CHAPTER 19
Stepper Motors

19.0 Introduction

Stepper motors are special motors that are used when motion and position have to be precisely controlled. As their name implies, stepper motors rotate in discrete steps, each step corresponding to a pulse that is supplied to one of its stator windings. Depending on its design, a stepper motor can advance by 90°, 45°, 18°, or by as little as a fraction of a degree per pulse. By varying the pulse rate, the motor can be made to advance very slowly, one step at a time, or to rotate stepwise at speeds as high as 4000 r/min.

Stepper motors can turn clockwise or counterclockwise, depending upon the sequence of the pulses that are applied to the windings.

The behavior of a stepper motor depends greatly upon the power supply that drives it. The power supply generates the pulses, which in turn are usually initiated by a microprocessor. The pulses are counted and stored, clockwise (cw) pulses being (+) while counterclockwise (ccw) pulses are (−). As a result, the net number of steps is known *exactly* at all times. It follows that the number of revolutions is always precisely known to an accuracy of one step. This permits the motor to be used as a precise positioning device in machine tools, X-Y plotters, typewriters, tapedecks, valves, and printers.

In this chapter we will cover the operating principle of the more common stepper motors, together with their properties and limitations. We will also discuss the types of drives used to actuate these machines.

19.1 Elementary stepper motor

A very simple stepper motor is shown in Fig. 19.1. It consists of a stator having three salient poles and a 2-pole rotor made of soft iron. The windings can be successively connected to a dc power supply by means of three switches A, B, C.

When the switches are open, the rotor can take up any position. However, if switch A is closed, the resulting magnetic field created by pole 1 will attract the rotor and so it will line up as shown. If we now open switch A and simultaneously close switch B, the rotor will line up with pole 2. In so doing, it will rotate ccw by 60°. Next, if we open switch B and simultaneously close switch C, the rotor will turn ccw by an additional 60°, this time lining up with pole 3.

Clearly, we can make the rotor advance ccw in 60° steps by closing and opening the switches in the sequence A, B, C, A, B, C, ... Furthermore, we

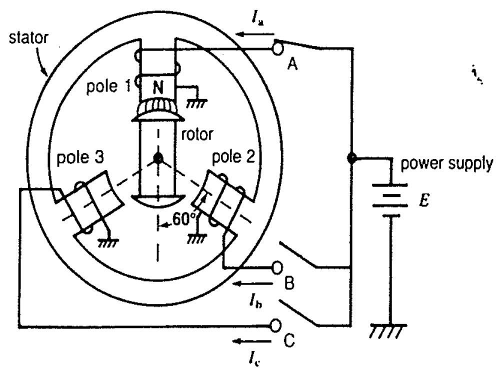


Figure 19.1
Simple stepper motor in which each step moves the rotor by 60°.

can reverse the rotation by operating the switches in the reverse sequence A, C, B, A, C, B. . . . In order to fix the final position of the rotor, the last switch that was closed in a switching sequence must remain closed. This holds the rotor in its last position and prevents it from moving under the influence of external torques. In this stationary state the motor will remain locked provided the external torque does not exceed the *holding torque* of the motor.

In moving from one position to the next, the motion of the rotor will be influenced by the inertia and the frictional forces that come into play. We now examine the nature of these forces.

19.2 Effect of inertia

Suppose the motor operates at no-load and that the rotor has a low inertia and a small amount of bearing friction. It is initially facing pole 1. Let this correspond to the zero degree (0°) angular position. At the moment switch A opens and switch B closes, the rotor will start accelerating ccw toward pole 2. It rapidly picks up speed and soon reaches the center line of pole 2, where it should come to rest. However, the rotor is now moving with considerable speed and it will overshoot the center line. As it does so, the magnetic field of pole 2 will pull it in the opposite direction, thereby braking the rotor. The rotor will come to a halt and start moving in the opposite (cw) direction. Picking up speed, it will again overshoot the center line of pole 2, whereupon the magnetic field will exert a pull in the ccw direction.

The rotor will therefore oscillate like a pendulum around the center line of pole 2. The oscillations will gradually die out because of bearing friction. Fig. 19.2 shows the angular position of the rotor as a function of time. The rotor starts at 0° (center of pole 1) and reaches 60° (center line of pole 2) after 2 ms. It overshoots the center line by 30° before coming to a halt (at 3 ms). The rotor now moves in reverse and again crosses the center line at $t = 4$ ms.

The oscillations continue this way, gradually diminishing in amplitude until the rotor comes to rest at $t > 10$ ms.

The reader will note that in Fig. 19.2 we have also drawn the instantaneous speed of the rotor as a function of time. The speed can be given in revolutions per second, but for stepper motors it is more meaningful to speak of degrees per second. The speed is momentarily zero at $t = 3$ ms, 5 ms, 7 ms, and becomes permanently zero at $t > 10$ ms. The speed is greatest whenever the rotor crosses the center line of pole 2. Clearly, the oscillations last a relatively long time before the rotor settles down.

Without making any other changes, suppose we increase the inertia of the rotor by mounting a flywheel on the shaft. We discover that both the period and the amplitude of the oscillations increase when the inertia increases. In Fig. 19.3, for example, the time to reach the 60° position has increased from 2 ms to 4 ms. Furthermore, the amplitude of the oscillations has increased. The rotor also takes a longer time to settle down (20 ms instead of 10 ms).

The oscillations can be damped by increasing the friction. For example, if the bearing friction is raised sufficiently, the oscillations shown in Fig. 19.3 can be suppressed so as to give only a single overshoot, shown in Fig. 19.4. In practice, the damping is accomplished by using an eddy-current brake or a viscous damper. A viscous damper uses a fluid such as oil or air to brake the rotor whenever it is

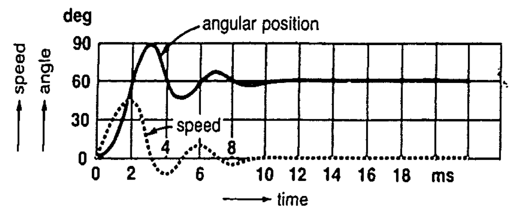


Figure 19.2
In moving from pole 1 to pole 2, the rotor oscillates around its 60° position before coming to rest. The speed is zero whenever the rotor reaches the limit of its overshoot.

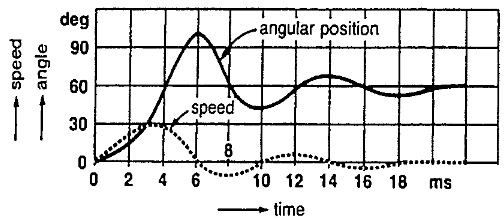


Figure 19.3
Same conditions as in Fig. 19.2, except that the inertia is greater. The overshoot is greater and the rotor takes longer to settle down.

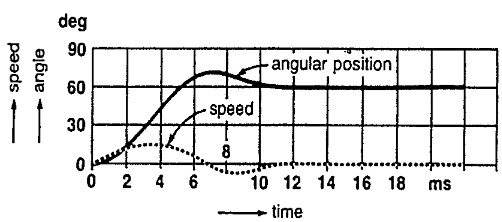


Figure 19.4
Same conditions as in Fig. 19.3, except that viscous damping has been added.

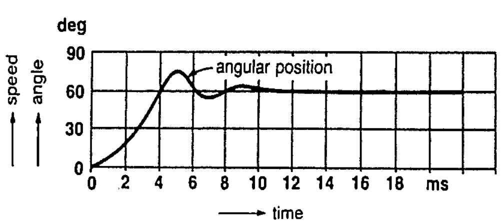


Figure 19.5
Same conditions as in Fig. 19.2, except that the rotor is coupled to a mechanical load.

moving. Viscous damping means that the braking effect is proportional to speed; it is therefore zero when the rotor is at rest.

19.3 Effect of a mechanical load

Let us return to the condition shown in Fig. 19.2, where the rotor has low inertia and a small amount of viscous damping due to bearing friction. If the rotor is coupled to a mechanical load while it is moving, the effect is shown in Fig. 19.5. As we would expect, it takes longer for the motor to attain the 60° position (compare 2 ms in Fig. 19.2 with 4 ms in Fig. 19.5). Furthermore, the overshoot is smaller and the oscillations are damped more quickly.

In summary, both the mechanical load and the inertia increase the stepping time. The oscillations also prolong the time before the rotor settles down. Therefore, in order to obtain fast stepping response, the inertia of the rotor (and its load) should be as small as possible and the oscillations should be suppressed by using a viscous damper.

The time to move from one position to the next can also be reduced by increasing the current in the winding. However, thermal limitations due to I^2R losses dictate the maximum current that can be used.

Returning to Fig. 19.1, let us excite the windings in succession so that the motor rotates. Fig. 19.6 shows the current pulses I_a, I_b, I_c and the instantaneous position of the rotor (as well as its speed) when the motor makes one-half revolution. We assume that the stepper motor has some inertia and that it is driving a mechanical load. Note that the speed of the rotor is zero at the beginning and at the end of each pulse. In this figure the pulses have a duration of 8 ms. Consequently, the stepping rate is 1000/8 = 125 steps per second. One revolution requires 6 steps, and so it takes $6 \div 125 = 0.048$ s to complete one turn. The *average* speed is, therefore, 60/0.048 = 1250 revolutions per minute. However, the stepper motor rotates in start-stop jumps and not as smoothly as an ordinary motor would.

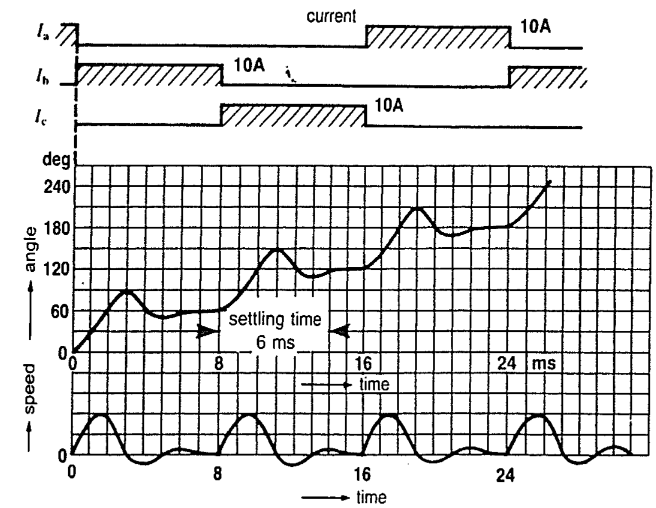


Figure 19.6
Graph of current pulses, angular position, and instantaneous speed of rotor during the first four steps. Three steps (24 ms) produce one half-revolution.

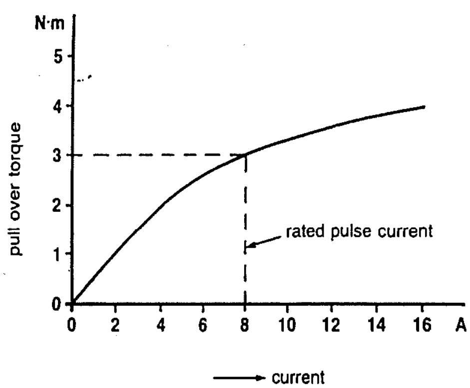


Figure 19.7
Graph of pull-over torque versus current of a stepper motor; diameter: 3.4 inches; length: 3.7 in; weight: 5.2 lbm.

19.4 Torque versus current

As mentioned previously, the torque developed by a stepper motor depends upon the current. Fig. 19.7 shows the relationship between the two for a typical stepper motor. When the current is 8 A, the motor develops a torque of 3 N·m. This is the torque that the motor can exert while moving from one position to the next, so it is called the *pull-over* torque.

When the motor is at rest, a holding current must continue to flow in the last winding that was excited so that the rotor remains locked in place.

19.5 Start-stop stepping rate

When the stepping motor inches along in the start-stop fashion shown in Fig. 19.6, there is an upper limit to the permissible stepping rate. If the pulse rate of the current in the windings is too fast, the rotor is unable to accurately follow the pulses, and steps will be lost. This defeats the whole purpose of the motor, which is to correlate its instantaneous position (steps) with the number of net (+ and −) pulses. In order to maintain synchronism, the rotor must settle down before advancing to the next position. Referring to Fig. 19.6, this means that the interval between successive steps must be at least 6 ms, which means that the stepping rate is limited to a maximum of 1000/6 = 167 steps per second (sps).

Bearing in mind what was said in Section 19.2, it is clear that the maximum number of steps per second depends upon the load torque and the inertia of the system. The higher the load and the greater the inertia, the lower will be the allowable number of steps per second.

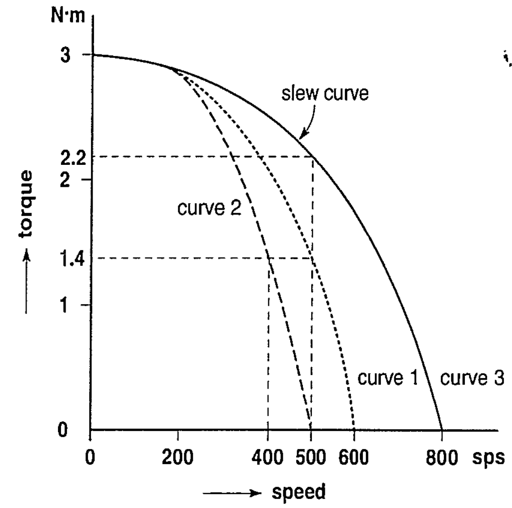


Figure 19.8
Start-stop and slewing characteristic of a typical stepper motor. Each step corresponds to an advance of 1.8 degrees.
Curve 1: start-stop curve with only stepper motor inertia
Curve 2: same conditions as curve 1, but with an additional load inertia of 2 kg·cm²
Curve 3: slewing curve

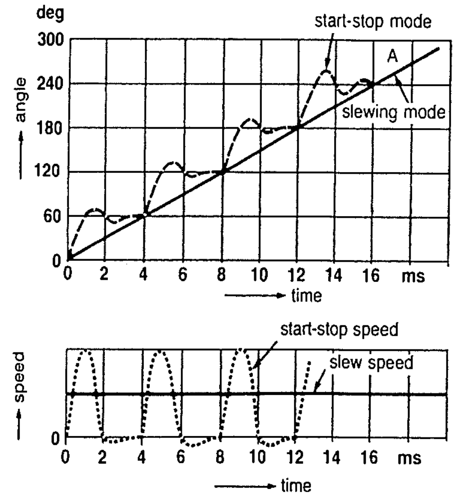


Figure 19.9
a. Angular position versus time curve when the stepper motor operates in the start-stop mode and the slewing mode. Stepping rate is the same in both cases.
b. Instantaneous speed versus time curve when the stepper motor operates in the start-stop and the slewing mode.

The start-stop stepping mode is sometimes referred to as the *start-without-error* mode. A start-without-error characteristic is shown by curve 1 in Fig. 19.8. It shows that if the stepper motor runs alone, under a load torque of, say, 1.4 N·m, the maximum possible stepping rate, without losing count, is 500 steps per second.

But if the motor drives a device having some inertia, the permissible start-stop rate drops to about 400 steps per second for the same load torque (curve 2).

19.6 Slew speed

A stepper motor can be made to run at uniform speed without starting and stopping at every step. When the motor runs this way it is said to be *slewing*. Because the motor runs essentially at uniform speed, the inertia effect is absent. Consequently, for a given stepping rate, the motor can carry a greater load torque when it is slewing. Curve 3 in Fig. 19.8 shows the relationship between the load torque and the steps per second when the motor is slewing. For example, the motor can develop a torque of 2.2 N·m when it slews at 500 steps per second. However, if the load torque should exceed 2.2 N·m when the pulse rate is 500 sps, the motor will fall out of step and the position (steps) of the rotor will no longer correspond to the net number of pulses provided to its windings.

Fig. 19.9 shows the difference between the start-stop mode and slewing. Suppose the motor is turning at an average speed of 250 steps per second in both cases. The motor will therefore cover the same number of steps per second, namely 1 step every 4 ms. However, the angle (position) increases smoothly with time when the motor is slewing, and this is shown by the uniform slope of line 0A (Fig. 19.9a). The corresponding slew speed is constant (Fig. 19.9b).

On the other hand, in the start-stop mode, the angle increases stepwise. Consequently, the speed continually oscillates between a maximum and zero and its *average* value is equal to the slew speed (Fig. 19.9b).

19.7 Ramping

When a stepper motor is carrying a load, it cannot suddenly go from zero to a stepping rate of, say, 5000 sps. In the same way, a motor that is slewing at 5000 sps cannot be brought to a dead stop in one step. Thus, to bring a motor up to speed, it must be accelerated gradually. Similarly, to stop a motor that is running at high speed, it must be decelerated gradually—always subject to the condition that the instantaneous position of the rotor must correspond to the number of pulses. The process whereby a motor is accelerated and decelerated is called *ramping.* During the acceleration phase, ramping consists of a progressive increase in the number of driving pulses per second.

The ramping phase is usually completed in a fraction of a second. The ramp is generated by the power supply that drives the stepper motor. Furthermore, it is programmed to retain precise position control over the motor and its load.

19.8 Types of stepper motors

There are 3 main types of stepper motors:

- variable reluctance stepper motors
- permanent magnet stepper motors
- hybrid stepper motors

Variable reluctance stepper motors are based upon the principle illustrated in Fig. 19.1. However, to obtain small angular steps, of the order of 1.8° (instead of the 60° jumps shown in the figure), the structure of the stator and rotor has to be modified to create many more poles. This is done by using a circular rotor and milling out slots around its periphery. The teeth created thereby constitute the salient poles of the rotor, of which there may be as many as 100.

As to the stator, it often has four, five, or eight main poles, instead of the three shown. However, the pole-faces are also slotted so as to create a number of teeth. These teeth are the real salient poles on the stator. The typical construction of a toothed 8-pole stator is shown in the circular insert of Fig. 19.13. For a given drive system, it is the number of teeth (salient poles) on the rotor and stator that determines the angular motion per step. Steps of 18°, 15°, 7.5°, 5°, and 1.8° are common.

Permanent magnet stepper motors are similar to variable reluctance motors, except that the rotor has permanent N and S poles. Fig. 19.10 shows a permanent magnet motor having 4 stator poles and 6 rotor poles, the latter being permanent magnets. Due to the permanent magnets, the rotor remains lined up with the last pair of stator poles that were excited by the driver. In effect, the motor develops a *detent torque* which keeps the rotor in place even when no current flows in the stator windings.

Coils A1, A2 are connected in series, as are coils B1, B2. Starting from the position shown, if coils B are excited, the rotor will move through an angle of 30°. However, the direction of rotation depends upon the direction of current flow. Thus, if the cur-

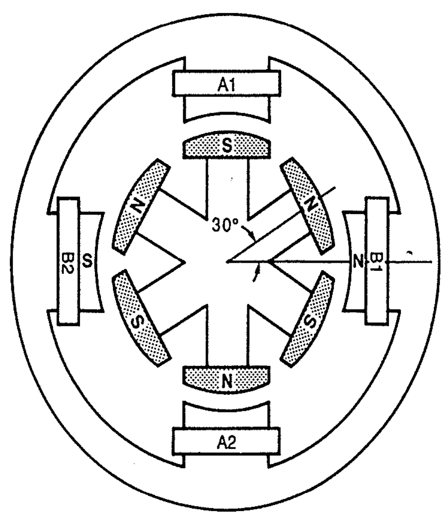
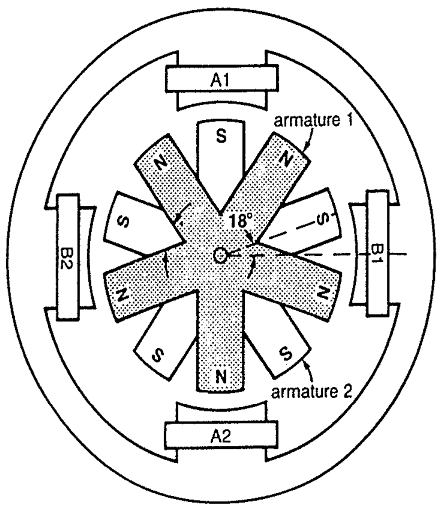
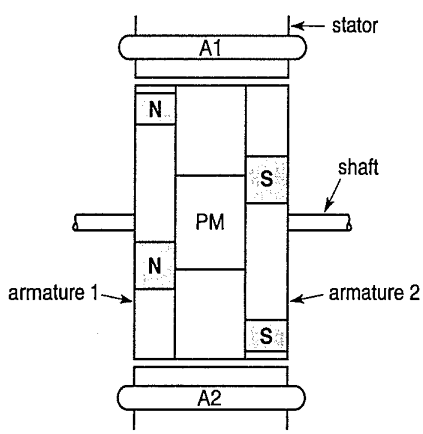


Figure 19.10
Permanent magnet stepper motor that advances 30° per step.



(a)

Figure 19.11a
Hybrid motor having a 4-pole stator and two 5-pole armatures mounted on the same shaft. The salient poles on the first armature are all N poles, while those on the second armature are all S poles. Each step produces an advance of 18°.



(b)

Figure 19.11b
Side view of the rotor, showing the permanent magnet PM sandwiched between the two armatures. The 4-pole stator is common to both armatures.

rent in coils B produces N and S poles as shown in Fig. 19.10, the rotor will turn ccw. Stepper motors that have to develop considerable power are usually equipped with permanent magnets.

Hybrid stepper motors have two identical soft-iron armatures mounted on the same shaft. The armatures are indexed so that the salient poles interlap. Fig. 19.11a shows two 5-pole armatures that are driven by a 4-pole stator. This arrangement makes the motor look like a variable reluctance motor. However, a permanent magnet PM is sandwiched between the armatures (Fig. 19.11b). It produces a unidirectional axial magnetic field, with the result that all the poles on armature 1 are N poles, while those on armature 2 are S poles.

Stator coils A1, A2 are connected in series, and so are stator coils B1, B2. The motor develops a small detent torque because of the permanent magnet, and the rotor will remain in the position shown in Fig. 19.11a. If we now excite coils B, the rotor will rotate by 18°, thereby lining up with stator poles B. The direction of rotation will again depend upon the direction of current flow in coils B.

Fig. 19.12 shows an exploded view of a hybrid stepping motor. Fig. 19.13 shows the special construction of a stator in which permanent magnets are embedded in the stator slots, in addition to the permanent magnet on the rotor.

Fig. 19.14a shows another type of hybrid motor and Fig. 19.14b is a cross-section view of its construction. Figs. 19.14c and 19.14d, respectively show the specifications and torque-speed characteristics of this motor. Note that the pull-out characteristic corresponds to the slewing curve while the pull-in characteristic corresponds to the start-without-error curve.

It should be noted that the number of poles on the stator of a stepper motor is never equal to the number of poles on the rotor. This feature is totally different from that in any other type of motor we have studied so far. Indeed, it is the difference in the number of poles that enables the motors to step as they do.

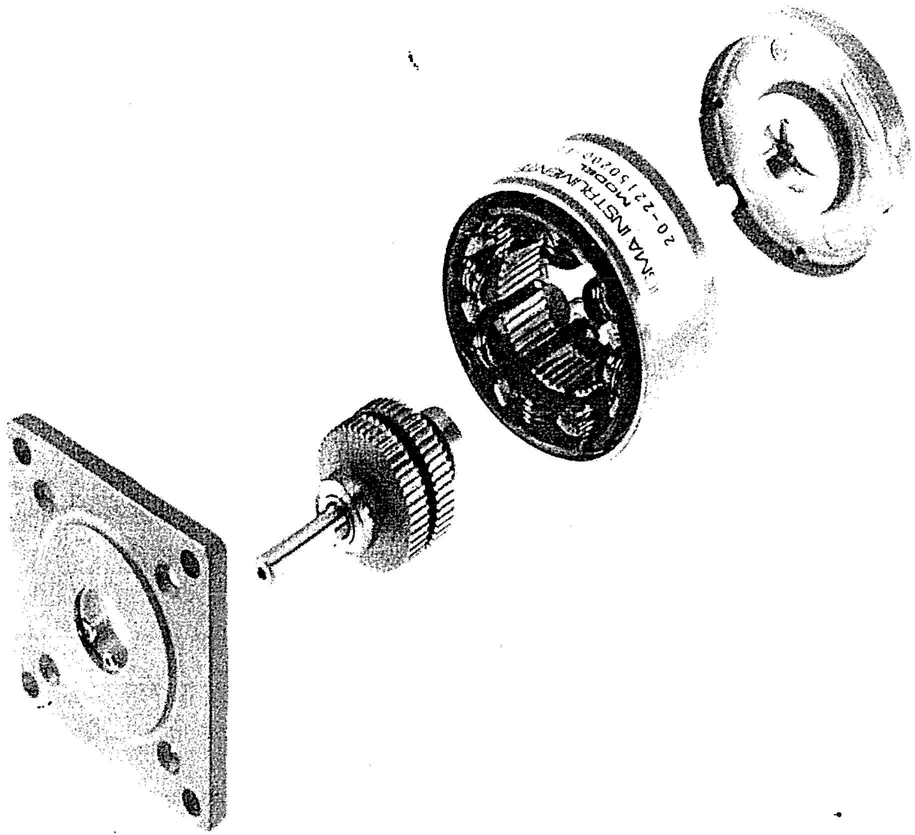


Figure 19.12
Exploded view of a standard hybrid stepping motor. The rotor is composed of two soft-iron armatures having 50 salient poles each. A short permanent magnet is sandwiched between the armatures. The stator has 8 poles, each of which has 5 salient poles in the pole face. Outside diameter of motor: 2.2 in; axial length: 1.5 in; weight: 0.8 lb. *(Courtesy of Pacific Scientific, Motor and Control Division, Rockford, IL)*

19.9 Motor windings and associated drives

Stepper motors use either a *bipolar* or a *unipolar* winding on the stator.

Bipolar Winding. In a 4-pole stator, the bipolar winding consists of the two coil sets A1, A2 and B1, B2 such as shown in Fig. 19.11. They are represented schematically in Fig. 19.15. The current I_a in coil set A reverses periodically, and the same is true for current I_b in coil set B. The coils are excited by a common dc source, and because the current pulses I_a, I_b must alternate, a switching means is required. The switches are represented by the contacts Q1 to Q8. In practice, transistors are used as switches because they can turn the current on and off at precise instants of time.

The coils can be excited sequentially in three different ways: (1) wave drive, (2) normal drive, and (3) half-step drive.

In the *wave drive* only one set of coils is excited at a time. The switching sequence for cw rotation is given in Table 19A and the resulting current pulses I_a, I_b are shown in Fig. 19.16. Note that the flux produced by I_a and I_b rotates by 90° per step.

In the *normal drive,* both sets of coils are excited at a time. The switching sequence for cw rotation is given

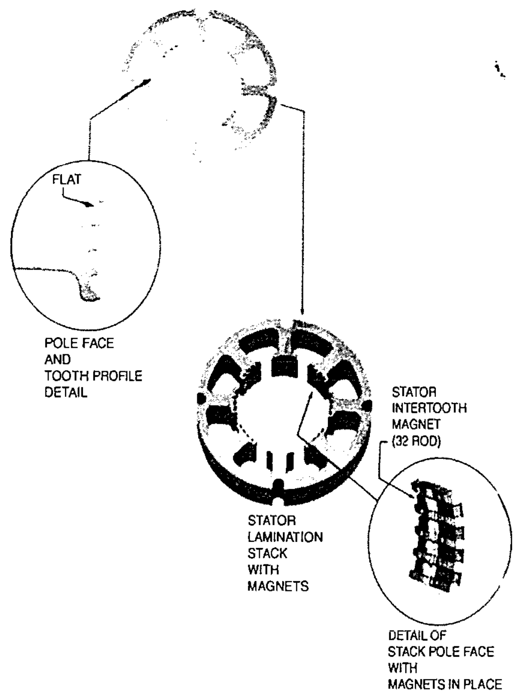


Figure 19.13
Stator lamination details and construction of an enhanced motor stator lamination stack assembly. Rare earth permanent magnets are fitted into the stator slots in addition to the permanent magnet of the hybrid rotor.
(Courtesy of Pacific Scientific, Motor and Control Division, Rockford, IL)

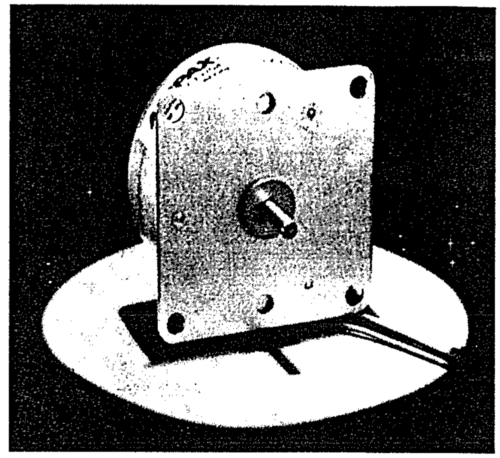


Figure 19.14a
External view of a hybrid stepper motor. It is equipped with bipolar windings rated to operate at 5 V. External diameter of motor: 1.65 in; axial length: 0.86 in; weight: 5.1 oz.
(Courtesy of AIRPAX © Corporate)

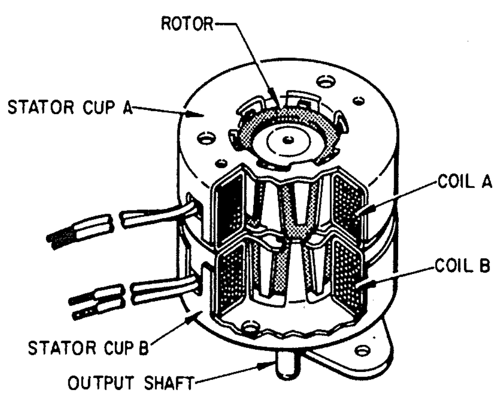


Figure 19.14b
Cross-section view of the hybrid stepper motor shown in Fig. 19.14a.
(Courtesy of AIRPAX © Corporate)

in Table 19B, and the resulting current pulses I_a, I_b are shown in Fig. 19.17. Note that the flux is oriented midway between the poles at each step. However, it still rotates by 90° per step. The normal drive develops a slightly greater torque than the wave drive.

The *half-step drive* is obtained by combining the wave drive and the normal drive. The switching sequence for cw rotation is given in Table 19C, and the resulting current pulses I_a, I_b are shown in Fig. 19.18. The flux now rotates only 45° per step. The main advantage of the half-step drive is that it improves the resolution of position and it tends to reduce the problem of resonance.

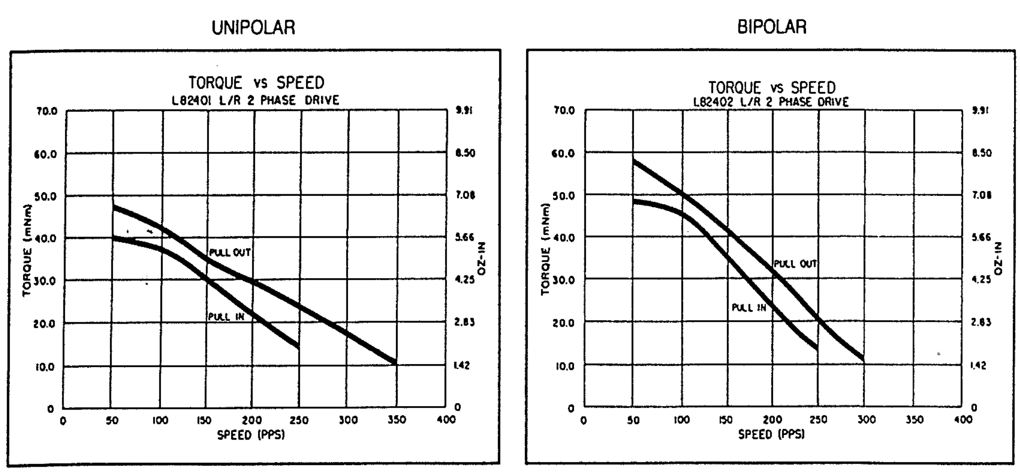
Unipolar Winding. The unipolar winding consists of two coils per pole instead of only one (Fig. 19.19a). *Unipolar* means that the current in a winding always flows in the same direction. The coil set A1, A2 produces flux in the opposite direction to coil set 1A, 2A. Consequently, when they are operated in sequence, an alternating flux is produced. The advantage of the unipolar winding is that the number of switching transistors drops from 8 to 4, and the transient response is slightly faster. Fig. 19.19b shows the schematic diagram of the windings and the switching sequence for a wave drive. The flux rotates in exactly the same way as shown in Fig. 19.16.

Specifications

Ordering Part No. (Add Suffix)	L82401 Unipolar		L82402 Bipolar	
Suffix Designation	–P1	–P2	–P1	–P2
DC Operating Voltage	5	12	5	12
Res. per Winding Ω	9.1	52.4	9.1	52.4
Ind. per Winding mH	7.5	46.8	14.3	77.9
Holding Torque mNm/oz-in*	73.4/10.4		87.5/12.4	
Rotor Moment of Inertia g • m²	12.5×10^{-4}			
Detent Torque mNm/oz-in	9.2/1.3			
Step Angle	7.5°			
Step Angle Tolerance*	.5°			
Steps per Rev.	48			
Max Operating Temp	100°C			
Ambient Temp Range Operating Storage	 – 20°C to 70°C – 40°C to 85°C			
Bearing Type	Bronze sleeve			
Insulation Res. at 500Vdc	100 megohms max			
Dielectric Withstanding Voltage	650 ± 50 VRMS 60 Hz for 1 to 2 seconds			
Weight g/oz	144/5.1			
Lead Wires	26 AWG			

*Measured with 2 phases energized.

Figure 19.14c
Specifications of the hybrid stepper motor shown in Fig. 19.14a. The motor can be built for either unipolar or bipolar operation at a rated driving voltage of either 5 V or 12 V.
(Courtesy of AIRPAX © Corporate)



NOTE: The above curves are typical.

Figure 19.14d
Typical torque-speed characteristics of the hybrid stepper motor shown in Fig. 19.14a. The pull-out curve corresponds to the slewing characteristics; the pull-in curve corresponds to the start-without-error characteristic.
(Courtesy of AIRPAX © Corporate)

19.10 High-speed operation

So far, we have assumed that the current pulse in a winding rises immediately to its rated value I at the beginning of the pulse and drops immediately to zero at the end of the pulse interval T_p (Fig. 19.20a). In practice, this does not happen because of the inductance of the windings. If a winding has an inductance of L henrys and a resistance of R ohms, its time constant T_o is equal to L/R seconds.

Let the coil be connected to a dc source of E volts by means of a transistor (Fig. 19.20b). A diode (D) is connected across the windings to prevent the high induced voltage from destroying the switching transistor at the moment it interrupts the current flow. The resulting current has the shape given in Fig. 19.20d.

How can we explain this pulse shape? When the transistor is switched on, the transient current i_1 only reaches its rated value $I = E/R$ after about 3 time constants, namely 3 T_o seconds. Then, when the transistor turns the line current off, the transient current i_2 continues to flow in the coil for about 3 T_o seconds (Fig. 19.20c). If this current pulse is compared with the ideal current pulse shown in Fig. 19.20a, we observe two important facts:

1. Because the current does not immediately rise to its final value when the transistor is turned on, the initial torque developed by the stepping motor is smaller than normal. As a result, the rotor does not move as quickly as we would expect.
2. When the transistor is turned off, current i_2 continues to circulate in the coil/diode loop.

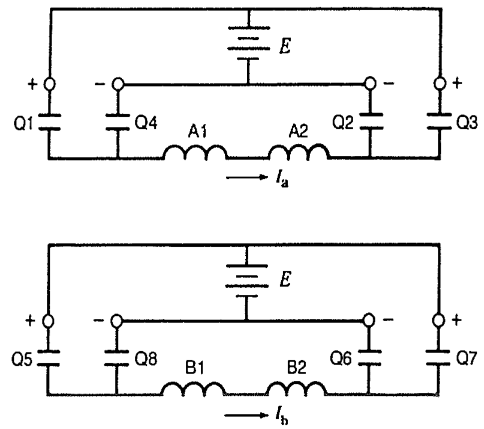
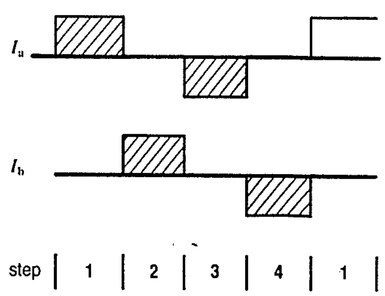


Figure 19.15
Schematic diagram showing how the stator coils A1, A2 and B1, B2 are connected to the common dc source by means of switches Q1 to Q8. The dc source is shown twice to simplify the connection diagram.

TABLE 19A WAVE SWITCHING SEQUENCE FOR CW ROTATION

Step	1	2	3	4	1
Q1 Q2	on	—	—	—	on
Q3 Q4	—	—	on	—	—
Q5 Q6	—	on	—	—	—
Q7 Q8	—	—	—	on	—



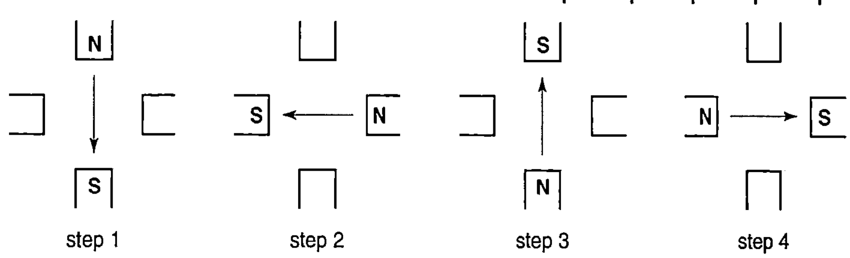


Figure 19.16
Current pulses in a wave drive and the resulting flux positions at each step. See Table 19A for switching sequence.

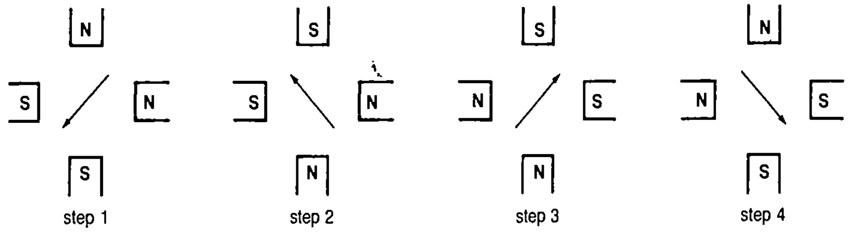
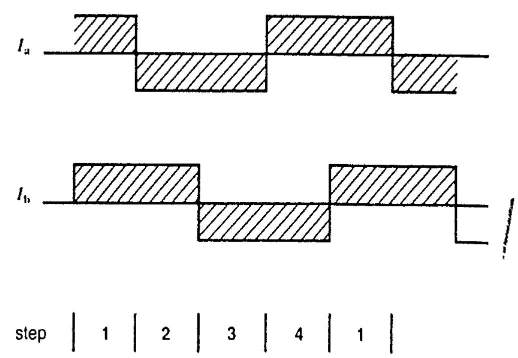


Figure 19.17
Current pulses in a normal drive and resulting flux positions at each step. See Table 19B for switching sequence.

TABLE 19B NORMAL SWITCHING SEQUENCE FOR CW ROTATION

Step		1	2	3	4	1
Q1	Q2	on	—	—	on	on
Q3	Q4	—	on	on	—	—
Q5	Q6	on	on	—	—	on
Q7	Q8	—	—	on	on	—



As a result, the effective duration of the pulse is $T_p + 3\ T_0$ instead of T_p. The pulse being thus prolonged by the component $3\ T_0$ means that we cannot switch from one coil to the next as quickly as we would have thought.

The shortest possible pulse that still permits the current to rise to its rated value I has a length of $6\ T_0$ seconds (Fig. 19.20e). It consists of $3\ T_0$ (current rises to its rated value) plus another $3\ T_0$ (current drops from I to zero). It so happens that the windings of stepper motors have time constants T_0 ranging from about 1 ms to 8 ms. Thus, the duration of one step can be no shorter than about 6×1 ms $= 6$ ms. This corresponds to a maximum stepping rate of about $1000/6 = 166$ steps per second. Such stepping rates are considered to be slow, and various means are used to speed them up.

19.11 Modifying the time constant

One way to quicken the stepping rate is to reduce the time constant T_0. This can be done by adding an external resistance to the motor windings and raising the dc voltage so that the same rated current I will flow. Such an arrangement is shown in Fig. 19.21. The external resistor has a value 4 times that of the coil resistance R, and the dc voltage is raised from E to $5\ E$ volts. As a result, the time constant drops by a factor of 5 (L/R to $L/5\ R$). This means that the maximum stepping rate can be increased by the same factor. Thus, stepping rates of the order of 1000 per second become feasible.

The only drawbacks to this solution are the following:

1. The power supply is more expensive because it has to deliver 5 times as much power (the voltage is $5\ E$ instead of E).
2. A lot of power is wasted in the external resistor, which means that the efficiency of the system is very low. Low efficiency is not too important in small stepping motors that develop only a few watts of mechanical power. But fast-acting stepper motors in the 100 W range must be driven by other means.

19.12 Bilevel drive

Bilevel drives enable us to obtain fast rise and fall times of current without using external resistors. The

TABLE 19C HALF-STEP SWITCHING SEQUENCE FOR CW ROTATION

Step		1	2	3	4	5	6	7	8	1
Q1	Q2	on	on	—	—	—	—	—	on	on
Q3	Q4	—	—	—	on	on	on	—	—	—
Q5	Q6	—	on	on	on	—	—	—	—	—
Q7	Q8	—	—	—	—	—	on	on	on	—

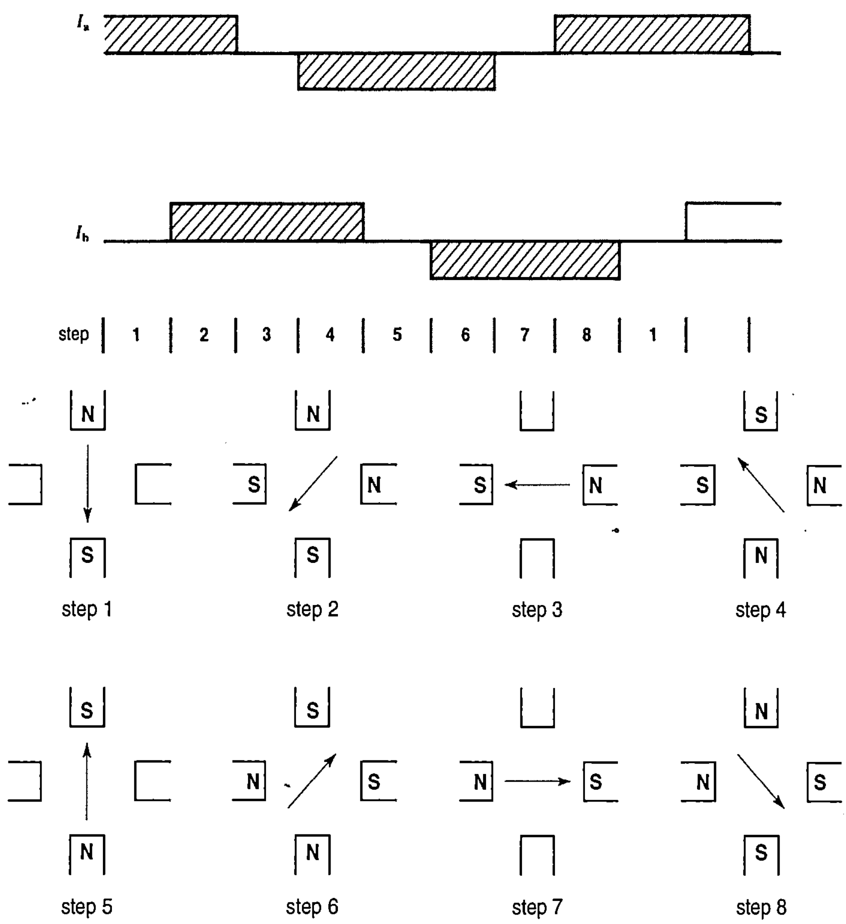
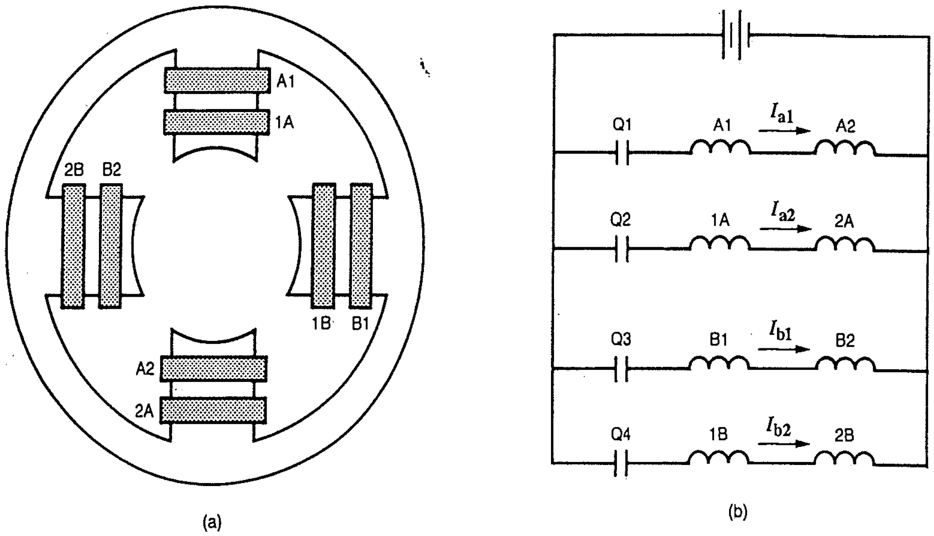


Figure 19.18
Current pulses in a half-step drive and resulting flux positions at each step. See Table 19C for switching sequence.

principle of a **bilevel drive** can be understood by referring to Fig. 19.22a. Switches Q1 and Q2 represent transistors that open and close the circuit in the manner explained below. Numerical values will be used to explain how the circuit behaves. Thus, the winding is assumed to have a resistance of 0.3 Ω, an inductance of 2.4 mH, and a rated current of 10 A. The power supply is 60 V with a tap at 3 V. Thus, if the



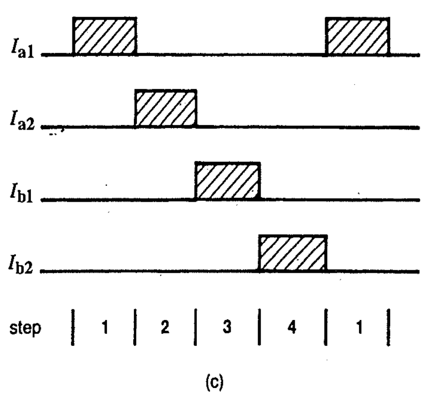


TABLE 19D WAVE SWITCHING SEQUENCE FOR CW ROTATION

Step	1	2	3	4	1
Q1	on	—	—	—	on
Q2	—	—	on	—	—
Q3	—	on	—	—	—
Q4	—	—	—	on	—

Figure 19.19
a. Coil arrangement in a 4-pole unipolar winding.
b. Schematic diagram of coils, switches, and power supply in a unipolar drive.
c. Current pulses in a wave drive using a unipolar winding. The flux rotates in the same way as in a bipolar winding. See Table 19D for switching sequence.

voltage were applied permanently, the resulting current in the winding would be 60 V/0.3 Ω = 200 A. This is much greater than the rated current of 10 A.

Switch Q1 is initially closed. The current pulse is initiated by closing Q2. Current then starts flowing as shown in Fig. 19.22b.

The time constant of this electronic circuit is T_0 = 2.4 mH/0.3 Ω = 8 ms. The initial rate of rise of current corresponds to a straight line OP that reaches 200 A in 8 ms. Thus, the current in the coil rises at a rate of 200 A/8 ms = 25 000 A/s. The time to reach 10 A is, therefore, 10/25 000 = 0.4 ms (Fig. 19.22c).

As soon as the current reaches this rated value, switch Q1 opens, which forces the current to follow the new path shown in Fig. 19.22d. The current is

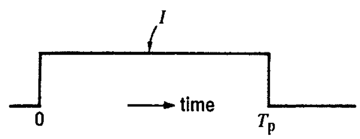


Figure 19.20a
Ideal current pulse in a winding.

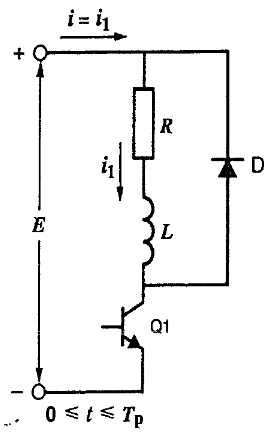


Figure 19.20b
Typical circuit of a switching transistor and coil connected to a dc source. The diode protects the transistor against overvoltage.

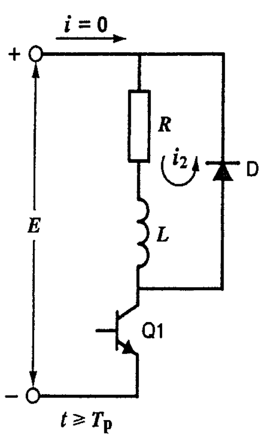


Figure 19.20c
Transient current in coil and diode when transistor is switched off.

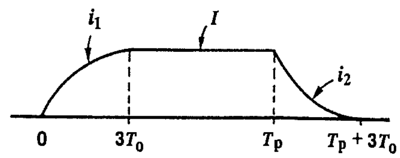


Figure 19.20d
Real current pulse.

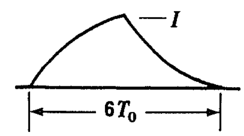


Figure 19.20e
Shortest possible current pulse that still attains the rated current *I*.

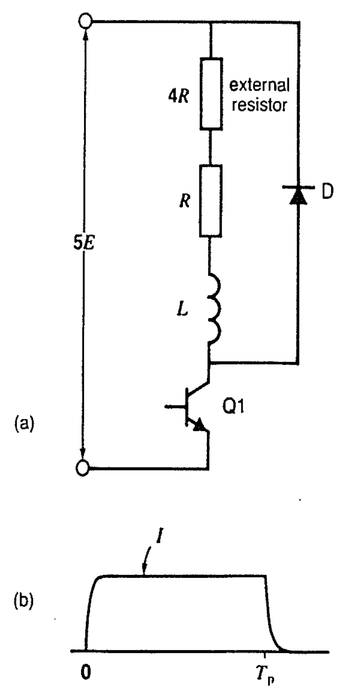


Figure 19.21
a. Circuit to increase the rate of growth and decay of current in the coil.
b. Resulting current pulse. Compare with Fig. 19.20d.

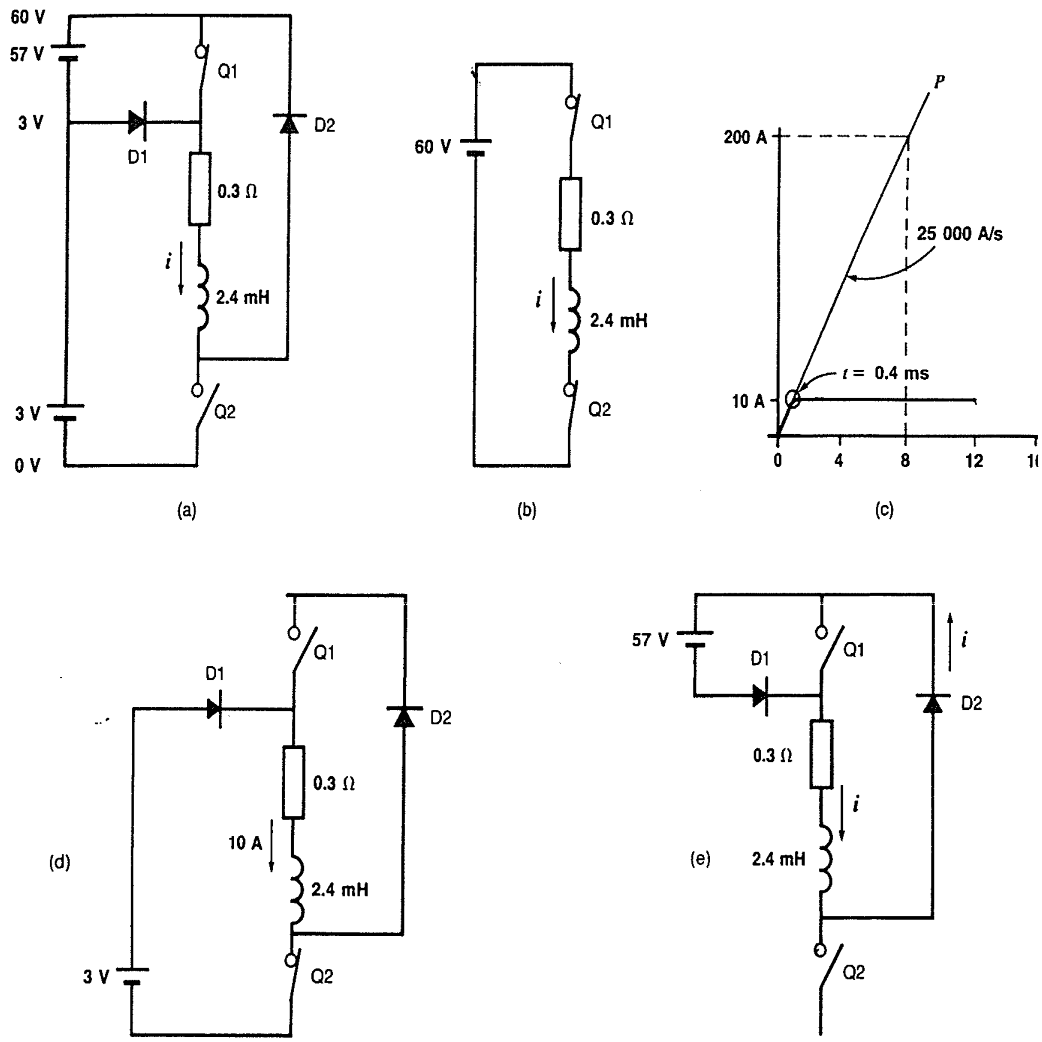


Figure 19.22
a. Circuit of a bilevel drive when current in coil is zero.
b. Equivalent circuit when current in coil is increasing.
c. Rate of increase of current and time to reach 10 A.
d. Equivalent circuit when current in coil is constant.
e. Equivalent circuit when current in coil is decreasing.

now fed by the 3 V source and remains fixed at 3 V/0.3 Ω = 10 A.

The current will stay at this value until we want to end the pulse, say after 5 ms. To terminate the pulse we open Q2, which forces the current to follow the path shown in Fig. 19.22e. The 57 V source now tries to drive a current through the coil that is opposite to *i*. Consequently, *i* will decrease. The time constant of the circuit is again 8 ms, and so the current will decrease at a rate of 57/60 × 25 000 = 23 750 A/s. It will therefore become zero after a time interval of 10/23 750 = 0.42 ms. The moment the current reaches zero, Q1 closes. This forces the current to remain zero until the next pulse is initiated. The resulting pulse shape is shown in Fig. 19.22f, together with the Q1, Q2 switching sequence that produces it.

In addition to bilevel drives, *chopper drives* are also used. Their principle of operation is similar to the bilevel method, except that the current is kept constant during the flat portion of the pulse by repeated on-off switching of the high voltage (60 V) rather than by using a low fixed dc voltage (3 V). Choppers are described in Chapter 21.

Electronic drives for stepper motors have become very sophisticated. Some of these circuit-board drives are shown in Figs. 19.23 and 19.24, together with the motors they control.

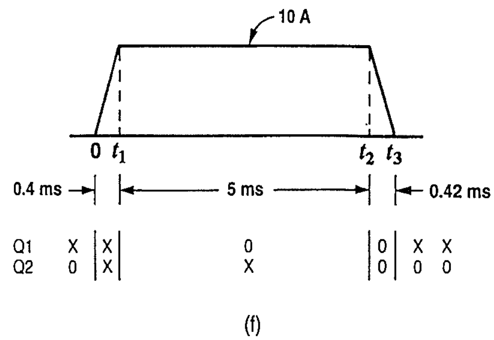


Figure 19.22f
Pulse waveshape using a bilevel drive. Note the switching sequence of Q1 and Q2 that creates it (x = closed, o = open).

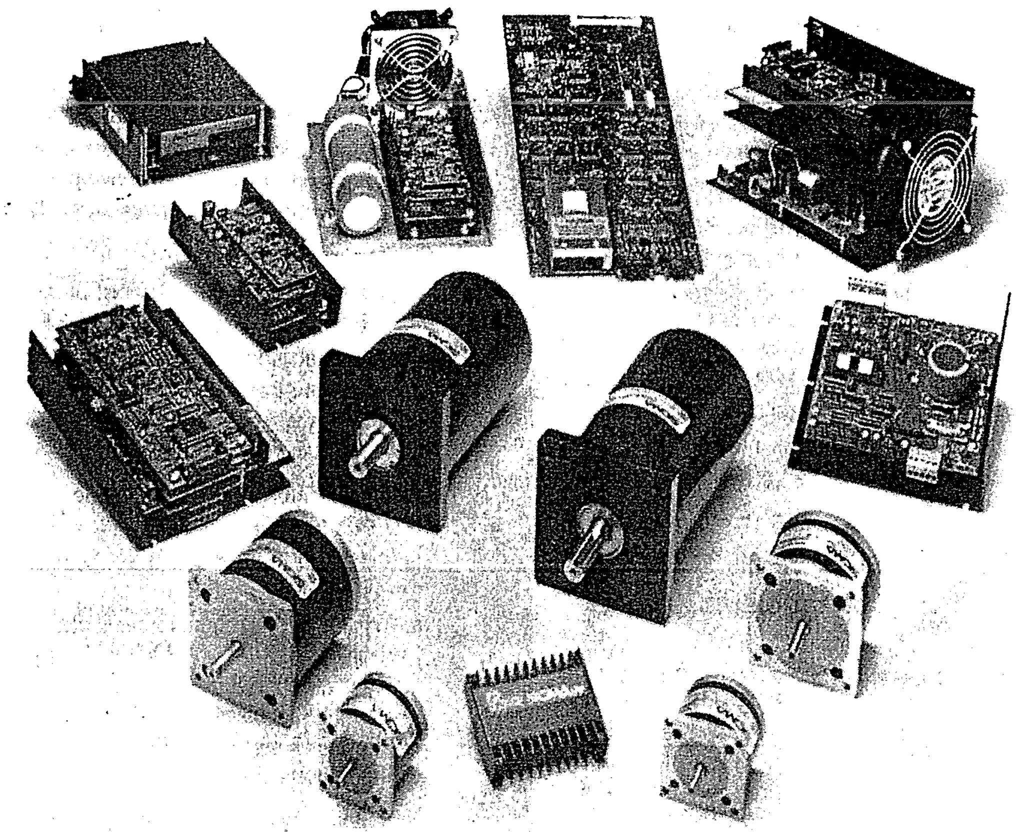


Figure 19.23
Typical electronic drives and the stepper motors they control.
(Courtesy of Pacific Scientific, Motor and Control Division, Rockford, IL)

19.13 Instability and resonance

When a stepper motor is operating at certain slewing speeds, it may become unstable. The rotor may turn erratically or simply chatter without rotating any more. This instability, often called resonance, is due to the natural vibration of the stepper motor, which manifests itself at one or more range of speeds. For example, the range of instability may lie between 2000 sps and 8000 sps. Nevertheless, it is possible to ramp through this range without losing step and thereby attain stable slewing speeds between 8000 and 15 000 sps.

19.14 Stepper motors and linear drives

Most stepper motors are coupled to a lead screw of some kind which permits the rotary motion to be converted to a linear displacement. Suppose, for example, that a stepper motor having 200 steps per revolution is coupled to a lead screw having a pitch of 5 threads per inch. The motor has to make $200 \times 5 = 1000$ steps to produce a linear motion of 1 inch. Consequently, each step produces a displacement of 0.001 in. By counting the pulses precisely, we can position a machine tool, X-Y arm, and so on, to a precision of one-thousandth of an inch over the full length of the desired movement.

This great precision without feedback is the reason why stepper motors are so useful in control systems.

Questions and Problems

Practical Level

19-1 What is the main use of stepper motors?

19-2 What is the difference between a reluctance and a permanent magnet stepper motor?

19-3 Describe the construction of a hybrid stepper motor.

19-4 A stepper motor advances 2.5° per step. How many pulses are needed to complete 8 revolutions?

19-5 Explain what is meant by *normal drive, wave drive,* and *half-step drive.*

Intermediate Level

19-6 The 2-pole rotor in Fig. 19.1 is replaced by a 4-pole rotor. Calculate the new angular motion per pulse.

19-7 Why is viscous damping employed in stepper motors?

19-8 When a stepper motor is ramping or slewing properly, every pulse corresponds to a precise angle of rotation. True or false?

19-9 The stepper motor in Fig. 19.10 is driven by a series of pulses having a duration of 20 ms. How long will it take for the rotor to make one complete revolution?

19-10 A stepper motor rotates 1.8° per step. It drives a lead screw having a pitch of 20 threads per inch. The lead screw, in turn, produces a linear motion of a cutting tool. If the motor is pulsed 7 times, by how much does the cutting tool move?

19-11 A stepper motor advances 7.5° per pulse. If its torque-speed characteristic is given by Fig. 19.8, calculate the power [watts] it develops when it is slewing

a. At 500 steps per second
b. At 200 steps per second

19-12 A stepper motor similar to that shown in Fig. 19.14 has a unipolar winding. It operates in the start-stop mode at a pulse rate of 150 per second, (see Fig. 19.14d).

a. What is the maximum torque it can develop?
b. How much mechanical power (millihorsepower) does it develop?
c. How much mechanical energy [J] does it produce in 3 seconds?

19-13 For a given load torque, the stepping rate can be increased by increasing the rate of rise and rate of fall of the current in the windings. Name two ways this can be accomplished.