Stepper Motors:

The terms *stepper motor*, *stepping motor*, and *step motor* are synonymous and are often used interchangeably.

There are three basic types of stepper motors:

1. *Variable-reluctance (VR) stepper motors, which have soft-iron (ferromagnetic) rotors*
2. *Permanent-magnet (PM) stepper motors, which have magnetized rotors*
3. *Hybrid (HB) stepper motors, which have two stacks of rotor teeth forming the two poles of a permanent magnet located along the rotor axis*

The VR and PM steppers operate in a somewhat similar manner:

- Specifically, the *stator magnetic field (polarity) is stepped* so as to change the minimum reluctance (or detent) position of the rotor in increments.
- Hence, both types of motors undergo similar changes in reluctance (magnetic resistance) during operation.
- A disadvantage of VR steppers is that as the rotor is not magnetized, the holding torque is practically zero when the stator windings are not energized (i.e., power-off conditions). Hence, it is not capable to hold the mechanical load at a given position under power-off conditions, unless mechanical brakes are employed.
- An HB stepper motor possesses characteristics of both VR steppers and PM steppers.
    - The rotor of an HB stepper motor consists of two rotor segments connected by a shaft.
    - Each rotor segment is a toothed wheel and is called a stack.
    - The two rotor stacks form the two poles of a permanent magnet located along the rotor axis.
    - Hence, an entire stack of rotor teeth is magnetized to be a single pole (which is different from the case of a PM stepper where the rotor has multiple poles).

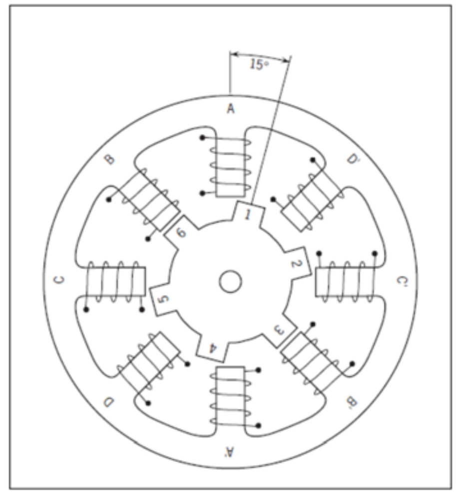


Figure 1. Cross-section of a variable-reluctance (VR) motor.

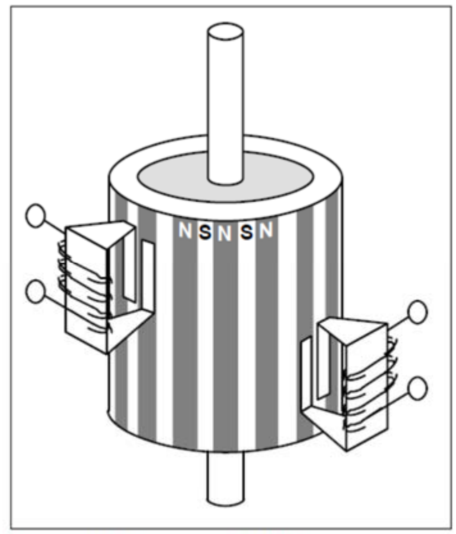


Figure 2. Principle of a PM or tin-can stepper motor.

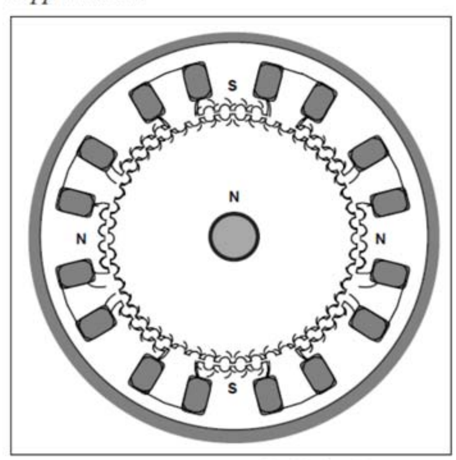
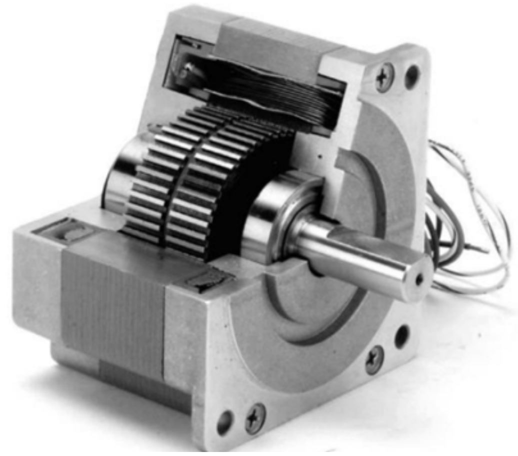


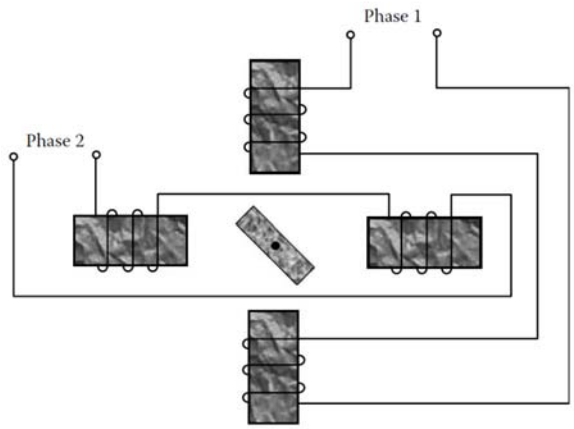
Figure 3. Cross-section of a hybrid stepper motor.

- The *rotor polarity of an HB stepper can be provided either by a permanent magnet, or by an electromagnet using a coil activated by a unidirectional dc source and placed on the stator to generate a magnetic field along the rotor axis.*
- A photograph of the internal components of a *two-stack stepping motor* is given in figure.



Permanent-Magnet Stepper Motor

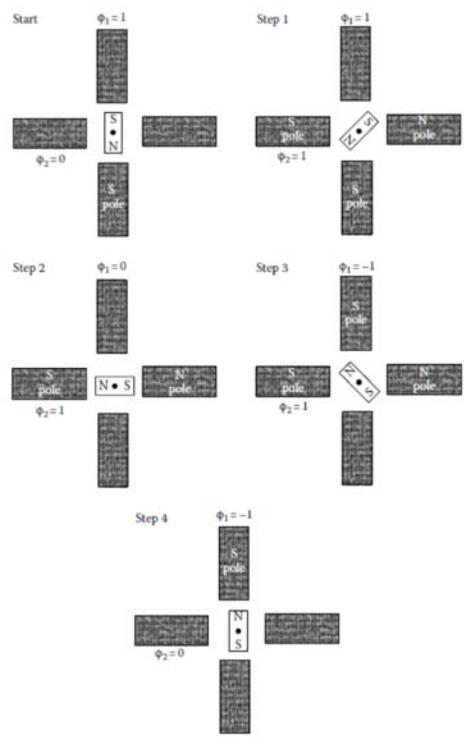
To explain the operation of a PM stepper motor, consider the simple schematic diagram shown in figure.



- The stator has two sets of windings (i.e., two *phases*) placed at 90°.
- This arrangement has four *salient poles* in the stator, each pole geometrically separated by a 90° angle from the adjacent one. The rotor is a two-pole permanent magnet. Each phase can take one of the three states 1, 0, and −1, which are defined as follows:
  1. State 1: current in a specified direction
  2. State −1: current in the opposite direction
  3. State 0: no current

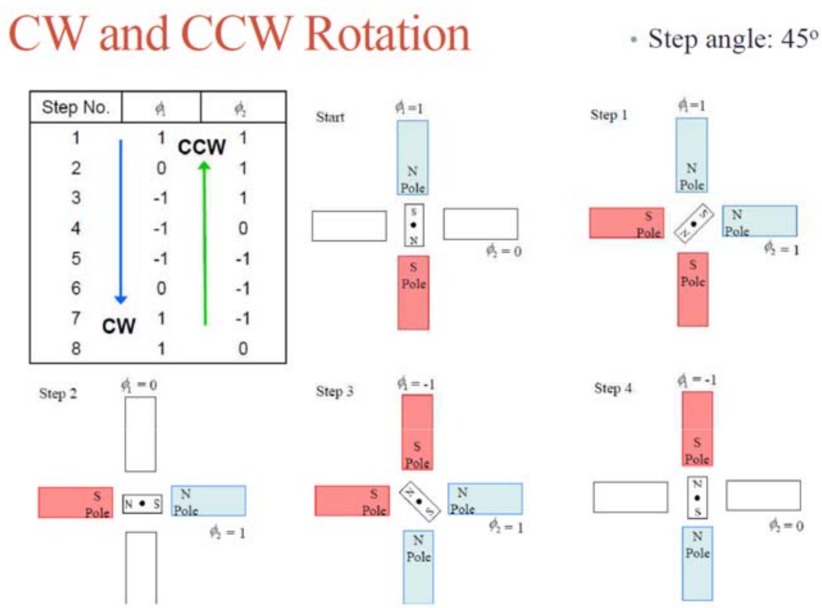
Note that:

- As −1 is the complement state of 1, in some literature the notation 1′ is used to denote the state −1.
- By switching the currents in the two phases in an appropriate sequence, either a clockwise (CW) rotation or a counterclockwise (CCW) rotation can be generated. The CW rotation sequence is shown.

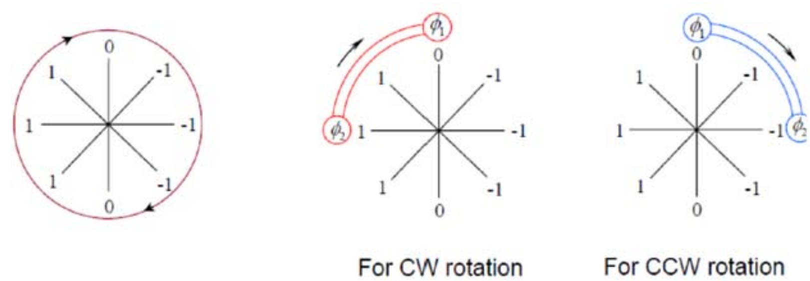


- ϕ_i *denotes* the state of the i_{th} phase.
- The step angle for this motor is 45°. At the end of each step, the rotor assumes the minimum reluctance position that corresponds to the particular magnetic polarity pattern in the stator. This is a stable equilibrium configuration and is known as the detent position for that step.
- Note: *Reluctance measures the magnetic resistance* in a flux path.

- When the stator currents (phases) are switched for the next step, the minimum reluctance position changes (rotates by the step angle) and the rotor assumes the corresponding stable equilibrium position and the rotor turns through a single step (45° in this example).



Observe that in one complete rotation of the rotor, the state of each phase sweeps through one complete cycle of the switching sequence in figure in the CW direction.



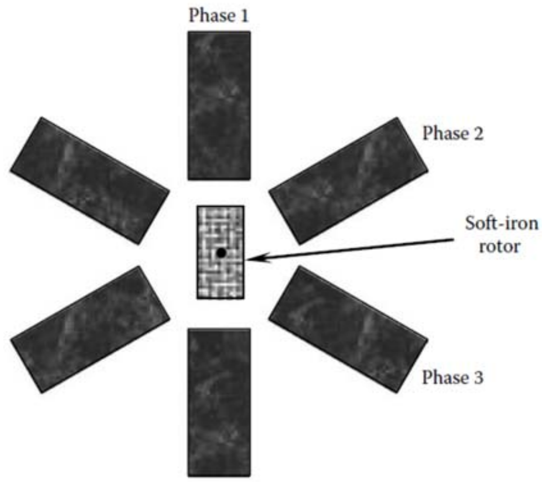
- For CW rotation of the motor, the state of phase 2 (ϕ_2) lags the state of phase 1 (ϕ_1) by two steps.
- For CCW rotation, ϕ_2 leads ϕ_1 by two steps.
- Hence, instead of eight pairs of numbers, just eight numbers with a delay operation would suffice to generate the phase-switching logic.
- This approach is faster and more effective because the switching logic for a stepper motor.

Increasing Resolution:

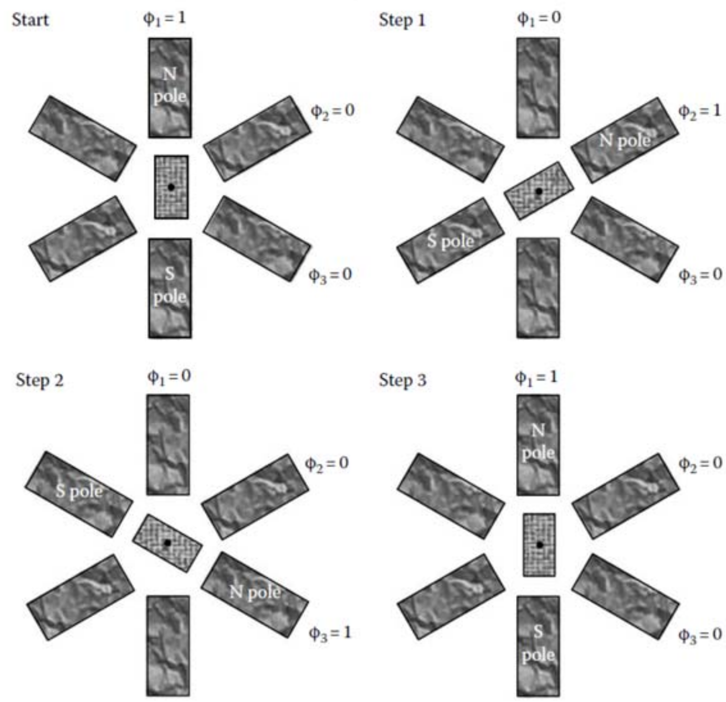
- A stepping resolution of 45 degrees is too coarse for most applications. We can increase the resolution by adding the rotor pole pairs.
    - e.g.: Stepping Resolution of 30 degrees
    - Common types are 30, 15, and 7.5 degrees.
    - For high precision, this solution is not cost effective.

Variable-Reluctance Stepper Motor

Now consider the VR stepper motor shown.



- The rotor is a non-magnetized soft-iron (ferromagnetic) bar.
- The *full-stepping sequence for CW rotation is shown in figure below. The step angle is 60°.* Only one phase is energized at a time in order to execute full stepping.
- With VR steppers, *the direction of the current (the polarity of a stator pole pair) is not reversed in the full-stepping sequence;* only the states 1 and 0 (i.e., on and off) are used for each phase.
- In the *case of half stepping, however, two phases have to be energized simultaneously during some steps*.
- Furthermore, *current reversals are needed in half stepping, thus requiring more elaborate switching circuitry.*
- The *advantage, however, is that the step angle would be halved to 30°, thereby providing improved motion* resolution.

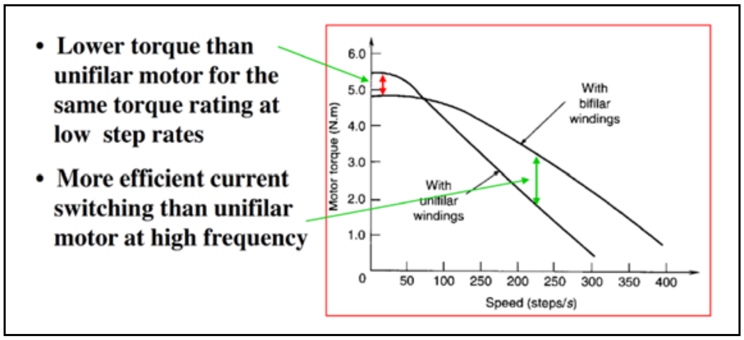


- When *two phases are activated simultaneously,* the *minimum reluctance position is halfway between the corresponding pole pairs (i.e., 30° from the detent position* that is obtained when only one of the two phases is energized), which enables half stepping.
- It follows that, *depending on the energizing sequence of the phases*, *either full stepping or half stepping would be possible*.
- *Micro-stepping provides much smaller step angles achieved by changing the phase currents by small increments (rather than just the states on, off, and reversal)* so that the detent (equilibrium) position of the rotor shifts in correspondingly small angular increments.

Polarity Reversal:

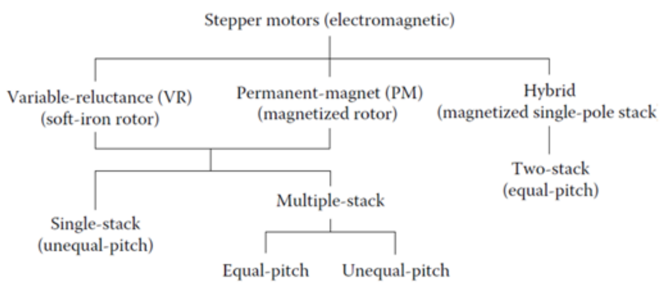
The polarity of a stator pole can be reversed in two ways:

- There is only one set of windings for a group of stator poles. This is the case of unifilar windings. Polarity of the poles is reversed by reversing the direction of current in the winding.
- There are two sets of windings for a group of stator poles. This is the *case of bifilar windings (i.e., double-file or two-coil windings*).
- Only *one set of windings is energized at a time, producing one polarity for this group* of poles. *The other set of windings produces the opposite polarity*.
- *Note*: **One winding with a center tap may be used in place of two windings.** The other two terminals of the coil are given opposite (i.e., positive and negative) voltages.



Stepper Motor Classification:

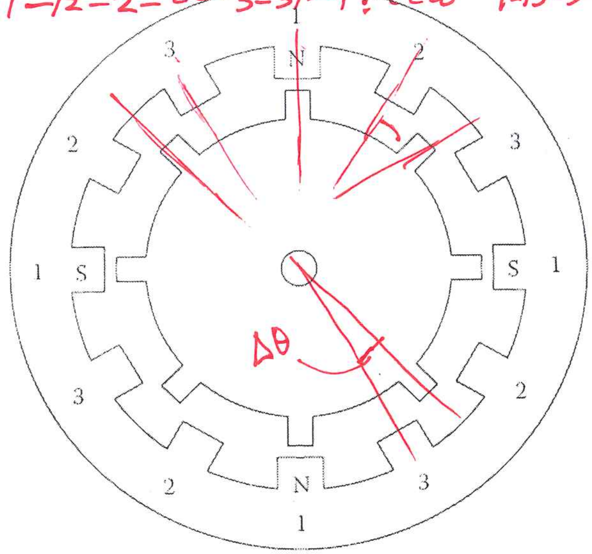
- Most classifications of stepper motors are *based on the nature of the motor rotor.*
- One such classification considers the magnetic character of the rotor. Specifically, as discussed before:
  - o VR stepper motor has a soft-iron rotor, whereas
  - o PM stepper motor has a magnetized rotor.
- Another practical classification that is based on the number of stacks of teeth (or rotor segments) present on the rotor shaft. In particular, an HB stepper motor has two stacks of teeth.
- Further *sub-classifications are possible, depending on the tooth pitch (angle between adjacent teeth) of the stator and the tooth pitch of the rotor*.
- In a *single-stack stepper motor*:
  - o The rotor tooth pitch and the stator tooth pitch generally have to be unequal
  - o So that *not all teeth in the stator are ever aligned with the rotor teeth at any instant*.
  - o It is the *misaligned teeth that exert the magnetic pull*, *generating the driving torque*.
  - o In each motion increment, the rotor turns to the minimum reluctance (stable equilibrium) position corresponding to that particular polarity distribution of the stator.
- In multiple-stack stepper motors:
  - o Operation is possible even when the rotor tooth pitch is equal to the stator tooth pitch, provided that at least one stack of rotor teeth is rotationally shifted (misaligned) from the other stacks by a fraction of the rotor tooth pitch.
  - o In this design, it is this inter-stack misalignment that generates the drive torque for each motion step. It is obvious that unequal-pitch multiple-stack steppers are also a practical possibility. In this design, each rotor stack operates as a separate single-stack stepper motor. The stepper motor classifications described thus far are summarized in Figure 8.8.



Full step CCW : 1-2-3-1, 1-3-2-1 CW

$\frac{1}{2}$ step : 1-12-2-23-3-31-1 : CCW   1-13-3-32-2-21-1 CW

Single-Stack Stepper Motors:



Phase Winding $p = 3$.

Rotor Teeth $n_r = 8$; Soft iron

Stator Teeth $n_s = 12$

Poles per phase $m = 4$

Stator pitch $\theta_s = \dfrac{360}{n_s}$

Rotor pitch $\theta_r = \dfrac{360}{n_r}$

Step Angle $\Delta\theta$: Smallest Misalignment between stator pole and adjacent Rotor tooth in any stable equillibrium.

$$\left.\begin{aligned} \Delta\theta &= \theta_r - r\theta_s \quad (\theta_r > \theta_s) \\ \Delta\theta &= \theta_s - r\theta_r \quad (\theta_r < \theta_s) \end{aligned}\right\}$$

r is the largest positive integer such that $\Delta\theta > 0$

i.e. Largest feasible r such that a misalignment occurs.

Since $n_s = 12 \rightarrow \theta_s = \frac{360}{12} = 30^\circ$

$n_r = 8 \rightarrow \theta_r = \frac{360}{8} = 45^\circ$

$\Delta\theta = \theta_r - \theta_s = 15^\circ$; Each Switching Corresponds to rotation θ.

If phase-1 is off, phase-2 is ON; Rotor will turn 15° CCW

If phase-3 is ON, Rotor will turn 15° CW

If phase-1 is ON + phase 2 is ON 7.5° is also possible.

Full stepping 1-2-3-1 CCW ; 1-3-2-1 CW

$\frac{1}{2}$ stepping 1-12-2-23-3-31-1 CCW; 1-31-3-23-2-12-1 CW

Se have p phases meaning the whole switching angle is: PΔθ ; $\theta_r = P\Delta\theta$

P-switches.

From Original Equation $\Delta\theta = \theta_r - r\theta_s$

Substituting $\theta_r = P\Delta\theta$ above.

$$\theta_r = r\theta_s + \frac{\theta_r}{P} \quad (\theta_r > \theta_s).$$

For Equation $\Delta\theta = \theta_s - r\theta_r \; (\theta_r < \theta_s)$

$$\theta_s = r\theta_r + \frac{\theta_r}{P} \quad (\theta_r < \theta_s).$$

θ_r = rotor tooth pitch angle

θ_s = stator tooth pitch angle

P = # of phases in stator

r = Largest feasible positive Integer

pitch angle definition. $\frac{360°}{n_r} = \frac{r \times 360}{n_s} + \frac{360}{p n_r}$

or $n_s = r n_r + \frac{n_s}{p}$; $(n_s > n_s)$

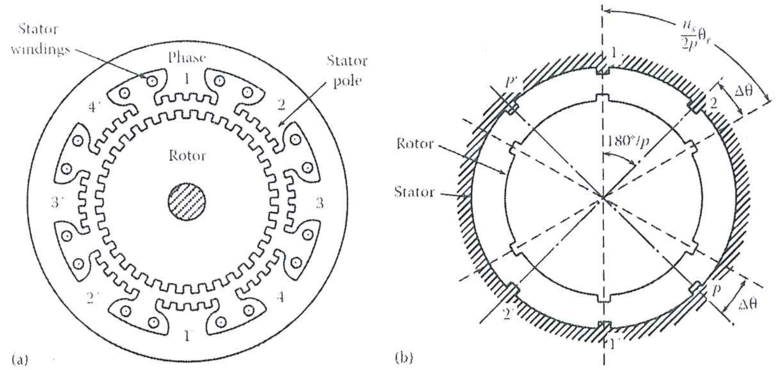
and $n_r = r n_s + \frac{n_s}{p} \; (n_s < n_r)$

Finally # of ~~Revolutions~~ steps

$$n = \frac{360}{\Delta\theta}$$

Read Examples 8.1, 8.2, 8.3

Advantages of Toothed Construction:



The toothed construction of the stator and the rotor of a stepper motor has many advantages.

1. It improves the motion resolution (step angle), which now depends on the tooth pitch. Very small step angles can be achieved as a result.
2. It enhances the concentration of the magnetic field, which generates the motor torque. This means improved torque characteristics.
3. The torque and motion characteristics become smoother (smaller ripples and less jitter) as a result of the distributed tooth construction.

In the case shown in figure above, *the stator teeth are equally spaced but the pitch (angular spacing) is not identical to the pitch of the rotor teeth.*
In the toothed-stator construction, *ns represents the number of teeth rather than the number of poles in the stator*. The number of rotor teeth has to be increased in proportion.

Governing Equations:

Considering $\theta_r > \theta_s$ (i.e. $n_r < n_s$)

$\theta_r - \theta_s$: offset between rotor and stator pitch

# of rotor teeth n_s/mp

$\therefore \Delta\theta = \frac{n_s}{mp}(\theta_r - \theta_s)$; $\theta_r > \theta_s$; p: # of phases; m: # of stator poles per phase

$\Delta\theta = \frac{\theta_r}{p}$; True for toothed construction as well

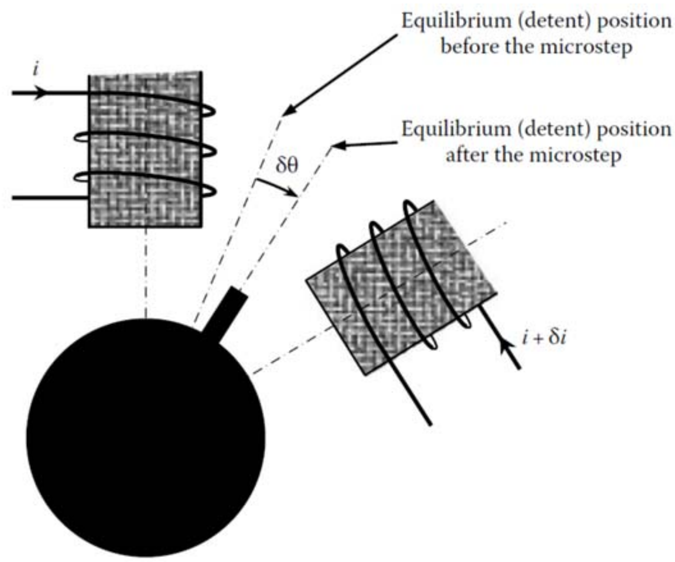
or $\theta_r = p\Delta\theta$ and $n_s = m\,p\,\theta_s$

$\Delta\theta = \frac{n_s}{mp}(\theta_r - \theta_s) \Longrightarrow n_s = n_r + m \quad (n_r < n_s)$

General Formula: $\boxed{n_s = n_r \pm m}$ # of stator poles per phase

Read Example 8.4.

Micro-Stepping:



- Microstepping is achieved by properly changing the phase currents in small steps, instead of switching them on and off (as in the case of full stepping and half stepping).
- The principle behind this can be understood by considering two identical stator poles (wound with identical windings), as shown in diagram.

- When the *currents through the windings are identical (in magnitude and direction) the resultant magnetic field will lie symmetrically between the two poles*.

- If *the current in one pole is decreased while the other current is kept unchanged, the resultant magnetic field will move closer to the pole with the larger current*.

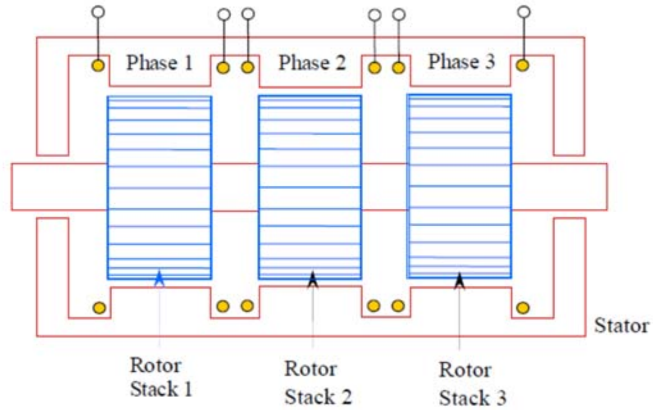
- As the detent position (equilibrium position) depends on the position of the resultant magnetic field, *it follows that very small step angles can be achieved simply by controlling (varying the relative magnitudes and directions of) the phase currents.*

- *Step angles of 1/125 of a full step* or smaller may be obtained through microstepping.

- *For example, 10,000 steps/revolution may be achieved.*

- Note: The step size in a sequence of microsteps is not identical. This is because stepping is done through microsteps of the phase current, which (and the magnetic field generated by it) has (have) a nonlinear relation with the physical step angle.

Multiple-Stack Stepper Motors



- Both equal pitch and unequal pitch constructions are possible.
- Smaller step angles are possible with unequal construction.
- For the equal pitch case, each stator segment has several poles and all poles of each stator segment are wound to the same phase.
- Misalignment can be achieved by two methods:
    1. The teeth in the *stator segments are aligned* but the *teeth in the rotor segments are misaligned* consecutively by 1/3 pitch angle.
    2. The teeth in the *rotor segments are aligned* but the *teeth in the stator segments are misaligned* consecutively by 1/3 pitch angle.

- Both full stepping and half stepping can be achieved.
- For full stepping the step angle is θs/3 = θr/3.
- Stepping sequence 1-2-3-1 would turn the rotor in one direction and
- 1-3-2-1 would turn in the other.
- For half stepping they are 1-12-2-23-3-31-1 and 1-13-3-32-2-21-1
- The full stepping angle if there are s-stacks:

$$\Delta\theta = \frac{\theta_r}{s} = \frac{\theta_s}{s} = \frac{\theta}{s}$$

- Very fine angular resolutions can be achieved with unequal multi-stack stepper motors. Switching logic of these stepper motors is more complex.
- Since the step angle of a non-toothed single stack stepper motor is (θr–θs)

$$\Delta\theta = \frac{\theta_r - \theta_s}{s}$$

- For a tooth-pole multi-stack motor:

$$\Delta\theta = \frac{n_s(\theta_r - \theta_s)}{mps} \qquad \Delta\theta = \frac{\theta_r}{ps}$$