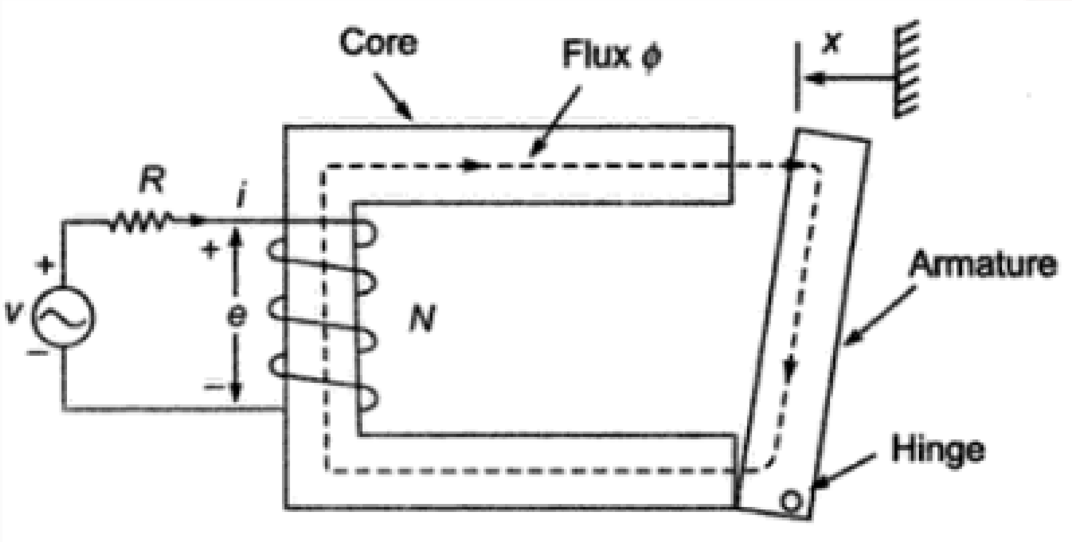
- The energy stored when there is a change in flux or flux linkages can be written as,

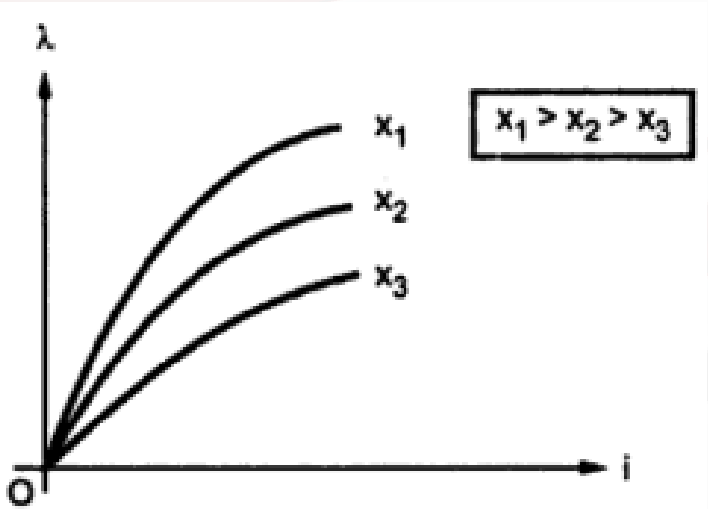
$$W_f = \int_0^{\lambda} i(\lambda)d\lambda = \int_0^{\phi} \mathcal{F}(\phi)d\phi \quad ----2$$

Magnetic Field Energy Stored

i – λ Relationship

- It is similar to the magnetization curve which varies with ***x***.
- The air-gap between armature and core varies with ***x***.
- Total reluctance of the magnetic path decreases with increase in ***x***.





$$i = i(\lambda, x)$$

$$\lambda = \lambda(i, x)$$

Magnetic Field Energy Stored

- Depending upon the independent variable, the stored field energy is also a function of i, x or λ, x.

$$\therefore W_f = W_f(\lambda, x) \quad or \quad W_f = W_f(i, x)$$

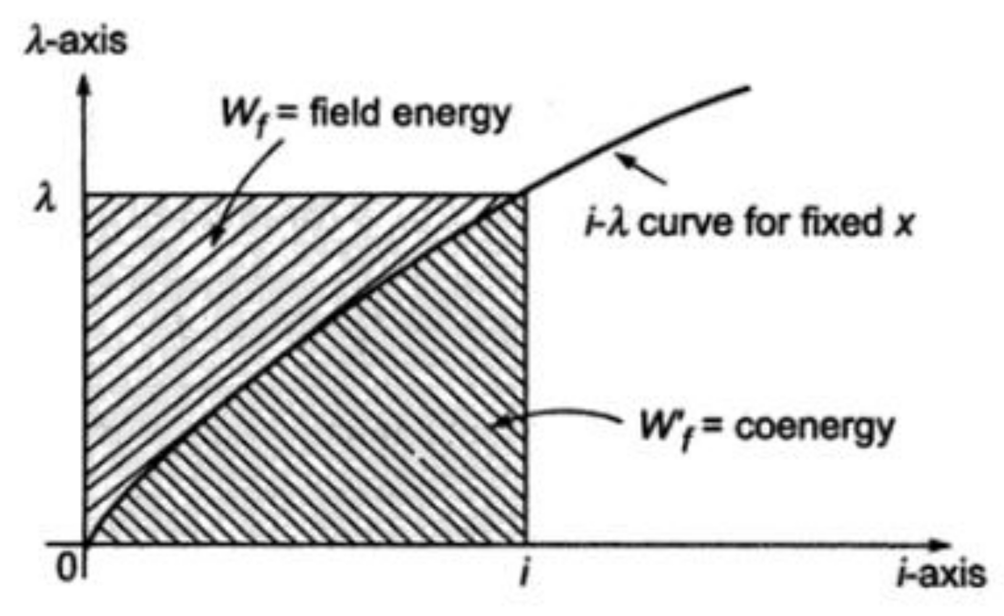
- If x is changed, then energy interchange takes place between the magnetic field and mechanical system.
- If x is constant, then energy interchange takes place between electric system and magnetic field.

Concept of Co – Energy

- As per equation 2, the field energy is the area between λ axis and i-λ curve.
- The area between ***i*** axis and i-λ curve is called co-energy and it is given as,

$$\therefore W_f'(i, x) = i.\lambda - W_f(\lambda, x) --- 3$$

$$\therefore W_f' = \int_0^i \lambda di$$



Concept of Co – Energy

- If i-λ relationship is assumed linear, then the field energy and co-energy will be equal. Hence,

$$W_f = W_f' = \frac{1}{2} i\lambda ----4$$

- We know that the coil inductance is,

$$L = \frac{N\phi}{i} = \frac{\lambda}{i}; \qquad \therefore \lambda = L.i \;\; and \; i = \frac{\lambda}{L}$$

$$\therefore W_f = W_f' = \frac{1}{2}\frac{\lambda^2}{L} = \frac{1}{2}L.i^2 ----5$$

- Where L is a function of x.

Concept of Co – Energy

- It is clear that the field energy W_f is a function of two independent variables λ and x.

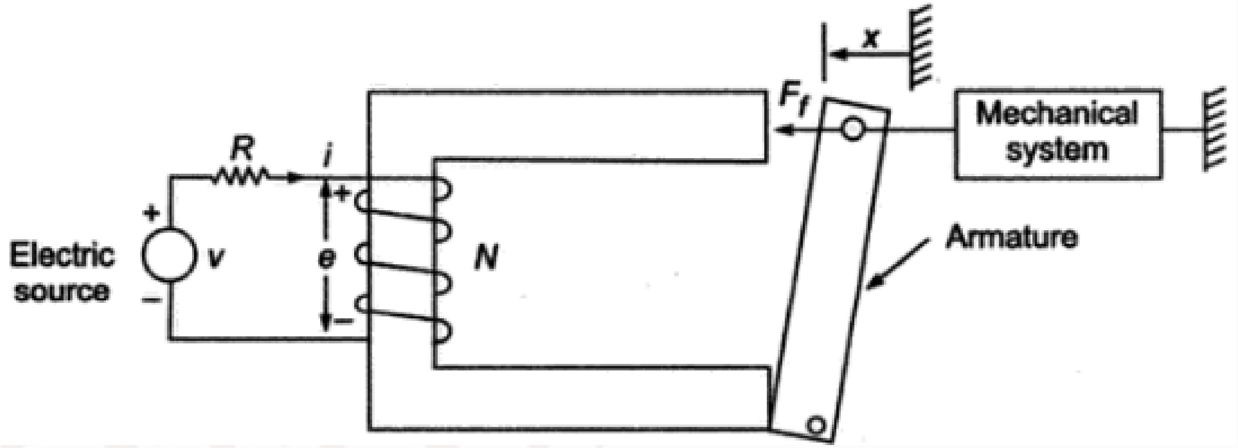
$$W_f(\lambda, x) = \frac{1}{2}\frac{\lambda^2}{L(x)} ---- -6$$

- The co-energy W_f' is a function of two independent variables iand x.

$$W_f'(i, x) = \frac{1}{2}L(x)i^2 ---- -7$$

Mechanical Force

- Consider an attracted armature relay where the magnetic field produces a mechanical force F_f which moves the armature to a distance of dx.



- The mechanical work done is given by,

$$dW_m = F_f dx$$

- Mechanical energy output = Electrical energy input – Stored field energy

$$F_f dx = id\lambda - dW_f ---- -8$$

- In such electromechanical systems, the independent variables can be (i,x) or (λ,x)

Case 1: Independent variables are (i,x). i.e current constant

- Thus λ changes as i and x changes. Hence,

$$\lambda = \lambda(i, x)$$

$$d\lambda = \frac{\partial \lambda}{\partial i} di + \frac{\partial \lambda}{\partial x} dx ---- -9$$

$$W_f = W_f(i, x)$$

$$dW_f = \frac{\partial W_f}{\partial i} di + \frac{\partial W_f}{\partial x} dx ---- -10$$

Substituting eqn 9 and eqn 10 in eqn 8, we get,

$$F_f dx = i\frac{\partial \lambda}{\partial i} di + i\frac{\partial \lambda}{\partial x} dx - \frac{\partial W_f}{\partial i} di - \frac{\partial W_f}{\partial x} dx$$

$$F_f dx = \left(i\frac{\partial \lambda}{\partial x} - \frac{\partial W_f}{\partial x}\right) dx + \left(i\frac{\partial \lambda}{\partial i} - \frac{\partial W_f}{\partial i}\right) di$$

$$F_f dx = \left(i\frac{\partial \lambda}{\partial x} - \frac{\partial W_f}{\partial x}\right) dx$$

$$F_f = i\frac{\partial \lambda}{\partial x} - \frac{\partial W_f}{\partial x}$$

$$F_f = \frac{\partial}{\partial x}(i\lambda - W_f)$$

Case 2: Independent variables are (λ,x). i.e voltage constant

- Thus i changes as λ and x changes. Hence,

$$i = i(\lambda, x)$$

$$W_f = W_f(\lambda, x)$$

$$dW_f = \frac{\partial W_f}{\partial \lambda} d\lambda + \frac{\partial W_f}{\partial x} dx ---- -11$$

Substituting eqn 10 in eqn 8, we get,

$$F_f dx = i d\lambda - \frac{\partial W_f}{\partial \lambda} d\lambda - \frac{\partial W_f}{\partial x} dx$$

$$F_f dx = -\frac{\partial W_f}{\partial x} dx + \left(i - \frac{\partial W_f}{\partial \lambda}\right) d\lambda$$

$$F_f = -\frac{\partial W_f(\lambda, x)}{\partial x}$$

Summary

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- Energy balance
- Types of magnetic systems
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- Concept of Co-energy
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