SSC-JE 2025

Staff Selection Commission

Junior Engineer Examination

Electrical Engineering

Electrical Machines

(Volume - 2)

(DC Machines and Synchronous Machines)

Well Illustrated **Theory** *with*
Solved Examples and **Practice Questions**

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PUBLICATIONS

Electrical Machines

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Chapter 1

Basic Concepts in Rotating Electrical Machines

1.1 Introduction

- An electromechanical energy conversion device is one which converts electrical energy into mechanical energy or mechanical energy into electrical energy.
- 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.

1.2 Energy Conversion

- According to the principle of energy conversion, energy can neither be created nor destroyed, it can nearly be converted form 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.

Energy Balance Equation

- For a electrical motor:

  (Total electrical energy Input) = (Mechanical energy output) + (Total energy stored) + (Total energy dissipated)

  $W_{ei} = W_{mo} + (W_{es} + W_{ms})$ + (ohmic energy losses + coupling field energy losses) + (Energy losses in mechanical system)

  where, W_{ei} = Total electrical energy input from the supply mains.

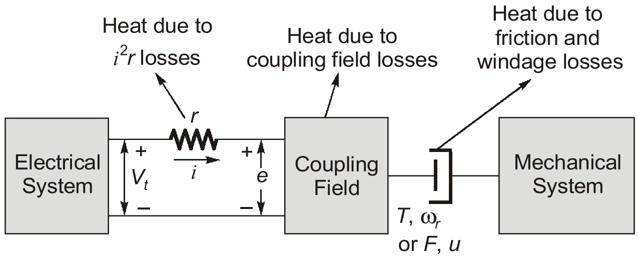
  W_{mo} = The mechanical energy output

  $W_{es} + W_{em}$ = Energy stored in magnetic field + Energy stored in mechanical system

  = Total energy stored in any device and Total energy dissipated

  = Energy dissipated in electric circuit as ohmic loss + Energy dissipated as magnetic core loss (hysteresis and eddy-current losses) + Energy dissipated in mechanical system (Friction and windage losses etc.)
- For generator action:

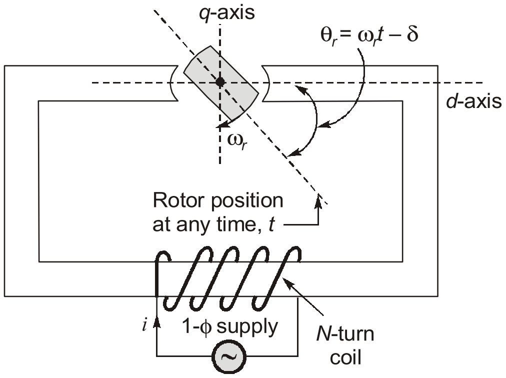
  Total Mechanical energy input = (Electrical energy output) + (Total energy stored) + (Total energy dissipated)
- (W_{ei} – ohmic energy losses) = ($W_{mo} + W_{ms}$ + Mechanical energy losses) + (W_{es} + Coupling field energy losses)
- $W_{\text{elec}} = W_{\text{mech}} + W_{\text{fld}}$



General representation of electromechanical energy conversion device

1.3 Reluctance Motor

- A single-phase reluctance motor is shown in figure. It has saliency (salient poles) both on the stator and rotor.



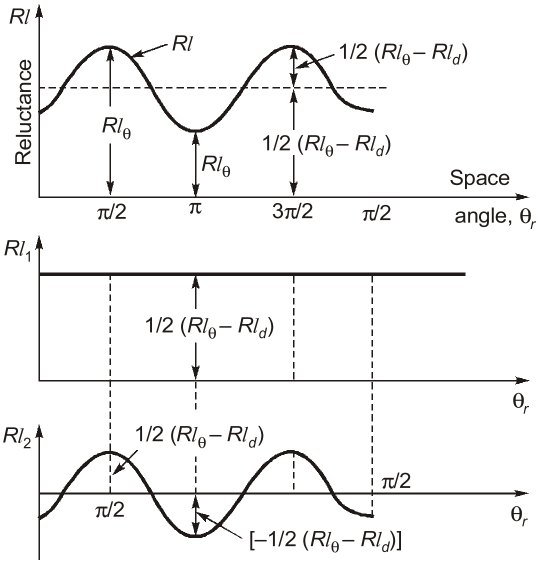
Single-phase reluctance motor

- The axis of the stator flux is indicated by a horizontal dotted line-this axis of stator poles is called stator direct axis (or d-axis). An axis 90° away from the d-axis is called quadrature axis.

NOTE:

The reluctance or permeance of the magnetic circuit depends on the relative angular position of the rotor and stator.

- Single phase voltage applied to N-turn coil establishes stator pulsating flux which crosses the air-gap along the stator pole axis.
- Space angle between stator axis and rotor axis,
  $$\theta_r = \omega_r t - \delta$$
  where δ is load angle and ω_r is shaft angular velocity in rad/sec.
- When $\theta_r = 0$, stator axis coincide with rotor axis. Reluctance offered to the stator flux, by two small air gaps in series with high permeability iron is minimum. This minimum reluctance is designated by Rl_d and also called direct axis reluctance.
- When the rotor long-axis is along the q-axis, i.e. when the space angle $\theta_r = 90°$, the reluctance offered to the stator flux, by two very large air gaps in series with high permeability iron is maximum. It is designated by Rl_q and also called quadrature-axis reluctance.
- The variation of reluctance Rl with θ_r depends on the shape of the stator and rotor poles and here this variation is assumed to be sine function of space angle or as shown in figure.



Variation of reluctance with space angle

- Constant reluctance, $$Rl_1 = \frac{1}{2}(Rl_q + Rl_d)$$
- The reluctance Rl_2 varies sinusoidally,

$$Rl_2 = -\frac{1}{2}(Rl_q - Rl_d)\cos 2q_r$$

- Total reluctance, $$Rl = Rl_1 + Rl_2$$

$$Rl = \frac{1}{2}(Rl_q + Rl_d) - \frac{1}{2}(Rl_q - Rl_d)\cos 2\theta_r$$

- The torque in terms of reluctance,

$$T_e = -\frac{1}{2}\phi^2 \frac{dR_l}{d\theta_r}$$

or $$T_e = -\frac{1}{2}\phi^2 (Rl_q - Rl_d)\sin 2\theta_r$$

- If the instantaneous flux varies sinusoidally,
$\phi = \phi_m \cos\omega t$ then Instantaneous torque,

$$T_e = -\frac{1}{4}\phi_m^2 (Rl_q - Rl_d)\left[\sin 2(\omega_r t - \delta) + \frac{1}{2}\sin 2(\omega_r t + \omega t - \delta) + \frac{1}{2}\sin(\omega_r t - \omega t - \delta)\right]$$

- When the shaft angular velocity ω_r is not equal to the time angular ω, then average torque over the complete cycle is zero.

$$T_{e(\text{av})} = 0; \quad \text{if } \omega_r \neq \omega$$

- If the rotor speed $\omega_r = \omega$ then average torque,

$$T_{e(av)} = \frac{1}{8}\phi_m^2 (Rl_q - Rl_d)\sin 2\delta$$

- Average torque in terms of inductance,

$$T_{e(av)} = \frac{1}{8}\omega\phi_m^2 N^2\left(\frac{1}{\omega L_q} - \frac{1}{\omega L_d}\right)\sin 2\delta$$

where, $\omega L_d = X_d$ = d-axis reactance

$\omega L_d = X_q$ = q-axis reactance

$L_d = \dfrac{N^2}{Rl_d}$ = d-axis inducctance

$L_q = \dfrac{N^2}{Rl_q}$ = q-axis inducctance

or,
$$T_{e(av)} = \frac{1}{8}\omega\,\phi_m^2 N^2\left(\frac{1}{X_q}-\frac{1}{X_d}\right)\sin 2\delta$$

- If the flux produced by coil mmf NI is confined to the stator. Then magnitude of counter or reaction emf E must be equal to the applied voltage V_t.

$$V_t = E = \sqrt{2}\pi\, Nf\phi_m$$

Average torque,
$$T_{e(av)} = \frac{V_t^2}{4\omega}\left(\frac{1}{X_q}-\frac{1}{X_d}\right)\sin 2\delta \quad \text{or} \quad T_{e(av)} = \frac{V_t}{4\omega}(I_q - I_d)\sin 2\delta$$

Here, I_d, I_q are the currents taken from the supply when rotor is held in minimum and maximum reluctance position respectively.

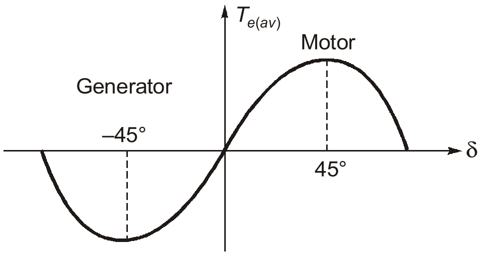
REMEMBER :

- The reluctance motor can develop torque only at the synchronous speed.
- Reluctance motor is not a self-starting motor.

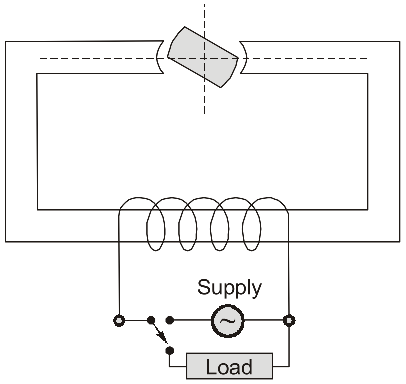
NOTE

A winding put in the rotor pole-faces, serves to produce induction motor torque during starting and as the shaft speed approaches synchronous speed, rotor pulls into step and continues running at synchronous speed.

- If load torque on the motor changes, then the angle δ adjusts itself till reluctance torque becomes equal to the load torque.
- With the increase of load on the motor, load angle δ increases till it reaches its maximum value of 45°. Any further increase in load on the motor, would cause it to stall (fall out of step or loose synchronism).
- The single-phase reluctance machine can be made to work as a generator also.
- For this purpose, the reluctance machine is started as a motor first by giving a supply of frequency ω. Once it starts rotating at synchronous speed supply is disconnected and load is connected. Then it starts converting mechanical energy into electrical energy.



Torque load angle characteristics



- As the mechanical power input to the shaft is increased, the space position of the rotor advances so that angle δ first decreases then becomes negative. As soon as δ becomes negative, the machine starts working as a generator converting the mechanical power input to the electrical output.

REMEMBER :

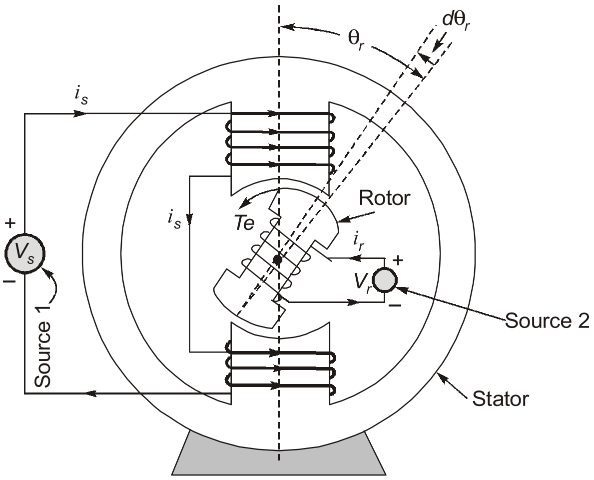
Reluctance torque is present only in those electrical machines in which the reluctance seen by the working flux varies with rotor movement.

Applications

Single-phase reluctance motors are used extensively in driving electric clocks and other timing devices because they operate at constant synchronous speed in case the supply frequency remains constant.

1.4 Doubly-excited Magnetic Machines

- A doubly-excited magnetic system is one which has two independent sources of excitations.



Double-excited magnetic system

- In above figure the stator with N_s turns energised from source 1 and rotor with N_r turns is excited from source 2. The mmf$_s$ produced by both stator and rotor winding is in the same direction and magnetic torque T_e is in the anti clockwise direction.
- The total torque developed by the doubly excited magnetic system.

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

where, dL_s = Differential change in self-inductance of stator winding

where, dL_r = Differential change in self-inductance of rotor winding

dM_{sr} = dM_{rs} = Differential change in mutual inductance between stator and rotor winding

i_s = Stator current

i_r = Rotor current

- If $i_r = 0$ then torque developed, $T_e = \frac{1}{2}i_s^2\frac{dL_s}{d\theta_r}$

The torque is developed because reluctance seen by the stator-produced flux changes with rotor position. A change of reluctance varies the self inductance L_s with θ_r.

- If $i_s = 0$ then torque developed $T_e = \frac{1}{2} i_r^2 \frac{dL_r}{d\theta_r}$

  The torque is developed because L_r is a function of rotor position.

Remember

- If only the stator is excited, then the stator flux would have a tendency to follow a minimum reluctance path and for doing this, the rotor turns anti-clockwise.
- If only the rotor is excited, the rotor flux would have a tendency to follow a minimum reluctance path and for achieving this the rotor again turns anti-clockwise.

- The last term $i_s i_r \frac{dM_{sr}}{d\theta_r}$ which depends on the current in both the stator and rotor windings and also on the angular rate of change of mutual inductance M_{sr}. This component of torque is commonly called the ***electromagnetic torque*** of electro-magnetic energy conversion devices.

Remember

Reluctance torque $\left(\frac{1}{2} i_s^2 \frac{dL_s}{d\theta_r} \text{ or } \frac{1}{2} i_r^2 \frac{dL_r}{d\theta_r}\right)$ does not depend on the direction of currents in stator or rotor windings. But the interaction torque $\left(i_s i_r \frac{dM_{sr}}{d\theta_r}\right)$ does depend on the direction of current i_s and i_r.

Application

Synchronous machines, loudspeakers, tachometers, d.c. shunt machines etc.

Important Point:

- In salient pole electrical machines, Reluctance is seen by stator flux varies with respect to q but constant for rotor when reluctance is seen by rotor flux.
- In non-salient or cylindrical type machines, reluctance seen by stator flux is constant but varies when reluctance is seen by rotor flux.
- Necessary condition for producing electromagnetic torque is number of stator poles must be equal to number of rotor poles otherwise no-electromagnetic torque is produced.

1.5 General Terms in Rotating Machines

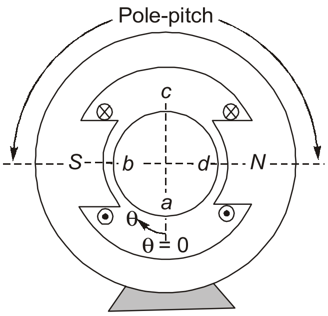


***Fig. (a) :** Elementary two pole machine*

- The above figure shows an elementary two-pole machine, with its 2 field coils excited by direct current. The flux density at the point a in between the 2 poles will be zero. Under the centre of the pole indicated by point *b*, the flux density would be maximum positive; at c it is zero and at point '*d*' it is again maximum but negative.
- South pole on the stator or north pole on the rotor, produces positive flux density.
- The variation of flux density *B*, along the air gap periphery is depicted in figure.

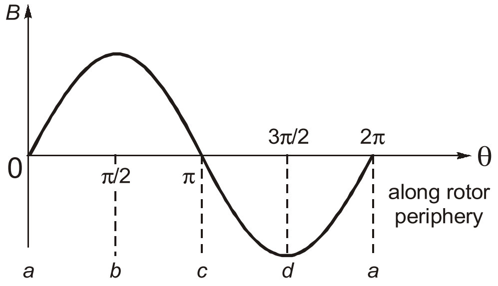


***Fig. (b) :** Flux density variation along air-gap periphery*

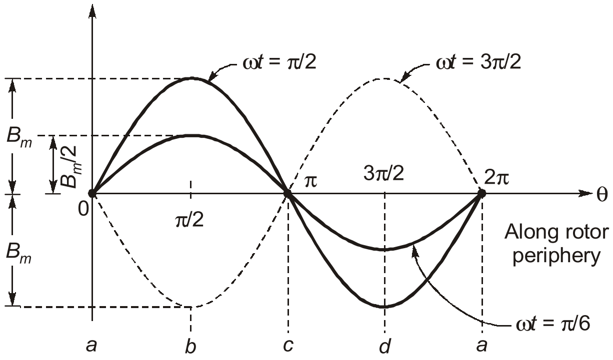
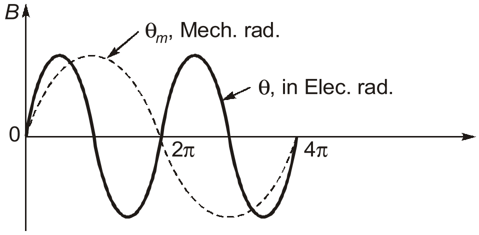


***Fig. (c) :** Pulsating flux*

- Suppose the field coils of Figure (a) are excited with alternating current $i = i_m \sin\omega t$. At $\omega t = 0$, current is zero and no field flux is produced.
- At $\omega t = \frac{\pi}{6}$, $i = \frac{I_m}{2}$ and maximum flux density under the pole is $\frac{B_m}{2}$.
- At $\omega t = \frac{\pi}{2}$, the flux density under the poles is B_m. After $\omega t = \frac{\pi}{2}$, the flux density wave starts decreasing. At $\omega t = \pi$, the flux density is again zero. After $\omega t = \pi$ is crossed, the direction of current in the field coils is reversed and consequently field poles of reversed polarity are created. At $\omega t = \frac{3\pi}{2}$, the flux density is $-B_m$.
- The axis of field a flux remains along bd. Such a flux is called alternating or pulsating-stationary flux.

Electrical and Mechanical Degrees



For 4-pole machine

- For a P-pole machine, $P/2$ cycles of emf will be generated in one revolution.

$$\theta_{\text{elect}} = \frac{P}{2}\theta_{\text{mech}} \quad \text{or} \quad \omega_e = \frac{P}{2}\omega_m$$

where ω_e is the angular speed in electrical radians per second and ω_m is the angular speed in mechanical radians per second.

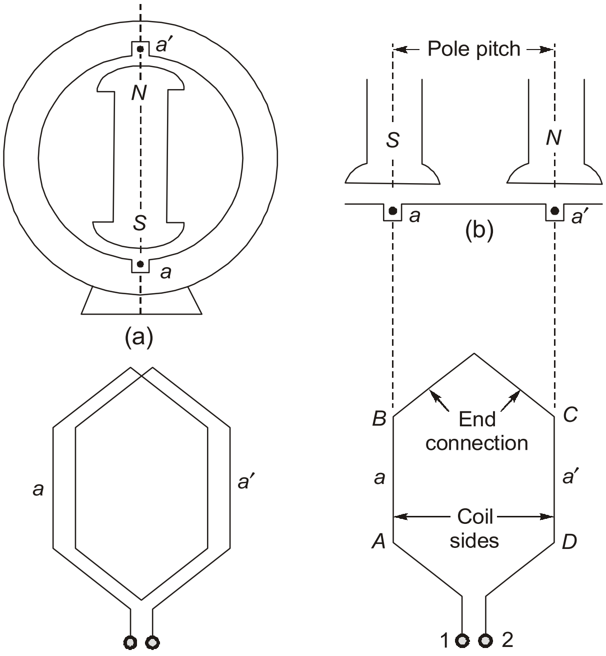
- If the speed N is in rpm, then

$$f = \frac{PN}{120}\ \text{Hz}$$

Pole-Pitch

The peripheral distance between two adjacent poles is called pole pitch. It is always expressed in electrical degrees and pole pitch is always equal to 180 electrical degree or π-electrical radians.

Coil



- The emf is generated in active lengths *AB* and *CD* only. These active lengths are called the two coil-sides of a coil.
- One turn consists of two conductors and one coil is made up of two coil-sides.