CHAPTER 15

Motors

Perhaps one of the most entertaining things to do with electronics is make some mechanical device move. Three very popular devices used to "make things move" include dc motors, RC servos, and stepper motors.

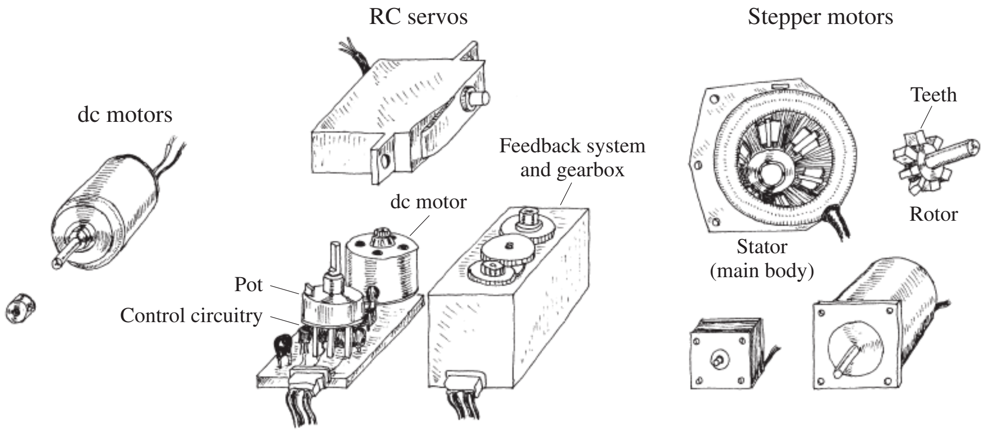


FIGURE 15.1

15.1 DC Continuous Motors

A *dc motor* is a simple two-lead, electrically controlled device that comes with a rotary shaft on which wheels, gears, propellers, etc., can be mounted. A dc motor generates a considerable amount of revolutions per minute (rpm) for its size and can be made to rotate clockwise or counterclockwise by reversing the polarity applied to the leads. At low speeds, dc motors provide little torque and minimal position control, making them impractical for pointlike position-control applications.

Generally, dc motors are available in many different shapes and sizes. Most dc motors provide rotational speeds anywhere between 3000 and 8000 rpm at a specific operating voltage typically set between 1.5 and 24 V. The operating voltage provided by the manufacturer tells you at what voltage the motor runs most efficiently. Now, the actual voltage applied to a motor can be made slightly lower to make the motor slower or can be elevated to make the motor faster. However, when the applied voltage drops to below around 50 percent of the specified operating voltage, the motor usually will cease to rotate. Conversely, if the applied voltage exceeds the operating voltage by around 30 percent, there is a chance that the motor will overheat and become damaged. In practice, as you will see in a second, the speed of a dc motor is most efficiently controlled by means of pulse-width modulation, whereby the motor is rapidly turned on and off. The width of the applied pulse, as well as the period between pulses, controls the speed of the motor. Also, it is worth noting that a freely running motor (no load) may draw little current (power). However, if a load is applied, the amount of current drawn by the motor's inner coils goes up immensely (up to 1000 percent or more). Manufacturers usually will provide what is called a *stall current* rating for their motors. This rating specifies the amount of current drawn at the moment the motor stalls. If your motor's stall current rating is not listed, it is possible to determine it by using an ammeter; slowly apply a force to the motor's shaft, and note the current level at the point when the motor stalls. Another specification given to dc motors is a torque rating. This rating represents the amount of force the motor can exert on a load. A motor with a high torque rating will exert a larger force on a load placed at a tangent to its rotational arm than a motor with a lower torque rating. The torque rating of a motor is usually given in lb/ft, g/cm, or oz/in.

15.2 Speed Control of DC Motors

Bad Designs

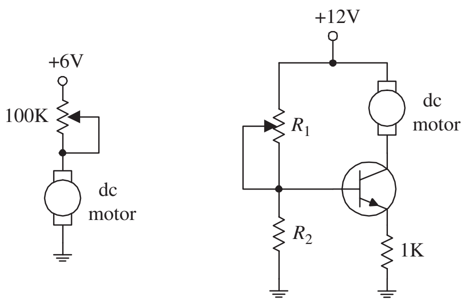


FIGURE 15.2

A seemingly obvious approach to control the speed of a dc motor would be simply to limit the current flow by using a potentiometer, as shown in the circuit to the left in the figure. According to Ohm's law, as the resistance of the pot increases, the current decreases, and the motor will slow down. However, using a pot to control the current flow is inefficient. As the pot's resistance increases, the amount of current energy that must be converted into heat increases. Producing heat in order to slow a motor down is not good—it consumes supply power and may lead to potentiometer meltdown. Another seemingly good but inefficient approach to control the speed of a motor is to use a transistor amplifier arrangement like the one shown to the right in the figure. However, again, there is a problem. As the collector-to-emitter resistance increases with varying base voltage/current, the transistor must dissipate a considerable amount of heat. This can lead to transistor meltdown.

Better Designs

UJT/SCR Control Circuit

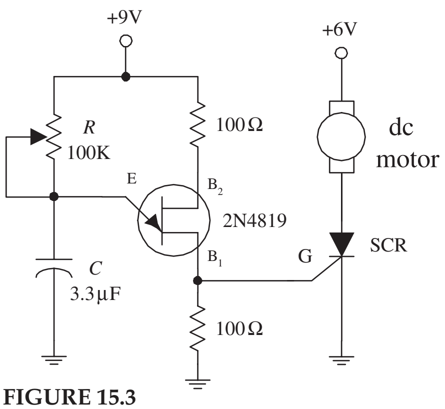
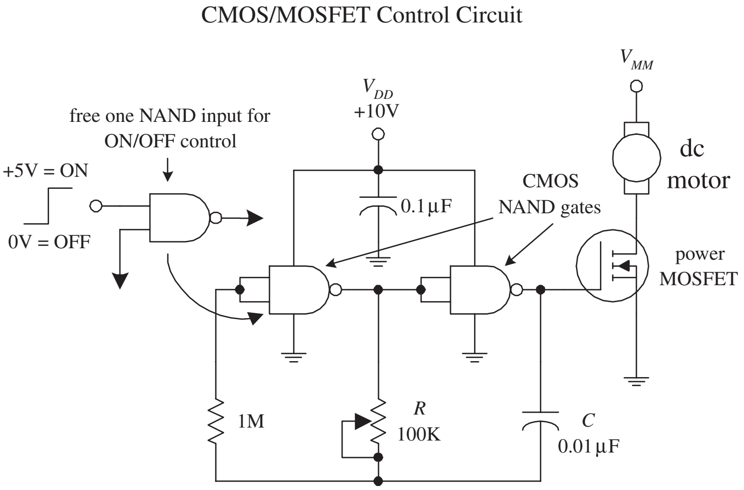


FIGURE 15.3

In order to conserve energy and prevent component meltdown, an approach similar to what was used in switching power supplies is used to control the speed of the motor. This approach involves sending the motor short pulses of current. By varying the width and frequency of the applied pulses, the speed of the motor can be controlled. Controlling a motor's speed in this manner prevents any components from experiencing continuous current stress. Figure 13.3 shows three simple circuits used to provide the desired motor-control pulses.

In the first circuit, a UJT relaxation oscillator generates a series of pulses that drives an SCR on and off. To vary the speed of the motor, the UJT's oscillatory frequency is adjusted by changing the RC time constant.



In the second circuit, a pair of NAND gates make up the relaxation oscillator section, while an enhancement-type power MOSFET is used to drive the motor. Like the preceding circuit, the speed of the motor is controlled by the oscillator's *RC* time constant. Notice that if one of the input leads of the left NAND gate is pulled out, it is possible to create an extra terminal that can be used to provide on/off controls that can be interfaced with CMOS logic circuits.

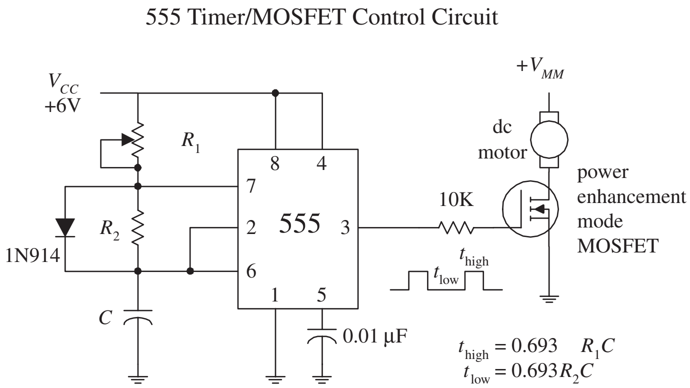


FIGURE 15.3 (*Continued*)

The third circuit is a 555 timer that is used to generate pulses that drive a power MOSFET. By inserting a diode between pins 7 and 6, as shown, the 555 is placed into low-duty cycle operation. R_1, R_2, and C set the frequency and on/off duration of the output pulses. The formulas accompanying the diagram provide the details.

A microcontroller-based dc control circuit with speed control is found in Chap. 13.

In many applications the 555 timer in this final circuit can be replaced by a microcontroller with a PWM output driving the MOSFET.

15.3 Directional Control of DC Motors

To control the direction of a motor, the polarity applied to the motor's leads must be reversed. A simple manual-control approach is to use a DPDT switch (see leftmost circuit in Fig. 15.4). Alternately, a transistor-driven DPDT relay can be used (see middle circuit). If you do not like relays, you can use a push-pull transistor circuit (see leftmost circuit). This circuit uses a complementary pair of transistors (similar betas and power rating)—one is an *npn* power Darlington, and the other is a *pnp* power Darlington. When a high voltage (e.g., +5 V) is applied to the input, the upper transistor (*npn*) conducts, allowing current to pass from the positive supply through the motor and into ground. If a low voltage (0 V) is applied to the input, the lower transistor (*pnp*) conducts, allowing current to pass through the motor from ground into the negative supply terminal.

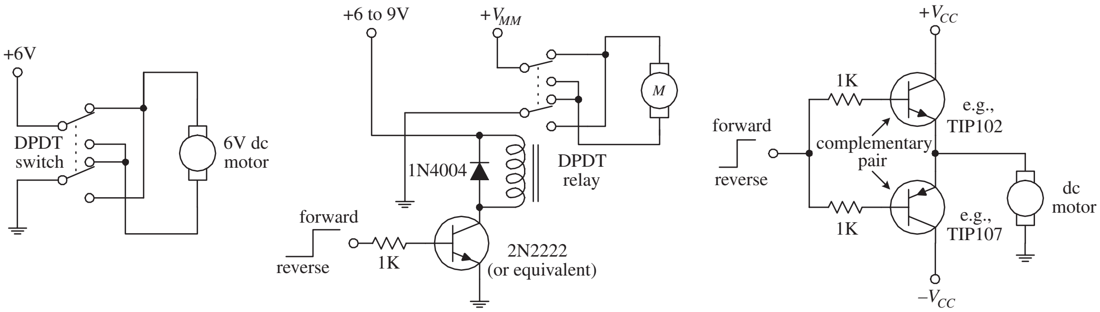


FIGURE 15.4

Another very popular circuit used to control the direction of a motor (as well as the speed) is the H-bridge. Figure 15.5 shows two simple versions of the H-bridge circuit. The left H-bridge circuit is constructed with bipolar transistors, whereas the right H-bridge circuit is constructed from MOSFETs. To make the motor rotate in the forward direction, a high (+5-V) signal is applied to the forward input, while no signal is applied to the reverse input (applying a voltage to both inputs at the same time is not allowed). The speed of the motor is controlled by pulse-width modulating the input signal. Here is a description of how the bipolar H-bridge works: When a high voltage is applied to Q_3's base, Q_3 conducts, which in turn allows the *pnp* transistor Q_2 to conduct. Current then flows from the positive supply terminal through the motor in the right-to-left direction (call it the *forward direction* if you like). To reverse the motor's direction, the high voltage signal is removed from Q_3's base and placed on Q_4's base. This sets Q_4 and Q_1 into conduction, allowing current to pass through the motor in the opposite direction. The MOSFET H-bridge works in a similar manner.

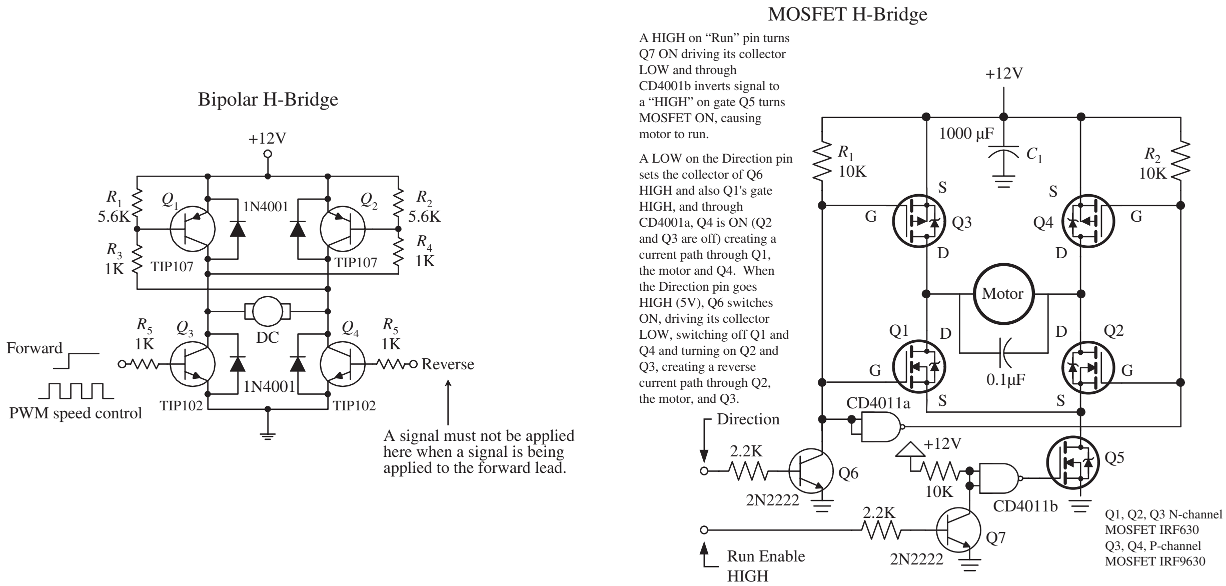


FIGURE 15.5

Now, it is possible to construct these H-bridge circuits from scratch, but it is far easier and usually cheaper to buy a motor-driven IC. For example, National Semiconductor's LMD18200 motor-driver IC is a high-current, easy-to-use H-bridge chip that has a rating of 3 A and 12 to 55 V. This chip is TTL and CMOS compatible and includes clamping diodes, shorted load protection, and a thermal warning interrupt output lead. The L293D (Unitrode) is another popular motor-driver IC. This chip is very easy to use and is cheaper than the LMD18200, but it cannot handle as much current and does not provide as many additional features. There are many other motor-driver ICs out there, as well as a number of prefab motor-diver boards that are capable of driving a number of motors. Check the electronics catalogs and Internet to see what is available.

15.4 RC Servos

Remote control (*RC*) *servos*, unlike dc motors, are motorlike devices designed specifically for pointerlike position-control applications. An RC servo uses an external pulse-width-modulated (PWM) signal to control the position of its shaft to within a small fraction of its maximum range of rotation. To alter the position of the shaft, the pulse width of the modulated signal is varied. The amount of angular rotation of an RC servo's shaft is limited to around 180 or 210° depending on the specific brand of servo. These devices can provide a significant amount of low-speed torque (due to an internal gearing system) and provide moderate full-swing displacement switching speeds. RC servos frequently are used to control steering in model cars, boats, and airplanes. They are also used commonly in robotics as well as in many sensor-positioning applications.

The standard RC servo looks like a simple box with a drive shaft and three wires coming out of it. The three wires consist of a power supply wire (usually black), a ground wire (usually red), and the shaft-positioning control wire (color varies based on manufacturer). Within the box there is a dc motor, a feedback device, and a control circuit. The feedback device usually consists of a potentiometer whose control dial is mechanically linked to the motor through a series of gears. When the motor is rotated, the potentiometer's control dial is rotated. The shaft of the motor is usually limited to a rotation of 180° (or 210°)—a result of the pot not being able to rotate indefinitely. The potentiometer acts as a position-monitoring device that tells the control circuit (by means of its resistance) exactly how far the shaft has been rotated. The control circuit uses this resistance, along with a pulse-width-modulated input control signal, to drive the motor a specific number of degrees and then hold. (The amount of holding torque varies from servo to servo.) The width of the input signal determines how far the servo's shaft will be rotated.

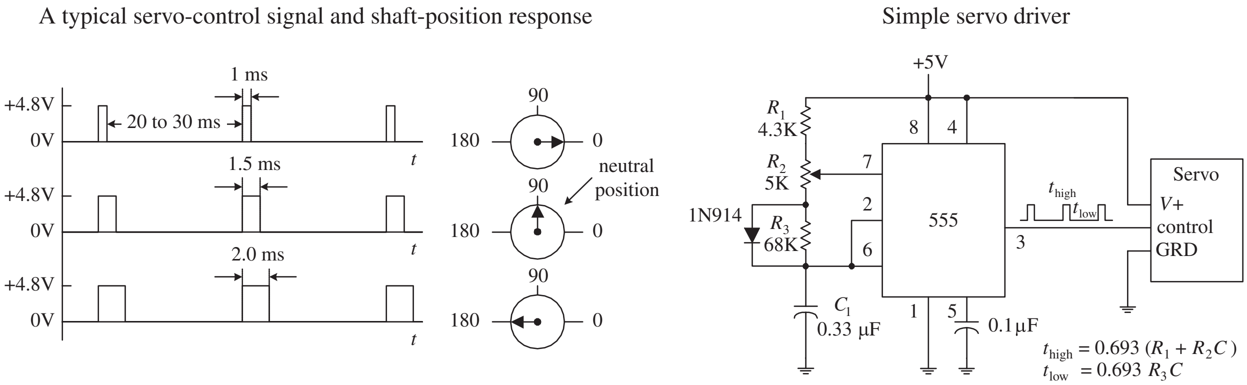


FIGURE 15.6

By convention, when the pulse width is set to 1.5 ms, the servo rotates its shaft to neutral position (e.g., 90° if the servo is constrained within a 0 to 180° range). To rotate the shaft a certain number of degrees from neutral position, the pulse width of the control signal is varied. To make the shaft go counterclockwise from neutral, a pulse wider than 1.5 ms is applied to the control input. Conversely, to make the shaft go clockwise from neutral, a pulse narrower than 1.5 ms is applied (see Fig. 15.6). Knowing exactly how much wider or narrower to make the pulse to achieve exact angular displacements depends largely on what brand of servo you are using. For example, one brand of servo may provide maximum counterclockwise rotation at 1 ms and maximum clockwise rotation at 2 ms, whereas another brand of servo may provide maximum counterclockwise rotation at 1.25 ms and maximum clockwise rotation at 1.75 ms. The supply voltage used to power servos is commonly 4.8 V but may be 6.0 V or so depending on the specific brand of servo. Unlike the supply voltage, the supply current drawn by a servo varies greatly, depending on servo's power output.

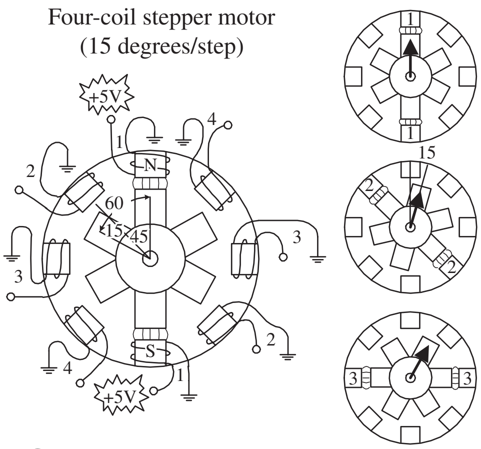
A simple 555 timer circuit like the one shown in Fig. 15.6 can be used to generate the servo control signal. In this circuit, R_2 acts as the pulse-width control. Servos also can be controlled by a microprocessor or microcontroller. See Chap. 13 for two microcontroller-based servo control circuits.

Now, when controlling servos within model airplanes, an initial control signal (generated by varying position-control potentiometers) is first sent to a radiowave modulator circuit that encodes the control signal within a carrier wave. This carrier wave is then radiated off as a radiowave by an antenna. The radiowave, in turn, is then transmitted to the model's receiver circuit. The receiver circuit recovers the initial control signal by demodulating the carrier. After that, the control signal is sent to the designated servo within the model. If there is more than one servo per model, more channels are required. For example, most RC airplanes require a four-channel radio set; one channel is used to control the ailerons, another channel controls the elevator, another controls the rudder, and another controls the throttle. More complex models may use five or six channels to control additional features such as flaps and retractable landing gear. The FCC sets aside 50 frequencies in the 72-MHz band (channels 11–60) dedicated to aircraft use only. No license is needed to operate these radios. However, with an amateur (ham) radio operator's license, it is possible to use a radio within the 50-MHz band. Also, there are frequencies set aside within the 27-MHz band that are legal for any kind of model use (surface or air). If you are interested in radio-controlled RC servos, a good starting point is to check out an RC model hobby shop. These shops carry a number of transmitter and receiver sets, along with the servos.

As a final note, with a bit of rewiring, a servo can be converted into a drive motor with unconstrained rotation. A simple way to modify the servo is to break the feedback loop. This involves removing the three-lead potentiometer (and unlinking the gear system so that it can rotate 360°) and replacing it with a pair of voltage-divider resistors (the output of the voltage divider replaces the variable terminal of the potentiometer). The voltage divider is used to convince the servo control circuit that the servo is in neutral position. The exact values of the resistors needed to set the servo in neutral position can be determined by using the old potentiometer and an ohmmeter. Now, to turn the motor clockwise, a pulse wider than 1.5 ms is applied to the control input. As long as the control signal is in place, the motor will keep turning and not stop—you have removed the feedback system. To turn the motor counterclockwise, a pulse narrower than 1.5 ms is applied to the control input.

15.5 Stepper Motors

Stepper motors, or *steppers*, are digitally controlled brushless motors that rotate a specific number of degrees (a step) every time a clock pulse is applied to a special translator circuit that is used to control the stepper. The number of degrees per step (resolution) for a given stepper motor can be as small as 0.72° per step or as large as 90° per step. Common general-purpose stepper resolutions are 15 and 30° per step. Unlike RC servos, steppers can rotate a full 360° and can be made to rotate in a continuous manner like a dc motor (but with a lower maximum speed) with the help of proper digital control circuitry. Unlike dc motors, steppers provide a large amount of torque at low speeds, making them suitable in applications where low-speed and high-precision position control is needed. For example, they are used in printers to control paper feed and are used to help a telescope track stars. Steppers are also found in plotter- and sensor-positioning applications. The list goes on. To give you a basic idea of how a stepper works, take a look at Fig. 15.7.



Here is a simple model depicting a 15° per step variable-reluctance stepper. The stationary section of the motor, called the *stator,* has eight poles that are spaced 45° apart. The moving section of the motor, called the *rotor,* is made from a ferromagnetic material (a material that is attracted to magnetic fields) that has six teeth spaced 60° apart. To make the rotor turn one step, current is applied, at the same time, through two opposing pole pairs, or coil pairs. The applied current causes the opposing pair of poles to become magnetized. This in turn causes the rotor's teeth to align with the poles, as shown in the figure. To make the rotor rotate 15° clockwise from this position, the current through coil pair 1 is removed and sent through coil pair 2. To make the rotor rotate another 15° clockwise from this position, the current is removed from coil pair 2 and sent through coil pair 3. The process continues in this way. To make the rotor spin counterclockwise, the coil-pair firing sequence is reversed.

FIGURE 15.7

15.6 Kinds of Stepper Motors

The model used in the last example was based on a variable-reluctance stepper. As it turns out, this model is incomplete—it does not show how a real variable-reluctance stepper is wired internally. Also, the model does not apply to a class of steppers referred to as *permanent-magnet steppers*. To make things more realistic, let's take a look at some real-life steppers.

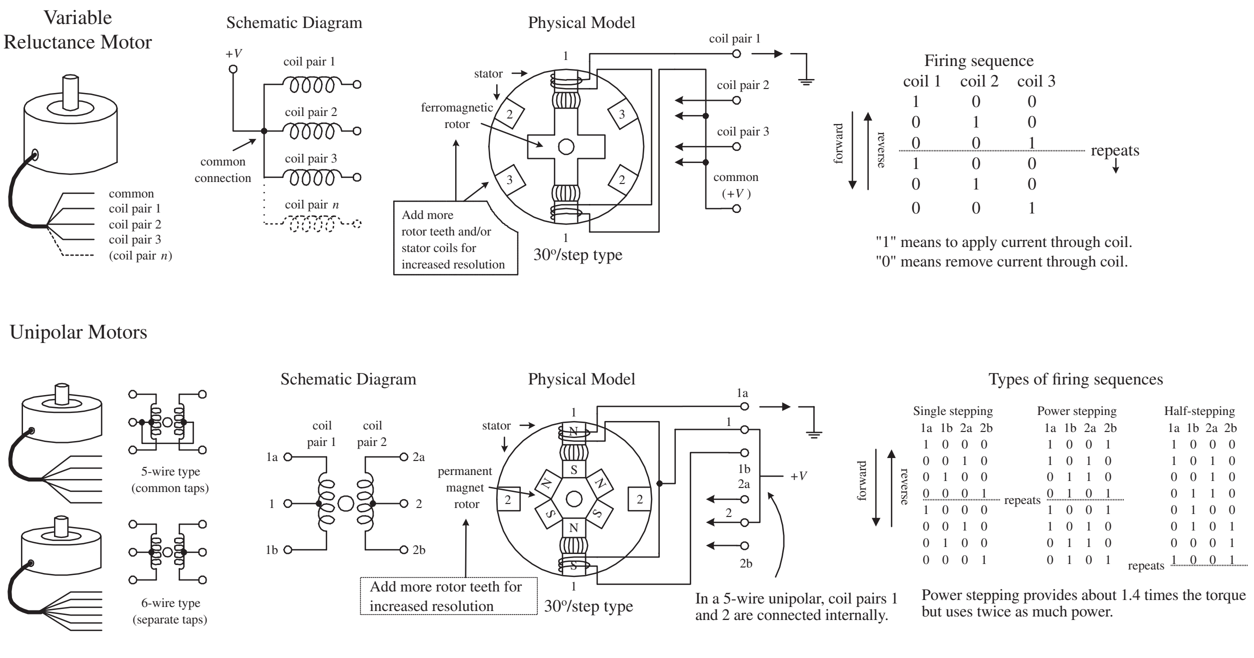


FIGURE 15.8

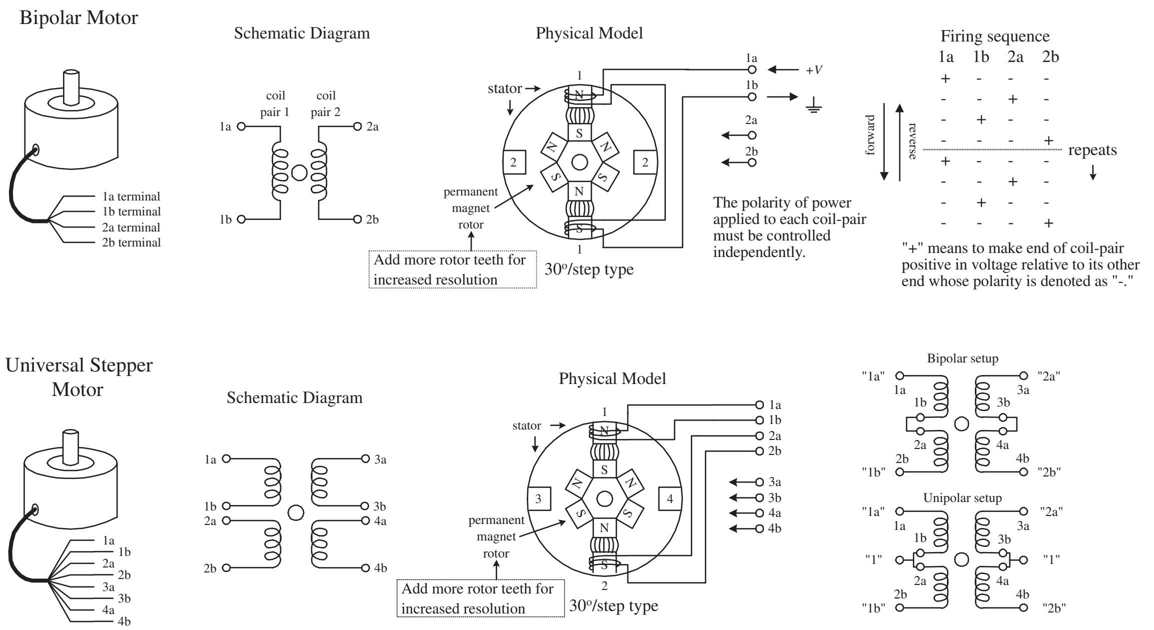


FIGURE 15.8 (*Continued*)

Variable-Reluctance Steppers

Figure 15.8 shows a physical model and schematic diagram of a 30° per step variable-reluctance stepper. This stepper consists of a six-pole (or three-coil pair) stator and a four-toothed ferromagnetic rotor. Variable-reluctance steppers with higher angular resolutions are constructed with more coil pairs and/or more rotor teeth. Notice that in both the physical model and the schematic, the ends of all the coil pairs are joined together at a common point. (This joining of the coil ends occurs internally within the motor's case.) The common and the coil pair free ends are brought out as wires from the motor's case. These wires are referred to as the *phase wires*. The common wire is connected to the supply voltage, whereas the phase wires are grounded in sequence according to the table shown in Fig. 15.8.

Permanent-Magnet Steppers (Unipolar, Bipolar, Universal)

UNIPOLAR STEPPERS

These steppers have a similar stator arrangement as the variable-reluctance steppers, but they use a permanent-magnet rotor and different internal wiring arrangements. Figure 15.8 shows a 30° per step unipolar stepper. It consists of a four-pole (or two-coil pair) stator with center taps between coil pairs and a six-toothed permanent-magnetic rotor. The center taps may be wired internally and brought out as one wire or may be brought out separately as two wires. The center taps typically are wired to the positive supply voltage, whereas the two free ends of a coil pair are alternately grounded to reverse the direction of the field provided by that winding. As shown in the figure, when current flows from the center tap of winding 1 out terminal 1a, the top stator pole "goes north," while the bottom stator pole "goes south." This causes the rotor to snap into position. If the current through winding 1 is removed, sent through winding 2, and out terminal 2a, the horizontal poles will become energized, causing the rotor to turn 30°, or one step. In Fig. 15.8, three firing sequences are shown. The first sequence provides full stepping action (what we just discussed). The second sequence, referred to as the *power stepping sequence*, provides full stepping action with 1.4 times the torque but twice the power consumption. The third sequence provides half stepping (e.g., 15° instead of the rated 30°). Half stepping is made possible by energizing adjacent poles at the same time. This pulls the rotor in-between the poles, thus resulting in one-half the stepping angle. As a final note, unipolar steppers with higher angular resolutions are constructed with more rotor teeth. Also, unipolars come in either five- or six-wire types. The five-wire type has the center taps joined internally, while the six-wire type does not.

BIPOLAR STEPPERS

These steppers resemble unipolar steppers, but their coil pairs do not have center taps. This means that instead of simply supplying a fixed supply voltage to a lead, as was the case in unipolar steppers (supply voltage was fixed to center taps), the supply voltage must be alternately applied to different coil ends. At the same time, the opposite end of a coil pair must be set to the opposite polarity (ground). For example, in Fig. 15.8, a 30° per step bipolar stepper is made to rotate by applying the polarities shown in the firing sequence table to the leads of the stepper. Notice that the firing sequence uses the same basic drive pattern as the unipolar stepper, but the “0” and “1” signals are replaced with “+” and “–” symbols to show that the polarity matters. As you will see in the next section, the circuitry used to drive a bipolar stepper requires an H-bridge network for every coil pair. Bipolar steppers are more difficult to control than both unipolar steppers and variable-reluctance steppers, but their unique polarity-shifting feature gives them a better size-to-torque ratio. As a final note, bipolar steppers with higher angular resolutions are constructed with more rotor teeth.

UNIVERSAL STEPPERS

These steppers represent a type of unipolar-bipolar hybrid. A universal stepper comes with four independent windings and eight leads. By connecting the coil windings in parallel, as shown in Fig. 15.8, the universal stepper can be converted into a unipolar stepper. If the coil windings are connected in series, the stepper can be converted into a bipolar stepper.

15.7 Driving Stepper Motors

Every stepper motor needs a driver circuit that can control the current flow sent through the coils within the stepper’s stator. The driver, in turn, must be controlled by a logic circuit referred to as a *translator*. We will discuss translator circuits after we have covered the driver circuits.

Figure 15.9 shows driver networks for a variable-reluctance stepper and for a unipolar stepper. Both drivers use transistors to control current flow through the motor’s individual windings. In both driver networks, input buffer stages are added to protect the translator circuit from the motor’s supply voltage in the event of transistor collector-to-base breakdown. Diodes are added to both drivers to protect the transistors and power supply from inductive kickback generated by the motor’s coils. (Notice that the unipolar driver uses extra diodes because inductive kickback can