Chapter 2

Principles of Electro Mechanical Energy Conversion

LEARNING OBJECTIVES

After reading this chapter, you will be able to understand:

- Single excited magnetic systems
- Electrical energy input
- Doubly excited magnetic systems
- MMF produced by polyphase machines
- Armature windings
- Distributed windings
- Pole-pitch
- Coil-pitch or coil-span
- Simplex and multiplex windings
- Closed-winding terms
- Simplex wave winding
- Multiplex lap and wave windings
- Open windings or AC armature windings

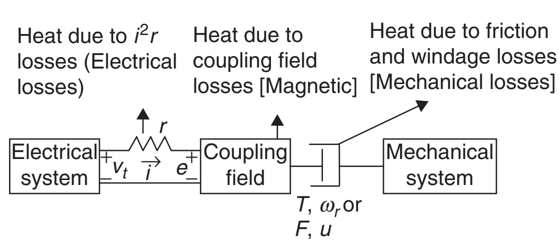
Introduction

Conversion of other forms of energy into electrical energy is a common practice owing to the advantage of electrical energy as it can be transmitted, utilized and controlled more easily, reliably and efficiently. Energy conversion devices are required at both ends of an electrical system, since energy is neither available and nor required in electrical form. An electromechanical energy conversion device is one which converts electrical energy into mechanical energy or vice versa. The operating principles of energy-conversion devices are similar, but their structural details differ depending upon their function. Energy conversion process is basically a reversible process. However in practice, the electromechanical energy conversion devices may be designed and constructed to suit one particular mode of conversion or the other. The electro-mechanical-energy conversion principles are developed with field energy as basis as the field energy concept is more general and broad-based, since it is applicable to all devices possessing rotational, linear or vibratory motions. The energy storing capacity of the magnetic field is much greater (about 25,000 times) than that of the electric field. In view of this fact, electromechanical energy conversion devices with magnetic field as the coupling medium between electrical and mechanical systems are more common in commercial applications.

Various electromechanical energy conversion devices may be categorized as under:

1. Low energy conversion devices such as telephone receivers, loud-speakers, microphones, low signal transducers, etc.
2. The second category consists of force, or torque-producing devices with limited mechanical motion such as electromagnets, relays, moving-iron instruments, moving-coil instruments, actuators, etc.
3. The third category includes bulk energy conversion and utilization devices such as generators and motors. Motors and generators are continuous energy conversion devices.

An electromechanical energy conversion device consists of three essential parts, namely, electrical system, coupling field and mechanical as shown in following figure. The coupling field may be magnetic or electric.



General representation of electromechanical conversion device.

When energy is converted from one form to another, the law of conservation of energy can be invoked. According to this law, energy can neither be created nor be destroyed, it can merely be converted from one form into another.

In an energy conversion device, out of the total input energy, some energy is converted into the required form, some energy is stored and the rest is dissipated. The energy balance equation includes these four terms. For a motor, it can be written as

$$\begin{pmatrix}\text{Total electrical} \\ \text{energy input}\end{pmatrix} = (\text{Mechanical energy output}) + (\text{Total energy stored}) + (\text{Total energy dissipated}) \qquad (1)$$

For generator action

$$\begin{pmatrix}\text{Total mechanical} \\ \text{energy input}\end{pmatrix} = (\text{Electrical energy output}) + (\text{Total energy stored}) + (\text{Total energy dissipated}) \qquad (2)$$

The energy balance equation, i.e., Eq. (1) can be written in more specific terms as

$$\begin{aligned} W_{ei} = W_{mo} &+ (W_{es} + W_{ms}) \\ &+ (\text{Ohmic energy losses}) \\ &+ (\text{Coupling field energy losses}) \\ &+ (\text{Energy losses in mechanical system}) \end{aligned}$$

The subscripts e, m, I, s and o stand for electrical, mechanical input, stored and output respectively.

The various forms of energies involved in Eq. (1) for an electromechanical energy conversion device are given below:

1. Total electrical energy input from the supply mains is W_{ei}.
2. The mechanical energy output is W_{mo}.
3. Total energy stored in any device = Energy stored in magnetic field, W_{es} + Energy stored in mechanical system, W_{ms}.
4. Total energy dissipated = Energy dissipated in electric circuit as ohmic losses + Energy dissipated as magnetic core loss (hysteresis and eddy-current losses) + Energy dissipated in mechanical system (friction and windage losses etc.).

Associated the losses with the corresponding systems Eq. (1) can be rewritten as

$$\begin{pmatrix}\text{Electric energy input} \\ -\text{ ohmic losses}\end{pmatrix} = \begin{pmatrix}\text{Mechanical energy} \\ \text{output + energy} \\ \text{stored in mechanical} \\ \text{system + mechanical} \\ \text{losses (friction \& windage)}\end{pmatrix} + \begin{pmatrix}\text{Energy stored in the} \\ \text{coupling field +} \\ \text{coupling filed} \\ \text{energy losses}\end{pmatrix} \qquad (2a)$$

or

$$W_{elec} = W_{mech} + W_{fld}$$

where

W_{elec} = Net energy input to the coupling field.
W_{mech} = The total energy converted to mechanical form.

[Mechanical energy output + Energy stored in the mechanical system + friction and windage losses] and W_{fld} = Total energy absorbed by the coupling field [which is equal to the sum of both the stored field energy w_{es} and the coupling field energy losses]

$$W_{elec} = W_{mech} + W_{fld} \qquad (2b)$$

The electrical losses (ohmic and coupling – field losses) as well as mechanical losses (friction and windage losses), though always present, play no basic role in the energy conversion process.

Equation (2b) can be written in differential form as

$$dW_{elec} = dW_{mech} + dW_{fld} \qquad (3)$$

where

dW_{elec} = differential electrical energy input to coupling field
dW_{mech} = differential mechanical energy output
dW_{fld} = differential change in energy stored in the coupling field.

From Eq. (1), the differential electrical energy input in time dt is

$$dW_{ei} = v_t i\, dt$$

ohmic loss in resistance r in time dt is $i^2 r\, dt$.

∴ Differential electrical energy input or net energy input to the coupling field,

$$\begin{aligned} dW_{elec} &= dW_{ei} - \text{ohmic loss} \\ &= (V_t - ir)\, i\, dt = ei\, dt \qquad (4) \end{aligned}$$

Equation (3) now becomes

$$ei\, dt = dW_{mech} + dW_{fld} \qquad (5)$$

Energy balance Eq. (5) is obtained by applying law of conservation of energy to the motoring mode. This Eq. (5) along with faradays laws of electromagnetic induction forms the fundamental basis for the analysis of energy-conversion devices.

The coupling field is the link between electrical and mechanical systems.

In order that a moving member can rotate, or move, with respect to the stationary member, an air gap must exist in between the stator and rotator. The energy stored in the coupling field acts as interaction medium between electrical and mechanical systems.

This energy stored in the coupling field must produce action and reaction on electrical and mechanical systems for the conversion of energy from electrical to mechanical (motoring mode) or from mechanical to electrical (generating mode).

If the output is mechanical, the coupling field must react with the electrical system in order to absorb electrical energy from it. In a motor, this reaction is the back emf or counter emf 'e'. The coupling field extracts energy proportional to $e.i$ from the electrical system, converts and delivers energy proportional to $T.\ \omega_r$ (or F.u) to the mechanical system.

If the output is electrical, the coupling field must react with the mechanical system so as to absorb mechanical energy from it. In a generator this reaction is counter-torque T (or reaction torque), opposite to the applied mechanical torque of the prime mover.

Thus, the reaction of the coupling field on the electrical or mechanical system is essential for the process of electromechanical energy conversion.

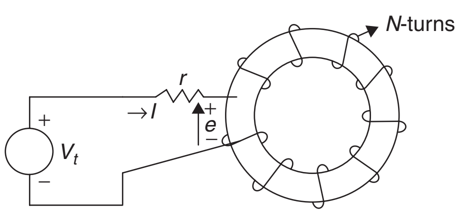
The induced emf 'e' and torque, T are called electromechanical coupling terms as they are associated with the coupling field.

Electromechanical energy conversion devices are slow-moving because of the inertia associated with mechanical components. Therefore the coupling field must be slowly varying and as such the nature of this field is quasi-static. Electromagnetic radiation from the coupling field is almost negligible.

Single Excited Magnetic Systems

Electrical Energy Input

Consider a simple magnetic system of a toroid, excited by a single coil as shown in the figure.



Applying KVL for the electrical circuit, the instantaneous voltage equation can be obtained as $V_t = ir + e$

where e is the reaction emf (or back emf) taken as a voltage drop in the direction of current.

$$\therefore e = \frac{d\psi}{dt} \text{ and } V_t = ir + \frac{d\psi}{dt}$$

Where ψ denotes the instantaneous flux linkages with the circuit, multiplying both sides of Eq. (2) we have

$$V_t\, idt = i^2\, r\, dt + id\psi$$

or $$(V_t - ir)idt = id\psi$$

or $$e\ idt = id\psi$$

$$dW_{elec} = v'_t\, i\, dt = dW_{ei} - \text{ohmic loss} = (v_t - ir)\, i\, dt = eidt.$$

If the toroidal core is made of good magnetic material (ferro-magnetic material), most of the flux would be confined to the core. Assuming that flux ϕ links all the N turns of the coil, we have flux linkages, $\psi = N\phi$

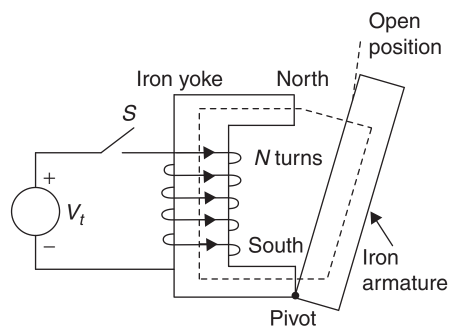
$$dW_{elec} = id\ \psi$$
$$= iN\, d\phi = F\, d\phi \qquad (6)$$

where ϕ is the instantaneous value of the coil flux and $F = iN$ is the instantaneous coil mmf. From Eq. (6) it is evident that the flux linkages of the system must change for the toroid to extract energy from the supply system.

These changing flux linkages cause the generation of reaction emf e (or back emf or counter emf). The flow of current against the reaction emf e causes the extraction of energy from the electrical system or in other words e equals the extracted power from electrical system.

Magnetic Field Energy Stored

Consider a simple magnetic relay shown in following figure.



Initially the switch 'S' and the armature are in open position. When switch 'S' is closed, current i flows through the coil, setting up a flux. The magnetic field thus produced, creates north and south poles on yoke and armature respectively. As a result of the magnetic field there is established a magnetic force that acts on the armature tending to shorten the air-gap. If the armature is not allowed to move, the mechanical work done is zero. i.e. $dW_{mech} = 0$. Therefore from the energy balance equation,

$$dW_{elec} = 0 + dW_{fld}$$

The above relation infers that when the movable part of any physical system is kept fixed, the entire electrical energy input is stored in the magnetic field.

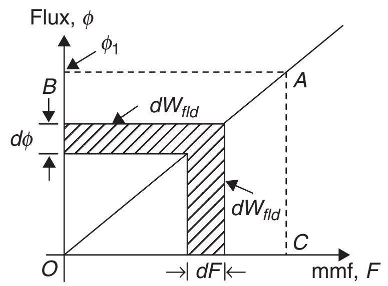
$$\therefore \qquad dw_{fld} = dW_{elec} = id\psi = F{\cdot}d\phi$$

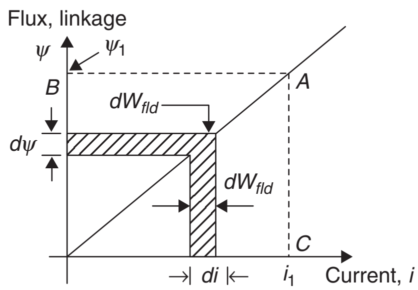
If the initial flux is zero, the magnetic field energy stored W_{fld}, in establishing a flux ϕ, or flux linkage ψ, is given by

$$W_{fld} = \int_0^{\psi_1} i \cdot d\psi = \int_0^{\phi} F \cdot d\phi$$

In the above equation, i must be expressed in terms of ψ and F in terms of ϕ.

When the armature is held open, then most of the mmf is consumed in the air gap and magnetic saturation may not occur. Then ψ and ϕ vary linearly with i and F, respectively.





For figure (a)

$$W_{fld} \int_0^{\phi_1} dW_{fld} = \int_0^{\phi_1} F \cdot d\phi = \text{area OABO}$$

For figure (b),

$$W_{fld} = \int_0^{\psi_1} dW_{fld} = \int_0^{\psi_1} i d\psi = \text{area OABO}$$

and area OACO $= \int dW_{fld}$

$$= \int_0^{F_i} \phi\, dF = \int_0^{i_i} \psi\, di$$

This area OACO is called the co-energy W'_{fld}. Co-energy has no physical significance, it is however useful in calculating the magnetic forces.

With no magnetic saturation

Area OABO = Area OACO or $W_{fld} = W'_{fld}$

and $W_{fld} + W'_{fld}$ = Area OCABO
= Area OABO + Area OACO
$= \phi_1 F_1 = \psi_1 i_1$

In general for a linear magnetic circuit,

$$W_{fld} = W'_{fld} = \frac{1}{2}\psi i = \frac{1}{2} F\phi$$

The magnetic stored energy and co-energy expressed in terms of reluctance and permeance is as follows.

mmf = (flux)(Reluctance)
$= \phi S$

$$= \frac{\phi}{\text{Permeance, } \Delta}$$

$$W_{fld} = W'_{fld} = \frac{1}{2}\phi^2 S = \frac{1}{2}\frac{\phi^2}{\Delta}$$

$$W_{fld} = W'_{fld} = \frac{1}{2}F^2\Delta = \frac{1}{2}\frac{F^2}{S}$$

In terms of self-inductance, $L = \dfrac{\psi}{i}$

$$W_{fld} = W'_{fld} = \frac{1}{2}Li^2 = \frac{1}{2}\frac{\psi^2}{L}$$

The stored magnetic energy W_{fld} and co-energy W'_{fld} can be written as follows

$$W_{fld} = W'_{fld} = \frac{1}{2}F\phi = \frac{1}{2}\psi^i$$

$$= \frac{1}{2}\phi^2 S = \frac{1}{2}\frac{\phi^2}{\Delta} = \frac{1}{2}\frac{F^2}{S}$$

$$= \frac{1}{2}F^2\Delta = \frac{1}{2}Li^2 = \frac{1}{2}\frac{\psi^2}{L}.$$

The magnetic stored energy density is given by

$$W_{fld} = \frac{1}{2}HB = \frac{1}{2}\mu H^2 = \frac{1}{2}\frac{B^2}{\mu} \quad \text{J/m}^3$$

For linear magnetic circuit

$$W'_{fld} = W_{fld}$$

Note: Here W'_{fld} is the co-energy density.

The field-energy approach serves as the physical basis for the generalized theory of electrical machines.

During the moz of armature the electromagnetic force or torque developed in any physical system acts in such a direction as to tend to

1. Decrease the magnetic stored energy at constant ψ or ϕ.
2. Increase both field stored and co-energy at constant current or mmf.
3. Decrease the reluctance.
4. Increase the permeance and inductance.
5. Decrease current i at constant flux linkages ψ or increase flux linkages ψ at constant i.

Examples of singly excited electromagnetic systems.

1. Moving iron instruments
2. Relays
3. Electromagnets
4. Reluctance motor, etc.

$$\text{Magnetic force, } f_e = \frac{-1}{2}\psi\frac{\partial i}{\partial x}(i, x)$$

If ψ is expressed in terms of i and x

$$f_e = \frac{1}{2} i \frac{\partial \psi}{\partial x}(i, x)$$

where 'x' is the displacement of the armature in the direction of magnetic force.

The electromagnetic torque,

$$T_e = \frac{-1}{2} \phi^2 \frac{dS}{d\theta} = \frac{1}{2} I^2 \frac{dL}{d\theta}$$

$$= \frac{-1}{2} \psi \frac{\partial i}{\partial \theta}(\psi, \theta)$$

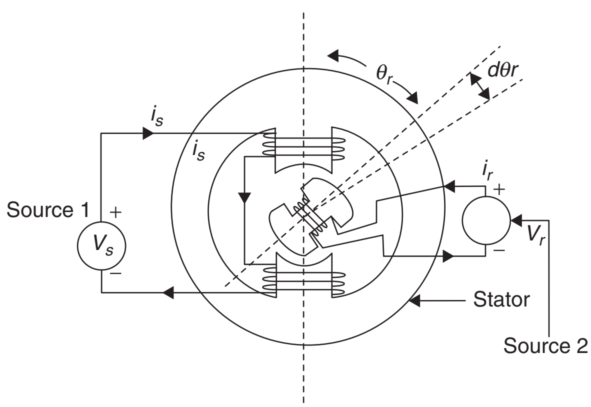
$$= \frac{1}{2} i \frac{\partial \psi}{\partial \theta}(i, \theta)$$

Doubly Excited Magnetic Systems

Most of the electromagnetic energy conversion devices belong to doubly excited or multiply excited magnetic systems. A doubly excited magnetic system is one which has two independent sources of excitations.

For example, Synchronous machines, DC shunt machines, loud speakers, tachometers, etc.

The following figure shows a simple model of doubly excited magnetic system.



Doubly excited magnetic system

The stator with N_s turns is energized from source 1 and the rotor with N_r turns is excited from source 2. The mmf's (or rmf's) produced by both the stator and rotor windings are in the same direction and the electromagnetic torque, T_e is in the counter clockwise direction as shown in fig. The magnetic saturation and hysteresis are neglected in the following developments. The differential electrical energy input dW_{elec} for the doubly excited system from two energy sources 1 and 2 is

$$dW_{elec} = i_s\, d\psi_s + i_r\, d\psi_r \tag{7}$$

where ψ_s and ψ_r are the instantaneous total flux linkages of stator and rotor windings respectively. Since the magnetic saturation is neglected, ψ_s and ψ_r can be expressed as

$$\psi_s = L_s\, i_s + M_{sr}\, i_r$$

$$\psi_r = L_r\, i_r + M_{rs}\, i_s$$

where L_s and L_r are the self-inductances of the stator and rotor windings, respectively, and

$M_{sr} = M_{rs}$ = mutual inductance between the stator and rotor windings.

Initially the space angle between stator and rotor axes is θ_r and both the currents i_s and i_r are assumed to be zero. On switching the stator and rotor windings to their respective energy sources, the currents rise from zero to i_s and i_r, respectively. If the rotor is not allowed to move, then $dW_{mech} = 0$.

$$\therefore \qquad dW_{elec} = 0 + dW_{fld}$$

Thus, with rotor held fixed, all the energy supplied by sources is stored in the magnetic field.

From Eq. (7)

$$dW_{fld} = dW_{elec} = i_s\, d\psi_s + i_r d\psi_r$$

$$= i_s\, d(L_s\, i_s + M_{sr}\, i_r) + i_r\, d(L_r\, i_r + M_{rs}\, i_s) \tag{8}$$

L_s, L_r and $M_{sr}(=M_{rs})$ are given by

$$L_s = \frac{N_s^{\,2}}{S_s},\; L_r = \frac{N_r^{\,2}}{S_r}$$

$$M_{sr} = M_{rs} = \frac{N_s N_r}{S_{sr}}$$

where S_s = reluctance seen by the stator flux
S_r = reluctance seen by the rotor flux
S_{sr} = reluctance seen by the resultant of stator and rotor fluxes.

Since the rotor is not allowed to move, the reluctances and therefore the inductances are constant.

$$\therefore \qquad dL_s = dL_r = dM_{sr} = dM_{rs} = 0$$

From Eq. (3), we can have

$$dW_{fld} = i_s\, L_s\, di_s + i_s\, M_{sr}\, di_r + i_r\, L_r\, di_r + i_r\, M_{sr}\, di_s$$

$$= i_s\, L_s\, di_s + i_r\, L_r\, di_r + M_{sr}\, d(i_s\, i_r)$$

Therefore, the magnetic field energy stored in establishing the currents from zero to i_s and i_r is given by

$$W_{fld} = L_s \int_0^{i_s} i_s\, d\, i_s + L_r \int_0^{i_r} i_r\, di_r + M_{sr} \int_0^{i_s} d(i_s\, i_r)$$

$$= \frac{1}{2} i_s^{\,2}\, L_s + \frac{1}{2} i_r^{\,2}\, L_r + M_{rs}\, i_s\, i_r$$

For obtaining the magnetic torque T_e, assume the rotor to move through a virtual displacement $d\theta_r$ in the direction of T_e. With rotor movement, reluctances S_s, S_r, S_{sr} and therefore L_s, L_r, M_{sr} must vary.

Therefore, the differential electrical energy input dW_{elec} during virtual displacement $d\theta_r$ is given by

$$dW_{elec} = i_s\, d[L_s\, i_s + M_{sr}\, i_r] + i_r\, d[L_r\, i_r + M_{sr}\, i_s]$$
$$= i_s\, L_s\, di_s + i_s^{\,2} dL_s + i_s\, M_{sr}\, di_r + i_s\, i_r\, dM_{sr}$$
$$+ i_r\, L_r\, di_r + i_r^2\, dL_r + i_r\, M_{sr}\, di_s + i_r\, i_s\, dM_{sr}$$

and the differential magnetic energy stored dW_{fld}, during the virtual displacement $d\theta_r$ is given by

$$dW_{fld} = \frac{1}{2} i_s^{\,2} dL_s + L_s i_s\, d\, i_s + \frac{1}{2} i_r^{\,2}\, dL_r + L_r\, i_r di$$
$$+ M_{sr}\, i_s\, d\, i_r + M_{sr}\, i_r\, d + i_s\, i_r\, dM_{sr} + i_s i_r dM_{sr}$$

The differential mechanical work done dW_{mech} during the virtual displacement $d\theta_r$ is given by

$$dW_{mech} = T_e\, d\theta_r$$

From the energy balance equation,

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

substituting the value of dW_{elec} dW_{mech} and dW_{mech} and on simplification, we get

$$T_e = \frac{1}{2} i_s^{\,2} \frac{dL_s}{d\theta_r} + \frac{1}{2} i_r^{\,2} \frac{dL_r}{d\theta_r} + i_s i_r \frac{d\,M_{sr}}{d\theta_r}$$

It can be seen from the above equation of T_e, that the differential changes di_s and di_r do not contribute to the production of magnetic torque T_e (In other words, T_e is independent of di_s and di_r)

Therefore torque depends on

1. Instantaneous values of currents i_s and i_r and
2. The angular rate of change of inductances,

If W_{fld} is differentiated with respect to the space angle θ_r (with constant i_s and i_r) then the electromagnetic torque T_e is given by

$$T_e = \frac{\partial W_{fld}}{\partial \theta_r}(i_s, i_r, \theta_r)$$

i.e., torque can be obtained from the space derivative of field energy expression, when it is expressed in terms of i_s, i_r and θ_r.

Integration of dW_{elec}, with constant currents, gives

$$W_{elec} = \int dw_{elec}$$
$$= i_s^{\,2}\, L_s + i_r^{\,2}\, L_r + 2 i_s\, i_r\, M_{sr}$$

For a linear magnetic circuit, $W_{fld} = W'_{fld}$

$$\therefore T_e = \frac{\partial W'_{fld}}{\partial \theta_r}(i_s, i_r, \theta)$$

If the electrical energy input takes place at constant currents, then half of it is converted to mechanical energy, and the remaining half is stored in the magnetic field at constant currents.

In other words, the magnetic energy stored at constant currents is equal to the mechanical work done.

The linear magnetic force f_e, for a doubly excited system can be obtained as follows.

The differential electrical energy input dW_{elec}, from two energy sources is

$$dW_{elec} = i_1\, d\psi_1 + i_2\, d\psi_2$$

Where

$$\psi_1 = L_1\, i_1 + M_{12}\, i_2$$
$$\psi_2 = L_2\, i_2 + M_{21}\, i_1$$

Also $M_{12} = M_{21}$

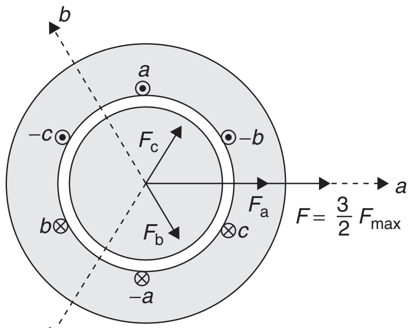
$$f_e = \frac{1}{2} i_1^2 \frac{dL_1}{dx} + \frac{1}{2} i_2^2 \frac{dL_2}{dx} + i_1\, i_2 \frac{dM_{12}}{dx}$$
$$f_e = \frac{\partial W_{fld}}{\partial x}(i_1, i_2, x)$$
$$= \frac{\partial W'_{fld}}{\partial x}(i_1, i_2, x)$$

MMF Produced by Polyphase Machines

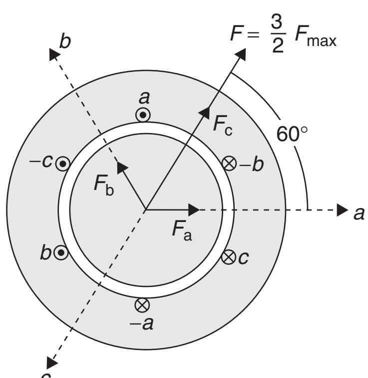
The production of a rotating mmf can be shown graphically. Consider the state of affairs at $t = 0$, the moment when the phase – a current is at its maximum value I_m. The mmf of phase a then has its maximum value F_{max}, as shown by the vector $F_a = F_{max}$ drawn along the magnetic axis of phase a in the two – pole machine shown schematically in figure (a). At this moment, currents i_b and i_c are both $I_m/2$ in the negative direction, as shown by the dots and crosses in figure (a) indicating the actual instantaneous directions. The corresponding mmf's of phases b and c are shown by the vectors F_b and F_c, both of magnitude $F_{max}/2$ drawn in the negative direction along the magnetic axes of phases b and c, respectively. The resultant, obtained by adding the individual contributions of the three phases, is a vector of magnitude $F = \frac{3}{2} F_{max}$ centred on the axis of phase α. It represents a sinusoidal space wave with its positive peak centred on the axis of phase α and having an amplitude $\frac{3}{2}$ times that of the phase–α contribution alone.

At a later time $\omega_e t = \pi/3$ the currents in phases α and b are a positive half maximum, and that in phase c is a negative maximum. The individual mmf components and their resultant are now shown in Figure (b). The resultant has the same amplitude as at $t = 0$, but it has now rotated counterclockwise 60 electrical degrees in space. Similarly, at $\omega_e t = 2\pi/3$ (when the phase-b current is a positive maximum and the phase–α and phase–c currents are a negative half maximum) the same resultant mmf distribution is again obtained, but it has rotated counterclockwise 60 electrical degrees still father and is now aligned with the magnetic axis of phase b figure c. As time passes, then, the resultant mmf wave retains its sinuso*id*al form and amplitude but rotates progressively around the air gap; the net result can be seen to be an mmf wave of constant amplitude rotating at a uniform angular velocity.

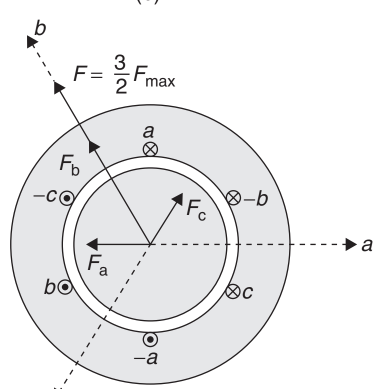
In one cycle the resultant mmf must be back in the position of Figure (a). The mmf wave therefore makes one revolution per electrical cycle in a two-pole machine. In a multipole machine the mmf wave trave*ls* one pole-pair per electrical cycle and hence one revolution in pole/2 electrical cycles.



(a)



(b)



(c)

Solved Examples

Example 1: A coil of 1000 turns on a core would create a flux of 2 m Wb when carrying a current of 1 A. Calculate the energy stored in the magnetic field.

Solution: Flux linkages $\Psi = N\phi$

$$= 1000 \times 2 \times 10^{-3}$$

$$= 2 \text{ Weber-turns}$$

Energy stored in the magnetic field

$$= \frac{1}{2}\psi i$$

$$= \frac{1}{2} \times 2 \times 1 = 1 \text{ J}$$

Example 2: One 800-turn flat coil with an area of 5×10^{-2} m^2 is rotating in a magnetic field of flux density 60×10^{-3} Wb/m^2

Solution: emf induced, $e = N\,\phi\,\omega \sin\theta$

Here $\theta = 90°$.

$$\phi = 5 \times 10^{-2} \times 60 \times 10^{-3}$$

$$= 3 \times 10^{-3} \text{ Wb}$$

$$\omega = \frac{2\pi \times 1500}{60} = 50\pi \text{ rad/s}$$

And $N = 800$ turns

$$e = 800 \times 3 \times 10^{-3} \times 50\pi$$

$$= 377 \text{ V}$$

Armature Windings

There are two types of windings that are used in rotating electrical machines, namely

1. Concentrated windings
2. Distributing windings

Concentrated Winding

All the turns of the winding are wound together in series to form one multi-turn coil. In concentrated windings, all the turns have the same magnetic axis.

Example: Field winding of salient-pole synchronous machines and DC machines, primary and secondary windings of a transformer.

Distributed Windings

All the winding turns are arranged in several full-pitch or fractional (short) – pitch coils which are housed in the slots spread around the air-gap periphery to form phase or commutator winding.

Example: Stator and rotor windings of induction machines, armature windings of both synchronous and DC machines.

The field (or exciting) windings produces the working flux. The armature winding is one in which working emf is induced by the working flux.

The armature windings, in general are classified as

1. Closed windings and
2. Open windings

The closed windings are used only for commutator machines, such as DC machines and AC commutator (e.g.: universal motor) machines. The open windings are used only for AC machines like synchronous machines, induction machines etc.

In closed windings, there is a closed path, i.e., if one starts from any point on the winding and traverses it, one again reaches the starting point from where one had started, whereas the open windings terminate at a suitable number of slip-rings or terminals.

Note: Three phase delta connected winding used for AC machines forms a closed circuit. This delta can, however, be open-circuited and reconnected in star if desired. The closed circuit in a delta connected winding is a result of interconnection of the armature windings of different phases. The closed windings used for commutator machines can, in no case, be open-circuited.

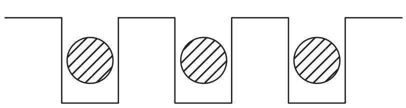
Some of the terms common to both the open and closed armature windings are described below.

1. **Conductor:** The active length of wire which takes part in energy-conversion process.
2. **Turn:** One turn consists of two conductors.
3. **Coil:** A coil may consist of any number of turns. E.g. a coil having one turn is called one-turn coil. A multi-turn coil is one which has more than one-turn.
4. **Coil-sides:** One coil with any number of turns has two coil-sides.
   No. of coil sides = 2 × No. of coils
   Each coil-side will have several conductors.

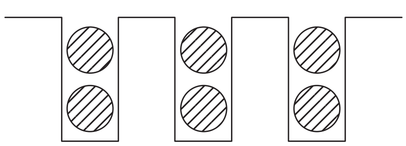
Single-layer and Double-layer Windings

In a single-layer winding, one coil-side occupies the total slot area.

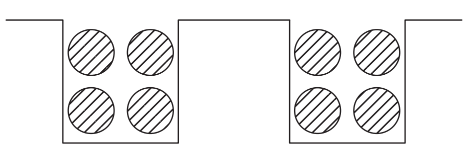
In case the slot contains even number of coil-sides (may be 2, 4, 6, etc.) the winding is referred to as a two-layer winding.



Single layer



Double layer winding (2 coil sides per slot)



Double layer winding (4 coil sides per slot)

The one occupying the upper portion of the slot is called top layer and the other bottom layer.

If one coil-side of a coil occupies the top position in a slot, the other occupies the bottom position in a slot which is one coil-pitch apart.

Advantages of double-layer windings:

1. Easier to house the winding in slots during repairs.
2. Leakage reactance is low which results in better performance.
3. Better induced emf waveform in case of generators.
4. In a single-layer winding, variety of coils that are of different sizes and shapes are used. In double-layer windings, identical diamond-shaped coils are used. So they are more economical.

Pole-pitch

The term 'pitch' indicates a particular method of measurement in terms of coil sides, teeth etc. A pole pitch is defined as the peripheral distance between identical points on two adjacent poles. Pole pitch is always equal to 180° electrical.

Coil-pitch or Coil-span

The distance between the two coil-sides of a coil measured in terms of teeth, slots or electrical degrees.

Chorded-coil

A coil with full-pitch will have the coil-span equal to the pole-pitch. If the coil-pitch is less than pole-pitch, then it is called chorded, short-pitch or fractional-pitch coil.

If there are S slots (or teeth) and P poles, then

$$\text{Pole pitch} = \frac{S}{P} \text{ slots per pole}$$

$$\text{For a full-pitched coil, coil pitch} = \frac{S}{P}$$

Incase coil-pitch < $\frac{S}{P}$ it results in chorded, short pitched or fractional-pitch winding. The coil-pitch is rarely greater than pole pitch. In such a case, for a full-pitched coil $\frac{S}{P}$ must be a positive integer.

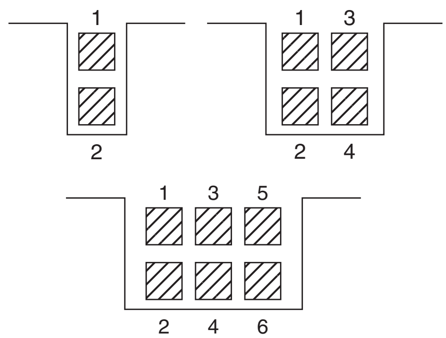
Simplex and Multiplex Windings

In case higher current ratings are to be obtained with given size of a conductor, multiplex windings are used.

In some cases, the number of parallel circuits may not be adequate enough from design considerations. For example in an 8-pole commutator machine, simplex wave winding gives only 2 parallel paths. In case the parallel paths required are in between 2 and 8 or more than 8, then multiplex windings are employed.

Closed-winding Terms

In commutator machines having closed windings, the coil sides for convenience are numbered as shown in the following figure.



The top coil-sides are numbered 1, 3, 5…. and bottom coil sides are numbered 2, 4, 6….

Back Pitch (Y_b)

The distance between the top and bottom coil sides of one coil, measured at the back of armature (or measured at the rear side of the commutator) is called back pitch.

Front Pitch (Y_f)

The distance between the two coil-sides connected to the same commutator segment, is called front pitch.

For convenience, Y_b and Y_f are expressed in terms of coil sides.

Winding Pitch (Y_w)

The distance between the two consecutive and similar top, or bottom coil sides as the winding progresses is called the winding pitch. It is expressed in terms of coil-sides. The winding pitch Y_w is always even, because it is equal to either the difference or the addition of two odd numbers Y_b and Y_f.

For simplex lap winding

$$Y_w = Y_b - Y_f \text{ (progressive)}$$
$$Y_w = Y_f - Y_b \text{ (retrogressive)}$$

For simplex wave winding

$$Y_w = Y_b + Y_f$$

Commutator Pitch (Y_c)

The distance between the two commutator segments, to which ends of one coil are joined, is called the commutator pitch. Y_c is always expressed in terms of commutator segments.

The armature windings are of two types, namely (i) Lap winding (ii) Wave winding.

In lap winding, the two coil-ends of a coil are connected to the two adjacent commutator segments. In other words, for simplex lap winding each commutator segment has two coil-ends connected to it one coil-end is from the top coil-side of the one coil and the other coil-end is from the bottom coil-side of the adjacent coil.

In simplex wave winding, the two coil-ends of a coil are bent in opposite directions and connected to the commutator segments which are approximately two pole-pitches (i.e., 360° electrical) apart. In wave winding also, each commutator segment has two coil-ends connected to it one from the top coil-side and the other from bottom coil-side.

If lap coils are traversed, the movement is forward and backward alternately, whereas for wave winding, the movement is forward (or backward for retrogressive) only. In both lap and wave windings, all the coils in one parallel path are connected in series.

Simplex Lap Windings

Let C be the number of armature coils and P the number of poles. Since each coil has two coil-sides, total number of coil-sides is $2C$. The back pitch Y_b, almost equal to pole pitch, must be odd

$$\therefore \qquad Y_b = \text{coil-sides per pole} \pm K \text{ or } Y_b = \frac{2C}{P} \pm K$$

where K is a number (integer or fraction) added to $2C/P$ to make Y_b an odd integer. Hence, $2C/P$ is equal to pole pitch in terms of coil-sides per pole.

For the progressive simplex lap winding

$$Y_w = Y_b - Y_f = +2 \text{ and } Y_c = \pm 1$$

For simplex retrogressive lap winding

$$Y_w = Y_b - Y_f = -2 \text{ and } Y_c = -1$$

Split Coils

In the process of winding design, a situation may arise where same coils with their top coil-sides together in one slot, may not have their bottom coil-sides together in another slot. Such cases arise only when there are more than two coil-sides per slot. These coils with their top coil-sides in one slot and bottom coil-sides in two different slots are called split coils. The split coils are helpful in commutation but the labour charges increase significantly.

Simplex Wave Winding

In simplex wave winding, two ends of a coil are connected to the commutator segments which are approximately 360° electrical apart.

The number of commutator segments is equal to the number of coils.

For a P-pole machine there are $P/2$ commutator pitches,

$$\frac{P}{2} Y_c = C \pm 1 \text{ or } Y_c = \frac{C \pm 1}{P/2}$$

where C is the number of coils or commentator segments.

Winding pitch for a simplex wave winding is

$$Y_w = \frac{2C \pm 2}{P/2} = 2Y_C$$

Note: +sign for progressive and –sign for retrogressive windings.

Wave winding is also known as series winding. The cause of designating it as wave windings is that during the traverse of a parallel path, one moves through the winding in a wave like progression.

Dummy Coils

For simplex wave winding the equation $Y_c = \frac{C \pm 1}{P/2}$ must be satisfied. If this relation is not fulfilled, then two ends of one (or more) coil may be cut off, insulated and not connected to the commutator segments. This unused and inactive coil, though placed in the armature slots for mechanical balance is called a dummy or dead coil. In order to have symmetrical armature winding, a dummy coil should be avoided as far as possible. However, it may be used in low-rating commutator machines where armature core with existing number of slots have to be used in order to avoid extra expenditure on new punching tools etc.

Note: If dummy coils are to be avoided, then $\frac{S}{P/2}$ should not be an integer.

Multiplex Lap and Wave Windings

$Y_c = \pm m$ for lap winding and $Y_c = \frac{C \pm m}{P/2}$ for wave winding

Where m is multiplicity of winding.

In the above expressions for Y_c positive sign is used for progressive winding and negative sign for retrogressive winding.

The number of armature parallel paths, A. In lap winding, $A = mp$ and in wave winding $A = 2$ m.

Multiplex wave windings are rarely used in DC machines.

Double layer windings are used in DC machines invariably.

Example 3: A synchronous generator with a synchronous reactance of 1.3 p.u. is connected to an infinite bus whose voltage is 1 p.u., through an equivalent reactance of 0.2 p.u., for maximum output of 1.2 pu, the alternator emf must be

(A) 1.5 p.u. (B) 1.56 p.u.
(C) 1.8 p.u. (D) 2.5 p.u.

Solution: (C)

$$P = \frac{EV_t}{X} \sin\delta$$

$$P_{\max} = \frac{EV_t}{X}$$

$$\Rightarrow E = \frac{X P_{\max}}{V_t}$$

$$\Rightarrow \frac{(0.2+1.3)\times 1.2}{1} = 1.8 \text{ p.u.}$$

Equalizer Rings

In order to avoid overloading and sparking at the brushes which is caused by unequal emf's of parallel paths it is essential to take some steps so that circulating currents are not handled by the brushes. An equalizer ring is a low resistance conductor wire which connects together the points in the armature winding which should be at same potential whose function is to cause the armature currents to flow within the armature itself, without letting them pass through the brushes. It is used to provide equalizer rings at the back of the armature, i.e., at the other side of the commutator.

Note: Equalizer rings are not required for simplex wave windings even if there is magnetic unbalance because the coil-sides in two parallel paths are distributed under all the poles. Therefore both the parallel circuits affected equally ad there is no need of equalizer rings in simplex wave windings.

Advantages of Wave Windings Over Lap Windings

1. A wave winding required only two brushes (or two sets of brushes) whereas lap winding requires brushes equal to the number of poles.
   A wave winding may be fitted with as many brushes as the number of poles. In such a case, if one or more brushes develop poor contact with the commutator, the commutator machine continues operating satisfactorily whereas this is not possible in case of lap-connected machines.
2. Equalizer rings are required for lap-connected machines for obtaining better commutation, whereas wave windings do not require any equalizer ring.
3. Lap-connected machines require more brushes and equalizer rings hence they are costly compared to wave-connected machines.

Lap windings are used on low-voltage (medium power (50 to 500 kW) and high power (above 500 kW) machines. Wave windings are used on high voltage low-power (less than 50 kW) and medium power machines.

Wave windings are preferred because of the fact that they do not require equalizer-rings and are less expensive. However for armature currents more than 400 A, lap winding is the only choice. It is because for armature currents above 400 A, current per path in wave winding would be more than 200 A and such a high current leads to poor commutation in wave-wound machines.

In addition to Lap and wave windings, there is another type of winding called composite winding or frog-leg winding which is a combination of simplex lap and multiplex wave windings and requires no equalizer rings. This type of winding is used mainly on high-power commutator machines.

Open Windings or AC Armature Windings

AC machines do not require a commutator and their armature windings are open at one or more points. In commutator machines, the turns per coil are limited for obtaining better commutation. But in machines without commutator, there is no such restriction on the choice of number of turns per coil.

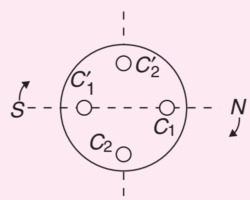
Closed or commutator windings are always double layer windings whereas AC armature windings may be single layer or double layer. Single layer windings are used for small AC machines, whereas double layer windings are used for machines above 5 kW.

Previous Years' Questions

1. A rotating electrical machine having its self-inductances of both the stator and the rotor windings, independent of the rotor position will be definitely not develop **[2004]**

(A) starting torque
(B) synchronizing torque
(C) hysteresis torque
(D) reluctance torque

2. Two magnetic poles revolve around a stationary armature carrying two coils ($c_1 - c'_1$, $c_2 - c'_2$) as shown in Figure. Consider the instant when the poles are in a position as shown. Identify the correct statement regarding the polarity of the induced emf at this instant in coil sides c_1 and c_2. **[2005]**



(A) ⊙ in c_1, no emf in c_2
(B) ⊗ in c_1, no emf in c_2
(C) ⊙ in c_2, no emf in c_1
(D) ⊗ in c_2, no emf in c_1

3. Distributed winding and short chording employed in AC machines will result in **[2008]**

(A) increase in emf and reduction in harmonics
(B) reduction in emf and increase in harmonics
(C) increase in both emf and harmonics
(D) reduction in both emf and harmonics.

Answer Keys

Previous Years' Questions

1. D **2.** A **3.** D