CHAPTER

8 Stepper Motors

OBJECTIVES

After studying this chapter, you should be able to:

- ❑ Explain what a stepper motor is, how it is different from a "regular" motor, and the applications it is used in.
- ❑ Understand the basic parts and operation of the three kinds of stepper motors: permanent magnet, variable reluctance, and hybrid.
- ❑ Differentiate between two-phase, three-phase, and four-phase stepper motors.
- ❑ Understand the different operational modes—single-step versus slew, single- and dual-phase excitation, half-step, and microstepping.
- ❑ Calculate the final position of a stepper motor, given the sequence of drive pulses.
- ❑ Explain the operation of stepper motor driver circuits.

INTRODUCTION

A **stepper motor** is a unique type of DC motor that rotates in fixed steps of a certain number of degrees. Step size can range from 0.9 to 90°. Figure 8.1 illustrates a basic stepper motor, which consists of a **rotor** and **stator**. In this case, the rotor is a permanent magnet, and the stator is made up of electromagnets (field poles). The rotor will move (or step) to align itself with an energized field magnet. If the field magnets are energized one after the other around the circle, the rotor can be made to move in a complete circle.

Stepper motors are particularly useful in control applications because the controller can know the exact position of the motor shaft without the need of position sensors. This is done by simply counting the number of steps taken from a known reference position. Step size is determined by the number of rotor and stator poles, and there is no **cumulative error** (the angle error does not increase, regardless of the number of steps taken). In fact, most stepper motor systems operate open-loop—that is, the controller sends the motor a determined number of step commands and assumes the motor goes to the right place. A common example is the positioning of the read/write head in a disk drive.

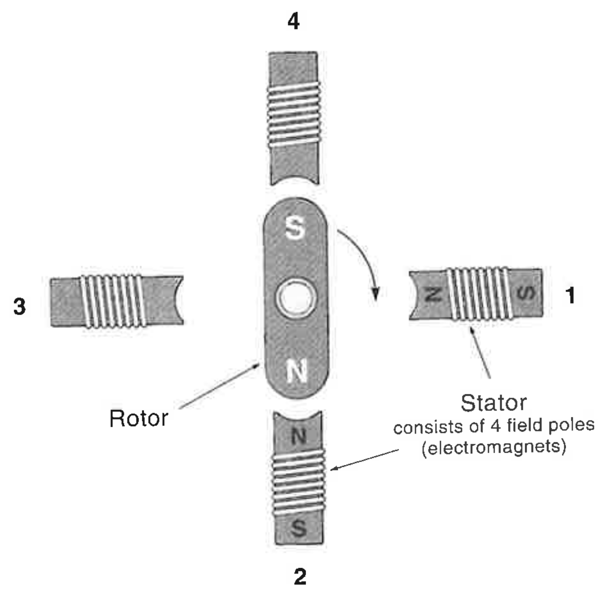


Figure 8.1
A PM 90° stepper motor.

Steppers have inherently low velocity and therefore are frequently used without gear reductions. A typical unit driven at 500 pulses/second rotates at only 150 rpm. Stepper motors can easily be controlled to turn at 1 rpm or less with complete accuracy.

There are three types of stepper motors: permanent magnet, variable reluctance, and hybrid. All types perform the same basic function, but some differences among them may be important in some applications.

8.1 PERMANENT MAGNET STEPPER MOTORS

The **permanent magnet (PM) stepper motor** uses a permanent magnet for the rotor. Figure 8.1 shows a simple PM stepper motor. The field consists of four poles (electromagnets). The motor works in the following manner: Assume the rotor is in the position shown with the south end up. When field coil 1 is energized, the south end of the rotor is attracted to coil 1 and moves toward it. Then field coil 1 is deenergized, and coil 2 is energized. The rotor pulls itself into alignment with coil 2. Thus, the rotor turns in 90° steps for each successive excitation of the field coils. The motor can be made to reverse by inverting the sequence.

One desirable property of the PM stepper motor is that the rotor will tend to align up with a field pole even when no power is applied because the PM rotor will be attracted to the closest iron pole. You can feel this "magnetic tug" if you rotate the motor by hand; it is called the detent torque, or residual torque. The detent torque is a desirable property in many applications because it tends to hold the motor in the last position it was stepped to, even when all power is removed.

As mentioned earlier, one big advantage of the stepper motor is that it can be used open-loop—that is, by keeping track of the number of steps taken from a known point, the exact shaft position is always known. Example 8.1 demonstrates this.

♦ EXAMPLE 8.1

A 15°/step stepper motor is given 64 steps CW (clockwise) and 12 steps CCW (counterclockwise). Assuming it started at 0°, find the final position.

Solution After completing 64 steps CW and 12 steps CCW, the motor has ended up 52 steps CW ($64 - 12 = 52$). Because there are 24 15°-steps per revolution ($360°/15° = 24$),

$$\frac{52}{24} = 2\frac{1}{6} = 2 \text{ rev} + \frac{1}{6} \text{ rev}$$

$$= 2 \text{ rev} + \frac{360°}{6}$$

$$= 2 \text{ rev} + 60°$$

Therefore, the motor has made two complete revolutions and is now sitting at 60° CW from where it started. ♦

Effect of Load on Stepper Motors

For the open-loop concept to work, the motor must actually step once each time it's commanded to. If the load is too great, the motor may not have enough torque to make the step. In such a case, the rotor would probably rotate a little when the step pulse was applied but then fall back to its original position. This is called **stalling**. If feedback is not used, the controller has no way of knowing a step was missed.

Within each step, the torque developed by the stepper motor is dependent on the shaft angle. In fact, the torque on the rotor is actually zero when it is exactly aligned with an energized field coil. Figure 8.2 illustrates how the motor can only provide torque when the rotor is *not* aligned. The first frame of Figure 8.2 shows a rotor pole approaching an energized field pole. The actual force of attraction is between the south (S) end of the rotor and the north (N) end of the field pole. As the rotor pole approaches the field pole, the attraction force (F) gets stronger but the torque component (T) gets weaker. When the rotor is pointing directly at the field pole (last frame in Figure 8.2), the torque component is zero. In practice, this means that the rotor may come to a stop before it is completely aligned with the energized field pole, at the point where the diminishing step torque just equals the load torque.

For the simple motor under discussion (Figure 8.1), the maximum torque occurs when the rotor is 90° (one step) away from the field pole (first frame of Figure 8.2.) It might seem that we should just plan to let the rotor lag one step behind the energized field pole to take advantage of the maximum torque, but this approach might cause the

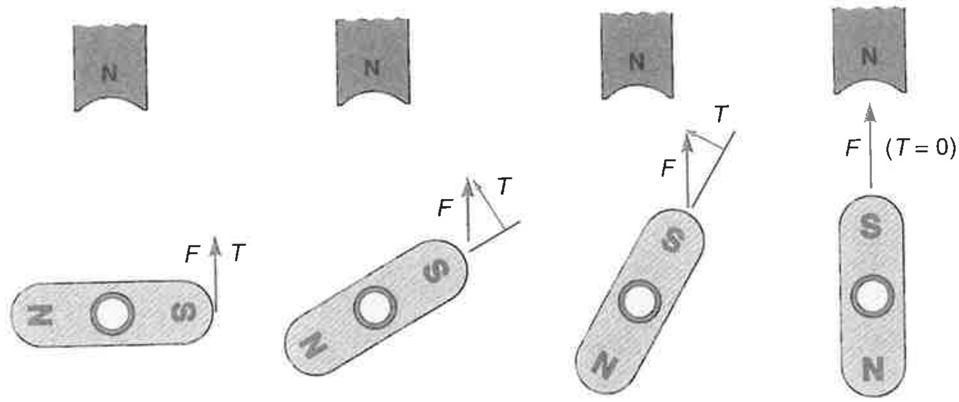


Figure 8.2
Torque goes to zero as the rotor aligns with the field pole.

motor to take a step backward instead of forward. Consider the situation in Figure 8.3(a) where the rotor has been stepping CCW and we have allowed it to lag a full step behind the energized pole (currently, pole 1). The next pole to be energized in the CCW sequence is pole 2 [Figure 8.3(b)]. The first problem here is that the rotor is pointing directly away from pole 2, so there will be little or no torque exerted. The second problem is that, in this balanced condition, the rotor will be equally attracted in either direction and we cannot reliably predict if it will turn CW or CCW.

For proper operation, *the rotor lag must not be to allowed exceed one-half the step size*, which would be 45° for the motor illustrated in Figure 8.3. This solves the preceding problems—namely, the motor will always turn in the direction it's supposed to, and it

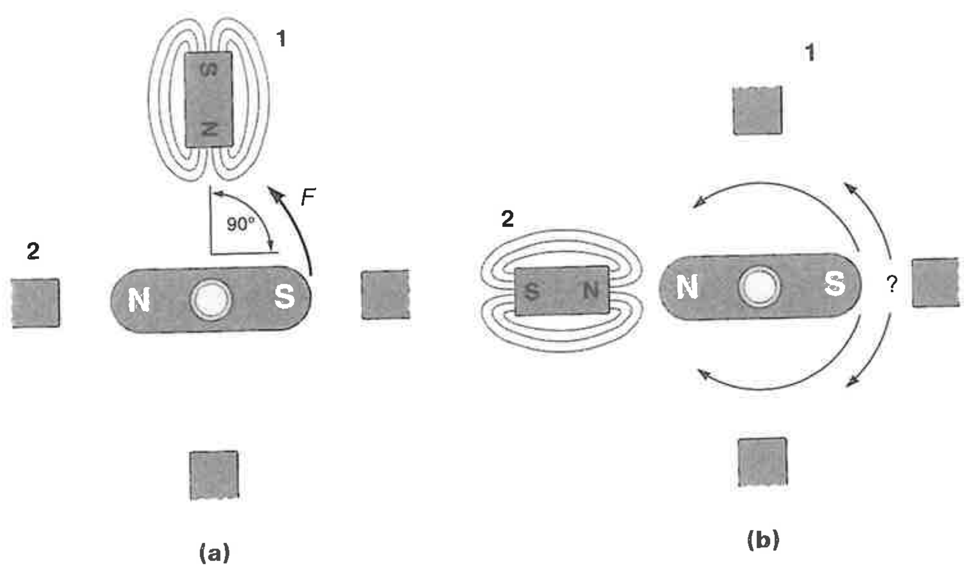


Figure 8.3
Illustrating what would happen if the rotor was allowed to lag a full step behind the field poles.

will not stall. (Recall that stalling occurs when the motor is too weak to take a step.) In practical terms, the dynamic torque, which is the power available when the motor is running, may only be about half of the maximum *static torque* (the torque required to displace the rotor when stopped). There is an exception to this rule: When the rotor is stepping rapidly (called *slewing*), the inertia can be counted on to keep the rotor going in the right direction. Slewing is discussed in the next section.

Modes of Operation

The stepper motor has two modes of operation: single step and slew. In the **single-step mode** or bidirectional mode, the frequency of the steps is slow enough to allow the rotor to (almost) come to a stop between steps. Figure 8.4 shows a graph of position versus time for single-step operation. For each step, the motor advances a certain angle and then stops. If the motor is only lightly loaded, overshoot and oscillations may occur at the end of each step as shown in the figure.

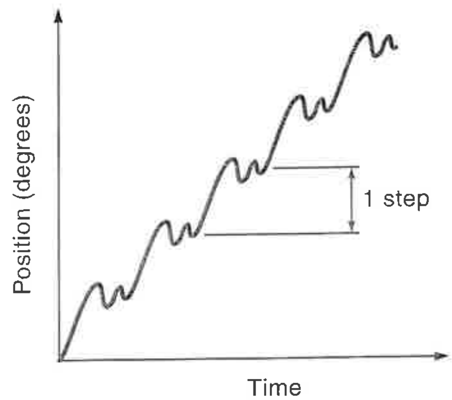


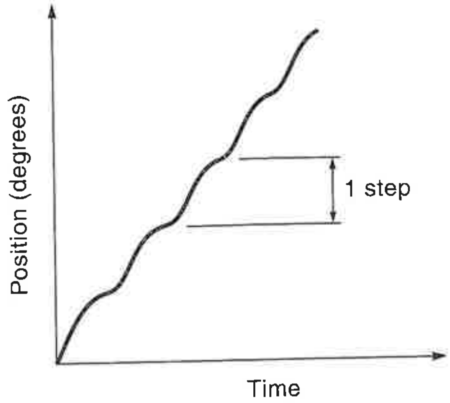
Figure 8.4
Position vs time for single-step mode.

The big advantage of single-step operation is that each step is completely independent from every other step—that is, the motor can come to a dead stop or even reverse direction at any time. Therefore, the controller has complete and instantaneous control of the motor's operation. Also, there is a high certainty that the controller will not lose count (and hence motor position) because each step is so well defined. The disadvantage of single-step mode is that the motion is slow and "choppy." A typical single-step rate is 5 steps/second which translates to 12.5 rpm for a 15°/step motor.

In the **slew mode**, or unidirectional mode, the frequency of the steps is high enough that the rotor does not have time to come to a stop. This mode approximates the operation of a regular electric motor—that is, the rotor is always experiencing a torque and rotates in a smoother, continuous fashion. Figure 8.5 shows a graph of position versus time for the slew mode. Although the individual steps can still be discerned, the motion is much less choppy than in single-step mode.

A stepper motor in the slew mode cannot stop or reverse direction instantaneously. If attempted, the rotational inertia of the motor would most likely carry the rotor ahead

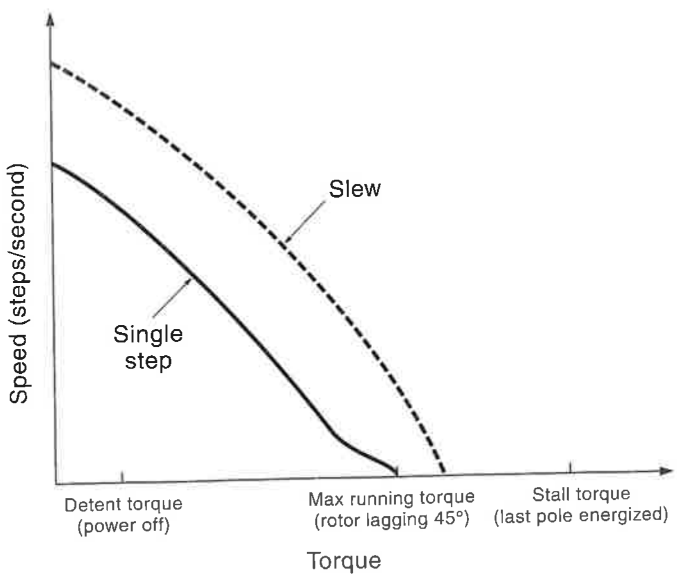
Figure 8.5
Position vs time for the slew mode.



a few steps before it came to rest. The step-count integrity would be lost. It is possible to maintain the step count in the slew mode by slowly ramping up the velocity from the single-step mode and then ramping down at the end of the slew. This means the controller must know ahead of time how far the motor must go. Typically, the slew mode is used to get the motor position in the "ballpark," and then the fine adjustments can be made with single steps. Slewing moves the motor faster but increases the chances of losing the step count.

Figure 8.6 shows the torque–speed curves for both the single-step and slew modes. The first observation is that available load torque diminishes as the stepping rate rises (this is true of all DC motors). Also, for the single-step mode, the price paid for the ability to stop or reverse instantaneously is less torque and speed. Looking along the x-axis, notice three different kinds of torques. The **detent torque** is the torque required to overcome the force of the permanent magnets (when the power is off). It is the little tugs

Figure 8.6
Torque–speed curves for single-step and slew modes.



you feel if you manually rotate the unpowered motor. The **dynamic torque**, which is the maximum running torque, is obtained when the rotor is lagging behind the field poles by half a step. The highest stall torque shown in Figure 8.6 is called the **holding torque** and results when the motor is completely stopped but with the last pole still energized. This is really a detent type of torque because it represents the amount of external torque needed to rotate the motor "against its wishes."

♦ EXAMPLE 8.2

A stepper motor has the following properties:

Holding torque: 50 in. · oz
Dynamic torque: 30 in. · oz
Detent torque: 5 in. · oz

The stepper motor will be used to rotate a 1-in. diameter printer platen (Figure 8.7). The force required to pull the paper through the printer is estimated to not exceed 40 oz. The static weight of the paper on the platen (when the printer is off) is 12 oz. Will this stepper motor do the job?

Solution The torque required to rotate the platen during printing can be calculated as follows:

$$\text{Force} \times \text{radius} = 40 \text{ oz} \times 0.5 \text{ in.} = 20 \text{ in.} \cdot \text{oz}$$

Therefore, the motor, with 30 in. · oz of dynamic torque, will be strong enough to advance the paper.

The torque on the platen from just the weight of the paper is calculated as follows:

$$\text{Force} \times \text{radius} = 12 \text{ oz} \times 0.5 \text{ in.} = 6 \text{ in} \cdot \text{oz}$$

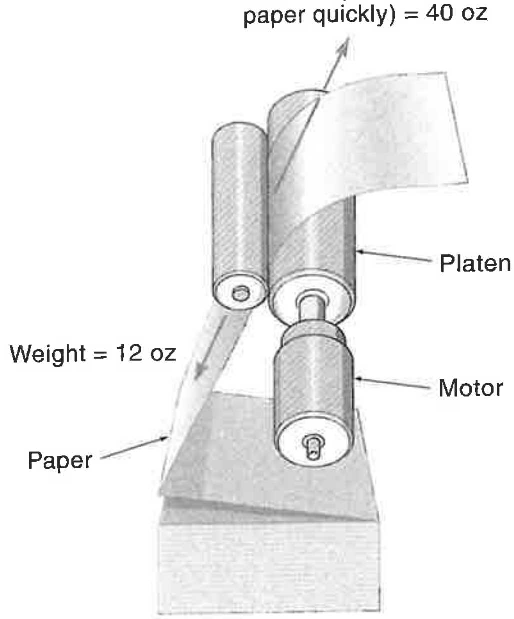


Figure 8.7
A stepper motor driving a printer platen (Example 8.2).

When the printer is on, the powered holding torque of 50 in. · oz is more than enough to support the paper. However, when the printer is off, the weight of the paper exceeds the detent torque of 5 in. · oz, and the platen (and motor) would spin backward. Therefore, we conclude that this motor is not acceptable for the job (unless some provision such as a ratchet or brake is used to prevent back spinning). ♦

Excitation Modes for PM Stepper Motors

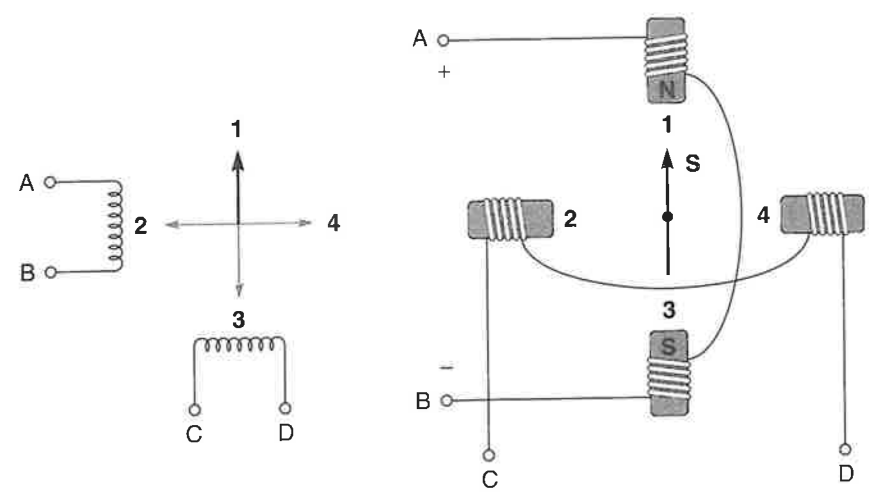
Stepper motors come with a variety of winding and rotor combinations. In addition, there are different ways to sequence energy to the field coils. All these factors determine the size of each step. **Phase** refers to the number of separate winding circuits. There are two-, three-, and four-phase steppers, which are discussed next.

Two-Phase (Bipolar) Stepper Motors

The **two-phase** (bipolar) **stepper motor** has only two circuits but actually consists of four field poles. Figure 8.8(a) shows the motor symbol, and Figure 8.8(b) shows how it is wired internally. In Figure 8.8(b), circuit AB consists of two opposing poles such that when voltage is applied (+A −B), the top pole will present a north end to the rotor and the bottom pole will present a south end. The rotor would tend to align itself vertically (position 1) with its south pole up (because, of course, opposite magnetic poles attract).

The simplest way to step this motor is to alternately energize either AB or CD in such a way as to pull the rotor from pole to pole. If the rotor is to turn CCW from position 1, then circuit CD must be energized with polarity C+ D−. This would pull the rotor to position 2. Next, circuit AB is energized again, but this time the polarity is reversed (−A +B), causing the bottom pole to present a north end to the rotor, thereby pulling

Figure 8.8
A two-phase (bipolar) stepper motor.



(a) Symbol **(b)** Wiring diagram

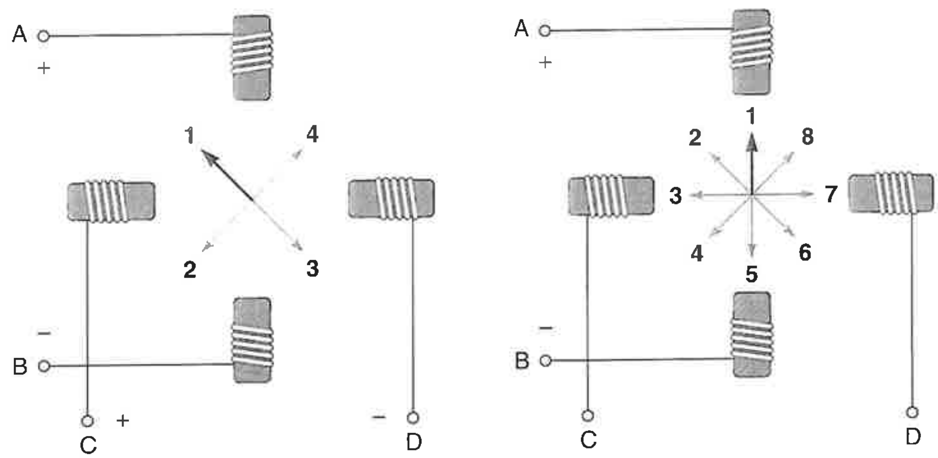
it to position 3. The term **bipolar** applies to this motor because the current is sometimes reversed. The voltage sequence needed to rotate the motor one full turn is shown below. Reading from top to bottom gives the sequence for turning CCW, reading from bottom up gives the CW sequence:

Circuit	Position
A+ B−	1
C+ D−	2
A− B+	3
C− D+	4

Another way to operate the two-phase stepper is to energize both circuits at the same time. In this mode, the rotor is attracted to two adjacent poles and assumes a position in between. Figure 8.9(a) shows the four possible rotor positions. The excitation sequence for stepping in this dual mode is as follows:

Circuits			Position
A+ B−	and	C+ D−	1
A− B+	and	C+ D−	2
A− B+	and	C− D+	3
A+ B−	and	C− D+	4

Figure 8.9
Additional operating modes for stepper motors.



(a) Dual excitation (energized for position 1)

(b) 8-step drive using "half steps"

Having two circuits on at the same time produces considerably more torque than the single-excitation mode; however, more current is consumed, and the controller is more complex.

Both methods produce **four-step drives**, that is, four steps per cycle. By alternating the single- and dual-excitation modes, the motor can be directed to take **half-steps**, as shown in Figure 8.9(b). Positions 1, 3, 5, and 7 are from the single-excitation mode, and positions 2, 4, 6, and 8 are from the dual-excitation mode. When driven this way, the motor takes eight steps per revolution and is called an **eight-step drive**. This is desirable for some applications because it allows the motor to have twice the position resolution. Even smaller steps are possible with a process called *microstepping*, which is discussed later in the chapter.

The motor described thus far in this section steps 90° in the four-step mode (and 45° in the eight-step mode). PM stepper motors commonly have a smaller step, as low as 30°. This is done by increasing the poles in the rotor. Figure 8.10 shows a 30° stepper motor; the rotor has six rotor poles. Assume that field poles AB have been energized, pulling the rotor into the position shown. Next, circuit CD is energized. Rotor poles *yz* will be attracted to poles CD and will have to rotate only 30° to come into alignment.

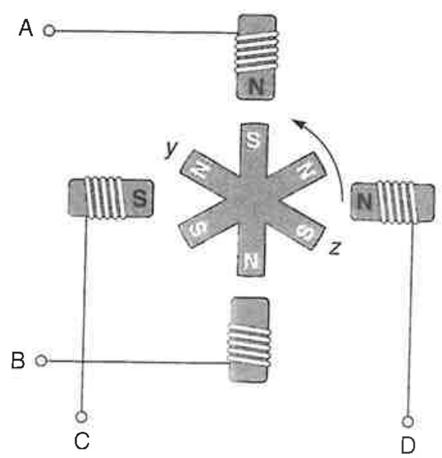


Figure 8.10
A 30° stepper motor with a six-pole rotor.

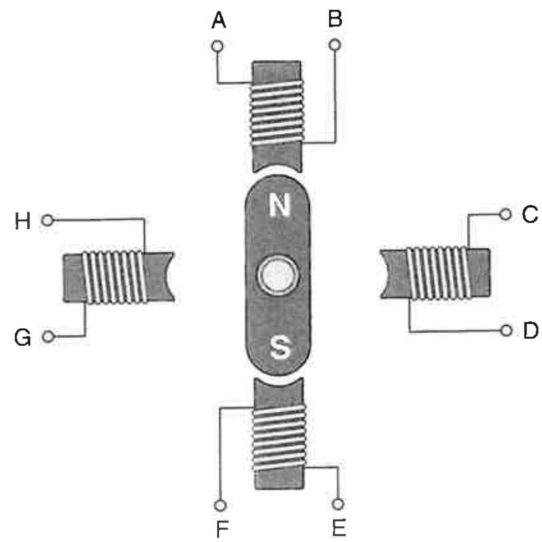
Four-Phase (Unipolar) Stepper Motors

The **four-phase** (unipolar) is the most common type of stepper motor (Figure 8.11). The term *four-phase* is used because the motor has four field coils that can be energized independently, and the term **unipolar** is applied because the current always travels in the same direction through the coils. The simplest way to operate the four-phase stepper motor is to energize one phase at a time in sequence (known as *wave drive*). To rotate CW, the following sequence is used:

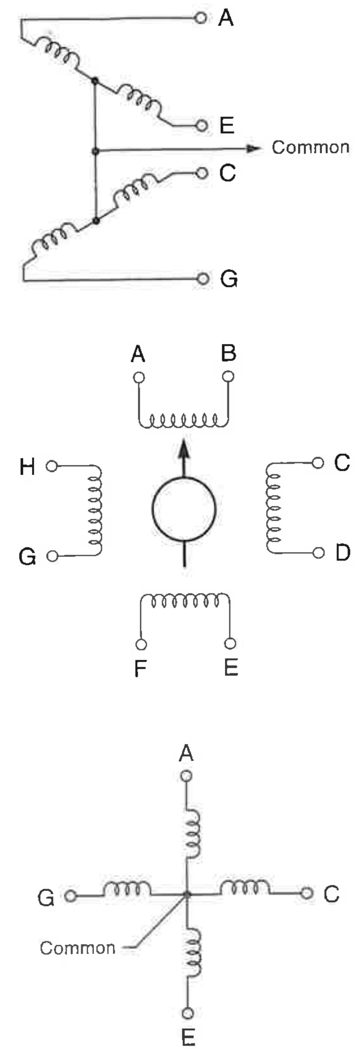
A B
C D
E F
G H

Compared with the two-phase bipolar motor, the four-phase motor has the advantage of simplicity. The control circuit of the four-phase motor simply switches the poles on and off in sequence; it does not have to reverse the polarity of the field coils. (However, the two-phase motor produces more torque because it is pushing and pulling at the same time.)

Figure 8.11
A four-phase (unipolar) stepper motor.



(a) Wiring diagram

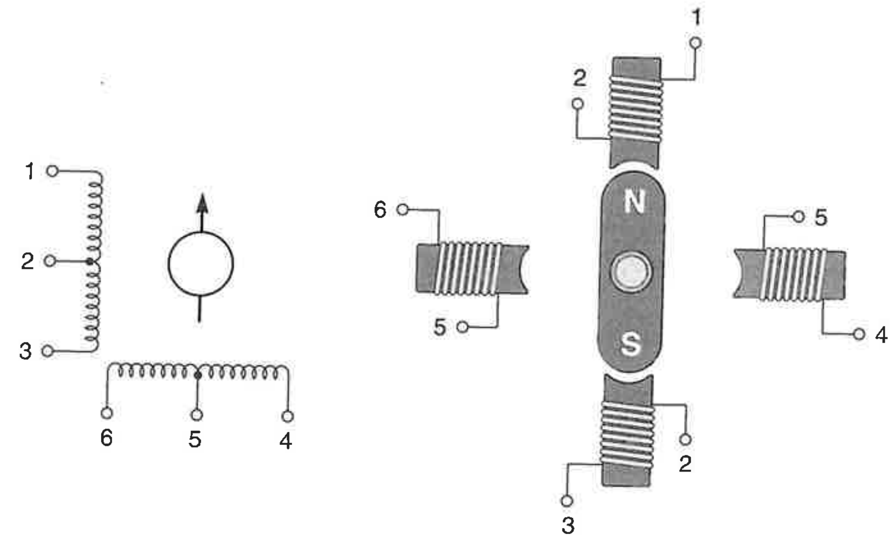


(b) Symbols

The torque of a four-phase stepper motor can be increased if two adjacent coils are energized at the same time, causing the rotor to align itself between the field poles [similar to that shown in Figure 8.9(a)]. Although twice the input energy is required, the motor torque is increased by about 40%, and the response rate is increased. By alternating single- and dual-excitation modes, the motor steps in half-steps, as shown in Figure 8.9(b).

Constructing motors so they can be used in either a two- or four-phase mode is common practice. This is done by bringing out two additional wires (from the two-phase motor) that are internally connected to points between the opposing field coils. Figure 8.12(a) shows the symbol for this type of motor, and Figure 8.12(b) shows the interior motor wiring. When such a motor is used in the two-phase mode, the center taps (terminals 2 and 5) are not used. When the motor is operated in the four-phase mode, the center taps become a *common return*, and power is applied to terminals 1, 4, 3, and 6 as required.

Figure 8.12
A four-phase stepper with center tap windings.

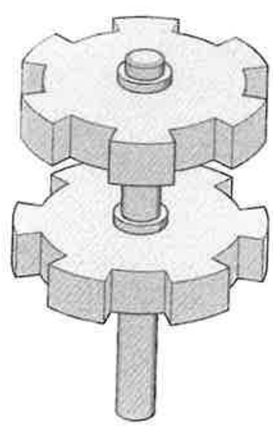


(a) Symbols **(b)** Wiring diagram

Available PM Stepper Motors

Almost all PM stepper motors available today have smaller step sizes than the simplified motors discussed so far. These motors are made by stacking two multipolled rotors (offset by one-half step), as illustrated in Figure 8.13. Typical step sizes for four-phase PM stepper motors are 30°, 15°, and 7.5°. Figure 8.14 is a specification sheet for a family of PM stepper motors. For example, the PF35–48C (continuous duty) motor has 48 steps/revolution (which is 7.5°), requires 133 mA at 12 V, and has a holding torque of 2.78 in. · oz.

Figure 8.13
Stacked-rotor design allows smaller steps.



8.2 VARIABLE RELUCTANCE STEPPER MOTORS

The **variable reluctance (VR) stepper motor** does not use a magnet for the rotor; instead, it uses a toothed iron wheel [see Figure 8.15(b)]. The advantage of not requiring the rotor to be magnetized is that it can be made in any shape. Being iron, each rotor tooth is

PF35 Series		Models					
		PF35-48				PF35-24	
Excitation Mode		2-2					
Step Angle	(°)	7.5				15	
Step Angle Tolerance	(%)	±5					
Steps per Revolution		48				24	
Rating		Continuous			Intermittent	Continuous	
Letter Designator		C	D	Q	C	C	D
Winding Type		Unipolar	Unipolar	Bipolar	Unipolar	Unipolar	Unipolar
DC Operating Voltage	(V)	12	5	5	24	12	5
Operating Current	(mA/ø)	133	313	310	266	133	313
Winding Resistance	(Ω/ø)	90	16	17	90	90	16
Winding Inductance	(mH/ø)	48	8.9	12	48	48	8.9
Holding Torque	(oz-in)	2.78		3.25	3.88	2.08	
Rotor Inertia	(oz-in²)	24.1×10^{-1}					
Starting Pulse Rate, Max.	(pps)	500		400	680	310	
Slewing Pulse Rate, Max.	(pps)	530		500	770	410	
Ambient Temp Range, Operating	(°C)	-10~+50					
Temperature Rise	(°C)	55			-	55	
Weight	(oz)	2.8					

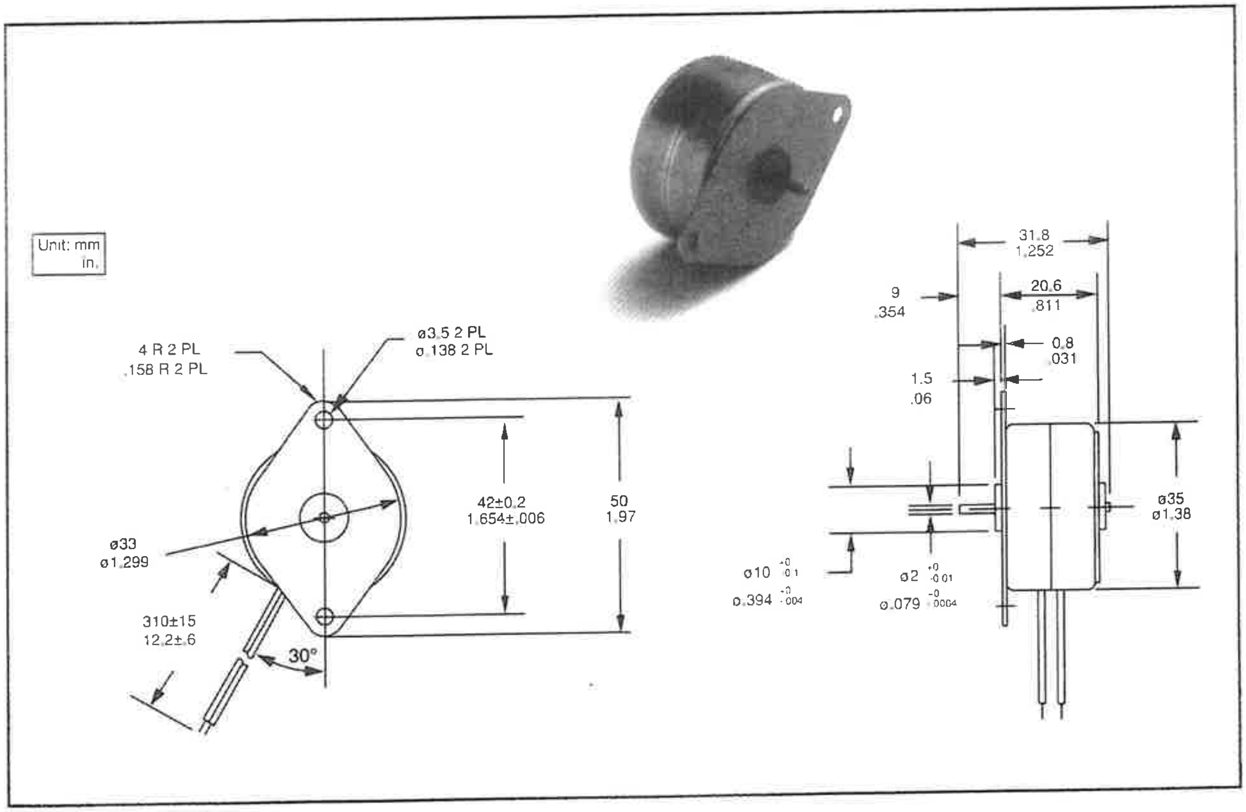
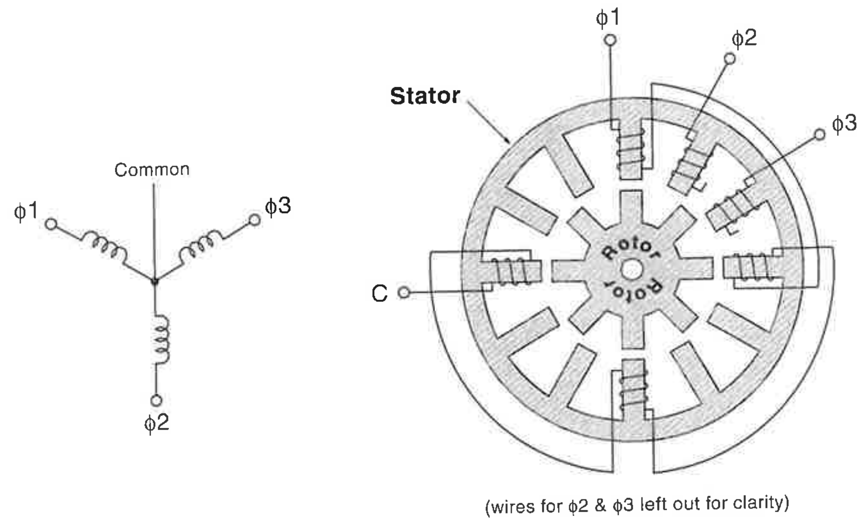


Figure 8.14 PM stepper motors. (Courtesy of Kollmorgen Motion Technologies Group)



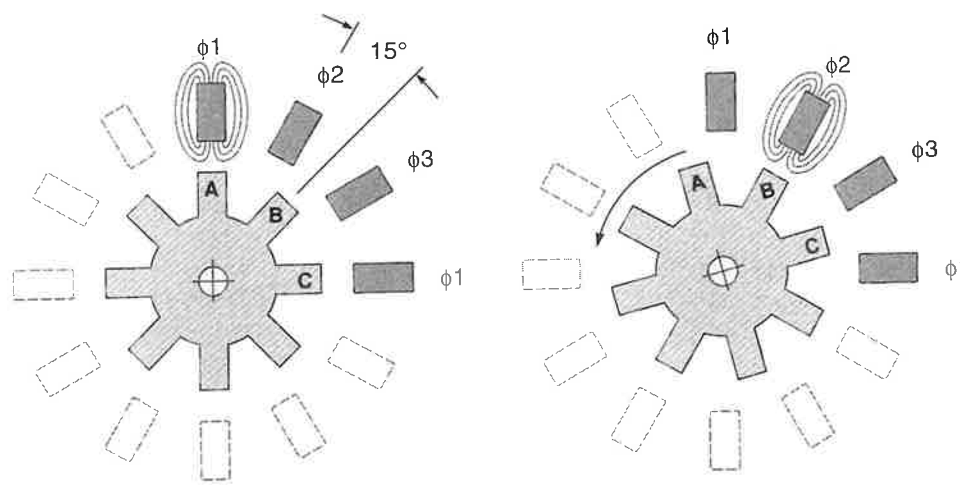
(a) Symbol **(b)** Construction

Figure 8.15
A three-phase VR stepper motor (15° step). (Wires for Ø2 and Ø3 left out for clarity.)

attracted to the closest energized field pole in the stator, but not with the same force as in the PM motor. This gives the VR motor less torque than the PM motor.

A VR motor usually has three or four phases. Figure 8.15(a) shows a typical **three-phase stepper motor**. The stator has three field pole circuits: Ø1, Ø2, and Ø3. Figure 8.15(b) shows that the actual motor has 12 field poles, where each circuit energizes four windings; you can see this by closely observing the Ø1 wire in Figure 8.15(b). Notice that the rotor has only 8 teeth even though there are 12 teeth in the stator. Therefore, the rotor teeth can never line up "one for one" with the stator teeth, a fact that plays an important part in the motor's operation.

Figure 8.16 illustrates the operation of the VR stepper motor. When circuit Ø1 is energized, the rotor will move to the position shown in Figure 8.16(a)—that is, a rotor tooth (A) is lined up with the Ø1 field pole. Next, circuit Ø2 is energized. Rotor tooth B,



(a) Pole ϕ1 energized **(b)** Pole ϕ2 energized

Figure 8.16
A 15° three-phase VR stepper motor (only four field poles shown for clarity.)

being the closest, is drawn toward it [Figure 8.16(b)]. Notice that the rotor has to move only 15° for this alignment. If circuit Ø3 is energized next, the rotor would continue CCW another 15° by pulling tooth C into alignment.

The step angle of the VR motor is the difference between the rotor and stator angles. For the motor of Figure 8.16, the angle between the field poles is 30°, and the angle between the rotor poles is 45°. Therefore, the step is 15° (45° − 30° = 15°). By using this design, the VR stepper motor can achieve very small steps (less than 1°). Small step size is often considered to be an advantage because it allows for more precise positioning.

The VR stepper motor has a number of functional differences when compared with the PM type. Because the rotor is not magnetized, it is weaker than a similar-sized PM stepper motor. Also, it has no detent torque when the power is off, which can be an advantage or disadvantage depending on the application. Finally, because of the small step size and reduced detent torque, the VR stepper motor has more of a tendency to overshoot and skip a step. This is a serious matter if the motor is being operated open-loop, where position is maintained by keeping track of the number of steps taken. To solve the problem, some sort of damping may be required. This can be done mechanically by adding friction or electrically by providing a slight braking torque with adjacent field poles.

8.3 HYBRID STEPPER MOTORS

The **hybrid stepper motor** combines the features of the PM and VR stepper motors and is the type in most common use today. The rotor is toothed, which allows for very small step angles (typically 1.8°), and it has a permanent magnet providing a small detent torque even when the power is off.

Recall that the step size of a PM motor is limited by the difficulty in making a multipole magnetized rotor. There is simply a limit to the number of different magnetizations that can be imposed on a single iron rotor. The VR stepper motor gets around this by substituting iron teeth (of which there can be many) for magnetized poles on the rotor. This approach allows for a small step angle, but it sacrifices the strength and detent torque qualities of the PM motor. The hybrid motor can effectively magnetize a multitoothed rotor and thus has the desirable properties of both the PM and VR motors.

Figure 8.17 illustrates the internal workings of the hybrid motor, which is considerably more complicated than the simple PM motor. The rotor consists of two toothed wheels with a magnet in between—one wheel being completely north in magnetization and the other being completely south. For each step, two opposing teeth on the north wheel are attracted to two south field poles, and two opposing teeth on the south wheel are attracted to two north field poles. The internal wiring is more complicated than it is for the PM or VR motors, but to the outside world this motor is just as simple to control.

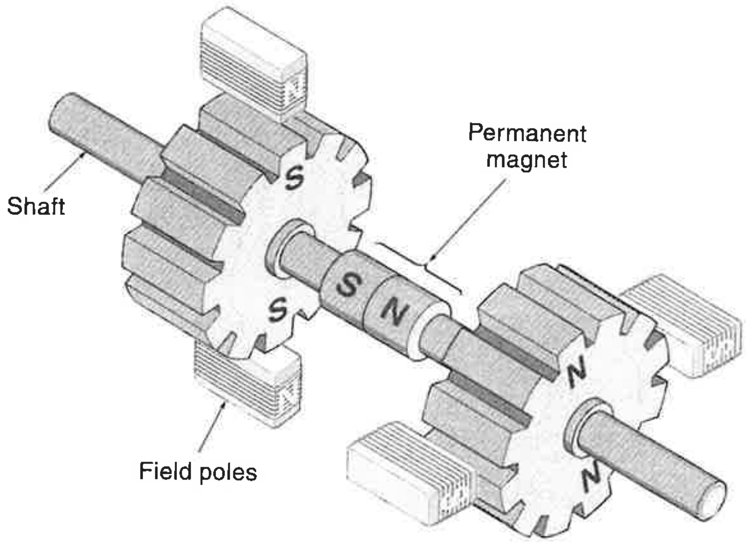


Figure 8.17
Internal construction of the hybrid stepper motor (only 2 poles per stator shown for clarity).

The theory of operation of the hybrid motor is similar to the VR motor in that the rotor and stator have a different number of teeth, and for each step, the closest energized teeth are pulled into alignment. However, the principles of magnetics require that, at any one time, half the poles be north and the other half be south. To maintain the magnetic balance, each pole must be able to switch polarity so that it can present the correct pole at the correct time. This is accomplished in one of two ways: For a bipolar motor, the applied voltage must be reversed by the driver circuit (similar to the two-phase PM motor). On the other hand, a unipolar motor has two separate windings of opposite direction on each field pole (called a *bifilar winding*), so each pole can be a north or a south. Therefore, the unipolar hybrid motor does not require a polarity-reversing driver circuit.

Figure 8.18 shows a specification sheet for a family of 1.8° hybrid stepping motors. For example, the 11-SHBD-45AB draws 0.3 A at 13.8 V and has a holding torque of 9.5 in. · oz, a running (dynamic) torque of 5.9 in. · oz, and a detent torque (unpowered) of 0.36 in. · oz. Unloaded, it can step at a rate of 1385 steps/minute.

8.4 STEPPER MOTOR CONTROL CIRCUITS

Figure 8.19 shows the block diagram for a stepper motor driving circuit. The *controller* decides on the number and direction of steps to be taken (based on the application). The *pulse sequence generator* translates the controller's requests into specific stepper motor coil voltages. The *driver amplifiers* boost the power of the coil drive signals. It should be

Bulletin SM 11/1.8

Size 11 1.8° stepper motors

Compact, light weight, high resolution stepper motors with high torque-to-size ratio

Features and Benefits

- Small size: 1.067" diameter
  1.500" long (excl. shaft)
- ±5% accuracy
- Half or full step (200 or 400 steps per revolution)
- High torque-to-size ratio
- Ball bearing construction
- Direct drive - no gearing
- Light weight
- Low cost

Typical applications

- Medical equipment
- Avionic instruments
- Robotics and automation
- Scanners
- Office equipment
- Battery operated equipment
- Chart recorders
- Test equipment
- Laser optics

STEPPER MOTOR SPECIFICATIONS	11-SHBD-45AB	11-SHBD-47AB	11-SHBD-49AB
INDEX ANGLE	1.8°±5%	1.8°±5%	1.8°±5%
FUNCTION	2ø HYBRID	4ø HYBRID	4ø HYBRID
STEPS PER REVOLUTION	200	200	200
INPUT VOLTAGE (DC)	13.8 REF.	9.6 REF.	14
INPUT CURRENT PER PHASE (AMPS) ± 10%	0.300	0.300	0.311
DC RESISTANCE PER PHASE (OHMS) ± 10%	46	32	45
INDUCTANCE PER PHASE (MH) REF.	51.3	22.4	28.4
NO LOAD RESPONSE RATE (PPS) MIN.	1140 (2)	875 (2)	810 (2)
NO LOAD SLEW RATE (PPS) MIN.	1385 (2)	1130 (2)	1225 (2)
HOLDING TORQUE (OZ-IN) MIN.	9.5 (2)	6.2 (2)	7.8 (2)
DYNAMIC TORQUE (OZ-IN) MIN.	5.9 (2)	3.9 (2)	4.3 (2)
DETENT TORQUE (OZ-IN) REF.	0.36	0.30	0.30
SHAFT RADIAL PLAY MAX.	0.0006 (0.015)	0.0006 (0.015)	0.0006 (0.015)
SHAFT END PLAY MAX. (1)	0.005 (0.13)	0.005 (0.13)	0.005 (0.13)
ROTOR INERTIA (GM-CM^2) REF.	3.3	3.8	3.6

(1) Shaft end play is spring loaded toward front of unit. (2) Measured with two phases on, L/R.

Figure 8.18 Hybrid stepper motors. (Courtesy of Litton Clifton Precision) clear that the stepper motor is particularly well suited for digital control; it requires no digital-to-analog conversion, and because the field poles are either on or off, efficient class C driver amplifiers can be used.

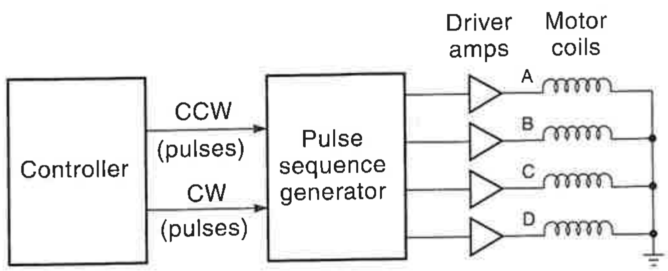
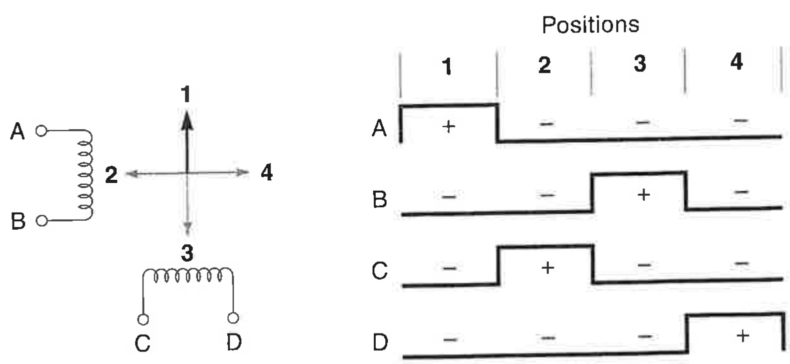


Figure 8.19
Block diagram of stepper motor control circuit.

Controlling the Two-Phase Stepper Motor

Controlling the two-phase bipolar stepper motor requires polarity reversals, making it more complicated than four-phase motor controllers. Figure 8.20 shows a two-phase stepper motor. The two circuits are designated AB and CD. The timing diagram shows the required waveforms for A, B, C, and D (CCW rotation). Looking down the position 1 column in Figure 8.20(b), we see A is positive and B is negative, so current will flow from A to B in circuit AB. Meanwhile C and D are both negative, effectively turning off circuit CD. For position 2 in the timing diagram, C is positive, and D is negative; causing current to flow from C to D in circuit CD while coil AB is completely off, and so on, for positions 3 and 4.



(a) Rotor positions

(b) Timing diagram (for CCW stepping "single excitation")

Figure 8.20
Two-phase (bipolar) stepper motor operation.

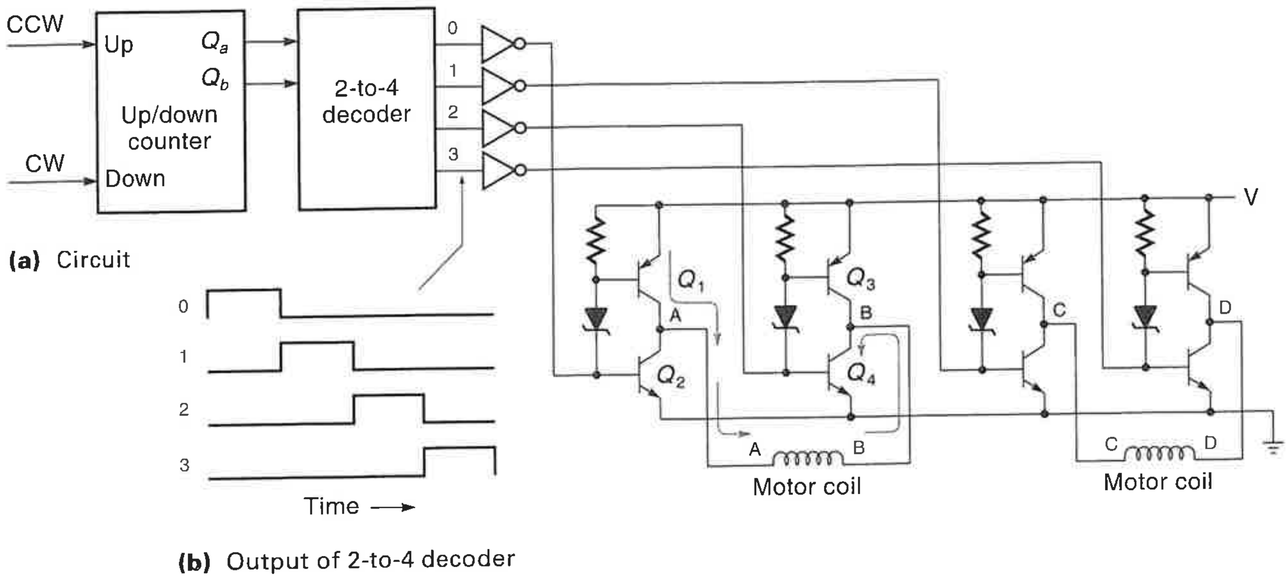


Figure 8.21 Complete interface circuit for a two-phase (bipolar) stepper motor.

A digital circuit such as the one shown in Figure 8.21(a) can be used to generate the timing waveforms. The up/down counter is a 2-bit counter that increments for each pulse received on its up input and decrements for each pulse received on the down input. Q_a and Q_b of the up/down counter are decoded in a 2-to-4 decoder. Because the counter is always in one of four states (00, 01, 10, 11), one (and only one) of the four decoder outputs is "high" at any particular time. Figure 8.21(b) shows the output of the decoder when the counter counts up (a result of CCW pulses from the controller).

The next task is to connect the timing signals from the decoder in such a way as to drive the motor coils. This can be accomplished with the power amplifier circuit shown on the right side of Figure 8.21(a). Notice there are four complementary–symmetry drivers, one for each end of each motor coil. When Q_1 and Q_4 are on, the current can flow through the motor in the direction shown. On the other hand, when Q_3 and Q_2 are on, the polarity is reversed, and the current flows the opposite direction through the motor. Finally, if Q_1 and Q_3 are off, no current flows through the motor coil.

The four outputs of the decoder (which must be inverted in this case) control the four complementary–symmetry transistor circuits. The resistor and diode in each circuit cause the upper transistor to be on when the lower transistor is off, and vice versa. Trace through the circuit for each step of the decoder, and you will see that the timing diagram of Figure 8.20(b) is reproduced. This arrangement will provide for the motor to step CCW when the counter counts up. When the counter counts down, the sequence will be backward, and the motor will step CW.

Controlling the Four-Phase Stepper Motor

The electronics needed to drive the four-phase stepper motor is simpler than for a two-phase motor because polarity reversals are not required. Figure 8.22 identifies the coils in a four-phase motor and shows the timing diagram for simple single-excitation

Figure 8.22
Four-phase (unipolar) stepper motor operation.

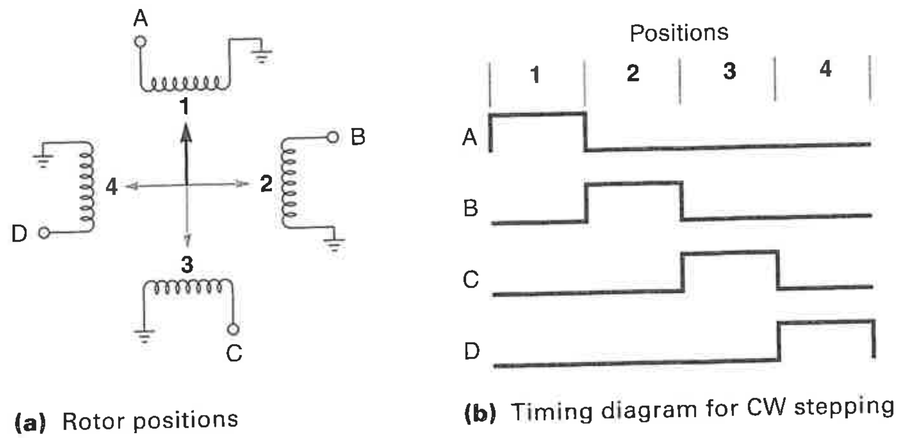
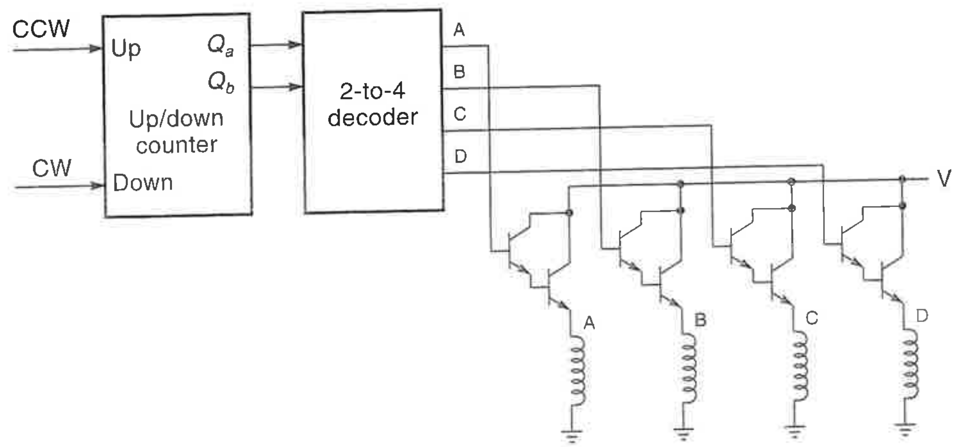


Figure 8.23
Complete interface for a four-phase stepper motor (simplified for clarity).



CW stepping. The timing is very straightforward and can easily be generated with the counter and decoder circuit shown in Figure 8.23.

The outputs of the decoder (Figure 8.23) are connected to four Darlington driver transistors. As timing signals A, B, C, and D go high in sequence, the corresponding transistors are turned on, energizing coils in the motor. The necessary four Darlingtons are available on a single IC such as the Allegro ULN-2064B (Figure 8.24). These amplifiers can supply up to 1.5 A and can be driven directly from TTL 5-V logic. (Note the diode to allow an escape path for current in the coil when the transistor is turned off.)

ICs designed specifically to drive stepper motors contain both the timing logic and power drivers in one package. One example is the Allegro UCN-5804B (Figure 8.25). The basic inputs are the step input (pin 11) and direction (pin 14). The motor will advance one step for each pulse applied to the step input pin, and the logic level on the direction pin determines if rotation will be CW or CCW. Notice that the output transistors are in the common emitter configuration (called *open collector*). The motor coils should be connected between the output pins and the supply voltage (as shown). When an output transistor turns on, it completes the circuit by providing a path to

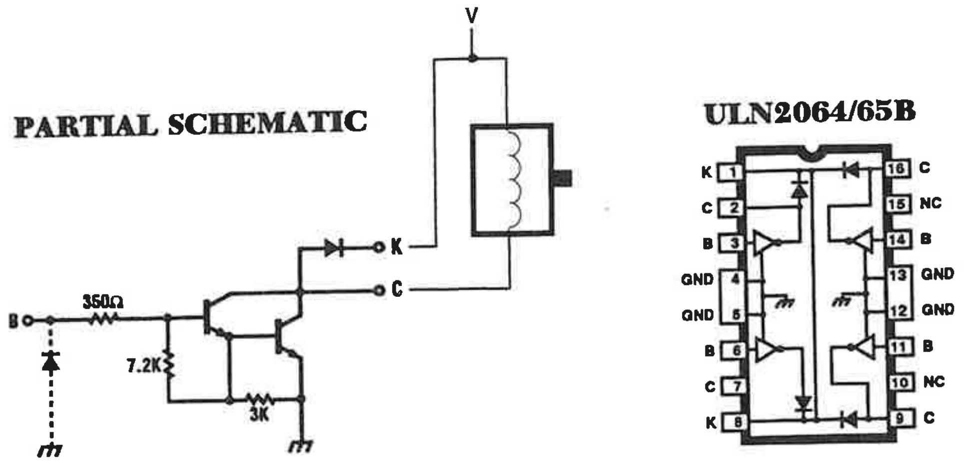
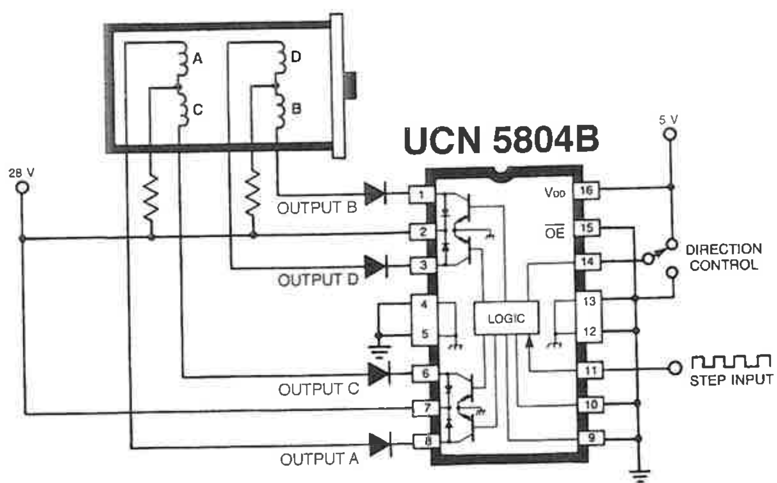


Figure 8.24
The Allegro ULN-2064B with four Darlington 1.5-A switches. (Courtesy of Allegro MicroSystems)

Figure 8.25 A unipolar stepper motor translator/driver (Allegro UCN-5804B). (Courtesy of Allegro MicroSystems)



(a) Driver circuit

WAVE-DRIVE SEQUENCE

← DIRECTION = L | → DIRECTION = H

Half Step = L, One Phase = H				
Step	**A**	**B**	**C**	**D**
POR	ON	OFF	OFF	OFF
1	ON	OFF	OFF	OFF
2	OFF	ON	OFF	OFF
3	OFF	OFF	ON	OFF
4	OFF	OFF	OFF	ON

TWO-PHASE DRIVE SEQUENCE

← DIRECTION = L | → DIRECTION = H

Half Step = L, One Phase = L				
Step	**A**	**B**	**C**	**D**
POR	ON	OFF	OFF	ON
1	ON	OFF	OFF	ON
2	ON	ON	OFF	OFF
3	OFF	ON	ON	OFF
4	OFF	OFF	ON	ON

HALF-STEP DRIVE SEQUENCE

← DIRECTION = L | → DIRECTION = H

Half Step = H, One Phase = L				
Step	**A**	**B**	**C**	**D**
POR	ON	OFF	OFF	OFF
1	ON	OFF	OFF	OFF
2	ON	ON	OFF	OFF
3	OFF	ON	OFF	OFF
4	OFF	ON	ON	OFF
5	OFF	OFF	ON	OFF
6	OFF	OFF	ON	ON
7	OFF	OFF	OFF	ON
8	ON	OFF	OFF	ON

(b) Modes of operation

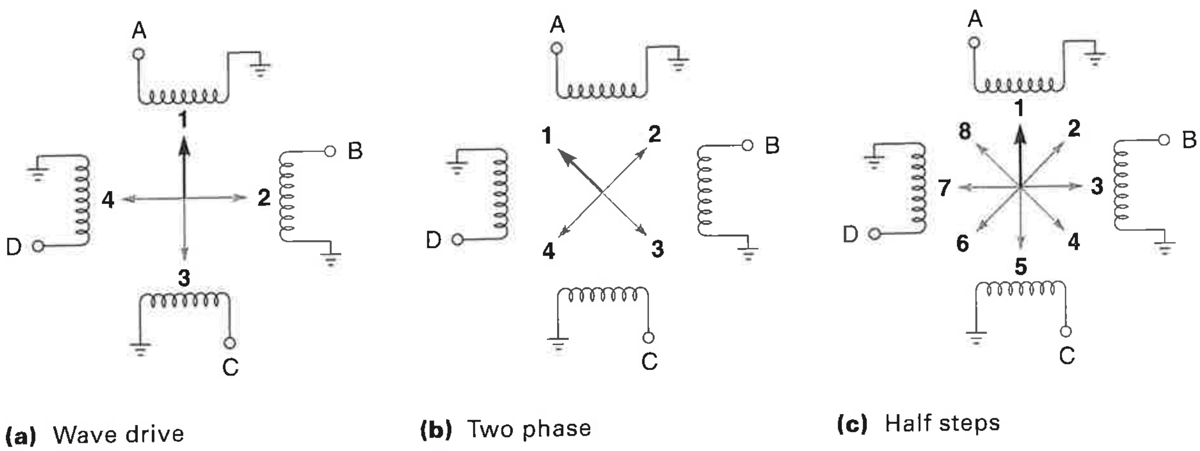


Figure 8.26 Three modes of operation for the Allegro UCN-5804B.

ground for the motor coil current. The three operating modes of the UCN-5804B are given in tabular form in Figure 8.25(b), and will be explained using Figure 8.26:

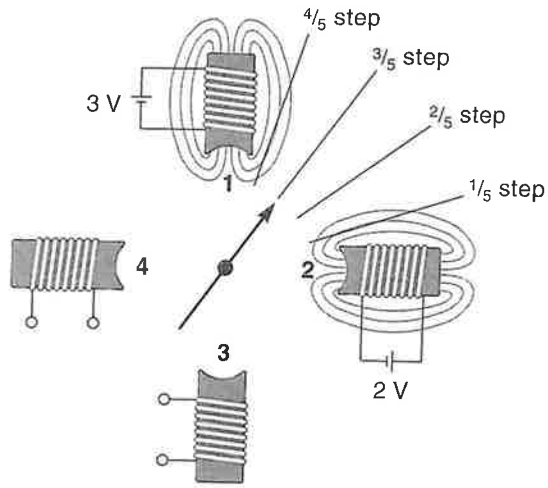
1. Figure 8.26(a) shows how the motor responds to the wave-drive sequence, a single-excitation mode where the coils A, B, C, and D are energized one at a time in sequence.
2. Figure 8.26(b) shows how the motor responds to the two-phase drive sequence, a dual-excitation mode where two adjacent phases are energized at the same time to give more torque.
3. Figure 8.26(c) shows how the motor responds to the half-step drive sequence, where the operation alternates between single- and dual-excitation modes, yielding eight half-steps per cycle.

Microstepping

Microstepping, a technique that allows a stepper motor to take fractional steps, works by having two adjacent field poles energized at the same time, similar to half-steps described earlier. In microstepping the adjacent poles are driven with different voltage levels, as demonstrated in Figure 8.27(a). In this case, pole 1 is supplied with 3 V and pole 2 with 2 V, which causes the rotor to be aligned as shown—that is, three-fifths of the way to pole 1. Figure 8.27(b) shows the voltages (for poles 1 and 2) to get five microsteps between each "regular" step. The different voltages could be synthesized with pulse-width modulation (PWM). The most commonly used microstep increments are 1/5, 1/10, 1/16, 1/32, 1/125, and 1/250 of a full step. Another benefit of microstepping (for delicate systems) is that it reduces the vibrational "shock" of taking a full step—that is, taking multiple microsteps creates a more "fluid" motion.

Two other points on microstepping: It does not require a special stepper motor, only special control circuitry, and the actual position of the rotor (in a microstepping system) is very dependent on the load torque.

Figure 8.27
Microstepping.



(a)

Pole 1	Pole 2	Position
5 V	0 V	Pole 1 (full step)
4 V	1 V	4/5 step
3 V	2 V	3/5 step
2 V	3 V	2/5 step
1 V	4 V	1/5 step
0 V	5 V	Pole 2 (full step)

(b)

Improving Torque at Higher Stepping Rates

It is important that the stepper motor develop enough torque with each step to drive the load. If it doesn't, the motor will stall (not step). When steps are missed, the controller no longer knows the exact position of the load, which may render the system useless.

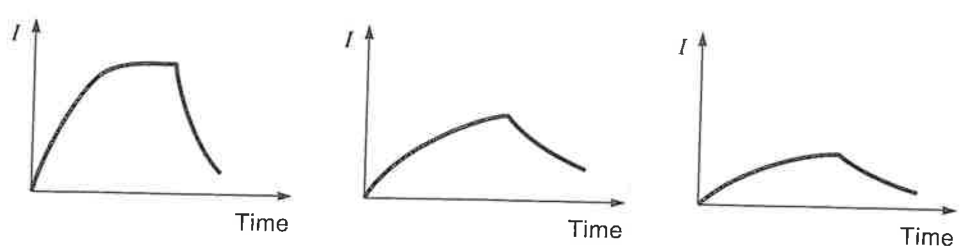
At higher stepping rates, two problems occur. First, if the load is accelerating, extra torque is needed to overcome inertia; second, the available motor torque actually diminishes at higher speeds. Recall that motor torque is directly proportional to motor current and that the average current decreases as the stepping rate increases. This is illustrated in Figure 8.28, which shows the motor current for three stepping rates. The problem is that the rate of change of current is limited by the circuit-time constant τ.

$$\tau = \frac{L}{R} \tag{8.1}$$

where

τ = time constant
L = motor inductance
R = motor coil resistance

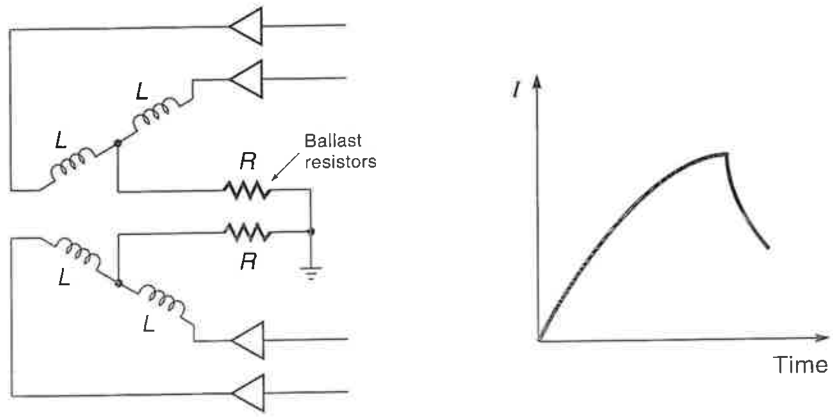
Figure 8.28
Coil current as a function of stepping speed.



(a) 100 steps/second (b) 500 steps/second (c) 1000 steps/second

You can see that as the stepping rate increases the current cannot build up in the field coils to as great a value. If we could reduce the value of the motor-time constant, the current could build up faster. One way to do this would be to increase the value of R in Equation 8.1. This can easily be done by adding external resistors (R) in series with the motor coils as shown in Figure 8.29(a). Such resistors are called **ballast resistors**, and their purpose is to improve the torque output at higher stepping rates (it also limits the current, which may be important in some cases). Stepper motor driver circuits that use ballast resistors are called **L/R drives**. Figure 8.29(b) shows the motor current with the ballast resistor added (for a rate of 1000 steps/second). Compare this with the last graph in Figure 8.28 to see the improvement.

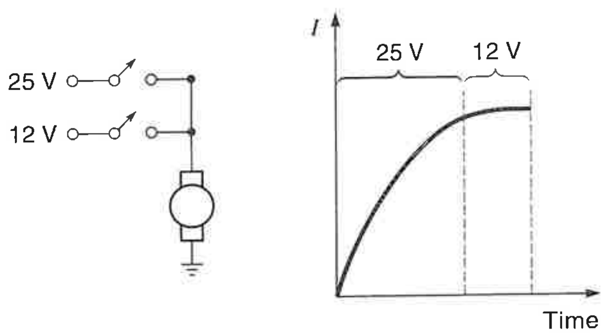
Figure 8.29
Effect of adding an external ballast resistor.



(a) Motor coils and ballast resistors **(b)** Coil current at 1000 steps/second with ballast resistor

Another way to improve motor torque at higher stepping rates is to use **bilevel drive**. In this approach, a high voltage is momentarily applied to the motor at the beginning of the step to force a fast in-rush of current. Then a lower voltage level is switched on to maintain that current. Figure 8.30(a) shows a simplified circuit to provide bilevel drive.

Figure 8.30
Principle of a bilevel drive.

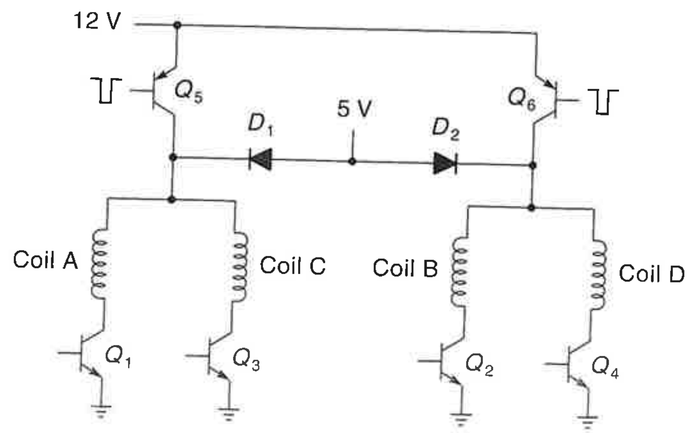


(a) **(b)**

The 25-V circuit is switched on, and the current rises rapidly [Figure 8.30(b)]. When the desired current level is reached, the 25-V circuit is switched off, and the 12-V circuit is switched on, which keeps the current at the desired level for the rest of the step time.

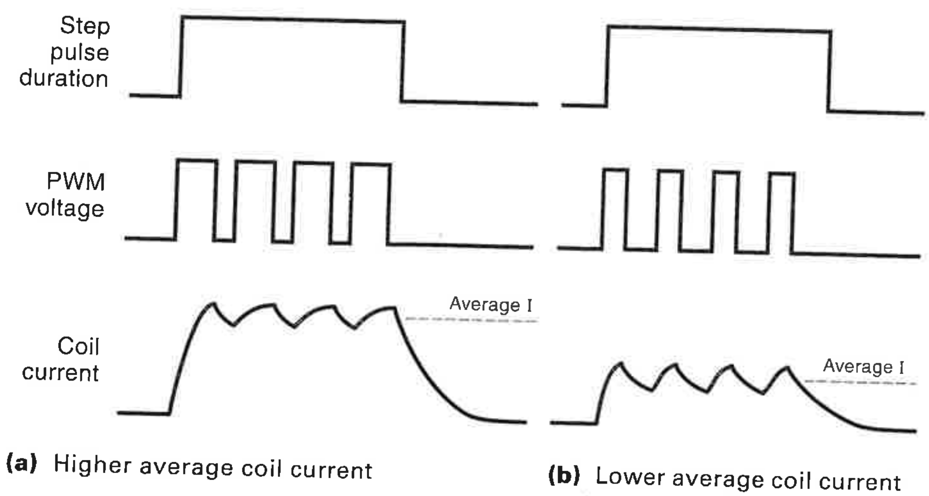
Figure 8.31 shows a bilevel-drive interface circuit. In this case, the higher voltage is 12 V, and the lower voltage is 5 V. The 12-V is switched through either Q_5 or Q_6 in response to a pulse from a timing circuit (not shown). The 5-V is applied through D_1 and D_2. These diodes keep the 12-V pulses from backing up into the 5-V power supply. The bilevel drive is more complex but allows the stepper motor to have more torque at higher stepping rates.

Figure 8.31
A bilevel-drive circuit.



Another approach for providing higher torque at faster stepping rates is the **constant current chopper drive**. Using PWM techniques, this driver circuit can deliver almost the same current to the motor at all speeds. A chopper-drive waveform is shown in Figure 8.32 and works in the following manner: A relatively high voltage is switched to the motor coil, and the current is monitored. When the current reaches a specified level, the voltage is cut off. After a short time, the voltage is reapplied, and the current again

Figure 8.32
A PWM (chopper drive) used to regulate stepper motor coil current.



increases, only to be cut off, and so on. Thus, in the same way that a thermostat can maintain a constant temperature by switching the furnace on and off, the chopper drive maintains a constant average current (within each drive pulse) by rapidly switching the voltage on and off. In summary, the chopper drive is another technique for providing good torque at high stepping rates. Stepper motor driver ICs are available, such as the Allegro A2919SB, with built-in PWM constant current capability.

8.5 STEPPER MOTOR APPLICATION: POSITIONING A DISK DRIVE HEAD

Example 8.3 illustrates many of the principles presented in this chapter and extends the discussion to show how software can control a stepper motor.

♦ EXAMPLE 8.3

A 30° four-phase stepper motor drives the read/write head on a floppy disk drive (Figure 8.33). The in-and-out linear motion is achieved with a leadscrew connected directly to the motor shaft. Each magnetic track on the disk is 0.025 in. apart (40 tracks/in.). The leadscrew has 20 threads/in.

The motor is driven by the UCN-5804B stepper motor interface IC. This IC requires only two inputs: step input and direction. A computer will supply these signals in response to toggle switch settings. A front panel contains eight toggle switches; seven are used to input (in binary) the number of tracks to move, and the eighth switch specifies direction—in or out. Write a program in BASIC that will cause the motor to step the number of tracks and direction specified by the switch settings.

Solution First we need to find the number of steps required to advance one track on the disk. If the leadscrew has 20 threads per inch, then rotating it one revolution (360°) will advance it 1 thread, which is 1/20 in. The following equation was set up by multiplying all the component transfer functions, including conversion factors as necessary (and oriented so that, if possible, the units would cancel):

$$\frac{0.025\ \cancel{\text{in.}}}{\text{track}} \times \frac{20\ \cancel{\text{threads}}}{\cancel{\text{in.}}} \times \frac{360\cancel{°}}{\cancel{\text{thread}}} \times \frac{1\ \text{step}}{30\cancel{°}} = \frac{6\ \text{steps}}{\text{track}}$$

Thus, the stepper motor must take six steps to advance one track on the disk.

The program must first read the switches, then calculate the required number of steps, and, finally, output the step command pulses, one by one, to the UCN-5804B. The direction bit must also be read and passed along to the UCN-5804B. Figure 8.34 shows a simplified flowchart of the program.

The next step is to translate the flowchart into a BASIC program. The complete program, along with line-by-line explanations, is given in Table 8.1. With BASIC we can only input or output 8 bits at a time. The input is the 8 bits from the switches. For output, only 2 of the 8 bits are used: the least significant bit (LSB) (D_0) for the step input pulse and the most significant bit (MSB) (D_7) for the direction command. The

Figure 8.33
The hardware setup for the stepper motor example.

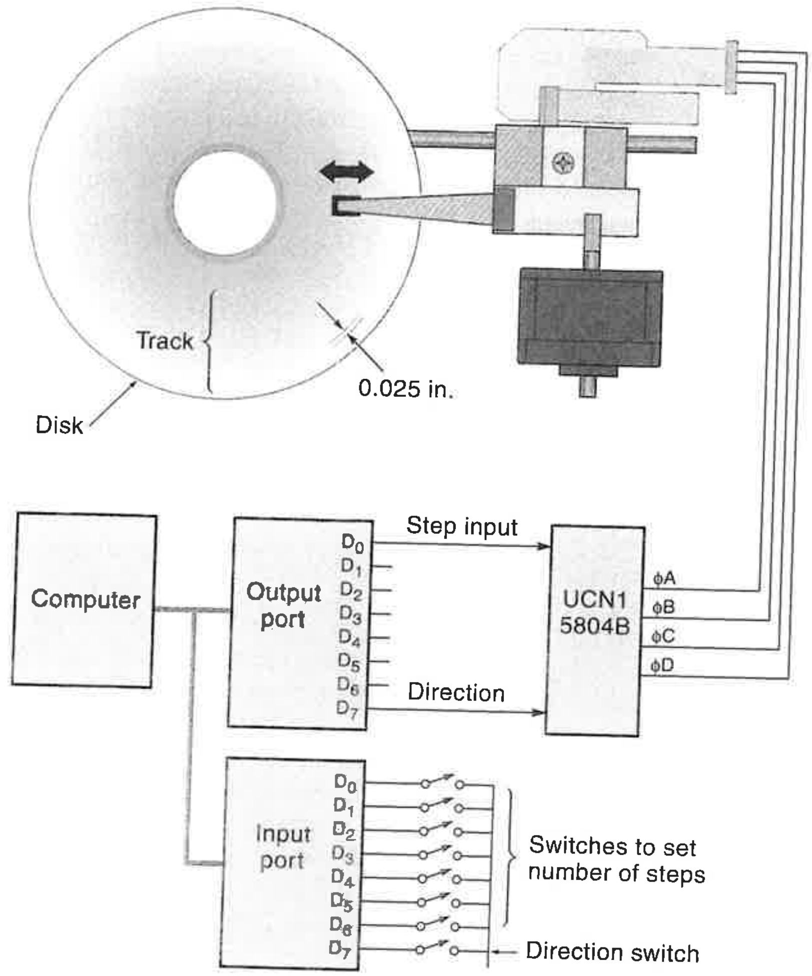


Figure 8.34
Flowchart for a program to drive a stepper motor.

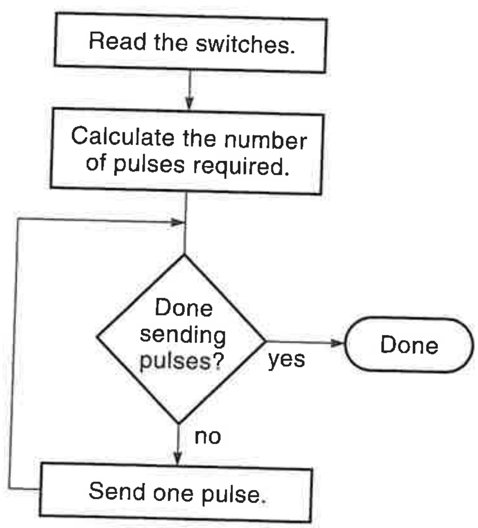


TABLE 8.1 BASIC Program to Control a Disk Drive Head

	Instruction	Explanation
10	`SW = INP(209)`	Input 8 bits of switch data.
20	`IF SW < 128 THEN`	If MSB = 0, then the direction bit = 0.
	`DIR = 0`	
	`ELSE`	
	`DIR = 128`	Otherwise, set direction bit = 1 (10000000 = 128)
	`SW = SW - 128`	and remove the MSB to leave the number of tracks.
	`END IF`	
30	`PUL = SW*6`	Calculate the number of pulses needed at 6 pulses per track.
40	`REM***** SEND PULSES****`	
50	`FOR I = 1 TO PUL`	Prepare to send PUL (number of pulses).
60	`HIGH = 1 + DIR`	Make the LSB a 1 and add a direction bit.
70	`OUT 208, 1`	Send out a "high" for the step pulse.
80	`FOR J=1 TO 100`	This is the time-delay loop for the pulse width.
90	`NEXT J`	
100	`LOW = 0 + DIR`	Make the LSB a 0 and add a direction bit.
110	`OUT 208, 0`	Send out a "low" to define the end of the pulse.
120	`FOR J = 1 TO 100`	This is the time-delay loop for the pulse being "low."
130	`NEXT J`	
140	`NEXT I`	Go back and send the next pulse.
END		

step input pulse is created by making the output (D_0) go "high" for a period of time and then bringing it "low" for a period of time. The direction bit, brought in as the MSB from the switches, is simply passed on through by the program and sent out as the MSB (actually it is stripped off the input data and added back later to the output word). The parallel I/O port addresses would, of course, depend on the system being used; in this case, the input switch port is 209 (decimal), and the output port to the motor has an address of 208 (decimal). ♦

SUMMARY

A stepper motor, a unique type of DC motor, rotates in fixed steps of a certain number of degrees: 30°, 15°, 1.8°, and so on. The rotor (the part that moves) is made of permanent magnets or iron and contains no coils and therefore has no brushes. Surrounding the rotor is the stator, which contains a series of field pole electromagnets. As the electromagnets are energized one after the other, the rotor is pulled around in a circle. Stepper motors used in position systems are usually operated open-loop, that is, without feedback sensors. The controller will step the motor so many times and expect the motor to be there.

The permanent magnet (PM) stepper motor uses permanent magnets in the rotor. This type of motor has a detent torque—a small magnetic tug that tends to keep it in the last position stepped to, even when the power is removed. PM motors have good torque capability but cannot take very small steps. The field coils of the PM motor can be driven in the two-phase or four-phase mode. The two-phase mode requires polarity reversals. Four-phase operation does not require polarity reversals and the timing is more straightforward.

The variable reluctance (VR) stepper motor uses a toothed iron wheel for the rotor (instead of permanent magnets). This allows VR motors to take smaller steps, but they are weaker and have no detent torque.

The hybrid stepper motor combines the features of both the PM and VR stepper motors and is the type in most common use today. Hybrid motors can take small steps (typically 1.8°) and have a detent torque. The internal construction of the hybrid motor is more complicated than the PM or VR motors, but the electrical operation is just as simple.

Stepper motors are driven from digital circuits that provide the desired number of stepping pulses (in the correct order) to the field coils. These pulses must usually be amplified with driver transistors (operating as switches) before being applied to the motor coils. ICs are available that can provide the proper sequencing and amplification in one chip.

GLOSSARY

ballast resistor A resistor placed in series with the motor coils to improve the torque at higher stepping rates; it works by reducing the motor-time constant.

bilevel drive A technique that uses two voltages to improve torque at higher stepping rates. A higher voltage is applied to the motor at the beginning of the step, and then a lower voltage is switched in.

bipolar motor A motor that requires polarity reversals for some of the steps; a two-phase motor is bipolar.

constant current chopper drive A drive circuit for stepper motors that uses PWM techniques to maintain a constant average current at all speeds.

cumulative error Error that accumulates; for example, a cumulative error of 1° per revolution means that the measurement error would be 5° after five revolutions.

detent torque A magnetic tug that keeps the rotor from turning even when the power is off; also called *residual torque*.

dynamic torque The motor torque available to rotate the load under normal conditions.

eight-step drive A two- or four-phase motor being driven in half-steps; the sequencing pattern has eight steps.

four-phase stepper motor A motor with four separate field circuits; this motor does not require polarity reversals to operate and hence is unipolar.

four-step drive The standard operating mode for two- or four-phase stepper motors taking full steps; the sequencing pattern has four states.

half-steps By alternating the standard mode with dual excitation mode, the angle of step will be half of what it normally is.

holding torque The motor torque available to keep the shaft from rotating when the motor is stopped but with the last field coil still energized.

hybrid stepper motor A motor that combines the features of the PM and VR stepper motors—that is, it can take small steps and has a detent torque.

L/R drive A stepper motor driver circuit that uses ballast resistors in series with the motor coils to increase torque at higher stepping rates.

microstepping A technique that allows a regular stepper motor to take fractional steps; it works by energizing two adjacent poles at different voltages and by balancing the rotor between.

permanent magnet (PM) stepper motor A motor that uses one or more permanent magnets for the rotor; this motor has a detent torque.

phase The number of separate field winding circuits.

rotor The internal part of the stepper motor that rotates.

single-step mode Operating the motor at a slow enough rate so that it can be stopped after any step without overshooting.

slew mode Stepping the motor at a faster rate than the single-step mode; used to move to a new position quickly. The motor will overshoot if the speed is not ramped up or down slowly.

stalling A situation wherein the motor cannot rotate because the load torque is too great.

stator The part of a stepper motor that surrounds the rotor and consists of field poles (electromagnets).

stepper motor A motor that rotates in steps of a fixed number of degrees each time it is activated.

three-phase stepper motor A motor with three separate sets of field coils; usually found with VR motors.

two-phase stepper motor A motor with two field circuits. This motor requires polarity reversals to operate and hence is bipolar.

unipolar motor A motor that does not require polarity reversals. A four-phase motor is unipolar.

variable reluctance (VR) stepper motor A motor that uses a toothed iron wheel for the rotor and consequently can take smaller steps but has no detent torque.

EXERCISES

Section 8.1

1. A 15° stepper motor is commanded to go 100 steps CW and 30 steps CCW from a reference point. What is its final angle?
2. A 7.5° stepper motor is commanded to go 50 steps CCW, 27 steps CW, and 35 steps CCW again. What is its final angle (referenced from its original position)?
3. Why can a stepper motor be operated open-loop in a control system?
4. What is the detent (or residual) torque in a PM stepper motor, and what causes it?
5. A stepper motor is being used as a crane motor in an expensive toy. The motor has the following properties: Holding torque = 35 in. · oz, dynamic torque = 20 in. · oz, and detent torque = 5 in. · oz. The motor turns a 1.5-in. diameter pulley around which a string is wound. How much weight can the crane lift? How much weight can the crane continue to support with the power on; with the power off?
6. List the stepping sequence you would use to make the two-phase motor of Figure 8.8 rotate CW.
7. List the stepping sequence you would use to make the two-phase motor of Figure 8.9 operate as an eight-step drive (CCW).
8. List the stepping sequence you would use to make the four-phase motor of Figure 8.11(a) operate as an eight-step drive (CCW).

Section 8.2

9. Explain the principle of operation of a VR stepper motor.
10. Does a VR stepper motor have a detent torque? Explain.

Section 8.3

11. Explain the principle of operation of a hybrid stepper motor.
12. What are the advantages of the hybrid stepper motor?

Section 8.4

13. A 5-V stepper motor is to be microstepped with one-tenth steps. List the voltage table required for this [similar to Figure 8.27(b)].
14. What is the purpose of a ballast resistor on a stepper motor drive, and how does it work?
15. What is the purpose of bilevel drive, and how does it work?
16. How does a chopper drive improve torque at higher stepping rates?

Section 8.5

17. A 1.8° stepper motor turns a leadscrew that has 24 threads per inch.
    a. How many steps will it take to advance the leadscrew 1.25 in.?
    b. What is the linear distance the leadscrew advances for each step?
18. A 7.5° stepper motor (four phase), controlled by a computer, is used to position a telescope through a gear train. The telescope must be positioned to within 0.01°. A front panel has toggle switches that are used to specify how far the telescope is to move (LSB = 0.01°). The total range of the telescope is 0–60°.
    a. How many toggle switches would be required?
    b. What gear ratio would you specify?
    c. Draw a block diagram of the system, showing all parts of the system and specifying the gear ratio.