# Stepper Motor Theory of Operation

Stepper motors provide a means for precise positioning and speed control without the use of feedback sensors. The basic operation of a stepper motor allows the shaft to move a precise number of degrees each time a pulse of electricity is sent to the motor. Since the shaft of the motor moves only the number of degrees that it was designed for when each pulse is delivered, you can control the pulses that are sent and control the positioning and speed. The rotor of the motor produces torque from the interaction between the magnetic field in the stator and rotor. The strength of the magnetic fields is proportional to the amount of current sent to the stator and the number of turns in the windings.

The stepper motor uses the theory of operation for magnets to make the motor shaft turn a precise distance when a pulse of electricity is provided. You learned previously that like poles of a magnet repel and unlike poles attract. Figure 1 shows a typical cross-sectional view of the rotor and stator of a stepper motor. From this diagram you can see that the stator (stationary winding) has eight poles, and the rotor has six poles (three complete magnets). The rotor will require 24 pulses of electricity to move the 24 steps to make one complete revolution. Another way to say this is that the rotor will move precisely 15° for each pulse of electricity that the motor receives. The number of degrees the rotor will turn when a pulse of electricity is delivered to the motor can be calculated by dividing the number of degrees in one revolution of the shaft (360°) by the number of poles (north and south) in the rotor. In this stepper motor 360° is divided by 24 to get 15°.

When no power is applied to the motor, the residual magnetism in the rotor magnets will cause the rotor to *detent* or align one set of its magnetic poles with the magnetic poles of one of the stator magnets. This means that the rotor will have 24 possible detent positions. When the rotor is in a detent position, it will have enough magnetic force to keep the shaft from moving to the next position. This is what makes the rotor feel like it is *clicking* from one position to the next as you rotate the rotor by hand with no power applied.

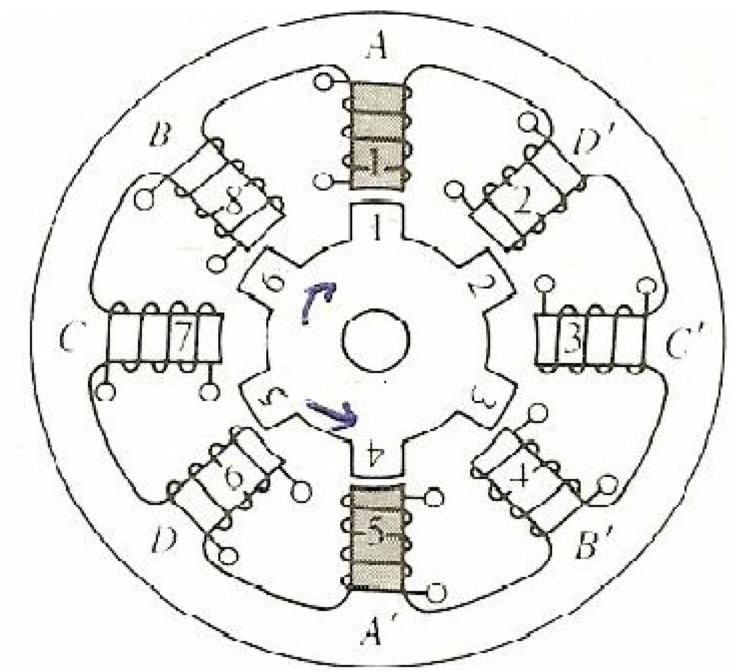



**Fig 1. Diagram that shows the position of the six-pole rotor and eight-pole stator of a typical stepper motor.**

When power is applied, it is directed to only one of the stator pairs of windings, which will cause that winding pair to become a magnet. One of the coils for the pair will become the North Pole, and the other will become the South Pole. When this occurs, the stator coil that is the North Pole will attract the closest rotor tooth that has the opposite polarity, and the stator coil that is the South Pole will attract the closest rotor tooth that has the opposite polarity. When current is flowing through these poles, the rotor will now have a much stronger attraction to the stator winding, and the increased torque is called *holding torque.*

By changing the current flow to the next stator winding, the magnetic field will be changed 45°. The rotor will only move 15° before its magnetic fields will again align with the change in the stator field. The magnetic field in the stator is continually changed as the rotor moves through the 24 steps to move a total of 360°. Figure 2 shows the position of the rotor changing as the current supplied to the stator changes.

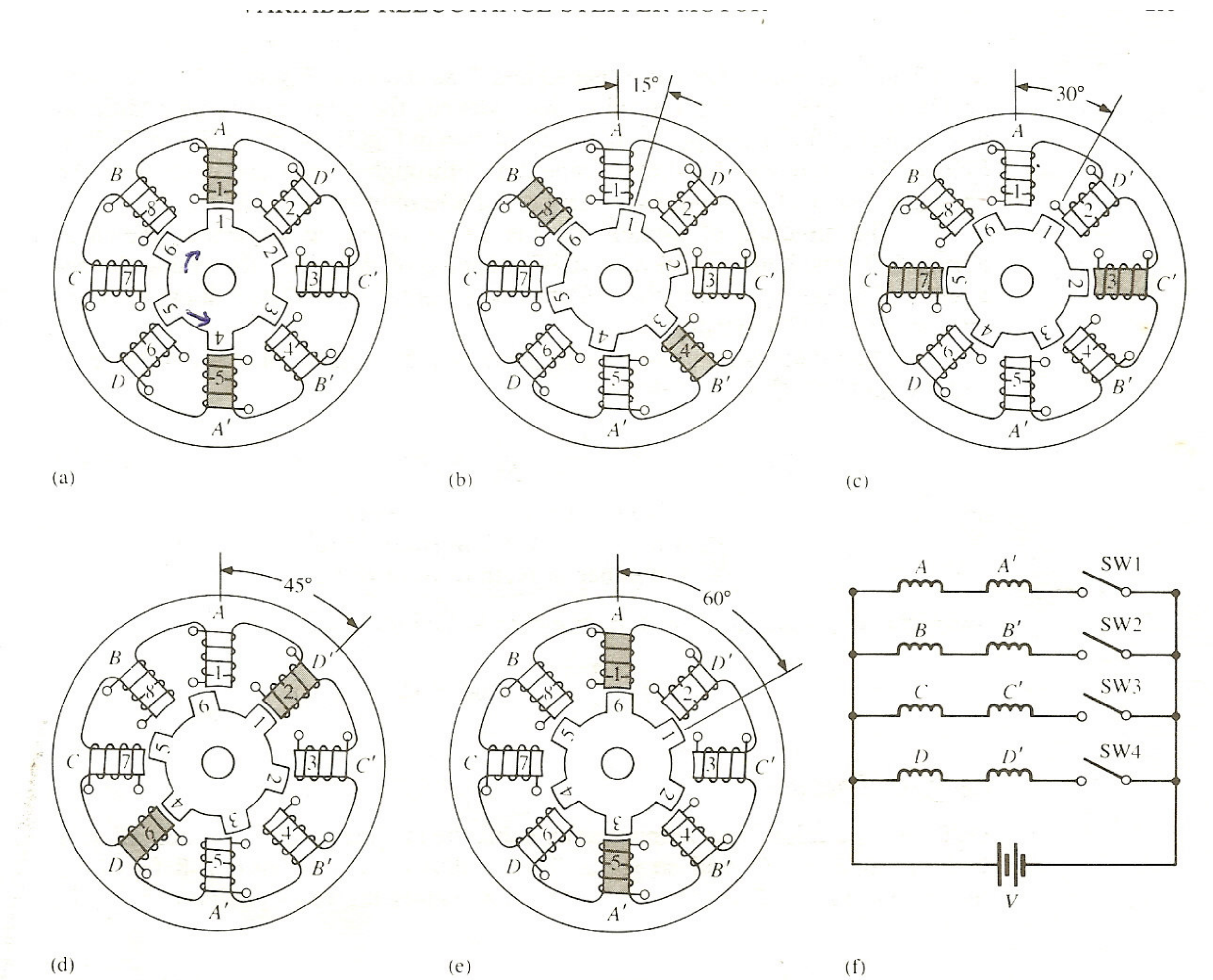



**FIGURE 2. Movement of the stepper motor rotor as current is pulsed to the stator. (a) Current is applied to the A and A' windings, so the A winding is north, (b) Current is applied to B and B' windings, so the B winding is north, (c) Current is applied to the C and C' windings, so the C winding is north, (d) Current is applied to the D and D' windings so the D winding is north. (e) Current is applied to the A and A' windings, so the A' winding is north.**

In Fig. 2a you can see that when current is applied to the A and A' stator windings, they will become a magnet with the top part of the winding being the North Pole, and the bottom part of the winding being the South Pole. You should notice that this will cause the rotor to move a small amount so that one of its south poles is aligned with the north stator pole (at A), and the opposite end of the rotor pole, which is the north pole, will align with the south pole of the stator (at A'). A line is placed on the south-pole piece so that you can follow its movement as current is moved from one stator winding to the next. In Fig. 2b current has been turned off to the A and A" windings, and current is now applied to the stator windings shown at the B and B' sides of the motor. When this occurs, the stator winding at the B' position will have the polarity for the south pole of the stator magnet, and the winding at the B position will have the north-pole polarity. In this condition, the next rotor pole that will be able to align with the stator magnets is the next pole in the clockwise position to the previous pole. This means that the rotor will only need to rotate 15° in the clockwise position for this set of poles to align itself so that it attracts the stator poles.

In Fig. 2c you can see that the C and C' stator windings are again energized, but this time the C winding is the north pole of the magnetic field and the C' winding is the south pole. This change in magnetic field will cause the rotor to again move 15° in the clockwise position until its poles will align with the C and C' stator poles. You should notice that the original rotor pole that was labeled 1 now moved three steps in the clockwise position.

In Fig.2d you can see that the D and D' stator windings are energized, the winding at D position is the north pole. This change in polarity will cause the rotor to move another 15° in the clockwise direction. You should notice that the rotor has moved four steps of 15° each, which means the rotor has moved a total of 60° from its original position. This can be verified by the position of the rotor pole that has the line on it, which is now pointing at the stator winding that is located in the 2 o'clock position.

In Fig.2e you can see that the A and A' stator windings are energized, the winding at A position is the south pole. This change in polarity will cause the rotor to move another 15° in the clockwise direction. You should notice that the rotor has moved four steps of 15° each, which means the rotor has moved a total of 75° from its original position. Thus the sequence of energizing ABCDA will move the rotor in the clockwise direction. It can be easily verified that for the counter clockwise direction the sequence should be ADCBA.

# Stepper Motor Switching Sequence

The stepper motor can be operated in three different stepping modes, namely, full-step, half-step, and micro-step.

## Full-Step

The stepper motor uses a four-step switching sequence, which is called a full-step switching sequence which is already described above.

## Half-Step

Another switching sequence for the stepper motor is called an *eight-step* or *half-step sequence.* The switching diagram for the half-step sequence is shown in Fig. 3. The main feature of this switching sequence is that you can double the resolution of the stepper motor by causing the rotor to move half the distance it does when the full-step switching sequence is used. This means that a 200-step motor, which has a resolution of 1.8°, will have a resolution of 400 steps and 0.9°. The half-step switching sequence requires a special stepper motor controller, but it can be used with a standard hybrid motor. The way the controller gets the motor to reach the half-step is to energize both phases at the same time with equal current.

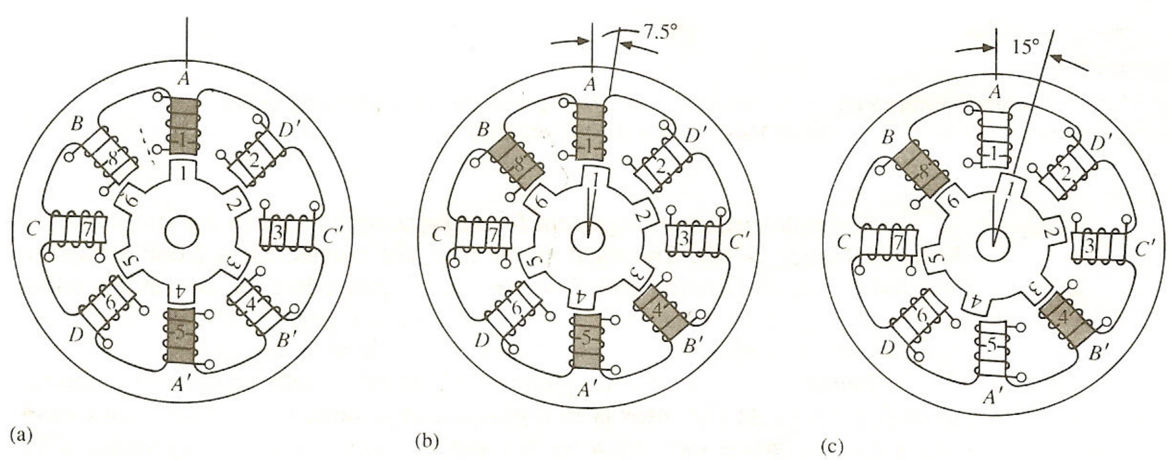



**FIGURE 3 The switching sequence for the eight-step input (half-step mode).**

In this sequence the first step has SW1 is on, and SW2,SW3 and SW4 are off. The sequence for the first step is the same as the full-step sequence. The second step has SW1 and SW2 are on and all of the remaining switches are off. This configuration of switches causes the rotor to move an additional half-step because it is acted upon by two equal magnetic forces and the rotor turns to the equilibrium position which is half a step angle. The third step has SW2 is on, and SW1, SW4 and SW3 are off, which is the same as step 2 of the full-step sequence. The sequence continues for eight steps and then repeats. The main difference between this sequence and the full-step sequence is that the energizing sequence for half step is A AB B BC C CD D DA.

## Micro Step Mode

The full-step and half-step motors tend to be slightly jerky in their operation as the motor moves from step to step. The amount of resolution is also limited by the number of physical poles that the rotor can have. The amount of resolution (number of steps) can be in-creased by manipulating the current that the controller sends to the motor during each step. The current can be adjusted so that it looks similar to a sine wave. Figure 4 shows the waveform for the current to each phase. From this diagram you can see that the current sent to each of the four sets of windings is timed so that there is always a phase difference with each other. The fact that the current to each individual phase increases and decreases like a sine wave and that is always out of time with the other phase will allow the rotor to reach hundreds of intermediate steps. In fact it is possible for the controller to reach as many as 500 micro steps for a full-step sequence, which will provide 100,000 steps for each revolution.

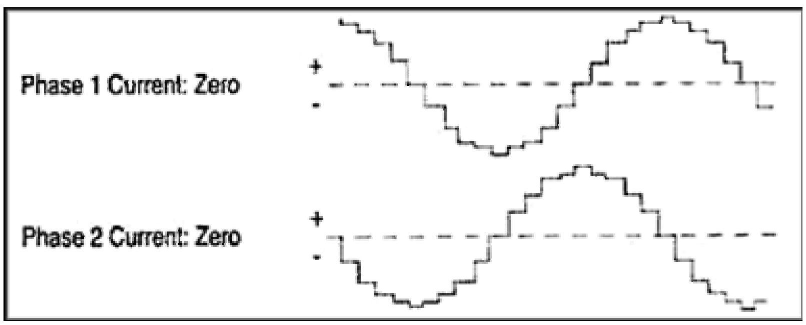



**FIGURE 4. Phase-current diagram for a stepper motor controller in micro step mode.**

# Types of Stepper Motors

## Stepper Motors Overview

**A stepper,** or **stepping motor** converts electronic pulses into proportionate mechanical movement. Each revolution of the stepper motor's shaft is made up of a series of discrete individual steps. A step is defined as the angular rotation produced by the output shaft each time the motor receives a step pulse. These types of motors are very popular in digital control circuits, such as robotics, because they are ideally suited for receiving digital pulses for step control. Each step causes the shaft to rotate a certain number of degrees. A **step angle** represents the rotation of the output shaft caused by each step, measured in degrees. Figure 5 illustrates a simple application for a stepper motor. Each time the controller receives an input signal, the paper is driven a certain incremental distance. In addition to the paper drive mechanism in a printer, stepper motors are also popular in machine tools, process control systems, tape and disk drive systems, and programmable controllers.

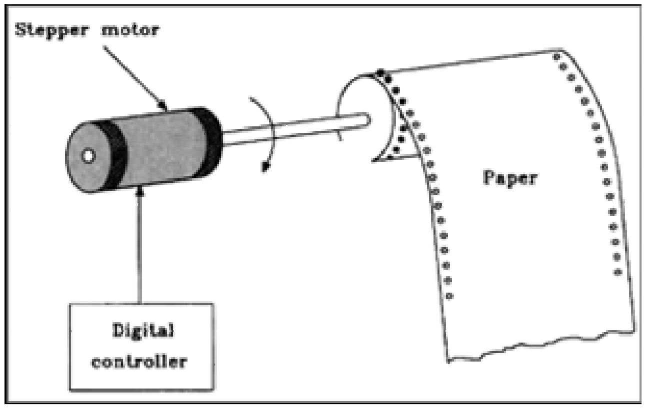


**Figure 5. Paper drive mechanism using stepper machine**

The most popular types of stepper motors are permanent-magnet (PM) and variable reluctance (VR).

## Permanent-magnet (PM) Stepper Motors

The **permanent-magnet stepper motor** operates on the reaction between a permanent-magnet rotor and an electromagnetic field. Figure 6 shows a basic two-pole PM stepper motor. The rotor shown in Figure 6(a) has a permanent magnet mounted at each end. The stator is illustrated in Figure 6(b). Both the stator and rotor are shown as having teeth. The teeth on the rotor surface and the stator pole faces are offset so that there will be only a limited number of rotor teeth aligning themselves with an energized stator pole. The number of teeth on the rotor and stator determine the step angle that will occur each time the polarity of the winding is reversed. Greater the number of teeth, smaller the step angle.

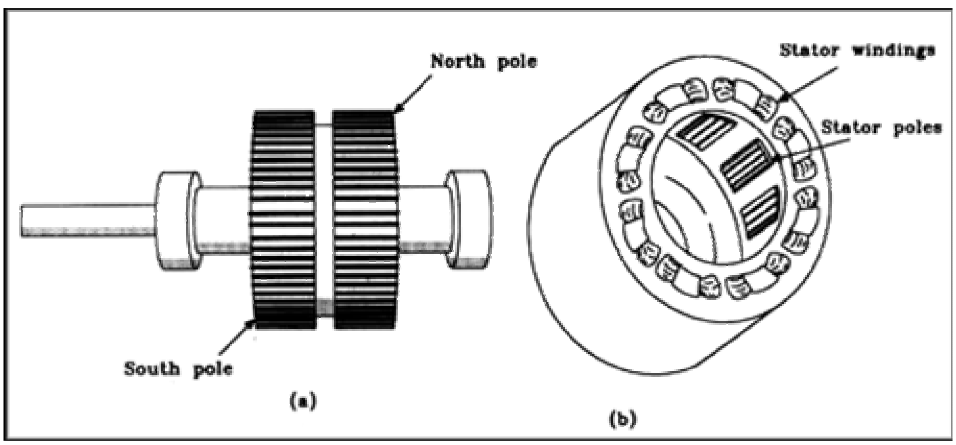


**Figure 6 Components of a PM stepper motor: (a) Rotor; (b) stator**

When a PM stepper motor has a steady DC signal applied to one stator winding, the rotor will overcome the residual torque and line up with that stator field. The **holding torque** is defined as the amount of torque required to move the rotor one full step with the stator energized. An important characteristic of the PM stepper motor is that it can maintain the holding torque indefinitely when the rotor is stopped. When no power is applied to the windings, a small magnetic force is developed between the permanent magnet and the stator. This magnetic force is called a **residual,** or **detent torque.** The detent torque can be noticed by turning a stepper motor by hand and is generally about one-tenth of the holding torque.

Figure 7(a) shows a permanent magnet stepper motor with four stator windings. By giving pulses the stator coils in a desired sequence, it is possible to control the speed and direction of the motor. Figure 7(b) shows the timing diagram for the pulses required to rotate the PM stepper motor illustrated in Figure 7(a). This sequence of positive and negative pulses causes the motor shaft to rotate counterclockwise in 90° steps. The waveforms of Figure 7(c) illustrate how the pulses can be overlapped and the motor made to rotate counterclockwise at 45° intervals.

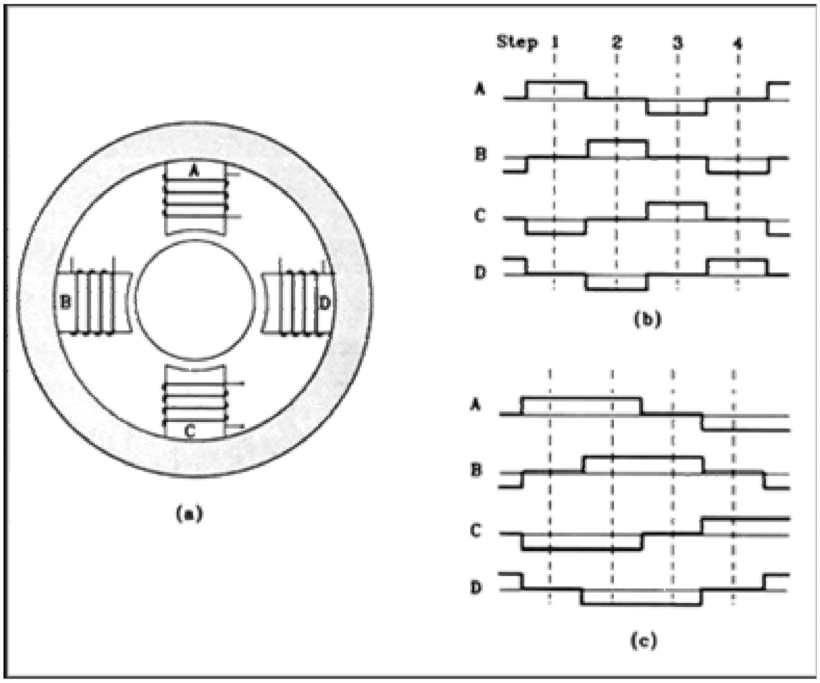


**Figure 7 (a) PM stepper motor; (b) 90 step; (c) 45 step.**

A more recent development in PM stepper motor technology is the **thin-disk rotor.** This type of stepper motor dissipates much less power in losses such as heat than the cylindrical rotor and as a result, it is considerably more efficient. Efficiency is a primary concern in industrial circuits such as robotics, because a highly efficient motor will run cooler and produce more torque or speed for its size. Thin-disk rotor PM stepper motors are also capable of producing almost double the steps per second of a conventional PM stepper motor. Figure 8 shows the basic construction of a thin-disk rotor PM motor. The rotor is constructed of a special type of cobalt-steel, and the stator poles are offset by one-half a rotor segment.

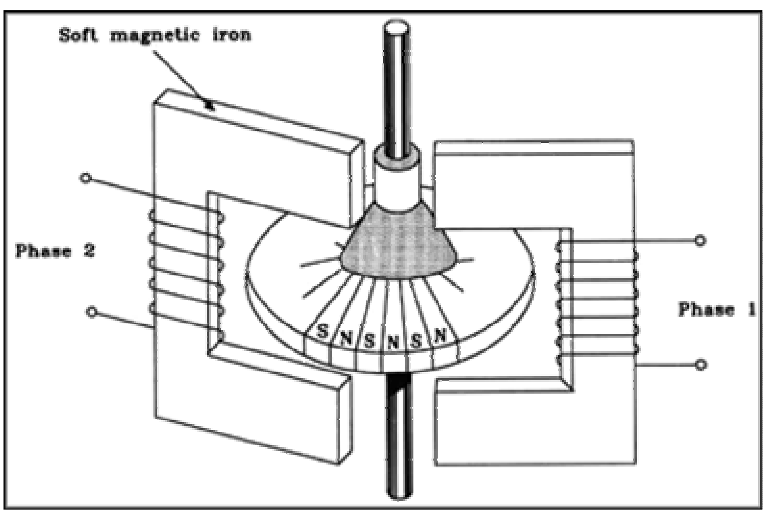


**Figure 8. Thin-disk rotor PM stepper motor.**

## Variable-reluctance (VR) Stepper Motors

The **variable-reluctance** (VR) **stepper motor** differs from the PM stepper in that it has no permanent-magnet rotor and no residual torque to hold the rotor at one position when turned off. When the stator coils are energized, the rotor teeth will align with the energized stator poles. This type of motor operates on the principle of minimizing the reluctance along the path of the applied magnetic field. By alternating the windings that are energized in the stator, the stator field changes, and the rotor is moved to a new position.

The stator of a variable-reluctance stepper motor has a magnetic core constructed with a stack of steel laminations. The rotor is made of unmagnetized soft steel with teeth and slots. The relationship among step angle, rotor teeth, and stator teeth is expressed using the following equation:

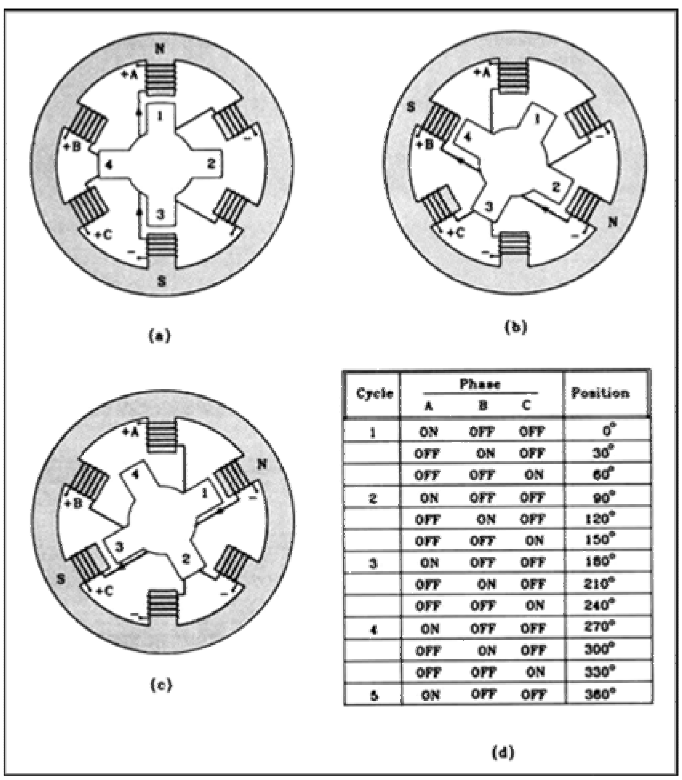
$$\Psi = \left( \frac{N_s - N_r}{N_s N_r} \right) 360° \quad \text{----------------------------(1)}$$

Where $\Psi$ = step angle in degrees

$N_s$ = Number of teeth on stator core

Nr = Number of teeth on rotor core

Figure 9 shows a basic variable-reluctance stepper motor. In this circuit, the rotor is shown with fewer teeth than the stator. This ensures that only one set of stator and rotor teeth will align at any given instant. The stator coils are energized in groups referred to as *phases.* In Figure 9, the stator has six teeth and the rotor has four teeth. According to Eq. (1), the rotor will turn 30° each time a pulse is applied. Figure 9 (a) shows the position of the rotor when phase A is energized. As long as phase A is energized, the rotor will be held stationary. When phase A is switched off and phase B is energized, the rotor will turn 30° until two poles of the rotor are aligned under the north and south poles established by phase B. The effect of turning off phase B and energizing phase C is shown in Figure 9 (c). In this circuit, the rotor has again moved 30° and is now aligned under the north and south poles created by phase C. After the rot or has been displaced by 60° from its starting point, the step sequence has completed one cycle. Figure 9 (d) shows the switching sequence to complete a full 360° of rotation for a variable-reluctance motor with six stator poles and four rotor poles. By repeating this pattern, the motor will rotate in a clockwise direction. The direction of the motor is changed by reversing the pattern of turning ON and OFF each phase.




| Cycle | Phase A | Phase B | Phase C | Position |
|---|---|---|---|---|
| 1 | ON | OFF | OFF | 0° |
| | OFF | ON | OFF | 30° |
| | OFF | OFF | ON | 60° |
| 2 | ON | OFF | OFF | 90° |
| | OFF | ON | OFF | 120° |
| | OFF | OFF | ON | 150° |
| 3 | ON | OFF | OFF | 180° |
| | OFF | ON | OFF | 210° |
| | OFF | OFF | ON | 240° |
| 4 | ON | OFF | OFF | 270° |
| | OFF | ON | OFF | 300° |
| | OFF | OFF | ON | 330° |
| 5 | ON | OFF | OFF | 360° |

(d)

**Figure 9. Variable-reluctance stepper motor and switching sequence.**

The VR stepper motors mentioned up to this point are all single-stack motors. That is, all the phases are arranged in a single stack, or plane. The disadvantage of this design for a stepper motor is that the steps are generally quite large (above 15°). **Multistack** stepper motors can produce smaller step sizes because the motor is divided along its axial length into magnetically isolated sections, or stacks. Each of these sections is excited by a separate winding, or phase. In this type of motor, each stack corresponds to a phase, and the stator and rotor have the same tooth pitch.

## Hybrid Stepper Motors

The **hybrid** step motor consists of two pieces of soft iron, as well as an axially magnetized, round permanent-magnet rotor. The term *hybrid* is derived from the fact that the motor is operated under the combined principles of the permanent magnet and variable-reluctance stepper motors. The stator core structure of a hybrid motor is essentially the same as its VR counterpart. The main difference is that in the VR motor, only one of the two coils of one phase is wound on one pole, while a typical hybrid motor will have coils of two different phases wound on one the same pole. The two coils at a pole are wound in a configuration known as a **bifilar** connection. Each pole of a hybrid motor is covered with uniformly spaced teeth made of soft steel. The teeth on the two sections of each pole are misaligned with each other by a half-tooth pitch. Torque is created in the hybrid motor by the interaction of the magnetic field of the permanent magnet and the magnetic field produced by the stator.

Stepper motors are rated in terms of the number of steps per second, the stepping angle, and load capacity in ounce-inches and the pound-inches of torque that the motor can overcome. The number of steps per second is also known as the **stepping rate.** The actual speed of a stepper motor is dependent on the step angle and **step** rate and is found using the following equation:

$$N = \frac{\Psi(s/s)}{6} \qquad \text{(2)}$$

Where N = motor speed in RPM

$\Psi$ = step angle in degrees
s/s = number of steps per second

Figure 10 shows a plot of the relationship between pull-in torque versus pulses per second for a typical stepper motor. From this curve, it is apparent that torque is greatest at zero steps per second and decreases as the number of steps increases.

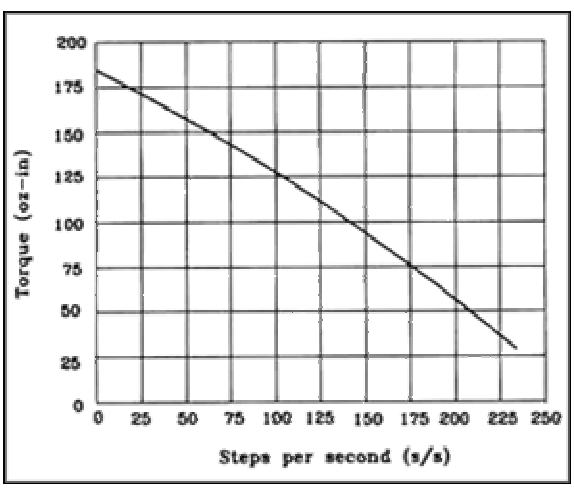



**Figure 10. Torque versus steps per second for a stepper motor.**

The direction of rotation is determined by applying the pulses to either the clockwise or counterclockwise drive circuits. Rotor displacement can be very accurately repeated with each succeeding pulse. Stepping motors are generally operated without feedback, which simplifies the control circuit considerably. One of the most common stepper motor drive circuits is the **unipolar** drive, shown in Figure 11. This circuit uses bifilar windings and four Darlington transistors to control the direction of rotation and the stepping rate of the motor.

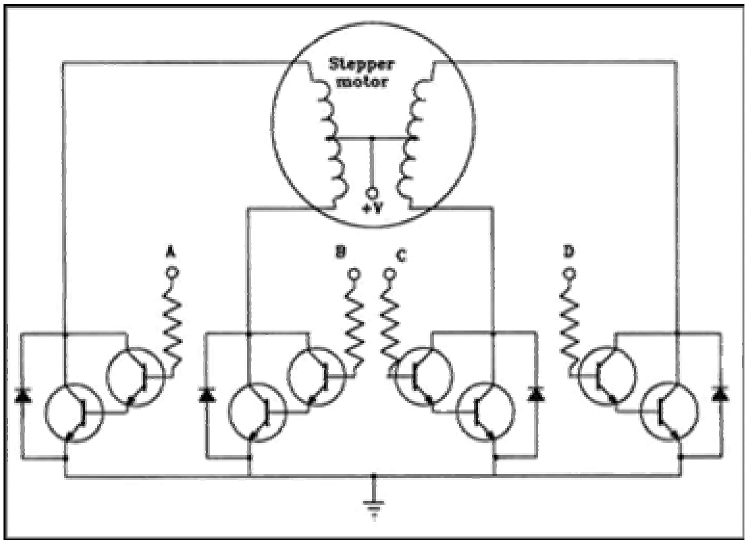



**Figure 11. Unipolar stepper motor drive.**

Stepper motor drivers are available in half-step or full-step configurations. Full-step drivers are the simplest in design and have a control sequence of two on-time periods followed by two off-time periods. The half-step mode of operation provides a smoother, quieter performance with higher speed capability and efficiency. Figure 12(a) shows the switching sequence wave shapes of a typical stepper motor. Each stepper motor winding is energized one in every four input pulses. Consequently, the pulse train for each winding has a 25 percent duty cycle. The stepper motor output shown in Figure 12(b) has a step angle of 30°.

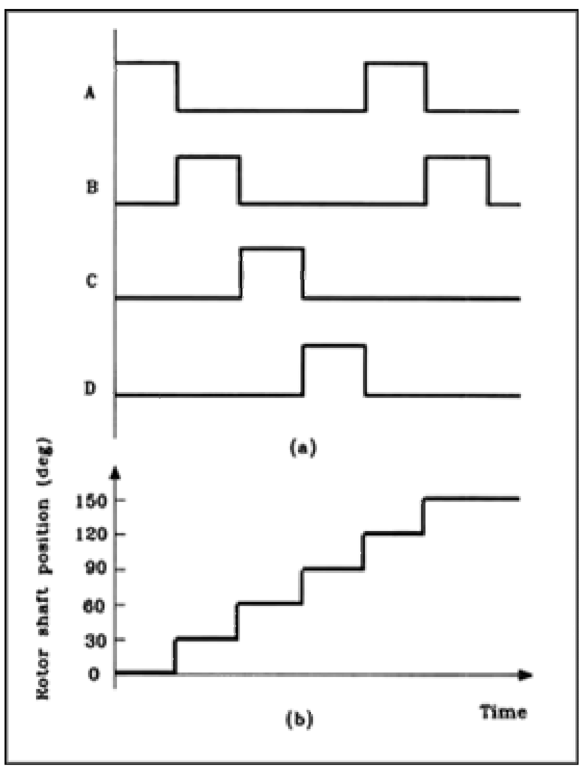



**Figure 12. Switching sequence waveshapes.**

# Stepper Motor Applications

Stepper motors are used in a wide variety of applications in industry, including computer peripherals, business machines, motion control, and robotics, which are included in process control and machine tool applications. A complete list of applications is shown below.

### Computer Peripherals

| Application | Use |
|---|---|
| Floppy Disc | position magnetic pickup |
| Printer | carriage drive |
| Printer | rotate character wheel |
| Printer | paper feed |
| Printer | ribbon wind/rewind |
| Printer | position matrix print head |
| Tape Reader | index tape |
| Plotter | X-Y-Z positioning |
| Plotter | paper feed |

### Business Machines

| Application | Use |
|---|---|
| Card Reader | position cards |
| Copy Machine | paper feed |
| Banking Systems | credit card positioning |
| Banking Systems | paper feed |
| Typewriters (automatic) | head positioning |
| Typewriters (automatic) | paper feed |
| Copy Machine | lens positioning |
| Card Sorter | route card flow |

### Process Control

| Application | Use |
|---|---|
| Carburetor Adjusting | air-fuel mixture adjust |
| Valve Control | fluid gas metering |
| Conveyor | main drive |
| In-Process Gaging | parts positioning |
| Assembly Lines | parts positioning |
| Silicon Processing | I. C. wafer slicing |
| I. C. Bonding | chip positioning |
| Laser Trimming | X-Y positioning |
| Liquid Gasket Dispensing | valve cover positioning |
| Mail Handling Systems | feeding and positioning |

| | |
|---|---|
| | letters |

**Machine Tool**

| Application | Use |
|---|---|
| Milling Machines | X-Y-Z table positioning |
| Drilling Machines | X-Y table positioning |
| Grinding Machines | downfeed grinding wheel |
| Grinding Machines | automatic wheel dressing |
| Electron Beam Welder | X-Y-Z positioning |
| Laser Cutting | X-Y-Z positioning |
| Lathes | X-Y positioning |
| Sewing | X-Y table positioning |