Electrical Engineering

Electric Machines

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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Electric Machines

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CHAPTER 1

Magnetic Circuits

Introduction

The electromagnetic system is an essential element of all rotating electric machinery and electromechanical device and static devices like the transformer. Electromechanical energy conversion takes place via the medium of a magnetic field or electrical field, but most practical converters use magnetic field as the coupling medium between electrical and mechanical systems. In transformers, the electrical energy convert from one electrical circuit to another electrical circuit via the medium of a magnetic field as the coupling medium between one electrical circuit to another electrical circuits. This is due to fact that the energy storing capacity of magnetic field is much greater than that of the electric field.

1.1 Magnetic Circuits

- The complete closed path followed by the lines of flux is called a magnetic circuit. In low power electrical machines, magnetic field is produced by permanent magnets. But in high-power electrical machinery and transformers, coupling magnetic field is produced by electric current.

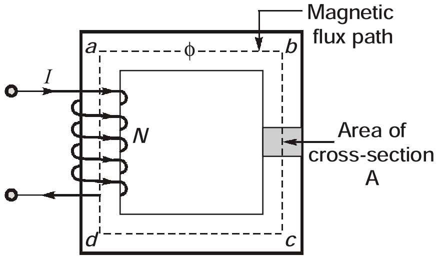


***Figure*-1.1 :** *Magnetic circuit*

- In a magnetic circuit, the magnetic flux is due to the presence of a magnetomotive force same as in an electric circuit, the current is due to the presence of a electromotive force.
- The mmf is created by a current flowing through one or more turns.

$$MMF = \text{Current} \times \text{Number of turns in the coil}$$

$$f = MMF = NI \text{ (ampere-turns) or (ATs)}$$

- The magnetic flux ϕ may be defined as the magnetomotive force per unit reluctance.

$$\boxed{\phi = \frac{\text{MMF}}{\text{Reluctance}}}$$

where reluctance in magnetic circuit is same as resistance in electric circuit.

- It means the opposition offered by the magnetic flux is called reluctance,

$$\boxed{Rl = \frac{l}{\mu A}} \text{ AT/wb}$$

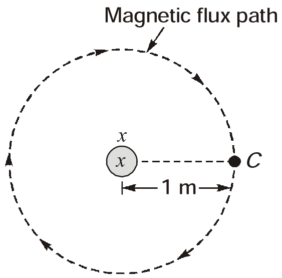


Figure-1.2

where,

l = length of the magnetic path

A = area of cross-section normal to flux path, m^2.

$\mu = \mu_0 \cdot \mu_r$ = permeability of the magnetic material

μ_r = relative permeability of the magnetic material

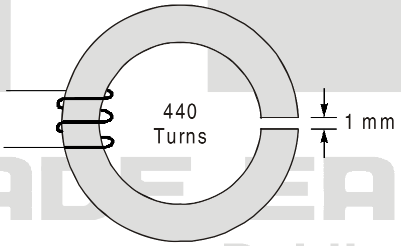
μ_0 = permeability of free space = $4\pi \times 10^{-7}$ H/m.

Here the concept of permeability can be understand in easy way with following examples.

Suppose a current I carrying conductor in a free space. (Figure 1.2).

According to the right hand grip rule, around the current carrying conductor a magnetic flux path is generated. Actually right hand grip rule stated that grip the conductor with thumb pointing in the direction of conductor current then four fingers give the direction of magnetic flux created by the current.

Example 1.1 An iron ring with a mean length of magnetic path of 20 cm and of small cross-section has an air gap of 1 mm. It is wound uniformly with a coil of 440 turns. A current of 1 A in the coil produces a flux density of $16\pi \times 10^{-3}$ Wb/m^2. Neglecting leakage and fringing, calculate the relative permeability of iron.



Solution:

The above figure shows an iron ring of mean length = 20 cm = ℓ_1

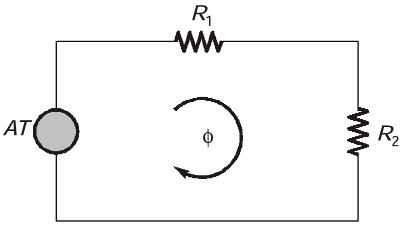
Length of air gap = 1 mm = 1×10^{-3} m = ℓ_1

Number of turns would = 440 turns = N

Current in the coil = 1 A = I

Flux density = $16\pi \times 10^{-3}$ Wb/m^2 = B

The electrical equivalent is as shown given figure,



Here, R_1 = Reluctance of iron.

R_2 = Reluctance of air gap.

$\therefore \quad AT = \phi(R_1 + R_2)$

$\phi = BA \; (A = \text{Area})$

$$AT = BA\left(\frac{\ell_1}{\mu_0\mu_1 A} + \frac{\ell_2}{\mu_0 A}\right) = \frac{B}{\mu_0}\left[\frac{\ell_1}{\mu_1} + \ell_2\right]$$

1.3 Fringing

At an air-gap in a magnetic core, the flux fringes out into neighboring air path as shown in the given Figure-1.3. Longer the air gap, more is the flux fringing. The effect of fringing flux is to increase the effective cross-sectional area of the air gap. As a result, flux density in the air gap is not uniform and average flux density gets reduced,

$$\therefore \qquad B = \frac{\phi}{A}$$

If area of air gap increases then total area of core with consideration of air gap increases. Then average flux density gets reduced.

1.4. Induced EMF

Faraday's law of electromagnetic induction states that an e.m.f is induced in a coil when the magnetic flux linking this coil change with time.

$$e \propto \frac{d\psi}{dt} \propto \frac{d(\phi N)}{dt}$$

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

where,
e = e.m.f. induced in volts
N = Number of turns in the coil
Ψ = $N\phi$ = Flux linkages with the coil, wb-turns
t = time, seconds.

Here minus (–) sign shows that induced current opposes very cause of its production. This theory is called Lenz's law. According to this law; the induced current develops a flux which always opposes the change responsible for inducing this current.

Example 1.4 The laws of electromagnetic induction (Faraday's and Lenz's laws) are summarized in the following equation:

(a) $e = iR$
(b) $e = \frac{Ldi}{dt}$
(c) $e = -\frac{d\Psi}{dt}$
(d) None of these

Solution: **(c)**

Example 1.5 "In all cases of electromagnetic induction, an induced voltage will cause a current to flow in a closed circuit in such a direction that the magnetic field which is caused by the current will oppose the change that produces the current" is the original statements of

(a) Lenz's law
(b) Faraday's law of magnetic induction
(c) Fleming's law
(d) Ampere's law

Solution: **(a)**

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Chapter 4

Synchronous Machine

Introduction

Alternator is a rotating machine, generating alternating voltage in case of DC machine, the alternating voltage generated in the armature is converted into DC voltage using commutator segments whereas in alternator the voltage is tapped through slip rings. Since alternator is used to produce AC voltages, no rotating commutator is needed. The armature need not necessarily be a rotating member. Practical considerations of design (especially the problem of insulation) make for a construction embodying a rotating field structure and a stationary armature called stator in all generator. The advantages of stationary armature are:

(*i*) The mechanical force (centrifugal force) on the armature coils is reduced; better insulation than in a rotating armature.

(*ii*) The high voltage (of the order of 11 kV, 33 kV and above) generated in the armature winding need not be brought to external circuit through slip rings and sliding contacts, but direct connection to the terminals can be made. Comparatively low voltage is to be supplied to the field (which is a rotating member) through slip rings. The frequency of the e.m.f. induced in an alternator is given by, $f = \dfrac{PN}{120}$.

Where P is the number of poles and N is the speed of the alternator in r.p.m. The rated speed of the alternator in turn depends upon the types of the prime movers used. The engine driven altimators run at very low speeds and turbine driven alternators run at high speeds.

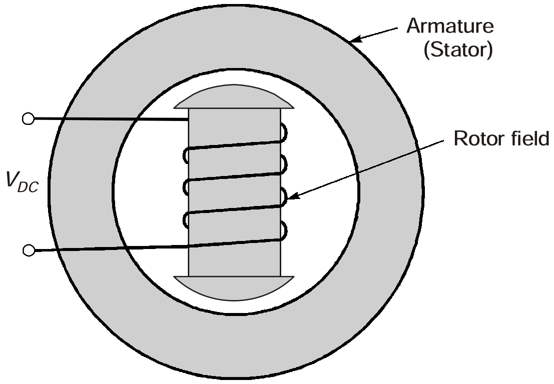

***Figure*-4.1 :** *Salient pole*

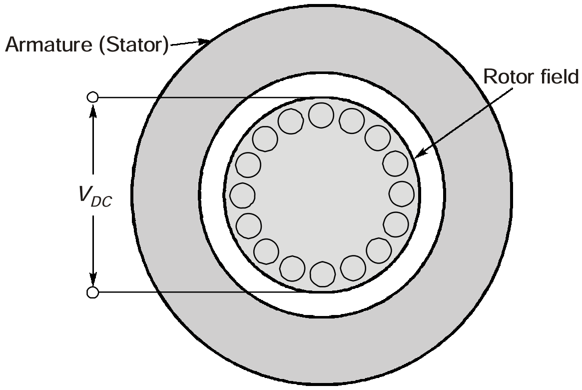

***Figure*-4.2 :** *Non-salient pole*

The field poles of the alternator which is a rotating member, is of two types:

(*i*) Salient poles (or) projecting poles for low speed machine and

(*ii*) Non-salient poles (or) wound rotor type for high speed machines.

The salient poles would cause excessive winding loss at high speeds and the poles may not withstand higher stresses at high speeds. Alternators with these two types of rotor are shown in Figure 4.1.

As in the case of DC machines, the armature core and field poles are made of silicon steel laminations to reduce the hysteresis and eddy current losses. The high speed, non-salient pole alternators of large capacity need forced ventilation. Hydrogen is advantageous as a cooling medium since its specific heat is $14\frac{1}{2}$ times greater than air and its thermal conductivity is 7 times greater than air.

4.1 Advantages of Rotating Field Alternator

Cooling can be provided easily if armature winding are placed on the stator. Field winding is lighter in weight if it is on the rotor, due to light weight inertia of rotor is lesser and the centrifugal forces at higher speed are less, so mechanical strength of the winding is higher.

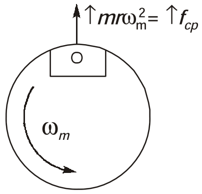

Figure-4.3
Rotating field alternator

- Wider teeth are on stator,

$$f = \frac{PN_s}{120}, \; P = \frac{6000}{N_s}$$

where, $f = 50$ Hz

- The stationary armature may be cooled more easily because the armature can be made large to provide a number of cooling ducts.
- A stationary armature is more easily insulated for the high voltage for which the alternator is designed. The generated voltage may be as high as 33 kV.
- The armature windings being stationary are not subjected to vibration and centrifugal forces.
- The rotating field is supplied with direct current, usually the field voltage is between 100 to 500 volts. Only two slip rings are required to provide direct current for the rotating field, while at least three slip rings would be required for a rotating armature. The insulation of the two relatively low voltage slip-rings from the shaft can be provided easily.
- The armature windings can be braced better mechanically against high electromagnetic forces due to large short circuit currents when the armature windings are in the stator.
- Rotating field is comparatively light and can be constructed for high speed rotation.
- **Note:** Where rotating field means field winding on the rotor and armature winding on the stator.

4.2 Construction of Three-Phase Synchronous Machines

Similar to other rotating machines, an alternator consists of two main parts namely, the stator and the rotor. The stator is the stationary part of the machine. It carries the armature winding in which the voltage is generated. The output of the machine is taken from the stator. The rotor is the rotating part of the machine. The rotor produces the main field flux.

4.2.1 Stator Construction

The various parts of the stator include the frame, stator core, stator windings and cooling arrangement. The frame may be of cast iron for small-size machines and of welded steel type for large size machines. In order to reduce hysteresis and eddy-current losses, the stator core is assembled with high grade silicon content steel laminations. A 3-phase winding is put in the slots cut on the inner periphery of the stator as shown in Figure 4.4. The winding is star connected. The winding of each phase is distributed over several slots. When current flows in a distributed winding it produces an essentially sinusoidal space distribution of e.m.f.

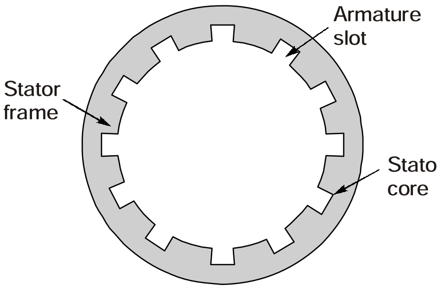

Figure-4.4 : *Alternator stator*

4.2.2 Rotor Construction

There are two types of rotor constructions namely, the Salient-pole type and the Cylindrical rotor type.

Salient-Pole Rotor

The term salient means 'protruding' or 'projecting'.

Thus, a salient-pole rotor consists of poles projecting out from the surface of the rotor core. Figure 4.5 shows the end view of a typical 6-pole salient-pole rotor. Salient-pole rotors are normally used for rotors with four or more poles.

Since the rotor is subject to changing magnetic fields, it is made of this steel laminations to reduce eddy current losses. Poles of identical dimensions are assembled by stacking laminations to the required length and then riveted together. After placing the field coil around each pole body, these poles are fitted by a dove-tail joint to a steel spider keyed to the shaft. Salient-pole rotors have concentrated winding on the poles.

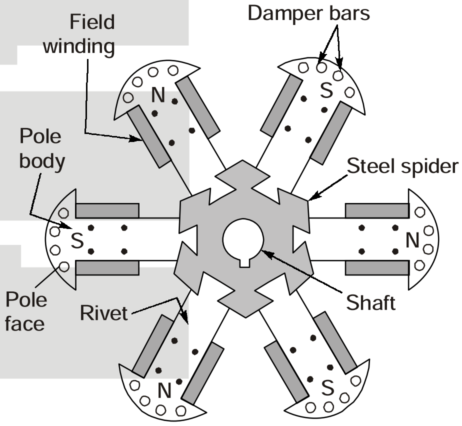

Figure-4.5 : *Six-salient-pole rotor*

Damper bars are usually inserted in the pole faces are so shaped that the radial air gap length increases from the pole centre to the pole tips so that the flux distribution in the air gap is sinusoidal. This will help the machine to generate sinusoidal emf.

The individual field-pole windings are connected in series to give alternate north and south polarities. The ends of the field windings are connected to a d.c. source (a d.c. generator or a rectifier) through the brushes on the slip rings. The slip rings are metal rings mounted on the shaft and insulated from it. They are used to carry current to or from the rotating part of the machine (usually a.c. machine) via carbon brushes.

Salient-pole generators have a large number of poles, and operate at lower speeds. A salient-pole generator has comparatively a large diameter and a short axial length. The large diameter accommodates a large number of poles.

Salient-pole alternators driven by water turbines are called hydro-alternators or hydrogenerators. Hydrogenerators with relatively higher speeds are used with impulse turbines and have horizontal configuration. Hydrogenerators with lower speeds are used with reaction and Kaplan turbines and have vertical configuration.

Example 4.2 Calculate the highest speed at which (a) 50 Hz (b) 60 Hz alternator can be operated.

Solution:

Since it is not possible to have fewer than 2 poles, the minimum value of $P = 2$

$$f = \frac{PN_s}{120}$$

$$N_s = \frac{120f}{P}$$

For a minimum value of P the N will be a maximum.

(a) $f = 50$ Hz, $P = 2$

$$N_s = \frac{120 \times 50}{2} = 3000 \text{ r.p.m.}$$

(b) $f = 60$ Hz, $P = 2$

$$\therefore \quad N_s = \frac{120 \times 60}{2} = 3600 \text{ r.p.m.}$$

4.4 Excitation Systems for Synchronous Machines

Excitation means production of flux by passing current in the field winding.

Direct current is required to excite the field winding on the rotor of the synchronous machines. For small machines, dc is supplied to the rotor field by a dc generator called exciter. This exciter may be supplied current by a smaller dc generator called pilot exciter. The main and pilot exciters are mounted on the main shaft of the synchronous machine (generator or motor). The dc output of the main exciter is given to the field winding of the synchronous machine through brushes and slip ring. In smaller machines, the pilot exciter may be omitted, but this arrangement is not very sensitive or quick acting when changes of the field current are required by the synchronous machine.

For medium size machines a.c. exciters are used in place of d.c. exciters. A.c. exciters are three-phase a.c. generators. The output of an a.c. exciter is rectified and supplied through brushes and springs to the rotor winding of the main synchronous machine.

For large synchronous generators with ratings of the order of few hundred megawatts, the excitation requirements become very large. The problem of conveying such amounts of power through high-speed sliding contacts becomes formidable. At present large synchronous generators and synchronous motors are using brushless excitation system. A brushless exciter is a small direct-coupled a.c. generator with its field circuit on the stator and the armature circuit on the rotor. The three-phase output of the a.c. exciter generator is rectified by solid-state rectifiers. The rectified output is connected directly to the field winding, thus eliminating the use of brushes and slip rings.

A brushless excitation system requires less maintenance due to absence of brushes and slip rings. The power loss is also reduced.

The d.c. required for the field of the exciter itself is sometimes provided by a small pilot exciter. A pilot exciter is a small a.c. generator with permanent magnets mounted on the rotor shaft and a three-phase winding on the stator. The permanent magnets of the pilot exciter produce the field current of the exciter. The exciter supplies the field current of the main machine. Thus, the use of a pilot exciter makes the excitation of the main generator completely independent of external supplies.

4.5 Voltage Generation

The rotor of the alternator is run at its proper speed by its prime mover. The prime mover is a machine which supplies the mechanical energy input to the alternator, the prime movers used for slow and medium speed alternators are water wheels or hydraulic turbines are used as prime movers in large alternators and run at high speeds. The steam turbine driven alternators are called turboalternators or turbogenerators. Poles of the rotor move under the armature conductors. On the stator, the field flux cuts the armature conductors. Therefore voltage is generated in these conductors. This voltage is of alternating nature since poles of alternative polarity successively pass by a given stator conductor. A 3-phase alternator has a stator with three sets of windings arranged so that there is a mutual phase displacement of 120° windings are connected in star

$$F_R = \frac{3}{2} f_m \cos(\omega t - \theta) = F_P \cos(\omega t - \theta)$$

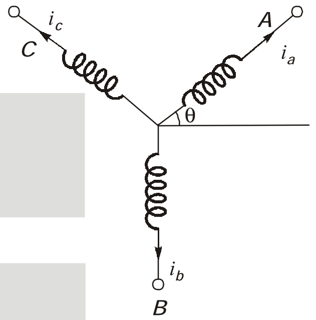

Figure-4.7

For 3-ϕ balanced winding,

$$i_a = I_m \cos \omega t$$
$$i_b = I_m \cos(\omega t - 120°)$$
$$i_c = I_m \cos(\omega t - 240°)$$

Peak along, $\theta = \omega t$

At ωt, $i_a = I_m$

f_{peak} is along, $\theta = 0$

i.e. along the axis of coil *A*,

At, $t = \dfrac{2\pi}{3\omega}$

i.e., $\omega t = \dfrac{2\pi}{3}$, $i_b = I_m$

Peak along $\theta = \dfrac{2\pi}{3}$, i.e. along the axis of coil *B*.

$$t = \frac{4\pi}{3}, \ \omega t = 240°, \ i_c = I_m$$

- Peak of the rotating field will be along the axis of that coil which carries peak current I_m at that instant.
- The induced emf in the coil is maximum at the instant when the coil is under the middle of the pole shoe.

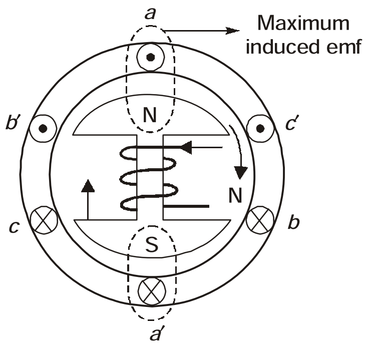

Figure-4.8 (a)

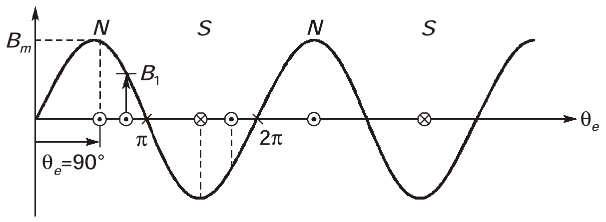

Figure-4.8 (b)

Example 4.14 A 100 kVA, 415 V (line), star-connected synchronous machine generates rated open circuit voltage of 415 V at a field current of 15 A. The short circuit armature current at a field current of 10 A is equal to the rated armature current. The per unit saturated synchronous reactance is

(a) 1.731 (b) 1.5 (c) 0.666 (d) 0.577

Solution: (a)

Synchronous impedance (line)

$$= \frac{\text{Open circuit line voltage}}{\sqrt{3} \times \text{short circuit phase current}} = \frac{415}{\sqrt{3}\left(\dfrac{100 \times 1000}{\sqrt{3} \times 415}\right)} = 1.722$$

Example 4.15 A synchronous motor is connected to an infinite bus at 1.0 pu voltage and draws 0.6 pu current at unity power factor. Its synchronous reactance is 1.0 pu and resistance is negligible. The excitation voltage (E) and load angle (δ) will respectively be

(a) 0.8 pu and 36.86° lag (b) 08 pu and 36.86° lead
(c) 1.17 pu and 30.96° lead (d) 1.17 pu and 30.96° lag

Solution: (d)

$$V = 1\,\angle 0 \text{ pu}; I_a = 0.6\,\angle 0$$
$$z_s = R_a + jX_s = 0 + j1 = 1\,\angle 90 \text{ pu}$$
$$E = V - I_a z_s = 1\,\angle 0 - 0.6\,\angle 0 \times 1\,\angle 90°$$
$$E\angle\delta = 1.166\,\angle{-30.96°} \text{ pu}$$
$$\therefore \quad \text{excitation voltage} = 1.17 \text{ pu}$$
$$\therefore \quad \text{load angle } (\delta) = 30.96°$$

4.13 Methods to Determine Voltage Regulation

It is defined as the change in terminal voltage expressed as the percentage (p.u) of the rated voltage when the load at a given power factor is removed with speed and field current remaining unchanged.

$$\text{V.R.} = \frac{E_f - V}{V} \text{ in p.u.} \Rightarrow \left.\frac{V_{nl} - V_{fl}}{V_{fl}}\right\} = \frac{E_f - v_t}{v_t} \times 100 \text{ in } \%$$

4.13.1 Emf Method or Synchronous Impedance Method or Pessimistic Method

EMF method is also called pessimistic method. This procedure however, tells us that the voltage regulation would always less than the actual value. MMF f_a is converted into emf. induced emf $\bar{E}$ lags behind the corresponding flux ϕ by 90° flux $\phi \propto E$ emf

$$\boxed{\phi \propto f}, \boxed{E \propto f}$$

Hence $\quad \text{E} \propto F, E = -jk\bar{f}$

or $\quad E = kf$

$$k = \text{constant}$$
$$E = -jk\bar{f}$$
$$\bar{f}_f = \bar{f}_r - \bar{f}_a \; I_a \text{ along } \bar{I}_a$$