Review Last Class

Induction Motor

Single-Phase Induction Motor

Synchronous Generator or Alternator

Synchronous Motor

Synchronous Motor

Some characteristic features of a synchronous motor:

1. **It runs either at synchronous speed or not at all**.
2. **It is not inherently self-starting**.
3. **It is capable of being operated under a wide range of power factors, both lagging and leading**.

Starting Method of a synchronous motor:

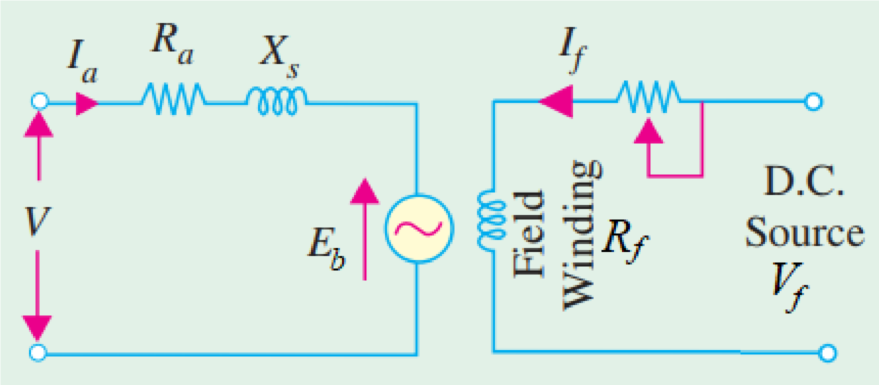
(*a*) Auxiliary drive

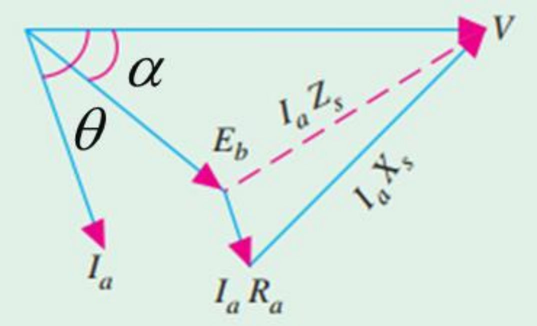
(induction motor or dc motor)

(*b*) Induction start

(using damper winding), etc

38.6 Equivalent Circuit of Synchronous Motor





$$E_R = V - E_b = I_a Z_s$$

$$I_a = \frac{E_R}{Z_s} = \frac{V - E_b}{Z_s}$$

V = Supply voltage

I_a = Armature current

R_a = Armature resistance

E_b = Back emf

X_s = Synchronous reactance

$Z_s = R_a + jX_s$ = Synchronous impedance

V_f = Field voltage

I_f = Field current

R_f = Field resistance

α = **Load or Power Angle**

θ = **Power Factor Angle**

38.7 Power Developed by a Synchronous Motor

The armature resistance of a synchronous motor is negligible as compared to its synchronous reactance. Neglecting the resistance, the circuit and the vector diagram is shown in **Fig. 38.10**.

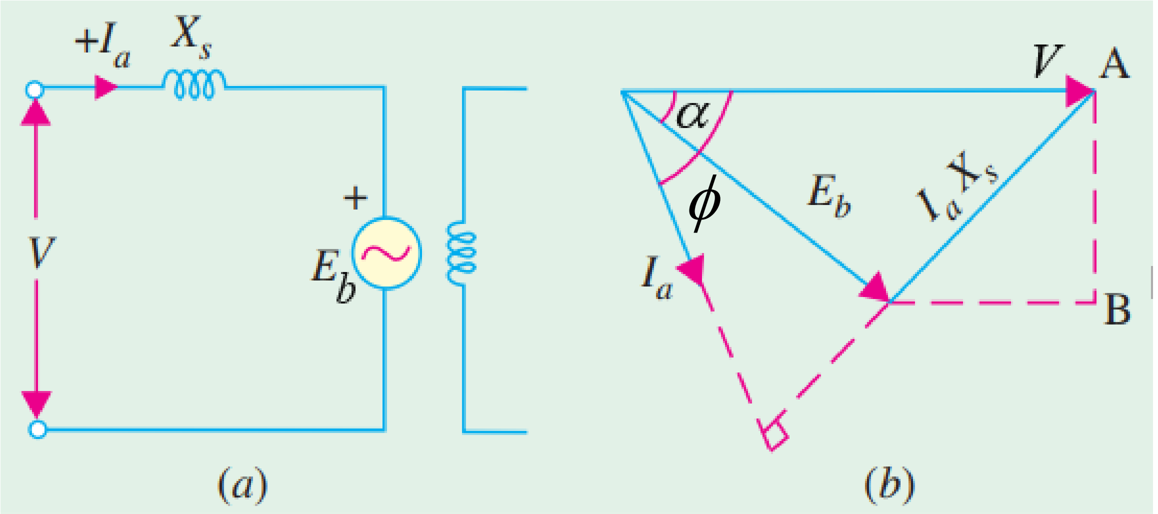


Fig. 38.10

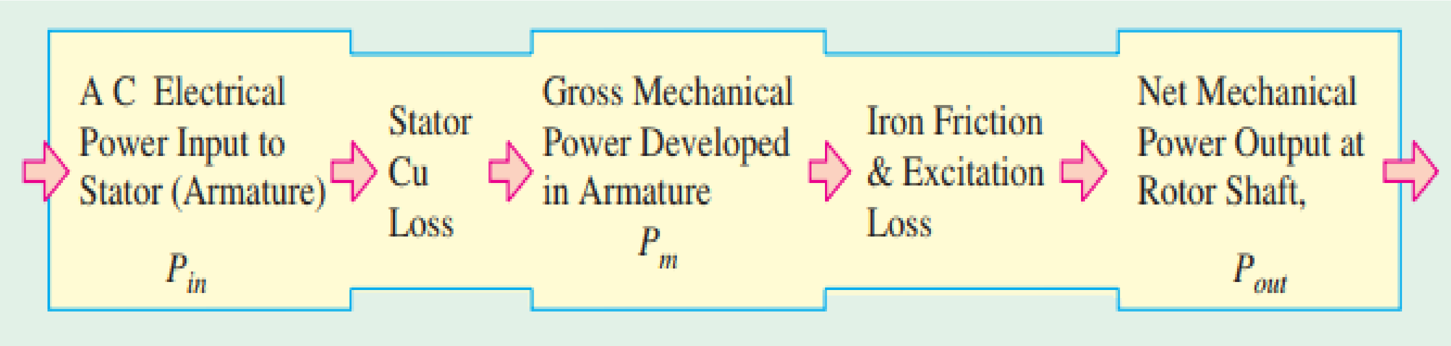
$$AB = E_b \sin\alpha = I_a X_s \cos\theta \qquad V I_a X_s \cos\theta = E_b V \sin\alpha$$

$$P_{in} = V I_a \cos\theta = \frac{E_b V}{X_s} \sin\alpha$$

Neglecting the stator Cu loss and considering the total three-phase power we have:

$$P_m = 3\frac{E_b V}{X_s} \sin\alpha$$

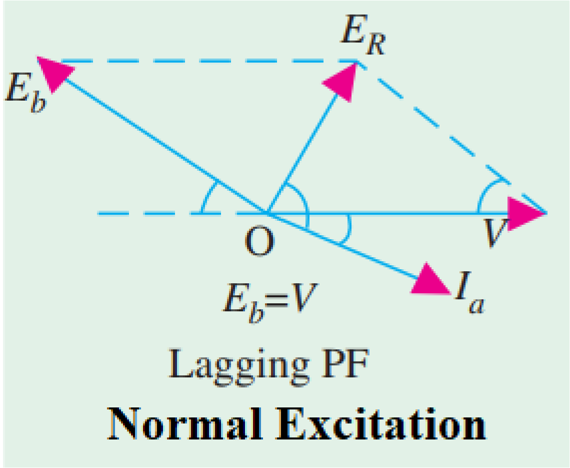
The gross torque developed by the motor is $T_g = 9.55 P_m / N_s$ N-m -N_s in rpm.



$$T_g = 9.55\frac{P_m}{N_s} = 28.65\frac{E_b V}{N_s X_s} \sin\alpha \quad \mathrm{N-m}$$

When $\alpha = 90^o$, the torque is maximum. The maximum torque is called ***pullout torque***.

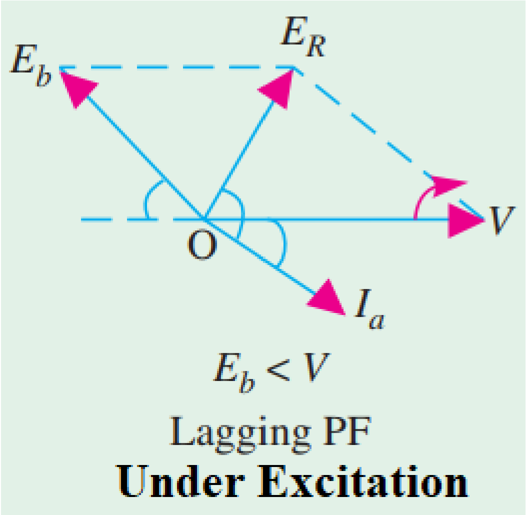
38.8 Synchronous Motor with Different Excitations

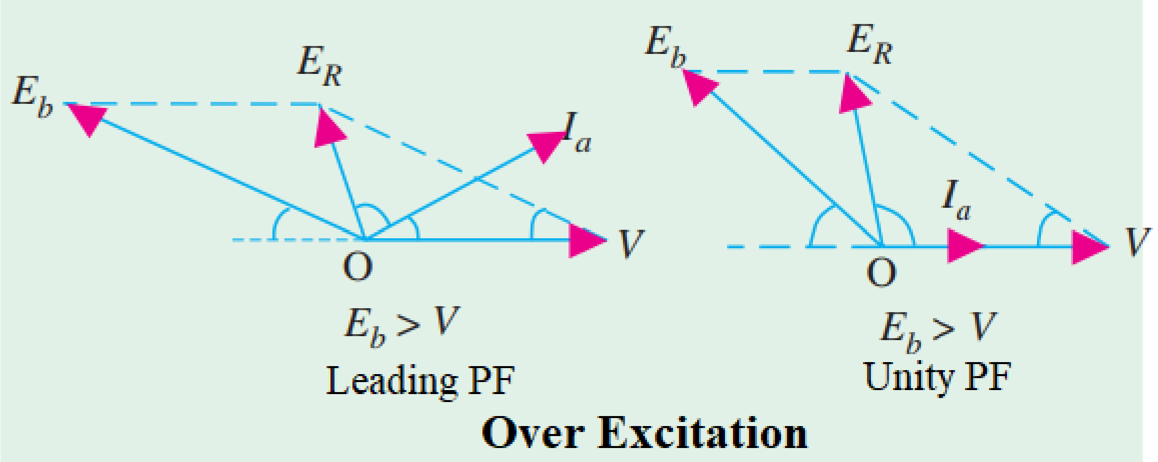


One of the important characteristics of the synchronous machine is that its power factor can be controlled by the field current. In other words, ***the power factor of the stator (or line) current can be controlled by changing the field excitation***.

A synchronous machine can be operated as:
(***a***) Normal excited mode ($E_b = V$) [Power factor lagging]
(***b***) Under excited mode ($E_b < V$) [Power factor lagging]
(***c***) Overexcited mode ($E_b > V$) [Power factor both leading and unity are possible]

Over Excited synchronous motor is used for power factor improvement.





Back EMF and Load or Power Angle Calculation for Different Power Factors

$$E_b = AC = \sqrt{AB^2 + BC^2} \qquad \alpha = \tan^{-1}\left(\frac{BC}{AB}\right)$$

For Lagging PF : $AB = V - I_a Z_s \cos(\theta - \phi)$; $BC = I_a Z_s \sin(\theta - \phi)$

For Leading PF : $AB = V + I_a Z_s \cos\{180° - (\theta + \phi)\}$; $BC = I_a Z_s \sin\{180° - (\theta + \phi)\}$

For Unity PF : $AB = V - I_a R_a$; $BC = I_a X_s$

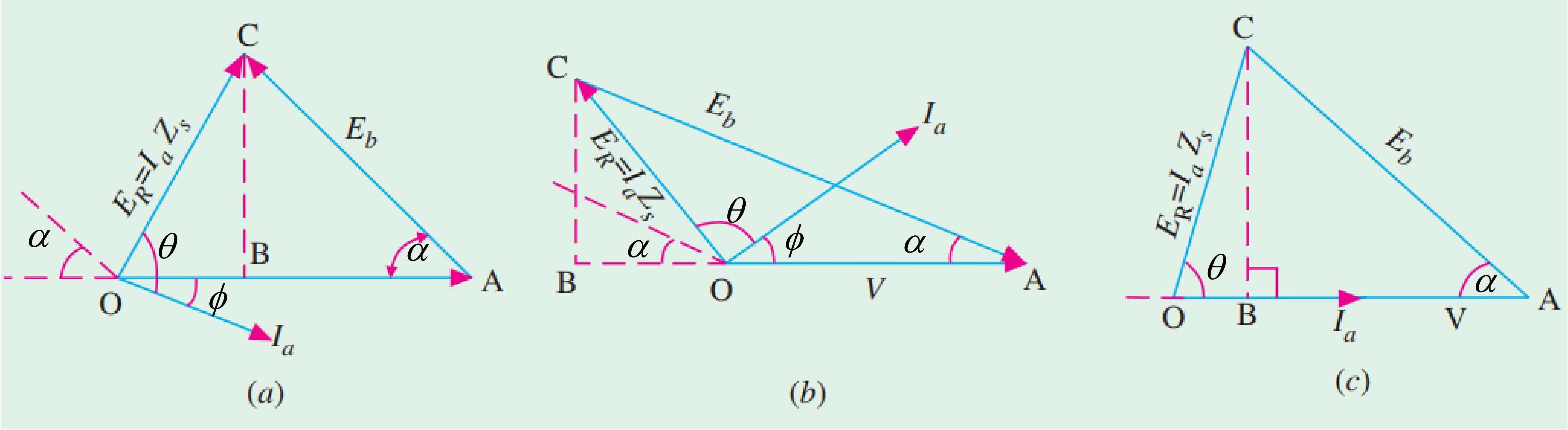


Fig. 38.14

Example 38.1. *A 75-kW, 3-φ, Y-connected, 50-Hz, 440-V cylindrical rotor synchronous motor operates at rated condition with 0.8 p.f. leading. The motor efficiency excluding field and stator losses, is 95% and X_S = 2.5 Ω. Calculate* **(*i*)** *mechanical power developed* **(*ii*)** *armature current* **(*iii*)** *back e.m.f.* **(*iv*)** *power angle and* **(*v*)** *maximum or pull-out torque of the motor.*

Solution. $N_S = 120 \times 50/4 = 1500$ rpm = 25 rps

(*i*) $P_m = P_{in} = P_{out} / \eta = 75 \times 10^3/0.95 =$ **78,950 W**

(*ii*) Since power input is known

$\therefore \quad \sqrt{3} \times 440 \times I_a \times 0.8 = 78{,}950; \quad I_a =$ **129 A**

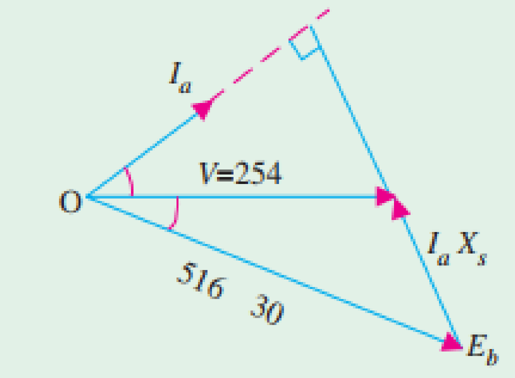


Fig. 38.11

(*iii*) Applied voltage/phase = 440/ $\sqrt{3}$ = 254 V. Let V = 254 ∠0° as shown in Fig. 38.11.

$$E_b = V - j\, I_a X_S = 254 \angle 0° - 129 \angle 36.9° \times 2.5 \angle 90° = 254 - 322\,(-0.6 + j\,0.8) = \mathbf{516 \angle{-30°}}$$

(*iv*) $\therefore \quad \alpha = $ **–30°**

(*v*) pull-out torque occurs when α = 90°

$$\text{maximum } P_m = 3\frac{E_b V}{X_S} \sin\alpha = 3\ \frac{256 \times 516}{2.5} = \sin 90° = 157{,}275 \text{ W}$$

$\therefore$ pull-out torque = $9.55 \times 157,275/1500 =$ **1,000 N-m**

Example 38.31. *A 3-ϕ, 3300-V, Y-connected synchronous motor has an effective resistance and synchronous reactance of 2.0 Ω and 18.0 Ω per phase respectively. If the open-circuit generated e.m.f. is 3800 V between lines, calculate* **(*i*)** *the maximum total mechanical power that the motor can develop and* **(*ii*)** *the current and p.f. at the maximum mechanical power.*

Solution. $\theta = \tan^{-1}(18/2) = 83.7°$; $V_{ph} = 3300/\sqrt{3} = 1905$ V; $E_b = 3800/\sqrt{3} = 2195$ V

Remembering that $\alpha = \theta$ for maximum power development (Ar. 38-10)

$$E_R = (1905^2 + 2195^2 - 2 \times 1905 \times 2195 \times \cos 83.7°)^{1/2} = 2744 \text{ volt per phase}$$

$$\therefore \quad I_a Z_S = 2,744 \text{ ; Now, } Z_S = \sqrt{2^2 + 18^2} = 18.11\ \Omega$$

$$\therefore \quad I_a = 2744/18.11 = 152 \text{ A/phase ; line current} = \mathbf{152\ A}$$

$$(P_m)_{max} \text{ per phase} = \frac{E_b V}{Z_S} - \frac{E_b^2 R_a}{Z_S^2} = \frac{2195 \times 1905}{18.11} - \frac{2195^2 \times 2}{18.11^2}$$

$$= 230,900 - 29,380 = 201520 \text{ W per phase}$$

Maximum power for three phases that the motor can develop *in its armature*

$$= 201,520 \times 3 = \mathbf{604,560\ W}$$

$$\text{Total Cu losses} = 3 \times 152^2 \times 2 = 138,700 \text{ W}$$

$$\text{Motor input} = 604,560 + 138,700 = 743,260 \text{ W}$$

$$\therefore \quad \sqrt{3} \times 3300 \times 152 \times \cos\phi = 743,260 \qquad \therefore \quad \cos\phi = \mathbf{0.855\ (lead).}$$

Permanent Magnet Synchronous Motor (PMSM)

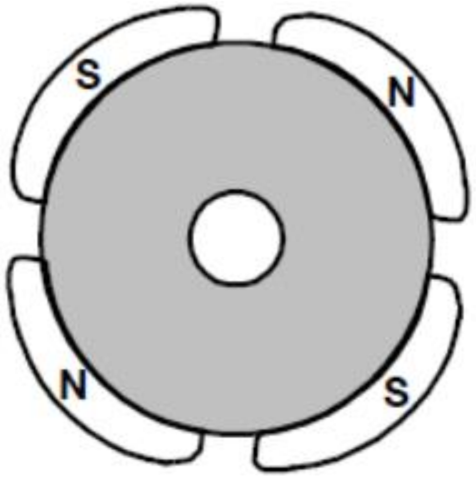
B. L. Theraja, A. K. Theraja, "A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines," S. Chand & Company Ltd.

Definition: A permanent magnet synchronous motor (PMSM) is a motor that uses permanent magnets to produce the air gap magnetic field rather than using electromagnets.

Construction: The permanent magnet synchronous motor construction is similar to the basic synchronous motor, ***but the only difference is with the rotor***. The rotor doesn't have any field winding, but the permanent magnets are used to create field poles.

Based on the mounting of the permanent magnet on the rotor, the construction of a permanent magnet synchronous motor is divided into two types.

Surface-mounted PMSM: In this construction, the magnet is mounted on the surface of the rotor. It is suitable for high-speed devices like robotics and tool drives. No reluctance torque. Less robust motor.



Buried PMSM or Interior PMSM: In this type of construction, the permanent magnet is embedded into the rotor. It is suitable for high-speed applications and gets robustness. Reluctance torque is due to the saliency of the motor.

Working Principal:

The permanent magnet synchronous motor working principle is similar to the synchronous motor. It depends on the rotating magnetic field that generates electromotive force at synchronous speed. When the stator winding is energized by giving the 3-phase supply, a rotating magnetic field is created in between the air gaps.

This produces the torque when the rotor field poles hold the rotating magnetic field at synchronous speed and the rotor rotates continuously. These motors are not self-starting motors, it is necessary to provide a variable frequency power supply.

Advantages:

The advantages of PMSM are:

- Provides higher efficiency at high speeds
- Available in small sizes at different packages
- Maintenance and installation is very easy than an induction motor
- Capable of maintaining full torque at low speeds.
- High efficiency and reliability
- Gives smooth torque and dynamic performance

Disadvantages:

The disadvantages of PMSM are:

- These type of motors are very expensive when compared to induction motors
- Somehow difficult to start-up because they are not self-starting motors.

Applications:

The PMSMs applications are:

Air conditioners, Refrigerators, AC compressors

Washing machines, which are direct-drive

Automotive electrical power steering

Large power systems to improve leading, and lagging power factor

Machine tools, Control of traction

Data storage units, Servo drives

Industrial applications like robotics, aerospace, and many more.

Reluctance Motor

B. L. Theraja, A. K. Theraja, “A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines,” S. Chand & Company Ltd.

Definition: A reluctance motor is a synchronous motor similar in construction to an induction motor, in which the member carrying the secondary circuit has the salient poles, without dc excitation. It starts as an induction motor but operates normally at synchronous speed.

Construction: A reluctance motor consists of:

(*i*) **A stator** carrying a single-phase winding along with an auxiliary winding to produce a synchronous-revolving magnetic field.

(*ii*) **A squirrel-cage rotor** having unsymmetrical magnetic construction. This is achieved by symmetrically removed some of the teeth from the squirrel-cage rotor to produce salient poles on the rotor as shown in the following figure. The rotor carries the short-circuited copper or aluminium bars and it acts as a squirrel cage rotor of an induction motor. If an iron piece is placed in a magnetic field, it aligns itself in a minimum reluctance position and gets locked magnetically.

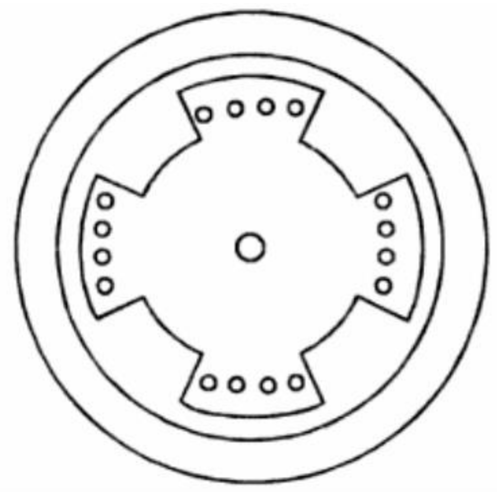
Working Principal:

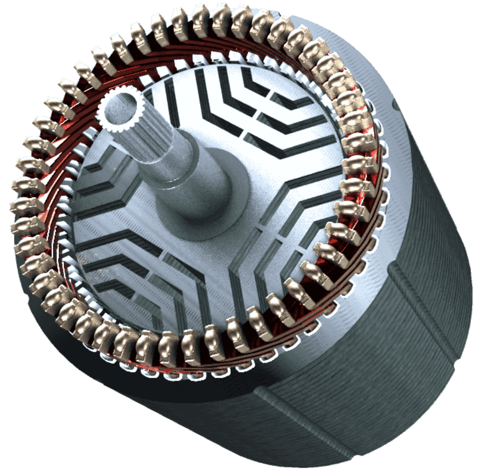
When power supply to stator rotating magnetic field is produced. The speed of this field is synchronous speed.

Rotor start to rotate like an induction motor due short-circuited copper or aluminium bars on the rotor.

When the rotor speed is about synchronous, stator magnetic field pulls rotor into synchronism i.e. minimum reluctance position and keeps it magnetically locked.

Then rotor continues to rotate with a speed equal to synchronous speed. Such a torque exerted on the rotor is called the *reluctance torque*. Thus finally the reluctance motor runs as a synchronous motor.





Advantages:

The reluctance motor has following advantages:

- No dc supply is necessary for rotor
- Constant speed characteristics
- Robust construction
- Less maintenance

Disadvantages:

The reluctance motor has following disadvantages:

- Less efficiency
- Poor power factor
- Need to very low inertia rotor
- Less capacity to drive the loads

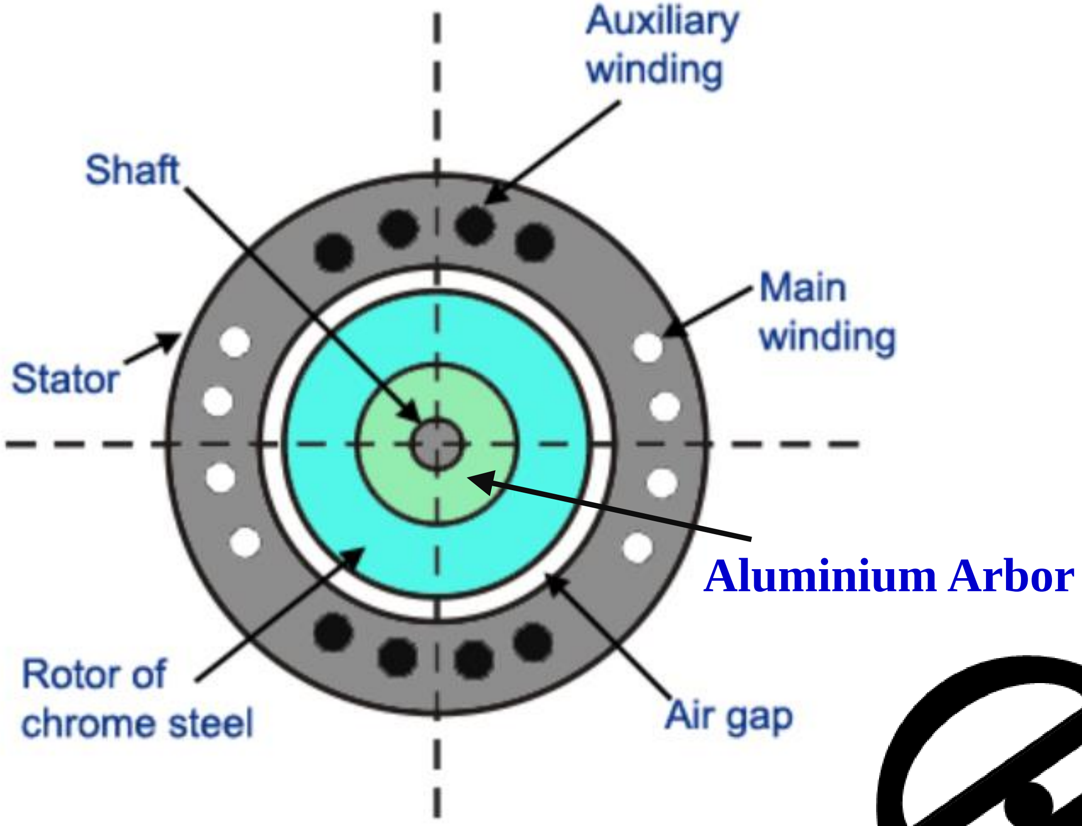
Application:

Reluctance Motor is used in signaling devices, control apparatus, automatic regulators, recording instruments, clock and all kinds of timing device, teleprinter, gramophone etc.

Hysteresis Motor

Definition: A hysteresis motor is a synchronous motor having ***cylindrical rotor*** starts by virtue of the hysteresis losses induced in its hardened steel secondary member by the revolving filed of the primary and operates normally at synchronous speed and runs on hysteresis torque because of the retentivity of the secondary core.
It is a single-phase motor whose operation depends upon the hysteresis effect i.e., magnetization produced in a ferromagnetic material lags behind the magnetizing force.

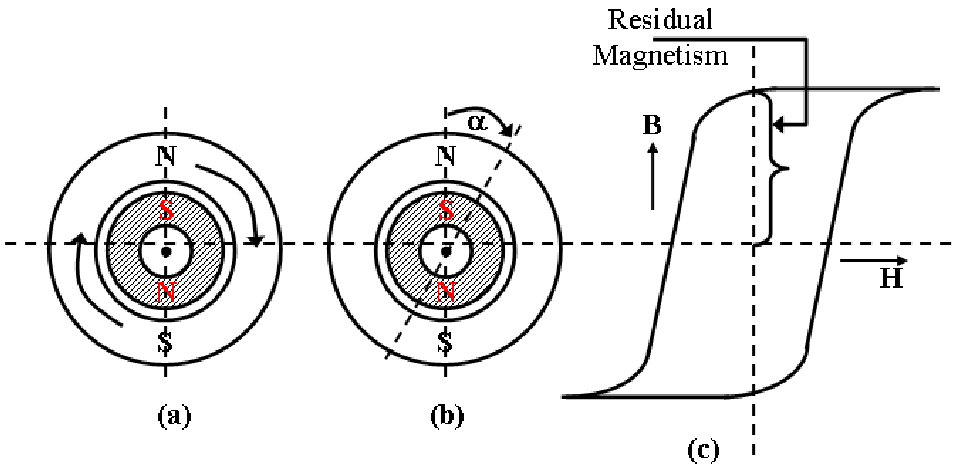
Construction: A reluctance motor consists of:
(*i*) **A stator** carrying a single-phase winding along with an auxiliary winding to produce a synchronous-revolving magnetic field. Shaded pole also can be used to produce revolving magnetic field.
(*ii*) **A rotor** of hysteresis motor is made of magnetic material (such as chrome, cobalt steel or alnico or alloy) that has high hysteresis loss due to large area of hysteresis loop.
Magnetic cylindrical portion of the rotor is assembled over shaft through ***arbor of non-magnetic material like brass***.



Working Principal:

When power is supply to stator, a rotating magnetic field is produced. The speed of this field is synchronous speed. The rotor, initially, starts to rotate due to eddy-current torque and hysteresis torque developed on the rotor. Once the speed is near about the synchronous, the stator pulls rotor into synchronism and eddy-current loss is vanishes.

Due to the hysteresis effect, rotor pole axis lags behind the axis of rotating magnetic field as shown in the following Figures. When the stator field moved forward, due to high residual magnetism (i.e. retentivity) the rotor pole strength remains maintained. So higher the retentivity, higher is the hysteresis torque. The high retentivity ensures the continuous magnetic locking between stator and rotor.



Advantages:

The advantages of hysteresis motor are:

1. No mechanical vibrations.
2. Operation is quiet and noiseless.
3. Suitability to accelerate inertia loads.
4. Possibility of multispeed operation by employing gear train.

Disadvantages:

The disadvantages of hysteresis motor are:

1. The output is about one-quarter that of an induction motor of the same dimension.
2. Low efficiency, power factor, torque
3. Available in very small sizes

Applications:

Due to noiseless operation it is used in sound recording instruments, sound producing equipments, high quality record players, electric clocks, teleprinters, timing devices et.

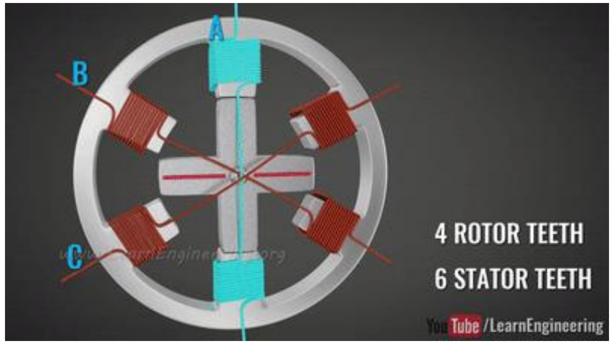
Stepper Motor

B. L. Theraja, A. K. Theraja, “A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines,” S. Chand & Company Ltd.

Stepper Motor

- Stepper motors are also called stepping motors or step motors.
- This motor rotates through a **fixed angular step** in response to each input current pulse received by its controller.

Step Angle:
The angle through which the motor shaft rotates for each command pulse is called the **step angle *β***.



- Smaller the step angle, greater the number of steps per revolution and higher the resolution or accuracy of positioning obtained.
- Step angles range from 0.72^o to 90^o.
- Most common step sizes are 1.8^o, 2.5^o, 7.5^o and 15^o.
- The value of step angle can be expressed either in terms of the rotor and stator poles (teeth) N_r and N_s respectively or in terms of the number of stator phases (m) and the number of rotor teeth.

$$\beta = \frac{(N_s - N_r)}{N_s . N_r} \times 360° = \frac{360°}{m\, N_r}$$

Example Problems

Example 39.1. A hybrid VR stepping motor has 8 main poles which have been castleated to have 5 teeth each. If rotor has 50 teeth, calculate the stepping angle.

Solution. $N_s = 8 \times 5 = 40; \quad N_r = 50$

$\therefore \quad \beta = (50 - 40) \times 360 / 50 \times 40 = 1.8^\circ.$

Example 39.2. A stepper motor has a step angle of 2.5°. Determine (a) resolution (b) number of steps required for the shaft to make 25 revolutions and (c) shaft speed, if the stepping frequency is 3600 pps.

Solution. (*a*) Resolution = $360^\circ / \beta = 360^\circ / 2.5^\circ = 144$ steps / revolution.

(*b*) Now, steps / revolution = 144. Hence, steps required for making 25 revolutions = $144 \times 25 = 3600$.

(*c*) $n = \beta \times f / 360^\circ = 2.5 \times 3600 / 360^\circ = 25$ rps

Advantages and Disadvantages of Stepper Motor

Advantages:

- Because of the precise increment of rotor movement, it is very easy to control the rotation speed precisely.
- Simplicity of construction and low maintenance cost are other advantages.
- Since the torque at low speed is comparatively higher in stepper motors, they are preferred in applications where high torque is needed at low speed.
- Very reliable since there are no contact brushes in the motor.

Disadvantages:

- It requires more amount of current than a normal dc motor.
- Resonances can occur if not properly controlled.
- Not easy to operate at extremely high speeds.
- Lack of feedback mechanism is another drawback as the feedback system is required to ensure safety.

Stepper Motor

Applications:

- Stepper motors are used for in motion-controlled positioning system as it is easy to produce precise position control with the help of computer-controlled stepper motors.
- They are widely used in biomedical equipment where precise and accurate position control is needed.
- Stepper motors are also present in disc drivers, computer printers and scanners, intelligent lighting, camera lenses.
- Stepper motors are preferred in robotics because of their precision characteristic.
- Because of its high reliability and precision, 3D cameras, X Y Plotters, CNC and some other camera platforms also impart stepper motors.

Types of Stepper Motor

Stepper motors can be divided into the following three basic categories:

i. Variable Reluctance Stepper Motor
ii. Permanent Magnet Stepper Motor
iii. Hybrid Stepper Motor

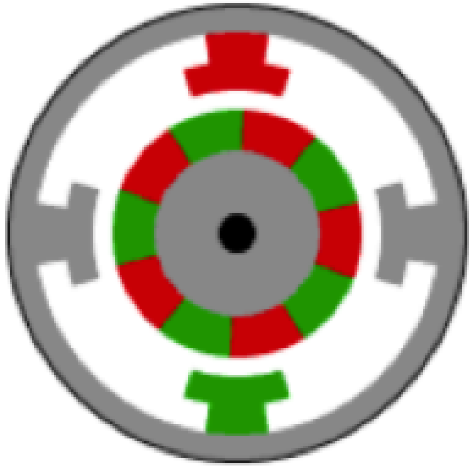

Variable reluctance motor

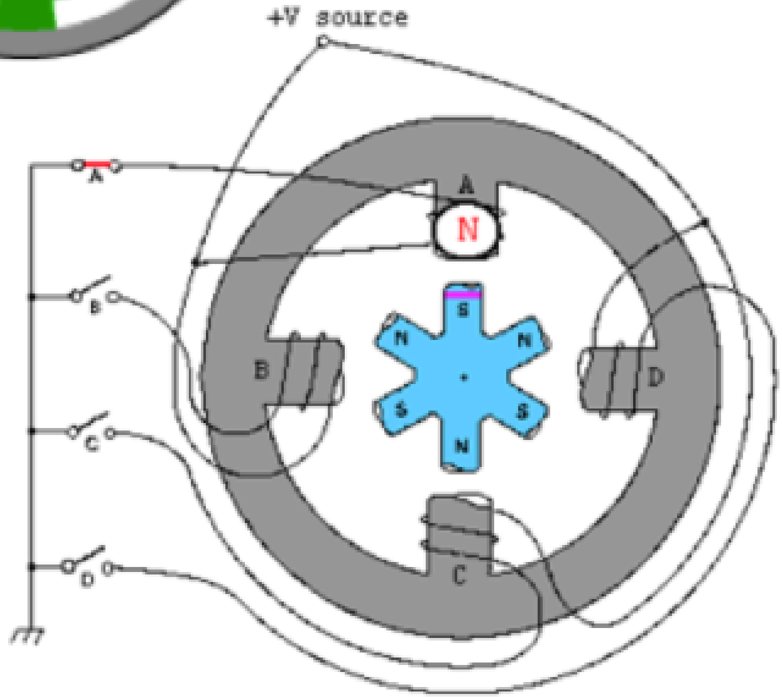

Permanent magnet stepper motor


Hybrid stepper motor

Full Step Operation

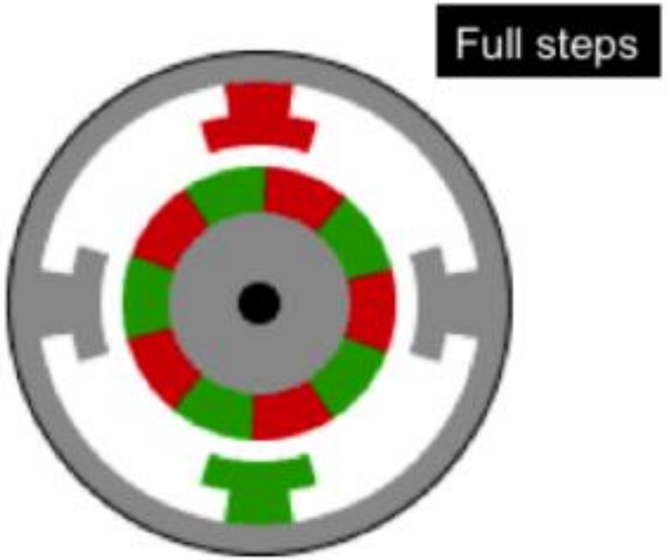
- The rotor of a permanent magnet in stepper motor consists of permanent magnets and the stator has two pairs of windings.
- Just as the rotor aligns with one of the stator poles, the second phase is energized.
- The two phases alternate on and off and also reverse polarity.
- There are four FULL steps. One phase lags the other phase by one step. This is equivalent to one forth of an electrical cycle or 90° .
- Electronic circuits are used to switch supply voltages to the appropriate windings in the stator to advance each step. (See animation.)

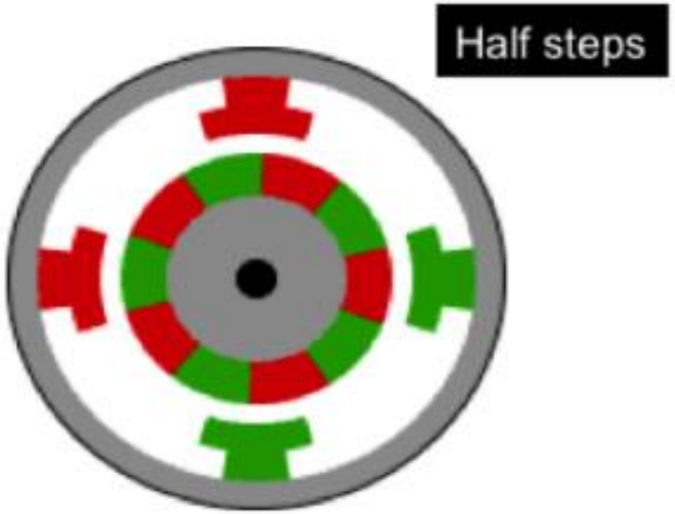




Half Step Operation

- By energizing two windings some of the time, we get a half-step stepper motor.
- The commutation sequence for a half-step stepper motor has eight steps instead of four.
- The main difference is that the second phase is turned on before the first phase is turned off. Thus, sometimes both phases are energized at the same time.
- During the half-steps the rotor is held in between the two full-step positions.
- A half-step motor has twice the resolution of a full step motor. It is very popular for this reason.
- Step resolution can also be increased with more poles in the stator, resulting in more steps.
- Stepper motors is normally run open loop without sensors or feedback.
- Good for applications such as printers.





Servo Motor

A **servomechanism**, or **servo** is an automatic device which uses error-sensing feedback to correct the performance of a mechanism.

A **servomotor** is an electromechanical device in which an electrical input determines the position of the armature of a motor.

Servos are used extensively in robotics and radio-controlled cars, airplanes, tracking and guidance systems, process controllers, computers and machine tools.

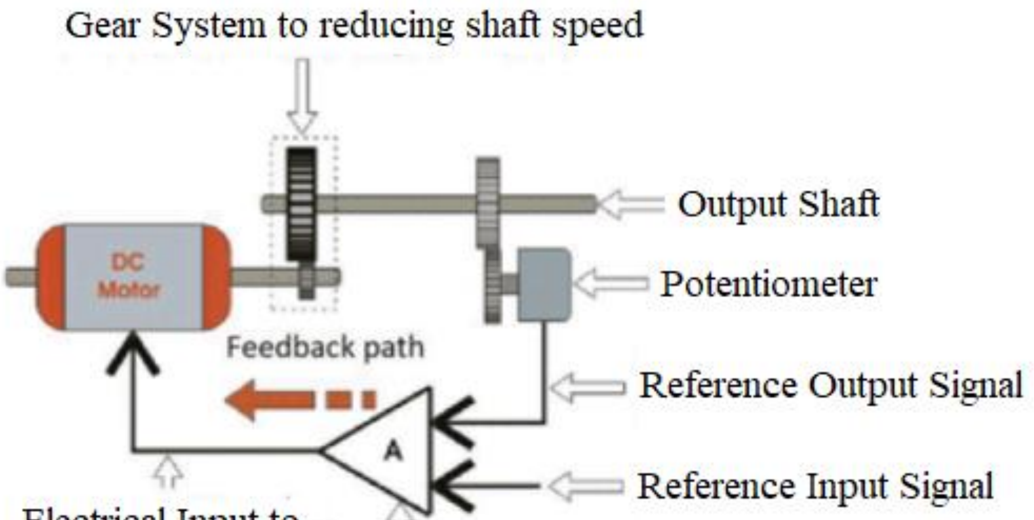



Fig. 4. DC servo motor

Servomotors are also called control motors and have high-torque capabilities.

They are not used for continuous energy conversion but only for precise speed and precise position control at high torques.

Their power ratings vary from a fraction of a watt up to a few 100 W.

They find wide applications in radar, tracking and guidance systems, process controllers, computers and machine tools.

Both DC and AC (2-phase and 3-phase) servomotors are used at present.

Servomotors differ in application capabilities from large industrial motors in the following respects:

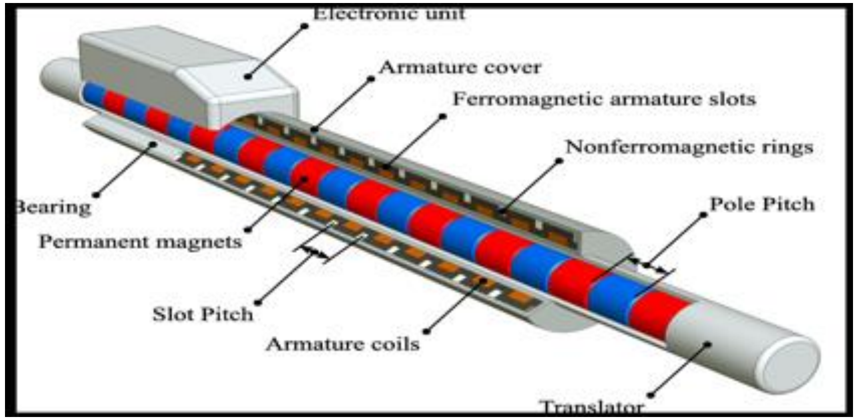
1. They produce high torque at all speeds including zero speed.
2. They are capable of holding a static (*i.e.* no motion) position.
3. They do not overheat at standstill or lower-speeds.
4. Due to low-inertia, they are able to reverse directions quickly.
5. They are able to accelerate and decelerate quickly.

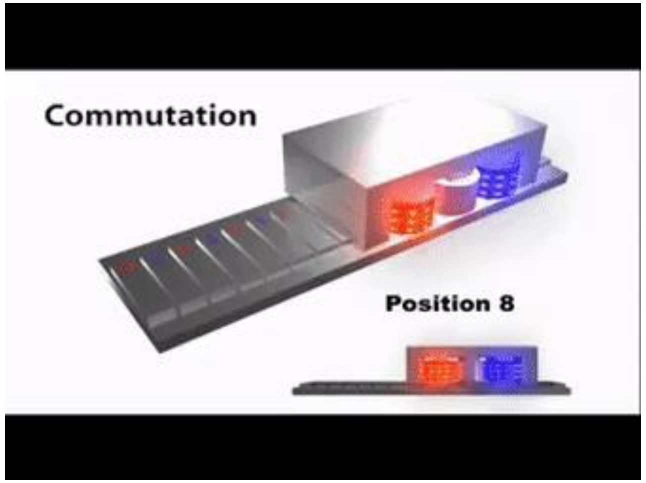
They are able to return to a given position time after-time without any drift.

Linear Motor

Linear Motor

- A linear motor is an electric motor that has had its stator and rotor "unrolled" thus instead of producing a torque (rotation) it produces a linear force along its length.
- However, linear motors are not necessarily straight.
- Characteristically, a linear motor's active section has ends, whereas more conventional motors are arranged as a continuous loop.





https://youtu.be/0_QBl6-_jJU

- Linear motors operate with an AC power supply and servo controller, which are often the same as those used for rotary servo motors.
- The linear motor primary part is connected to the power supply to produce a magnet field.
- By changing the current phase in the coils, the polarity of each coil is changed.
- The attractive and repelling forces between the coils in the primary part and the magnets in the secondary part cause the primary to move and generate a linear force.
- The rate of change of the current controls the velocity of the movement, and the amperage of the current determines the force generated.