Introduction to Electrical Circuits

Final Term
Lecture - 10

Reference Book:

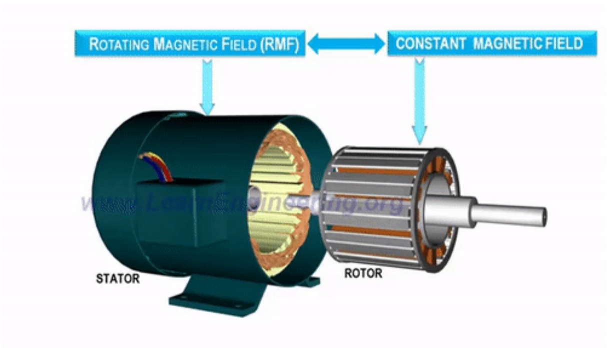
[1] Principles of Electrical Machines -V.K. Mehta, Rohit Mehta

[2] A Textbook of Electrical Technology , Volume- II, - B.L. Theraja, A.K. Theraja

Week No.	Class No.	Chapter No.	Article No., Name and Contents	Example No.
W12	FC10		**Synchronous Generator:** Basic principles and construction of a synchronous motor. Draw the circuit and vector diagram. Discuss about power flow diagram. Power developed by a synchronous motor (ex. 38.1, 20.1). Synchronous motor with different excitation. Power factor correction by using synchronous motor (ex. 38.31) **Stepper Motor.:** Basic principles, step angle (ex. 11.2, 39.1, 39.2), Applications, Difference between conventional motor and stepper motor, Stepper Motor Advantages and Disadvantages, Types of stepper motor (ex. 11.3), full and half step operation.	11.2, 11.3, 20.1, 38.1, 38.31, 39.1, 39.2.

Synchronous Motor

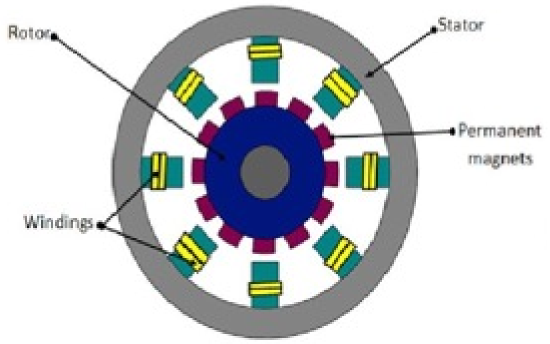
- A synchronous motor is electrically identical with an alternator or a.c. generator.
- An alternator when driven as a motor by connecting its armature winding to a 3-phase supply, it is then called a synchronous motor.
- A synchronous motor runs at synchronous speed ($N_s = 120f/P$). The only way to change its speed is to vary the supply frequency.
- This type of motor is not inherently self-starting.
- It is capable of being operated under a wide range of power factors, both lagging and leading. Hence, it can be used for power correction purposes, in addition to supplying torque to drive loads.



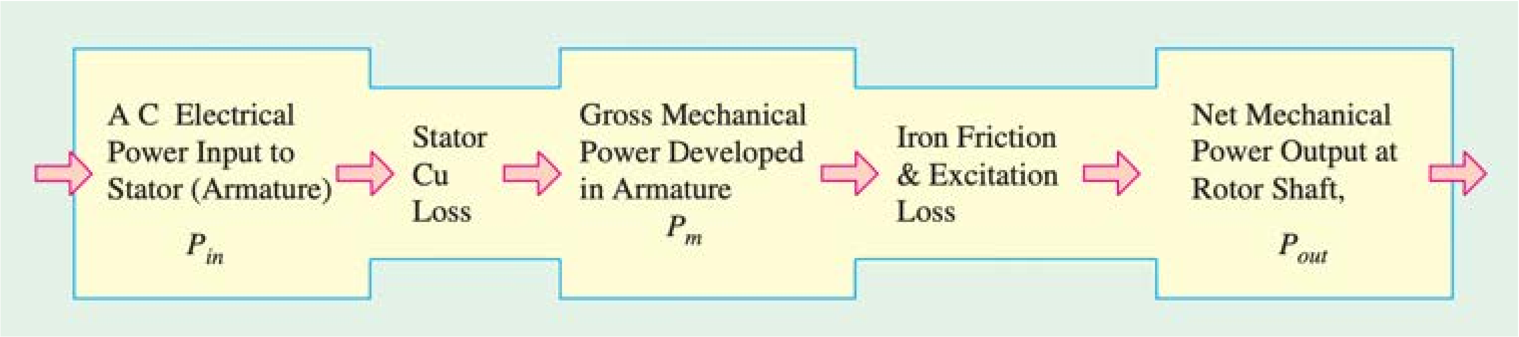
Construction:

Like an alternator, a synchronous motor has the following two parts:

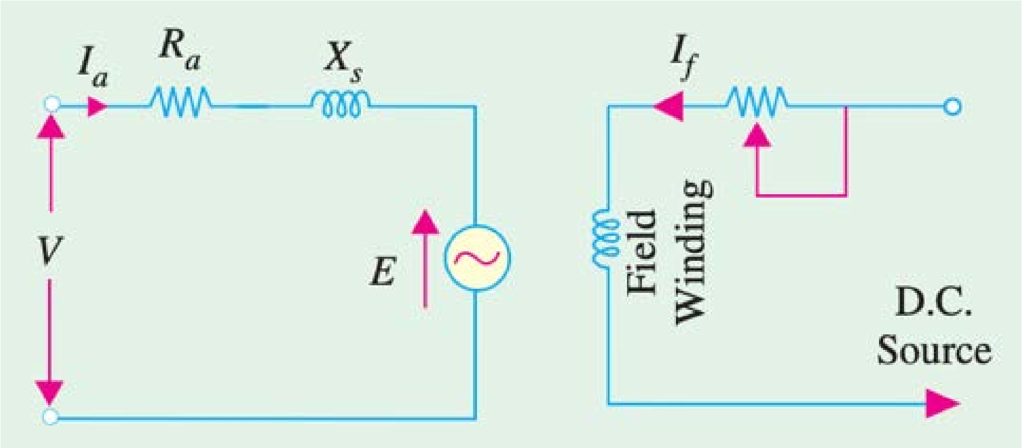
- **a stator** which houses 3-phase armature winding in the slots of the stator core and receives power from a 3-phase supply
- **a rotor** that has a set of salient poles excited by direct current to form alternate **N** and **S** poles. The exciting coils are connected in series to two slip rings and direct current is fed into the winding from an external exciter mounted on the rotor shaft.

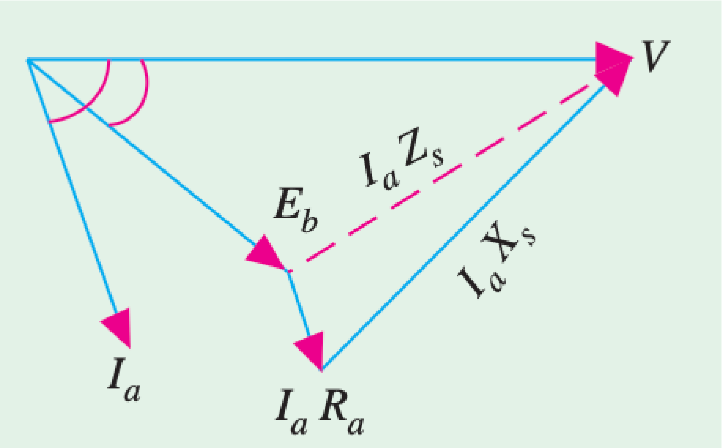


Power Flow Diagram



Equivalent Circuit of a Synchronous Motor





Power Developed by a Synchronous Motor

Except for very small machines, the armature resistance of a synchronous motor is negligible as compared to its synchronous reactance. Hence, the equivalent circuit for the motor becomes as shown in Fig. 38.10 (*a*). From the phasor diagram of Fig. 38.10 (*b*), it is seen that

$$AB = E_b \sin\alpha = I_a X_S \cos\phi$$

$$\text{or} \quad VI_a \cos\phi = \frac{E_b V}{X_S} \sin\alpha$$

Now, $VI_a \cos\phi =$ motor power input/phase

$$\therefore \quad P_{in} = \frac{E_b V}{X_S} \sin\alpha \quad \text{...per phase*}$$

$$= 3\frac{E_b V}{X_S} \sin\alpha \quad \text{... for three phases}$$

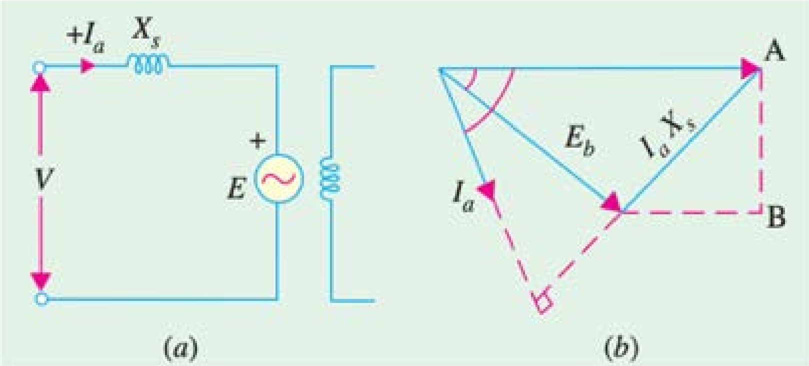


Fig. 38.10

Since stator Cu losses have been neglected, P_{in} also represents the gross mechanical power $\{P_m\}$ developed by the motor.

$$\therefore \quad P_m = \frac{3E_b V}{X_S} \sin\alpha$$

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

Example Problems

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**

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

Now, $V = E_b + j\,IX_S$ or $E_b = V - j\,I_a X_S = 254 \angle 0° - 129 \angle 36.9° \times 2.5 \angle 90° = 250 \angle 0° - 322 \angle 126.9° = 254 - 322 (\cos 126.9° + j \sin 126.9°) = 254 - 322(-0.6 + j\,0.8) =$ **516 ∠−30°**

(iv) $\therefore \qquad \alpha = $ **−30°**

(v) pull-out torque occurs when $\alpha = 90°$

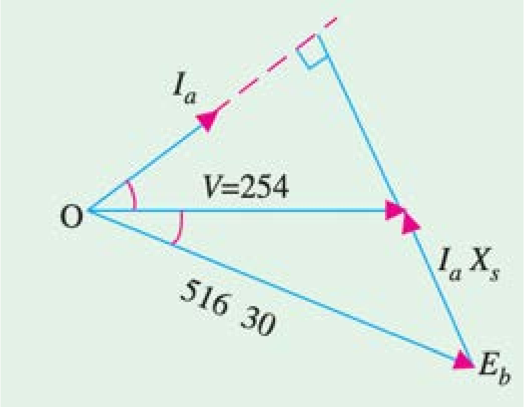


Fig. 38.11

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

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

Synchronous Motor with Different Excitations

A synchronous motor is said to have normal excitation when its $E_b = V$. If field excitation is such that $E_b < V$, the motor is said to be *under-excited*. In both these conditions, it has a lagging power factor as shown in Fig. 38.12.

On the other hand, if d.c. field excitation is such that $E_b > V$, then motor is said to be *over-excited* and draws a leading current, as shown in Fig. 38.13 (*a*). There will be some value of excitation for which armature current will be in phase with V, so that power factor will become unity, as shown in Fig. 38.13 (*b*).

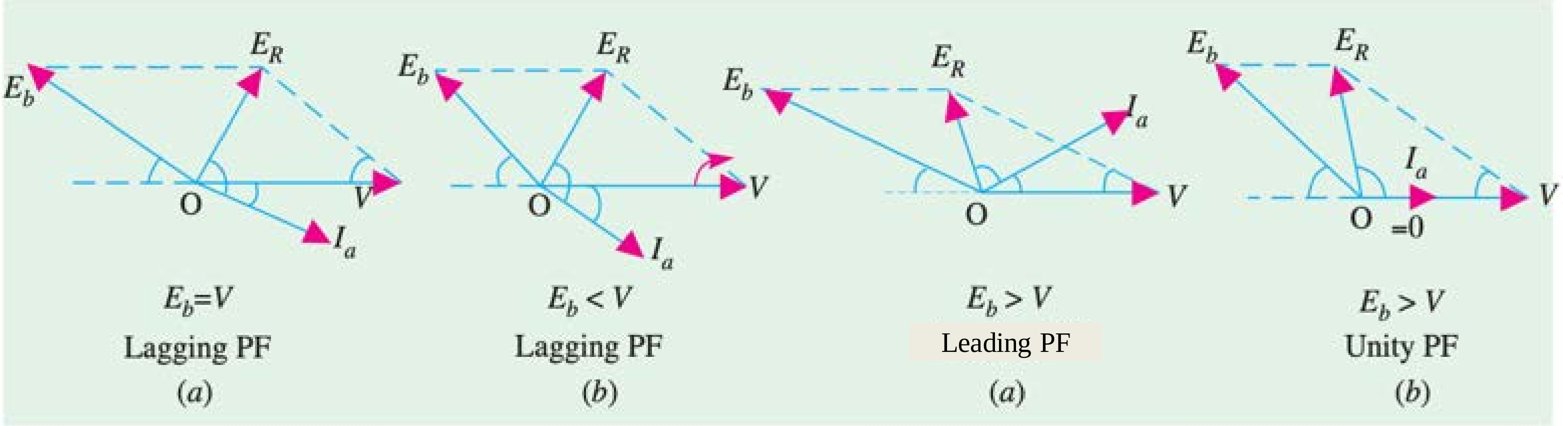
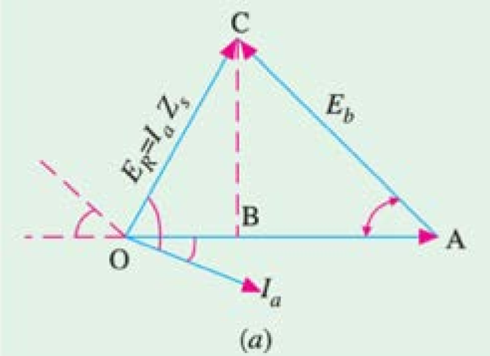


Fig. 38.12 Fig. 38.13

Synchronous Motor with Different Excitations

The value of α and back e.m.f. E_b can be found with the help of vector diagrams for various power factors, shown in Fig. 38.14.



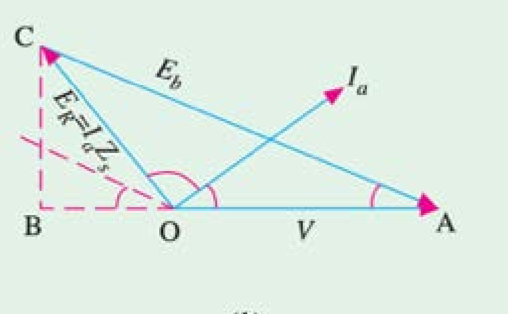
(a)

(i) Lagging p.f. As seen from Fig. 38.14 (a)

$$AC^2 = AB^2 + BC^2 = [V - E_R \cos(\theta - \phi)]^2 + [E_R \sin(\theta - \phi)]^2$$

$$\therefore \quad E_b = \sqrt{[V - I_a Z_S \cos(\theta - \phi)]^2 + [I_a Z_S \sin(\theta - \phi)]^2}$$

$$\text{Load angle} \quad \alpha = \tan^{-1}\left(\frac{BC}{AB}\right) = \tan^{-1}\left[\frac{I_a Z_S \sin(\theta - \phi)}{V - I_a Z_S \cos(\theta - \phi)}\right]$$

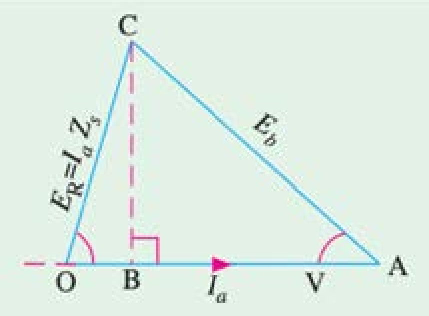


(b)

(ii) Leading p.f. [38.14 (b)]

$$E_b = V + I_a Z_S \cos[180^\circ - (\theta + \phi)] + j I_a Z_S \sin[180^\circ - (\theta + \phi)]$$

$$\alpha = \tan^{-1}$$



(c)

(iii) Unity p.f. [Fig. 38.14 (c)]

Here, $\quad OB = I_a R_a$ and $BC = I_a X_S$

$$\therefore \quad E_b = (V - I_a R_a) + j I_a X_S; \ \alpha = \tan^{-1}$$

Example Problems

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)

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

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

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

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

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

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

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

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

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

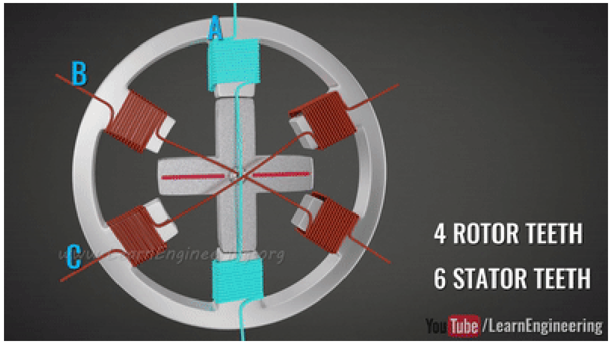
$$\therefore \quad \sqrt{3} \times 3300 \times 152 \times \cos\phi = 743{,}260 \qquad \therefore \quad \cos\phi = 0.855 \text{ (lead).}$$

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° to 90°.
- Most common step sizes are 1.8°, 2.5°, 7.5° and 15°.
- 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. $N_s = 8 \times 5 = 40; \quad N_r = 50$

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

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° / β = 360° / 2.5° = 144 steps / revolution.

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

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

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.

Difference Between Conventional Motor and Stepper Motor:

- Industrial motors are used to convert electric energy into mechanical energy, but they cannot be used for precision control of speed without using closed-loop feedback.
- Stepping motors are ideally suited for situations where either precise positioning or precise speed control or both are required in automation systems.
- Stepper motor is well-suited for open-loop position control because no feedback need be taken from the output shaft.

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.

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

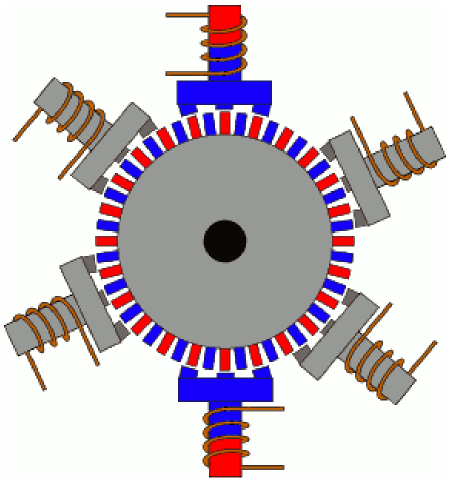

Variable reluctance motor

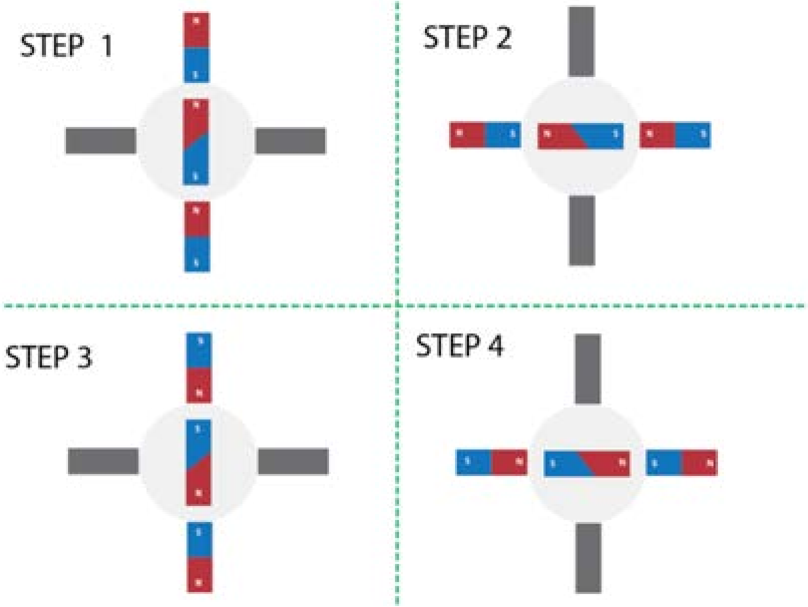

Permanent magnet stepper motor


Hybrid stepper motor

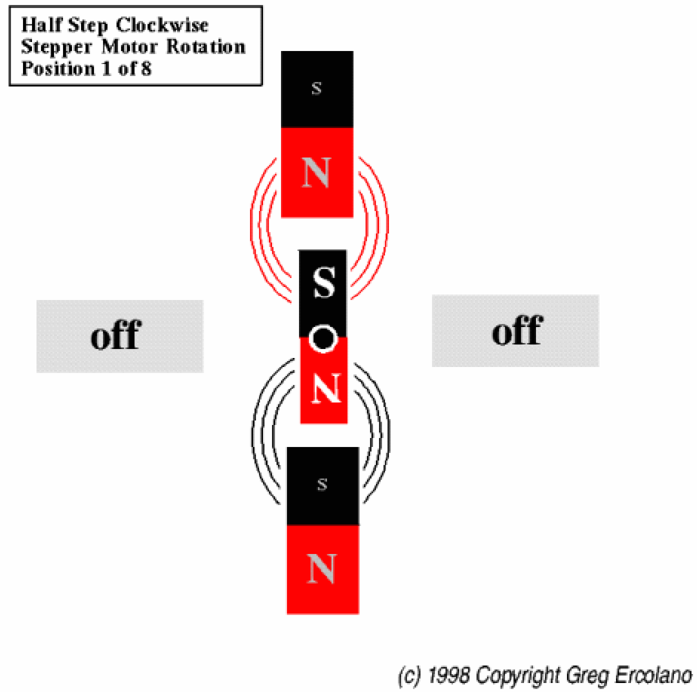
Full step operation

- In this mode the rotor moves through the basic angle of 1.8 degrees in a single step and thereby taking 200 steps to finish off a rotation.
- We can make this happen by energizing either only one phase of stator windings or two phases.
- Single phase on operation requires minimum amount of power from the driver circuit.
- In dual phase on operation, two phases are energized at the same time which results in increased torque and speed.





Half step operation



- The rotor moves through half the base angle in a single step which results in improved torque than single phase full step operation.
- Also it doubles smoothness of rotation and resolution.

https://www.youtube.com/watch?v=LwqQQqhqMq8

Thank You