CHAPTER 17

MOTOR CONTROL: RELAY, PWM, DC, AND STEPPER MOTORS

OBJECTIVES

Upon completion of this chapter, you will be able to:

- **Describe the basic operation of a relay**
- **Interface the PIC18 with a relay**
- **Describe the basic operation of an optoisolator**
- **Interface the PIC18 with an optoisolator**
- **Describe the basic operation of a stepper motor**
- **Interface the PIC18 with a stepper motor**
- **Code PIC18 programs to control and operate a stepper motor**
- **Define stepper motor operation in terms of step angle, steps per revolution, tooth pitch, rotation speed, and RPM**
- **Describe the basic operation of a DC motor**
- **Interface the PIC18 with a DC motor**
- **Code PIC18 programs to control and operate a DC motor**
- **Describe how PWM is used to control motor speed**
- **Code CCP programs to control and operate a DC motor**
- **Code ECCP programs to control and operate a DC motor**

This chapter discusses motor control and shows PIC18 interfacing with relays, optoisolators, stepper motors, and DC motors. In Section 17.1, the basics of relays and optoisolators are described. Then we show their interfacing with the PIC18. In Section 17.2, stepper motor interfacing with the PIC18 is shown. The characteristics of DC motors are discussed in Section 17.3, along with their interfacing to the PIC18. We will also discuss the topic of PWM (pulse width modulation). In Section 17.4, the CCP feature of PIC18 is used to control DC motors, while the ECCP usage in motor control is shown in Section 17.5. We use both Assembly and C in our programming examples.

SECTION 17.1: RELAYS AND OPTOISOLATORS

This section begins with an overview of the basic operations of electromechanical relays, solid-state relays, reed switches, and optoisolators. Then we describe how to interface them to the PIC18. We use both Assembly and C language programs to demonstrate their control.

Electromechanical relays

A *relay* is an electrically controllable switch widely used in industrial controls, automobiles, and appliances. It allows the isolation of two separate sections of a system with two different voltage sources. For example, a +5 V system can be isolated from a 120 V system by placing a relay between them. One such relay is called an electromechanical (or electromagnetic) relay (EMR) as shown in Figure 17-1. The EMRs have three components: the coil, spring, and contacts. In Figure 17-1, a digital +5 V on the left side can control a 12 V motor on the right side without any physical contact between them. When current flows through the coil, a magnetic field is created around the coil (the coil is energized), which causes the armature to be attracted to the coil. The armature's contact acts like a switch and closes or opens the circuit. When the coil is not energized, a spring pulls the armature to its normal state of open or closed. In the block diagram for electomechanical relays (EMR) we do not show the spring, but it does exist internally. There are all types of relays for all kinds of applications. In choosing a relay the following characteristics need to be considered:

1. The contacts can be normally open (NO) or normally closed (NC). In the NC type, the contacts are closed when the coil is not energized. In the NO, the contacts are open when the coil is unenergized.
2. There can one or more contacts. For example, we can have SPST (single pole, single throw), SPDT (single pole, double throw), and DPDT (double pole, double throw) relays.
3. The voltage and current needed to energize the coil. The voltage can vary from a few volts to 50 volts, while the current can be from a few mA to 20 mA. The relay has a minimum voltage, below which the coil will not be energized. This minimum voltage is called the “pull-in” voltage. In the datasheet for relays we might not see current, but rather coil resistance. The V/R will give you the pull-in current. For example, if the coil voltage is 5 V, and the coil resistance is 500 ohms, we need a minimum of 10 mA (5 V/500 ohms = 10 mA) pull-in current.

4. The maximum DC/AC voltage and current that can be handled by the contacts. This is in the range of a few volts to hundreds of volts, while the current can be from a few amps to 40 A or more, depending on the relay. Notice the difference between this voltage/current specification and the voltage/current needed for energizing the coil. The fact that one can use such a small amount of voltage/current on one side to handle a large amount of voltage/current on the other side is what makes relays so widely used in industrial controls. Examine Table 17-1 for some relay characteristics.

Table 17-1: Selected DIP Relay Characteristics (www.Jameco.com)

Part No.	Contact Form	Coil Volts	Coil Ohms	Contact Volts-Current
106462CP	SPST-NO	5 VDC	500	100 VDC-0.5 A
138430CP	SPST-NO	5 VDC	500	100 VDC-0.5 A
106471CP	SPST-NO	12 VDC	1000	100 VDC-0.5 A
138448CP	SPST-NO	12 VDC	1000	100 VDC-0.5 A
129875CP	DPDT	5 VDC	62.5	30 VDC-1 A

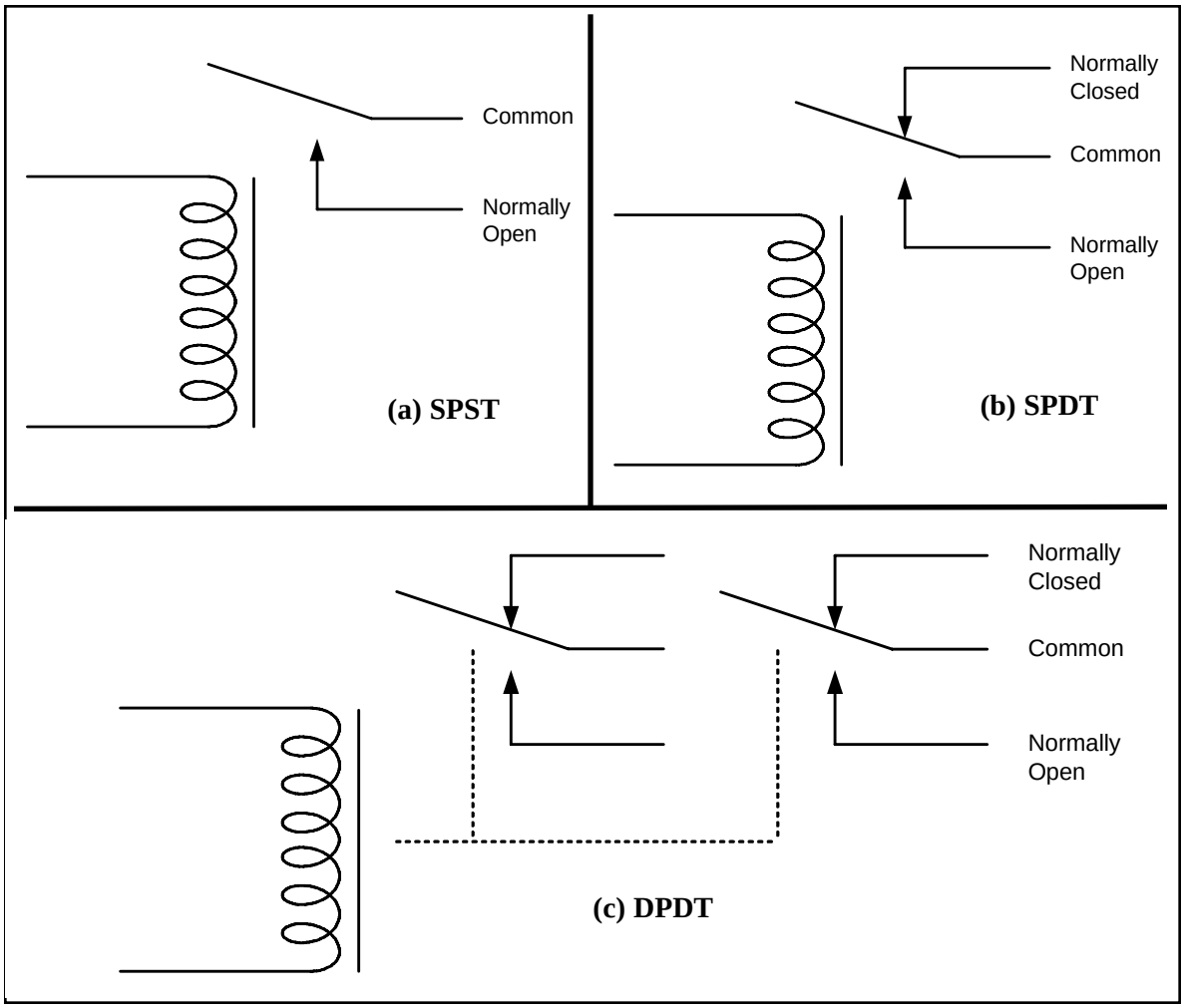


Figure 17-1. Relay Diagrams

Driving a relay

Digital systems and microcontroller pins lack sufficient current to drive the relay. While the relay's coil needs around 10 mA to be energized, the microcontroller's pin can provide a maximum of 1–2 mA current. For this reason, we place a driver, such as the ULN2803, or a power transistor between the microcontroller and the relay as shown in Figure 17-2.

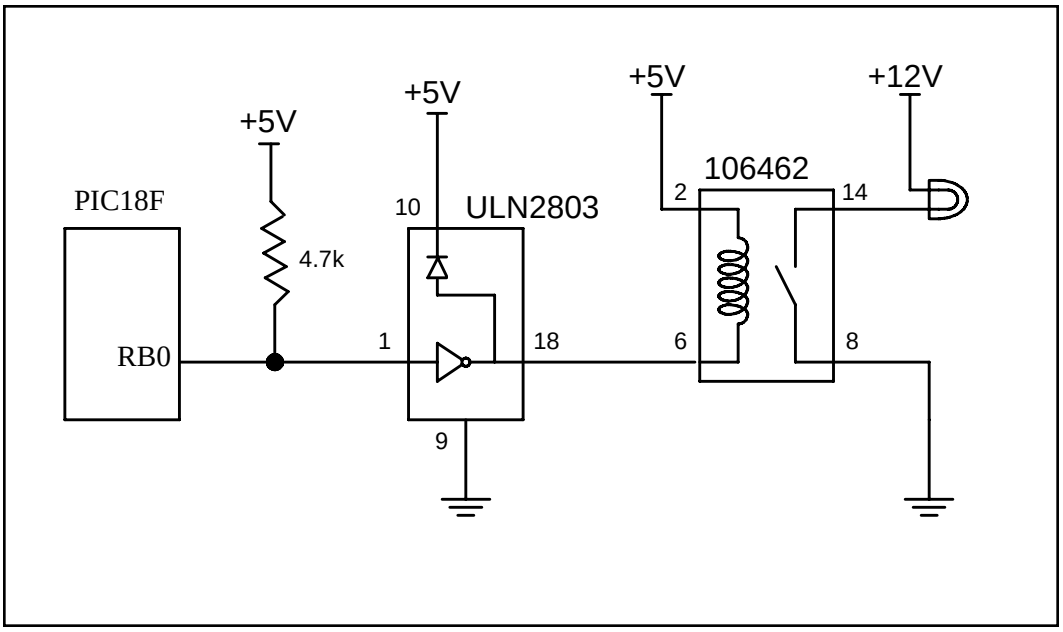


Figure 17-2. PIC18 Connection to Relay

Program 17-1 turns the lamp on and off shown in Figure 17-2 by energizing and de-energizing the relay every few ms.

```
;Program 17-1
R3    SET   0x20        ;set aside location 0x20 for R3
R4    SET   0x21        ;loc. 0x21 for R4
      ORG 0H
      BCF TRISB,0       ;PORTB.0 as output
OVER  BSF PORTB,0       ;turn on the lamp
      CALL DELAY
      BCF   PORTB,0     ;turn off the lamp
      CALL DELAY
      BRA OVER
DELAY MOVLW 0xFF
      MOVWF R4
D1    MOVLW 0xFF
      MOVWF R3
D2    NOP
      NOP
      DECF  R3,F
      BNZ   D2
      DECF R4,F
      BNZ   D1
      RETURN
```

Solid-state relay

Another widely used relay is the solid-state relay. See Table 17-2. In this relay, there is no coil, spring, or mechanical contact switch. The entire relay is made out of semiconductor materials. Because no mechanical parts are involved in solid-state relays, their switching response time is much faster than that of electromechanical relays. Another advantage of the solid-state relay is its greater life expectancy. The life cycle for the electromechanical relay can vary from a few hundred thousand to a few million operations. Wear and tear on the contact points can cause the relay to malfunction after a while. Solid-state relays, however, have no such limitations. Extremely low input current and small packaging make solid-state relays ideal for microprocessor and logic control switching. They are widely used in controlling pumps, solenoids, alarms, and other power applications. Some solid-state relays have a phase control option, which is ideal for motor-speed control and light-dimming applications. Figure 17-3 shows control of a fan using a solid-state relay (SSR).

Table 17-2: Selected Solid-State Relay Characteristics (www.Jameco.com)

Part No.	Contact Style	Control Volts	Contact Volts	Contact Current
143058CP	SPST	4–32 VDC	240 VAC	3 A
139053CP	SPST	3–32 VDC	240 VAC	25 A
162341CP	SPST	3–32 VDC	240 VAC	10 A
172591CP	SPST	3–32 VDC	60 VDC	2 A
175222CP	SPST	3–32 VDC	60 VDC	4 A
176647CP	SPST	3–32 VDC	120 VDC	5 A

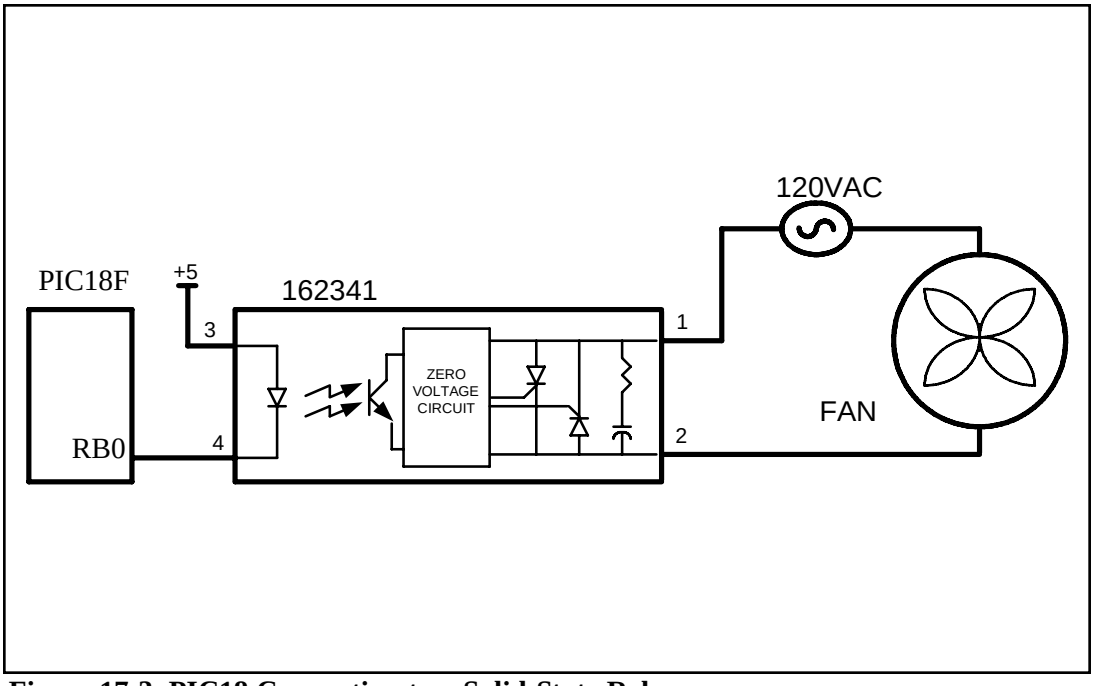


Figure 17-3. PIC18 Connection to a Solid-State Relay

Reed switch

Another popular switch is the reed switch. When the reed switch is placed in a magnetic field, the contact is closed. When the magnetic field is removed, the contact is forced open by its spring. See Figure 17-4. The reed switch is ideal for moist and marine environments where it can be submerged in fuel or water. Reed switches are also widely used in dirty and dusty atmospheres because they are tightly sealed.

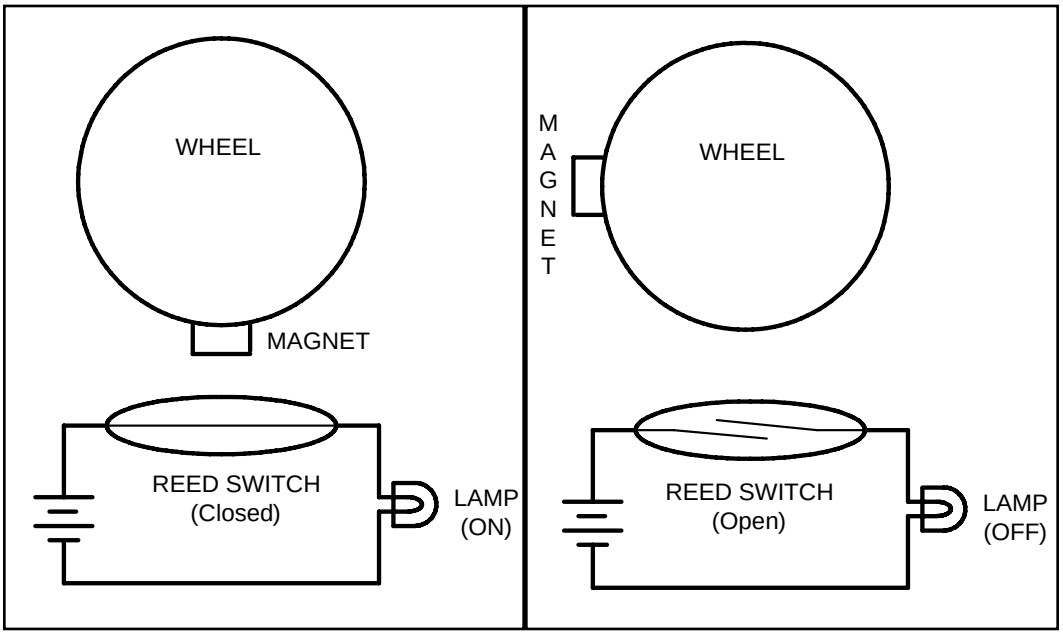


Figure 17-4. Reed Switch and Magnet Combination

Optoisolator

In some applications we use an optoisolator (also called optocoupler) to isolate two parts of a system. An example is driving a motor. Motors can produce what is called back EMF, a high-voltage spike produced by a sudden change of current as indicated in the V = Ldi/dt formula. In situations such as printed circuit board design, we can reduce the effect of this unwanted voltage spike (called ground bounce) by using decoupling capacitors (see Appendix C). In systems that have inductors (coil winding), such as motors, a decoupling capacitor or a diode will not do the job. In such cases we use optoisolators. An optoisolator has an LED (light-emitting diode) transmitter and a photosensor receiver, separated from each other by a gap. When current flows through the diode, it transmits a signal light across the gap and the receiver produces the same signal with the same phase but a different current and amplitude. See Figure 17-5. Optoisolators are also widely used in communication equipment such as modems. This device allows a computer to be connected to a telephone line without risk of damage from power surges. The gap between the transmitter and receiver of optoisolators prevents the electrical current surge from reaching the system.

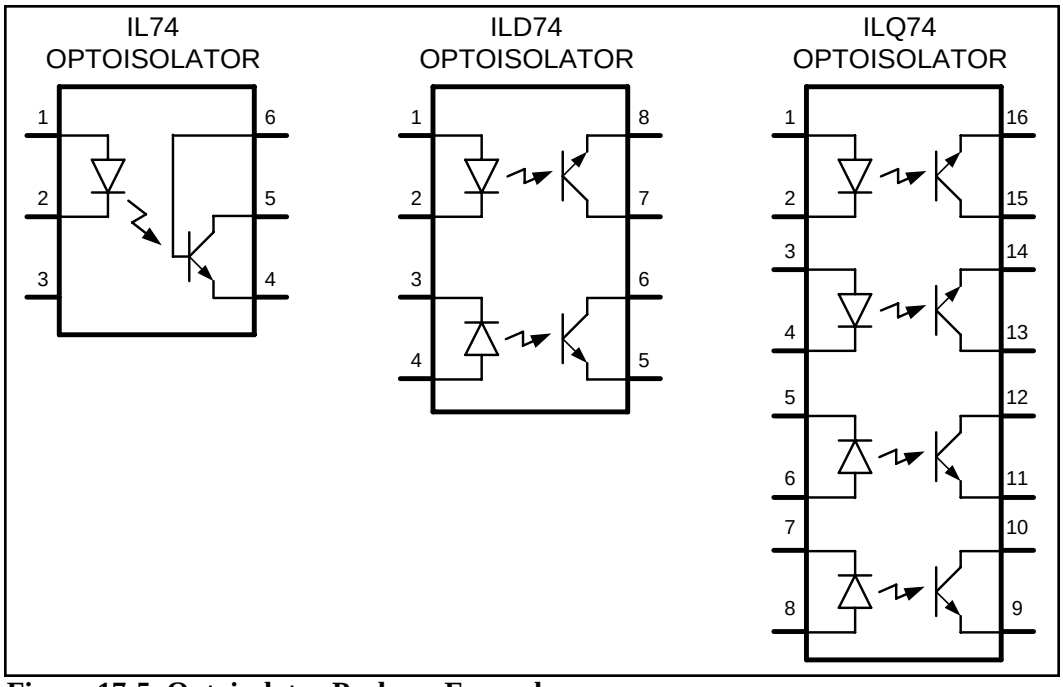


Figure 17-5. Optoisolator Package Examples

Interfacing an optoisolator

The optoisolator comes in a small IC package with four or more pins. There are also packages that contain more than one optoisolator. When placing an optoisolator between two circuits, we must use two separate voltage sources, one for each side, as shown in Figure 17-6. Unlike relays, no drivers need to be placed between the microcontroller/digital output and the optoisolators.

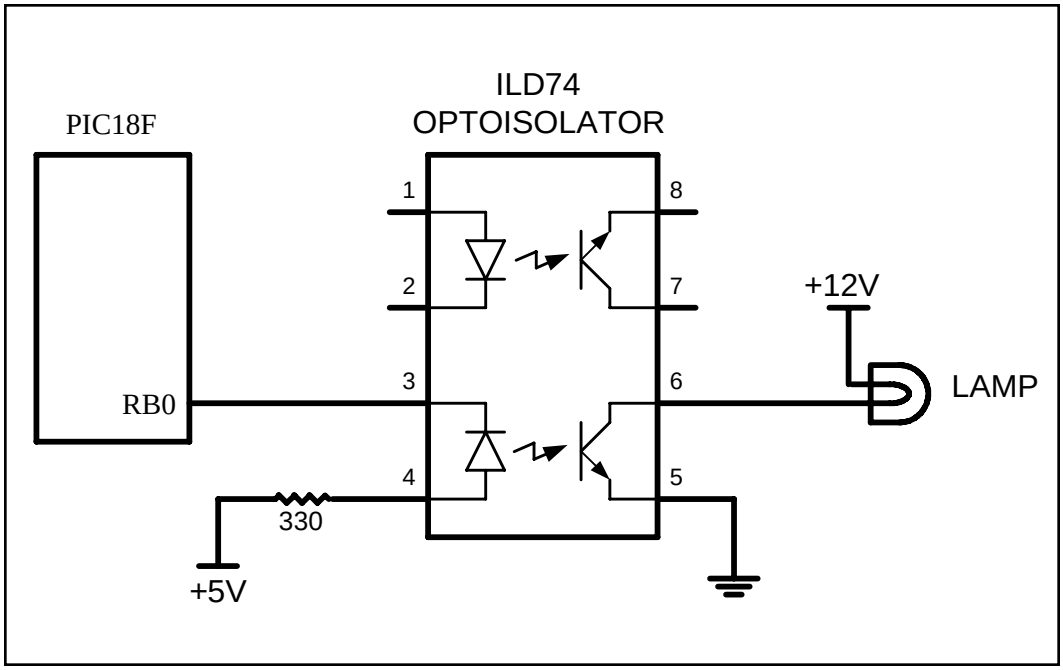


Figure 17-6. Controlling a Lamp via an Optoisolator

Review Questions

1. Give one application where would you use a relay.
2. Why do we place a driver between the microcontroller and the relay?
3. What is an NC relay?
4. Why are relays that use coils called electromechanical relays?
5. What is the advantage of a solid-state relay over EMR?
6. What is the advantage of an optoisolator over an EM relay?

SECTION 17.2: STEPPER MOTOR INTERFACING

This section begins with an overview of the basic operation of stepper motors. Then we describe how to interface a stepper motor to the PIC18. Finally, we use Assembly language programs to demonstrate control of the angle and direction of stepper motor rotation.

Stepper motors

A *stepper motor* is a widely used device that translates electrical pulses into mechanical movement. In applications such as disk drives, dot matrix printers, and robotics, the stepper motor is used for position control. Stepper motors commonly have a permanent magnet *rotor* (also called the *shaft*) surrounded by a *stator* (see Figure 17-7). There are also steppers called variable reluctance *stepper motors* that do not have a permanent magnet rotor. The most common stepper motors have four stator windings that are paired with a center-tapped common as shown in Figure 17-8. This type of stepper motor is commonly referred to as a *four-phase* or unipolar stepper motor. The center tap allows a change of current direction in

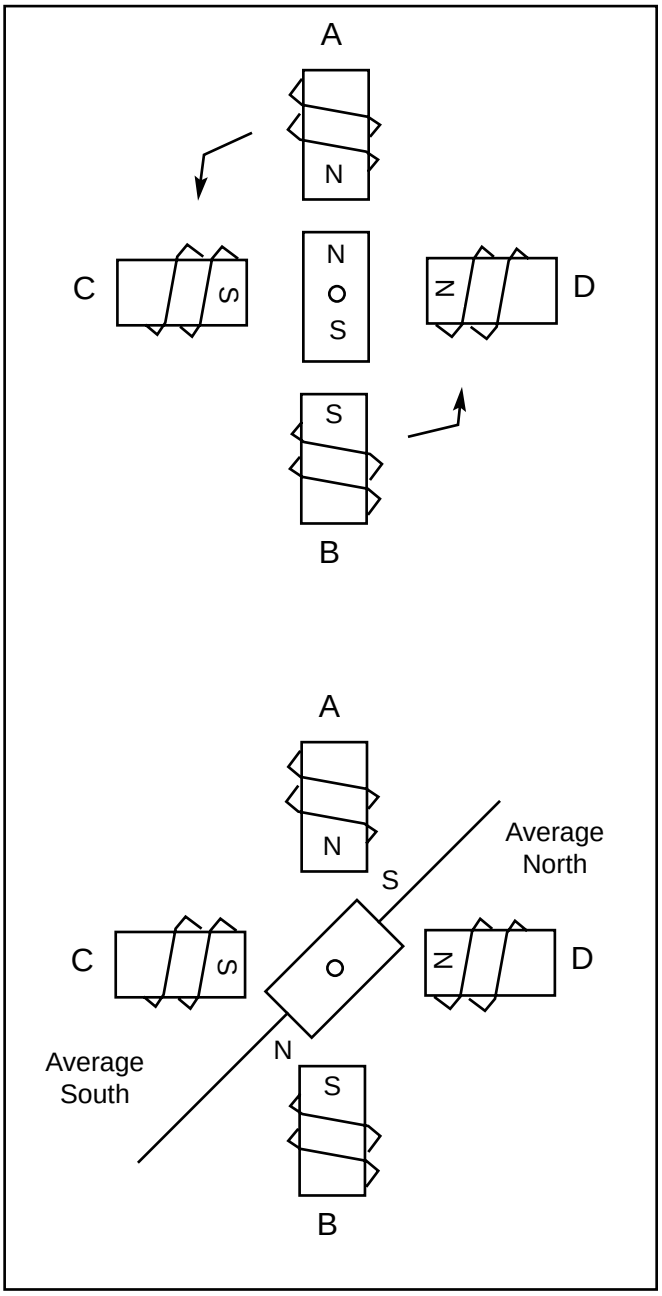


Figure 17-7. Rotor Alignment

each of two coils when a winding is grounded, thereby resulting in a polarity change of the stator. Notice that while a conventional motor shaft runs freely, the stepper motor shaft moves in a fixed repeatable increment, which allows one to move it to a precise position. This repeatable fixed movement is possible as a result of basic magnetic theory where poles of the same polarity repel and opposite poles attract. The direction of the rotation is dictated by the stator poles. The stator poles are determined by the current sent through the wire coils. As the direction of the current is changed, the polarity is also changed causing the reverse motion of the rotor. The stepper motor discussed here has a total of six leads: four leads representing the four stator windings and two commons for the center-tapped leads. As the sequence of power is applied to each stator winding, the rotor will rotate. There are several widely used sequences, each of which has a different degree of precision. Table 17-3 shows a two-phase, four-step stepping sequence.

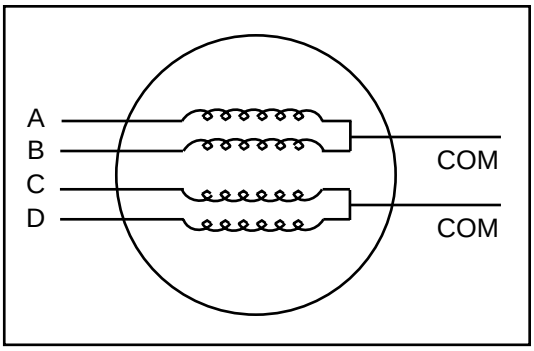


Figure 17-8. Stator Winding Configuration

Note that although we can start with any of the sequences in Table 17-3, once we start we must continue in the proper order. For example, if we start with step 3 (0110), we must continue in the sequence of steps 4, 1, 2, etc.

Table 17-3: Normal Four-Step Sequence

Clockwise ↓

Step #	Winding A	Winding B	Winding C	Winding D
1	1	0	0	1
2	1	1	0	0
3	0	1	1	0
4	0	0	1	1

↑ Counter-clockwise

Step angle

How much movement is associated with a single step? This depends on the internal construction of the motor, in particular the number of teeth on the stator and the rotor. The *step angle* is the minimum degree of rotation associated with a single step. Various motors have different step angles. Table 17-4 shows some step angles for various motors. In Table 17-4, notice the term *steps per revolution*. This is the total number of steps needed to rotate one complete rotation or 360 degrees (e.g., 180 steps × 2 degrees = 360).

Table 17-4: Stepper Motor Step Angles

Step Angle	Steps per Revolution
0.72	500
1.8	200
2.0	180
2.5	144
5.0	72
7.5	48
15	24

It must be noted that perhaps contrary to one's initial impression, a stepper motor does not need more terminal leads for the stator to achieve smaller steps. All the stepper motors

discussed in this section have four leads for the stator winding and two COM wires for the center tap. Although some manufacturers set aside only one lead for the common signal instead of two, they always have four leads for the stators. See Example 17-1. Next we discuss some associated terminology in order to understand the stepper motor further.

Example 17-1

Describe the PIC18 connection to the stepper motor of Figure 17-9 and code a program to rotate it continuously.

Solution:

The following steps show the PIC18 connection to the stepper motor and its programming:

1. Use an ohmmeter to measure the resistance of the leads. This should identify which COM leads are connected to which winding leads.
2. The common wire(s) are connected to the positive side of the motor's power supply. In many motors, +5 V is sufficient.
3. The four leads of the stator winding are controlled by four bits of the PIC18 port (RB0–RB3). Because the PIC18 lacks sufficient current to drive the stepper motor windings, we must use a driver such as the ULN2003 to energize the stator. Instead of the ULN2003, we could have used transistors as drivers, as shown in Figure 17-11. However, notice that if transistors are used as drivers, we must also use diodes to take care of inductive current generated when the coil is turned off. One reason that using the ULN2003 is preferable to the use of transistors as drivers is that the ULN2003 has an internal diode to take care of back EMF.

```
MyReg          SET   0x30             ;loc 30H for MyReg
R2             SET   0x20             ;loc 20H for R2 Reg
               CLRF  TRISB            ;Port B as output
               MOVLW 0x66             ;load step sequence
               MOVWF MyReg
BACK           MOVFF MyReg,PORTB      ;issue sequence to motor
               RRNCF MyReg,F          ;rotate right clockwise
               CALL DELAY             ;wait
               BRA   BACK             ;keep going
DELAY
               MOVLW 0xFF
               MOVWF R2
D1             NOP
               DECF R2,F
               BNZ D1
               RETURN
               END
```

Change the value of DELAY to set the speed of rotation.
We can use the single-bit instructions BSF and BCF instead of RRNCF to create the sequences.

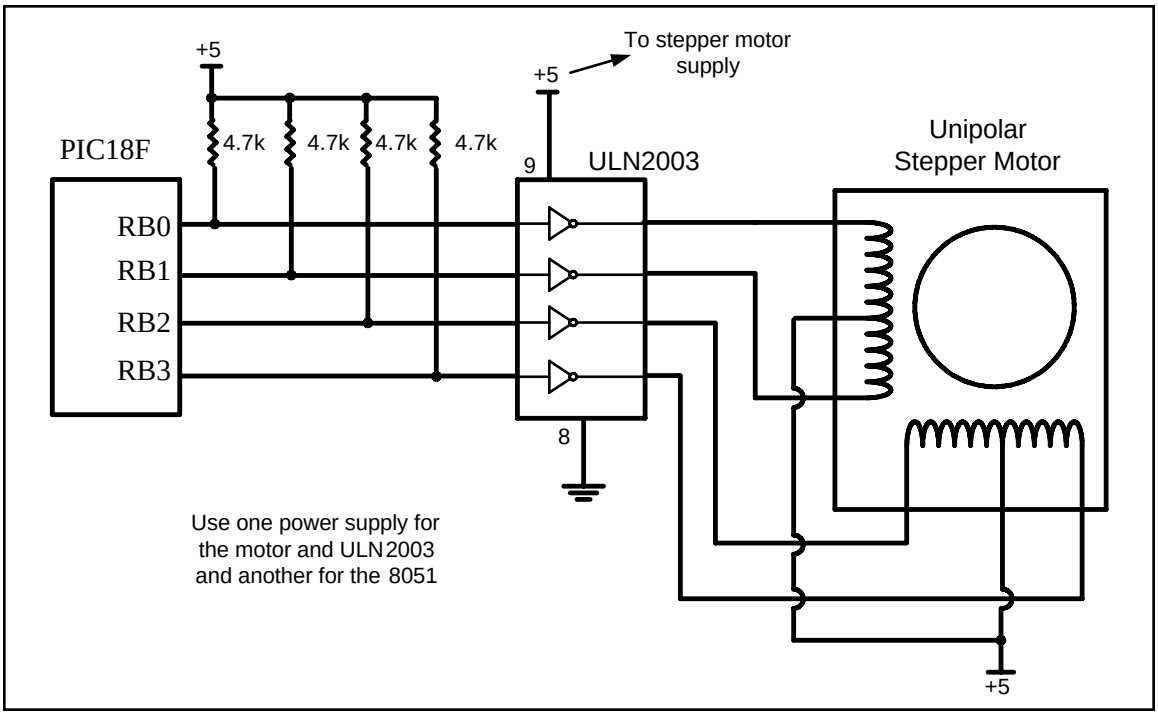


Figure 17-9. PIC18 Connection to Stepper Motor

Steps per second and rpm relation

The relation between rpm (revolutions per minute), steps per revolution, and steps per second is as follows.

$$Steps\ per\ second = \frac{rpm \times Steps\ per\ revolution}{60}$$

The 4-step sequence and number of teeth on rotor

The switching sequence shown earlier in Table 17-3 is called the 4-step switching sequence because after four steps the same two windings will be "ON". How much movement is associated with these four steps? After completing every four steps, the rotor moves only one tooth pitch. Therefore, in a stepper motor with 200 steps per revolution, the rotor has 50 teeth because $4 \times 50 = 200$ steps are needed to complete one revolution. This leads to the conclusion that the minimum step angle is always a function of the number of teeth on the rotor. In other words, the smaller the step angle, the more teeth the rotor passes. See Example 17-2.

Example 17-2

Give the number of times the four-step sequence in Table 17-3 must be applied to a stepper motor to make an 80-degree move if the motor has a 2-degree step angle.

Solution:

A motor with a 2-degree step angle has the following characteristics:

Step angle:	2 degrees	Steps per revolution:	180
Number of rotor teeth:	45	Movement per 4-step sequence:	8 degrees

To move the rotor 80 degrees, we need to send 10 consecutive 4-step sequences, because 10×4 steps $\times$ 2 degrees = 80 degrees.

Looking at Example 17-2, one might wonder what happens if we want to move 45 degrees, because the steps are 2 degrees each. To allow for finer resolutions, all stepper motors allow what is called an *8-step* switching sequence. The 8-step sequence is also called *half-stepping*, because in the 8-step sequence each step is half of the normal step angle. For example, a motor with a 2-degree step angle can be used as a 1-degree step angle if the sequence of Table 17-5 is applied.

Table 17-5: Half-Step 8-Step Sequence

Clockwise ↓

Step #	Winding A	Winding B	Winding C	Winding D
1	1	0	0	1
2	1	0	0	0
3	1	1	0	0
4	0	1	0	0
5	0	1	1	0
6	0	0	1	0
7	0	0	1	1
8	0	0	0	1

Counter-clockwise ↑

Motor speed

The motor speed, measured in steps per second (steps/s), is a function of the switching rate. Notice in Example 17-1 that by changing the length of the time delay loop, we can achieve various rotation speeds.

Holding torque

The following is a definition of holding torque: “With the motor shaft at standstill or zero rpm condition, the amount of torque, from an external source, required to break away the shaft from its holding position. This is measured with rated voltage and current applied to the motor.” The unit of torque is ounce-inch (or kg-cm).

Wave drive 4-step sequence

In addition to the 8-step and the 4-step sequences discussed earlier, there is another sequence called the wave drive 4-step sequence. It is shown in Table 17-6. Notice that the 8-step sequence of Table 17-5 is simply the combination of the wave drive 4-step and normal 4-step normal sequences shown in Tables 17-6 and 17-3, respectively. Experimenting with the wave drive 4-step sequence is left to the reader.

Table 17-6: Wave Drive 4-Step Sequence

Clockwise ↓

Step #	Winding A	Winding B	Winding C	Winding D
1	1	0	0	0
2	0	1	0	0
3	0	0	1	0
4	0	0	0	1

Counter-clockwise ↑

Table 17-7: Selected Stepper Motor Characteristics (www.Jameco.com)

Part No.	Step Angle	Drive System	Volts	Phase Resistance	Current
151861CP	7.5	unipolar	5 V	9 ohms	550 mA
171601CP	3.6	unipolar	7 V	20 ohms	350 mA
164056CP	7.5	bipolar	5 V	6 ohms	800 mA

Unipolar versus bipolar stepper motor interface

There are three common types of stepper motor interfacing: universal, unipolar, and bipolar. They can be identified by the number of connections to the motor. A universal stepper motor has eight, while the unipolar has six and the bipolar has four. The universal stepper motor can be configured for all three modes, while the unipolar can be either unipolar or bipolar. Obviously the bipolar cannot be configured for universal nor unipolar mode. Table 17-7 shows selected stepper motor characteristics. Figure 17-10 shows the basic internal connections of all three type of configurations.

Unipolar stepper motors can be controlled using the basic interfacing shown in Figure 17-11, whereas the bipolar stepper requires H-Bridge circuitry. Bipolar stepper motors require a higher operational current than the unipolar; the advantage of this is a higher holding torque.

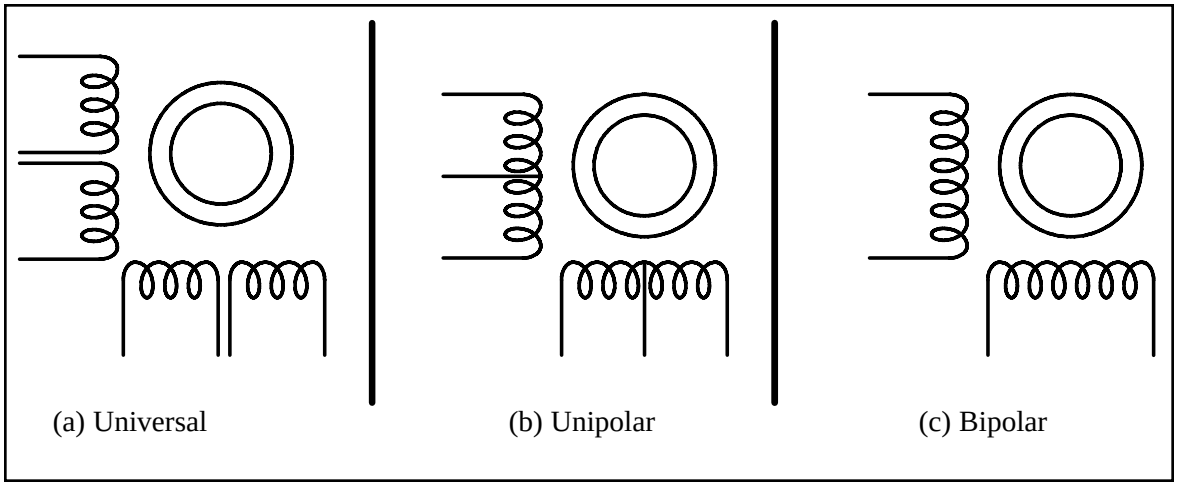


Figure 17-10. Common Stepper Motor Types

Using transistors as drivers

Figure 17-11 shows an interface to a unipolar stepper motor using transistors. Diodes are used to reduce the back EMF spike created when the coils are energized and de-energized, similar to the electromechanical relays discussed earlier. TIP transistors can be used to supply higher current to the motor. Table 17-8 lists the common industrial Darlington transistors. These transistors can accommodate higher voltages and currents.

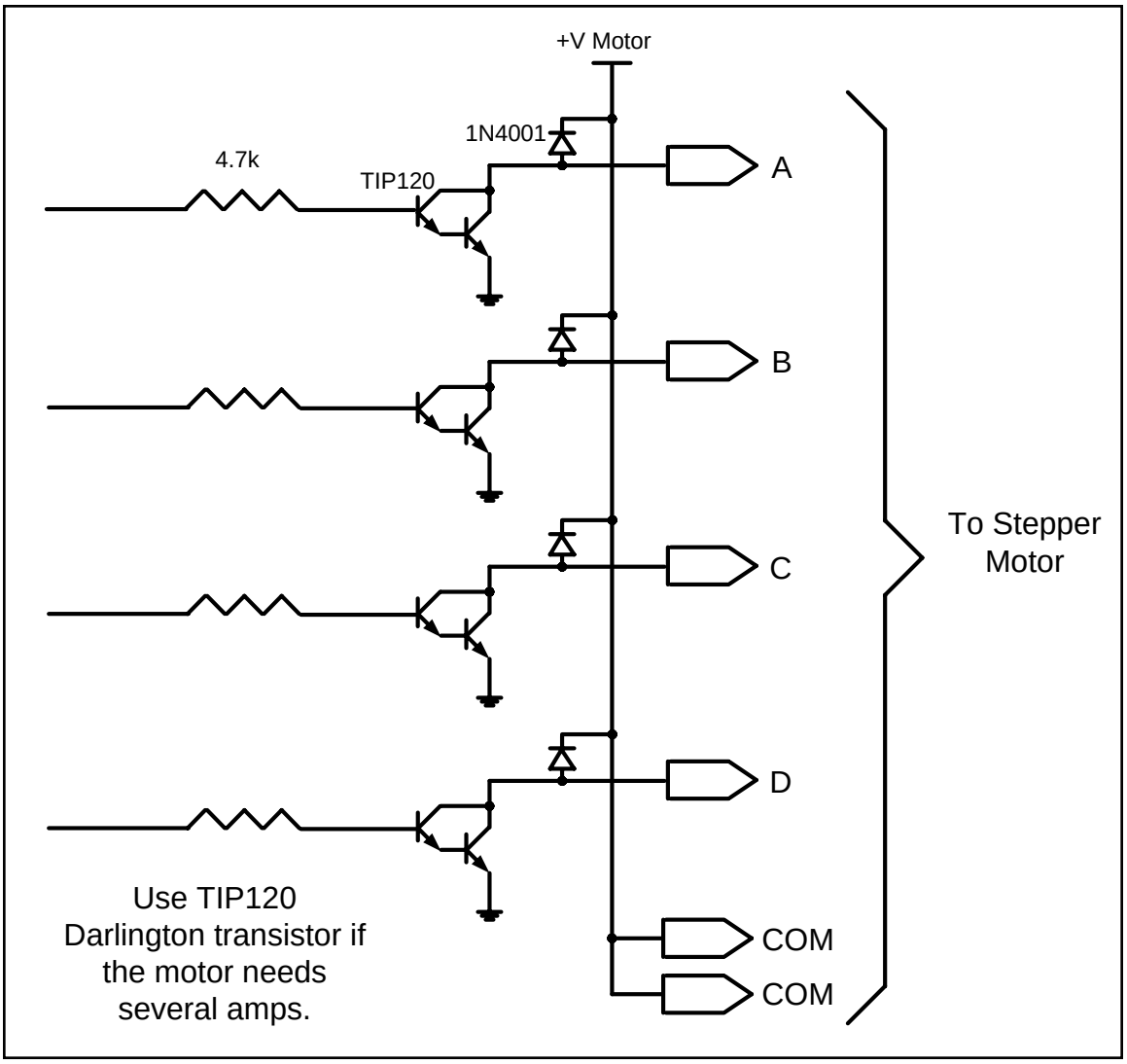


Figure 17-11. Using Transistors for Stepper Motor Driver

Table 17-8: Darlington Transistor Listing

NPN	PNP	Vceo (volts)	Ic (amps)	hfe (common)
TIP110	TIP115	60	2	1000
TIP111	TIP116	80	2	1000
TIP112	TIP117	100	2	1000
TIP120	TIP125	60	5	1000
TIP121	TIP126	80	5	1000
TIP122	TIP127	100	5	1000
TIP140	TIP145	60	10	1000
TIP141	TIP146	80	10	1000
TIP142	TIP147	100	10	1000

Controlling stepper motor via optoisolator

In the first section of this chapter we examined the optoisolator and its use. Optoisolators are widely used to isolate the stepper motor's EMF voltage and keep it from damaging the digital/microcontroller system. This is shown in Figure 17-12. See Examples 17-3 and 17-4.

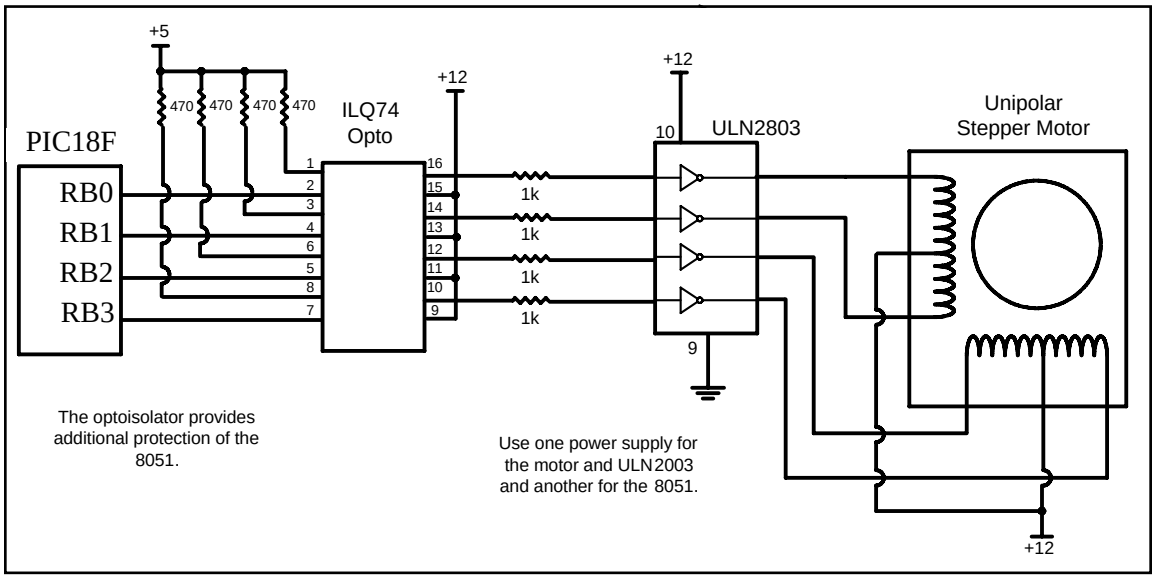


Figure 17-12. Controlling Stepper Motor via Optoisolator

Example 17-3

A switch is connected to pin RD7 (PORTD.7). Write a program to monitor the status of SW and perform the following:
(a) If SW = 0, the stepper motor moves clockwise.
(b) If SW = 1, the stepper motor moves counterclockwise.

Solution:

```
MyReg     SET  0x30            ;loc 30H for MyReg
          BSF  TRISD,RD7       ;RD7 as input pin
          CLRF TRISB           ;Port B as output
          MOVLW 0x66           ;load step sequence
          MOVWF MyReg
BACK      BTFSS PORTD,RD7      ;check the SW
          BRA  OVER       ;It is high. Make it clockwise
          MOVFF MyReg,PORTB    ;issue sequence to motor
          RRNCF MyReg,F        ;rotate right clockwise
          CALL DELAY           ;wait
          BRA  BACK            ;keep going
OVER      MOVFF MyReg,PORTB    ;issue sequence to motor
          RLNCF MyReg,F        ;rotate left clockwise
          CALL DELAY           ;wait
          BRA  BACK            ;keep going
```

Stepper motor control with PIC18 C

The PIC18 C version of the stepper motor control is given below. In this program we could have used << (shift left) and >> (shift right) as was shown in Chapter 7.

```
#include <p18f458.h>
void main()
  {
    TRISB=0x0;        //PORTB as output
    while(1)
      {
        PORTB = 0x66;
        MSDelay(100);
        PORTB = 0xCC;
        MSDelay(100);
        PORTB = 0x99;
        MSDelay(100);
        PORTB = 0x33;
        MSDelay(100);
      }
  }
```

Example 17-4

A switch is connected to pin RD7. Write a C program to monitor the status of SW and perform the following:
(a) If SW = 0, the stepper motor moves clockwise.
(b) If SW = 1, the stepper motor moves counterclockwise.

Solution:

```
#include <p18f458.h>
#define SW PORTDbits.RD7
void MSDelay(int ms);
void main()
  {
    TRISD=0x80;       //RD7 as input pin
    TRISB=0x0;        //PORTB as output
    while(1)
      {
        if(SW == 0)
          {
          PORTB = 0x66;
          MSDelay(100);
          PORTB = 0xCC;
          MSDelay(100);
          PORTB = 0x99;
          MSDelay(100);
          PORTB = 0x33;
          MSDelay(100);
          }
        else
          {
          PORTB = 0x66;
          MSDelay(100);
          PORTB = 0x33;
```

Example 17-4 Cont.

```
            MSDelay(100);
            PORTB = 0x99;
            MSDelay(100);
            PORTB = 0xCC;
            MSDelay(100);
            }
        }
   }

void MSDelay(unsigned int value)
   {
     unsigned int x, y;
     for(x=0;x<1275;x++)
       for(y=0;y<value;y++);
   }
```

Review Questions

1. Give the 4-step sequence of a stepper motor if we start with 0110.
2. A stepper motor with a step angle of 5 degrees has ____ steps per revolution.
3. Why do we put a driver between the microcontroller and the stepper motor?

SECTION 17.3: DC MOTOR INTERFACING AND PWM

This section begins with an overview of the basic operation of DC motors. Then we describe how to interface a DC motor to the PIC18. Finally, we use Assembly and C language programs to demonstrate the concept of pulse width modulation (PWM) and show how to control the speed and direction of a DC motor.

DC motors

A direct current (DC) motor is another widely used device that translates electrical pulses into mechanical movement. In the DC motor we have only + and – leads. Connecting them to a DC voltage source moves the motor in one direction. By reversing the polarity, the DC motor will move in the opposite direction. One can easily experiment with the DC motor. For example, small fans used in many motherboards to cool the CPU are run by DC motors. By connecting their leads to the + and – voltage source, the DC motor moves. While a stepper motor moves in steps of 1 to 15 degrees, the DC motor moves continuously. In a stepper motor, if we know the starting position we can easily count the number of steps the motor has moved and calculate the final position of the motor. This is not possible in a DC motor. The maximum speed of a DC motor is indicated in rpm and is given in the data sheet. The DC motor has two rpms: no-load and loaded. The manufacturer's data sheet gives the no-load rpm. The no-load rpm can be from a few thousand to tens of thousands. The rpm is reduced when moving a load and it decreases as the load is increased. For example, a drill turning a screw has a much lower rpm speed than when it is in the no-load situation. DC motors also have voltage and current ratings. The nominal voltage is the voltage for that motor under normal conditions, and can be from 1 to 150 V, depending on the motor. As we increase the voltage, the rpm goes up. The current rating is the current consump-

tion when the nominal voltage is applied with no load, and can be from 25 mA to a few amps. As the load increases, the rpm is decreased, unless the current or voltage provided to the motor is increased, which in turn increases the torque. With a fixed voltage, as the load increases, the current (power) consumption of a DC motor is increased. If we overload the motor it will stall, and that can damage the motor due to the heat generated by high current consumption.

Unidirectional control

Figure 17-13 shows the DC motor rotation for clockwise (CW) and counterclockwise (CCW) rotations. See Table 17-9 for selected DC motors.

Table 17-9: Selected DC Motor Characteristics (www.Jameco.com)

Part No.	Nominal Volts	Volt Range	Current	RPM	Torque
154915CP	3 V	1.5–3 V	0.070 A	5,200	4.0 g-cm
154923CP	3 V	1.5–3 V	0.240 A	16,000	8.3 g-cm
177498CP	4.5 V	3–14 V	0.150 A	10,300	33.3 g-cm
181411CP	5 V	3–14 V	0.470 A	10,000	18.8 g-cm

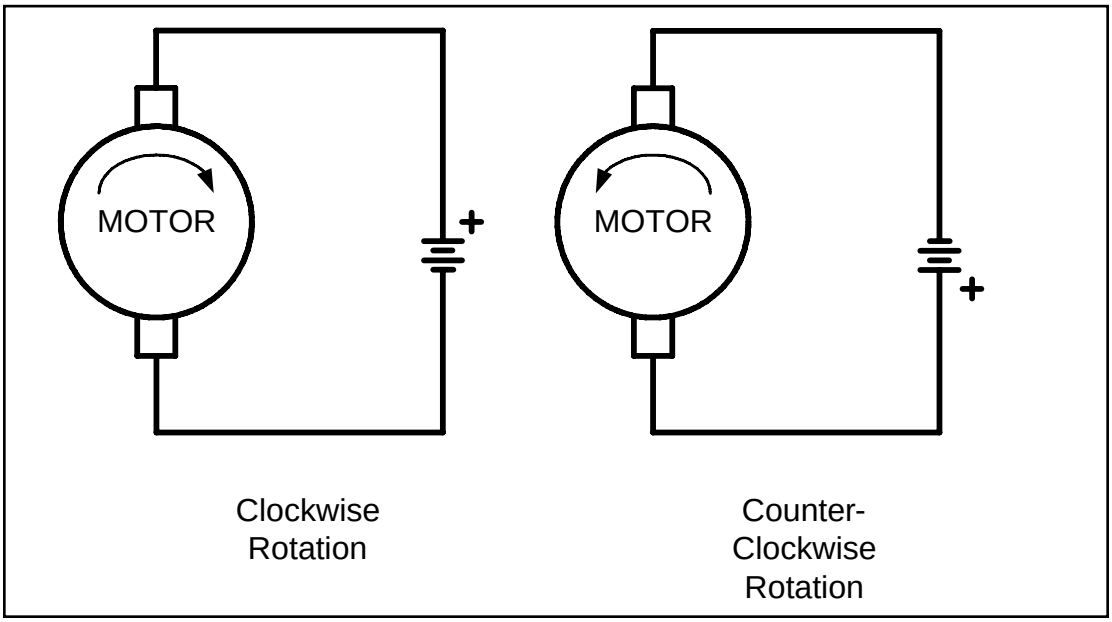


Figure 17-13. DC Motor Rotation (Permanent Magnet Field)

Bidirectional control

With the help of relays or some specially designed chips we can change the direction of the DC motor rotation. Figures 17-14 through 17-17 show the basic concepts of H-Bridge control of DC motors.

Figure 17-14 shows the connection of an H-Bridge using simple switches. All the switches are open, which does not allow the motor to turn.

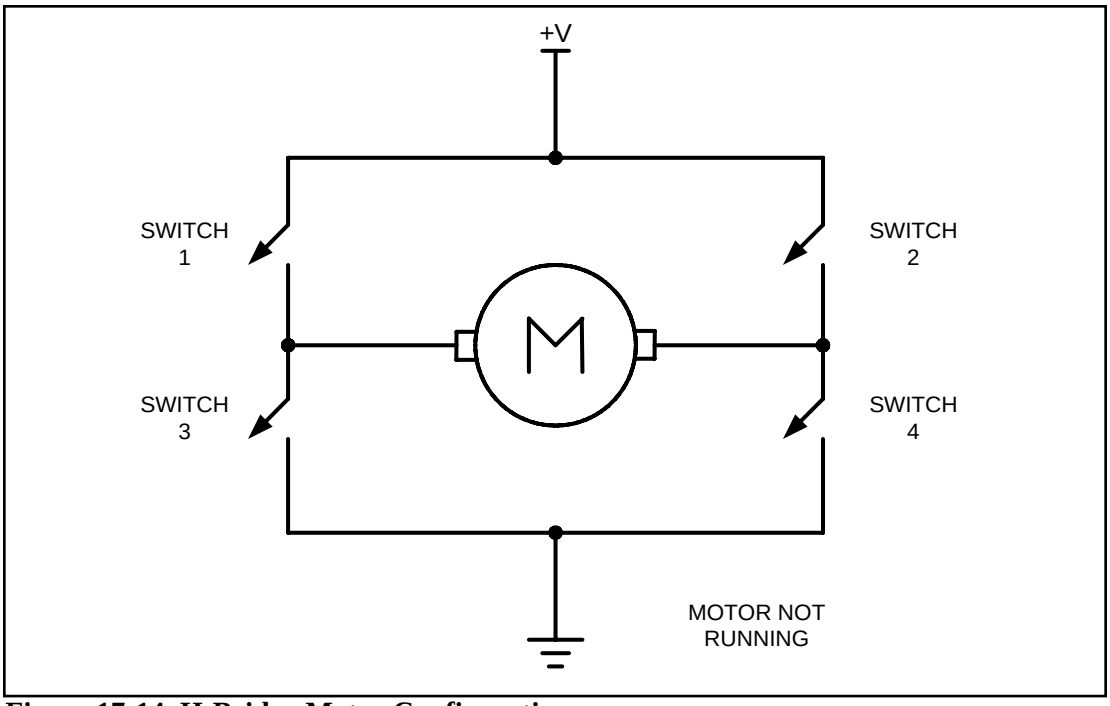


Figure 17-14. H-Bridge Motor Configuration

Figure 17-15 shows the switch configuration for turning the motor in one direction. When switches 1 and 4 are closed, current is allowed to pass through the motor.

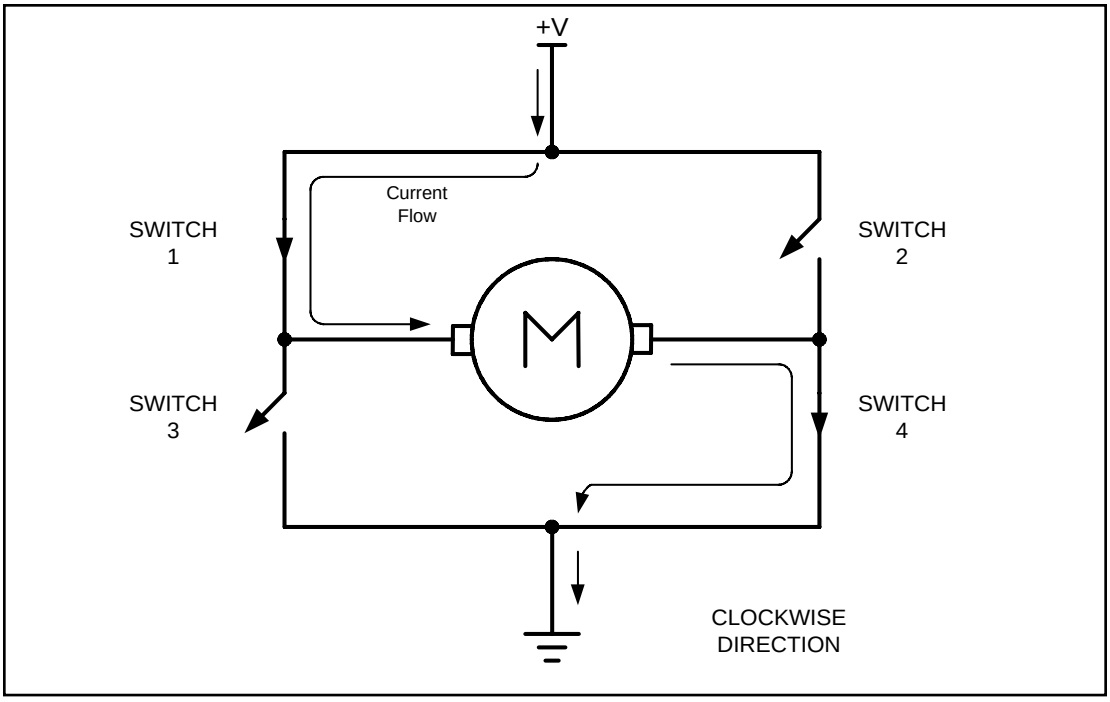


Figure 17-15. H-Bridge Motor Clockwise Configuration

Figure 17-16 shows the switch configuration for turning the motor in the opposite direction from the configuration of Figure 17-15. When switches 2 and 3 are closed, current is allowed to pass through the motor.

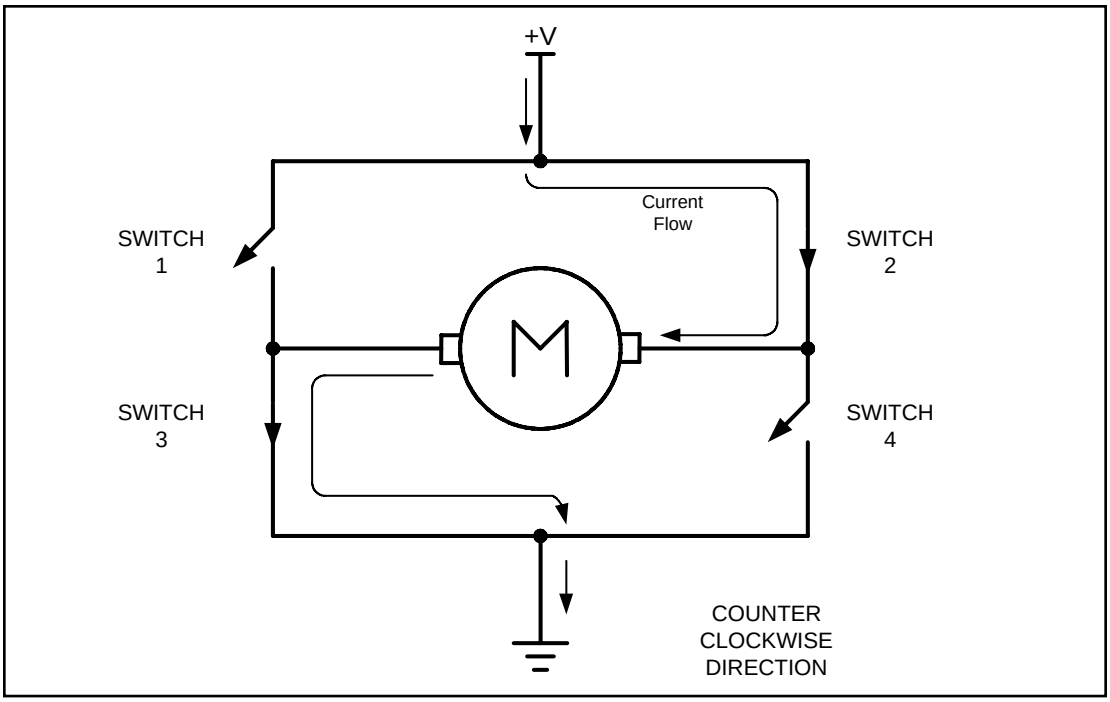


Figure 17-16. H-Bridge Motor Counterclockwise Configuration

Figure 17-17 shows an invalid configuration. Current flows directly to ground, creating a short circuit. The same effect occurs when switches 1 and 3 are closed or switches 2 and 4 are closed.

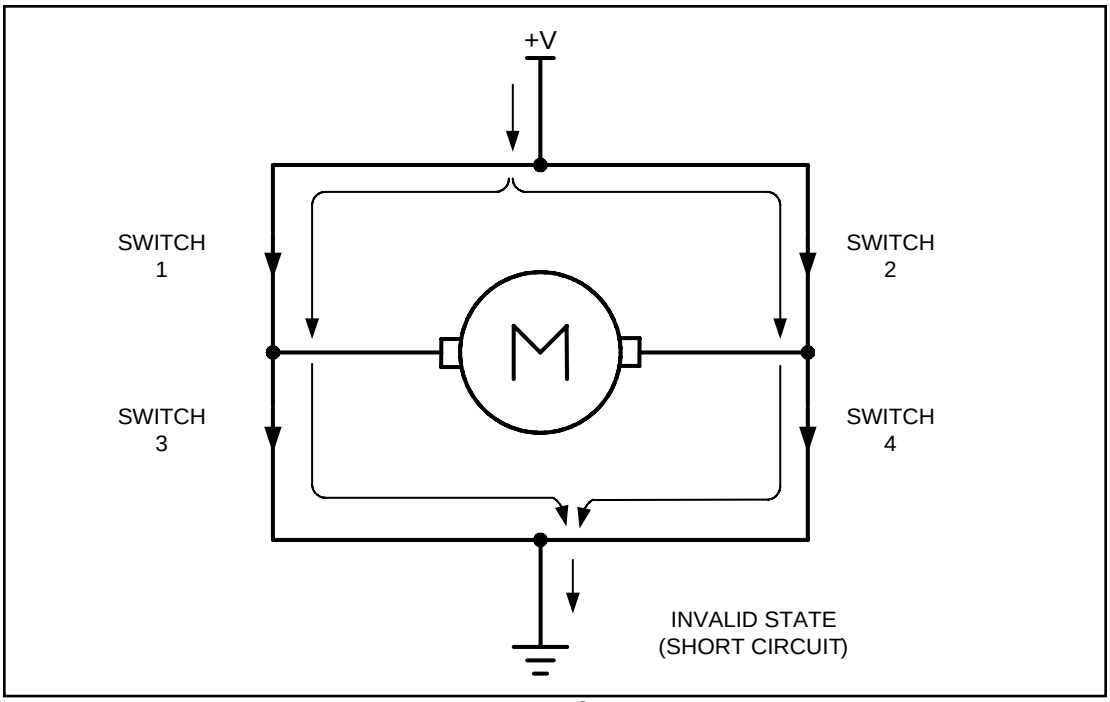


Figure 17-17. H-Bridge in an Invalid Configuration

Table 17-10 shows some of the logic configurations for the H-Bridge design.

H-Bridge control can be created using relays, transistors, or a single IC solution such as the L293. When using relays and transistors, you must ensure that invalid configurations do not occur.

Table 17-10: Some H-Bridge Logic Configurations for Figure 17-14

Motor Operation	SW1	SW2	SW3	SW4
Off	Open	Open	Open	Open
Clockwise	Closed	Open	Open	Closed
Counterclockwise	Open	Closed	Closed	Open
Invalid	Closed	Closed	Closed	Closed

Although we do not show the relay control of an H-Bridge, Example 17-5 shows a simple program to operate a basic H-Bridge.

Example 17-5

A switch is connected to pin RD7 (PORTD.7). Using a simulator, write a program to simulate the H-Bridge in Table 17-10. We must perform the following:
(a) If DIR = 0, the DC motor moves clockwise.
(b) If DIR = 1, the DC motor moves counterclockwise.

Solution:

```
      BCF TRISB,0                ;PORTB.0 as output for switch 1
      BCF TRISB,1                ;      .1   "          switch 2
      BCF TRISB,2                ;      .2   "          switch 3
      BCF TRISB,3                ;      .3   "          switch 4
      BSF TRISD,7                ;make PORTD.7 an input DIR
MONITOR:
      BTFSS PORTD,7
      BRA CLOCKWISE
      BSF PORTB,0                ;switch 1
      BCF PORTB,1                ;switch 2
      BCF PORTB,2                ;switch 3
      BSF PORTB,3                ;switch 4
      BRA MONITOR
CLOCKWISE:
      BCF PORTB,0                ;switch 1
      BSF PORTB,1                ;switch 2
      BSF PORTB,2                ;switch 3
      BCF PORTB,3                ;switch 4
      BRA MONITOR
```

View the results on your simulator. This example is for simulation only and should not be used on a connected system.

See http://www.MicroDigitalEd.com for additional information on using H-Bridges.

Figure 17-18 shows the connection of the L293 to an PIC18. Be aware that the L293 will generate heat during operation. For sustained operation of the motor, use a heat sink. Example 17-6 shows control of the L293.

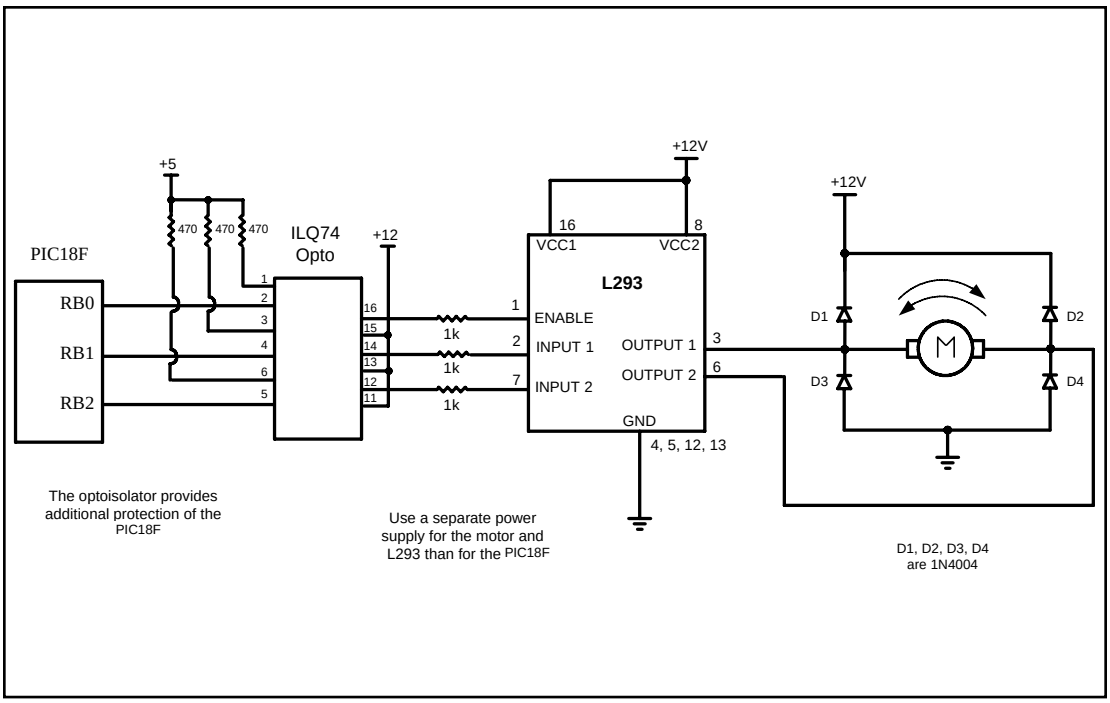


Figure 17-18. Bidirectional Motor Control Using an L293 Chip

Example 17-6

Figure 17-18 shows the connection of an L293. Add a switch to pin RD7 (PORTD.7). Write a program to monitor the status of SW and perform the following:

(a) If SW = 0, the DC motor moves clockwise.
(b) If SW = 1, the DC motor moves counterclockwise.

Solution:

```
      BCF   TRISB,0
      BCF   TRISB,1
      BCF   TRISB,2
      BSF   TRISD,7
      BSF   PORTB,0          ;enable the chip
CHK   BTFSS PORTD,7
      BRA   CWISE
      BCF   PORTB,1          ;turn the motor counterclockwise
      BSF   PORTB,2
      BRA   CHK
CWISE BSF   PORTB,1
      BCF   PORTB,2          ;turn motor clockwise
      BRA   CHK
```

Pulse width modulation (PWM)

The speed of the motor depends on three factors: (a) load, (b) voltage, and (c) current. For a given fixed load we can maintain a steady speed by using a method called *pulse width modulation* (PWM). By changing (modulating) the width of the pulse applied to the DC motor we can increase or decrease the amount of power provided to the motor, thereby increasing or decreasing the motor speed. Notice that, although the voltage has a fixed amplitude, it has a variable duty cycle. That means the wider the pulse, the higher the speed. PWM is so widely used in DC motor control that some microcontrollers come with the PWM circuitry embedded in the chip. In such microcontrollers all we have to do is load the proper registers with the values of the high and low portions of the desired pulse, and the rest is taken care of by the microcontroller. This allows the microcontroller to do other things. For microcontrollers without PWM circuitry, we must create the various duty cycle pulses using software, which prevents the microcontroller from doing other things. The ability to control the speed of the DC motor using PWM is one reason that DC motors are preferable over AC motors. AC motor speed is dictated by the AC frequency of the voltage applied to the motor and the frequency is generally fixed. As a result, we cannot control the speed of the AC motor when the load is increased. As was shown earlier, we can also change the DC motor's direction and torque. See Figure 17-19 for PWM comparisons.

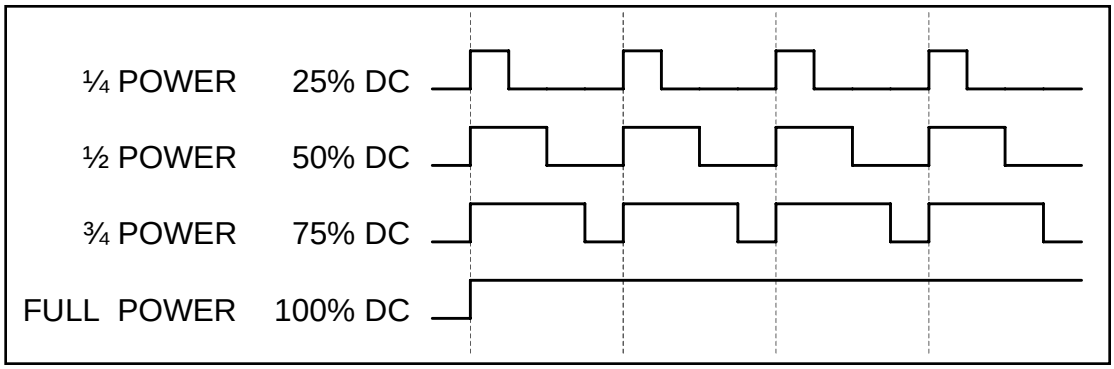


Figure 17-19. Pulse Width Modulation Comparison

DC motor control with optoisolator

As we discussed in the first section of this chapter, the optoisolator is indispensable in many motor control applications. Figures 17-20 and 17-21 show the connections to a simple DC motor using a bipolar and a MOSFET transistor. Notice that the PIC18 is protected from EMI created by motor brushes by using an optoisolator and a separate power supply.

Figures 17-20 and 17-21 show optoisolators for control of single directional motor control, and the same principle should be used for most motor applications. Separating the power supplies of the motor and logic will reduce the possibility of damage to the control circuity.

Figure 17-20 shows the connection of a bipolar transistor to a motor. Protection of the control circuit is provided by the optoisolator. The motor and PIC18 use separate power supplies. The separation of power supplies also allows the use of high-voltage motors. Notice that we use a decoupling capacitor across the motor; this helps reduce the EMI created by the motor. The motor is switched on by clearing bit P1.0.

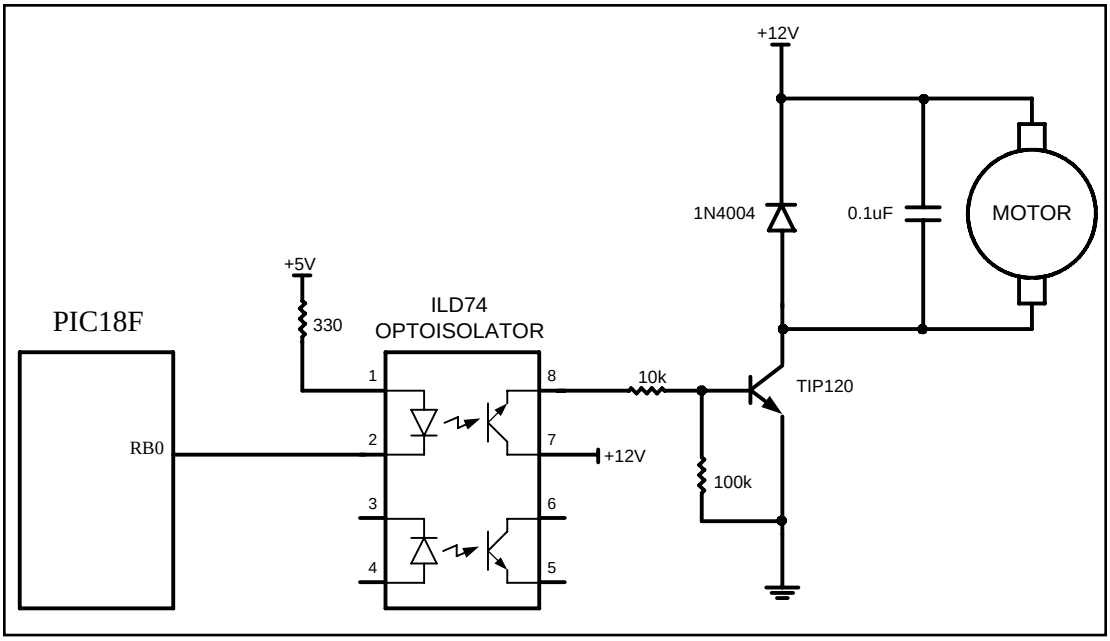


Figure 17-20. DC Motor Connection using a Darlington Transistor

Figure 17-21 shows the connection of a MOSFET transistor. The optoisolator protects the PIC18 from EMI. The zener diode is required for the transistor to reduce gate voltage below the rated maximum value. See Example 17-7.

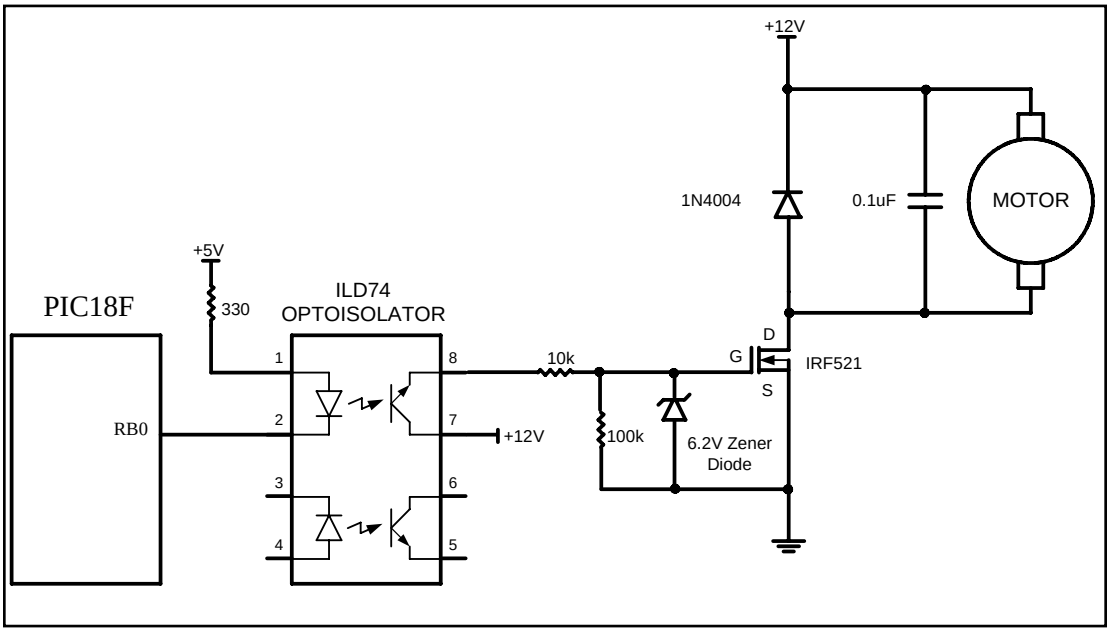


Figure 17-21. DC Motor Connection using a MOSFET Transistor

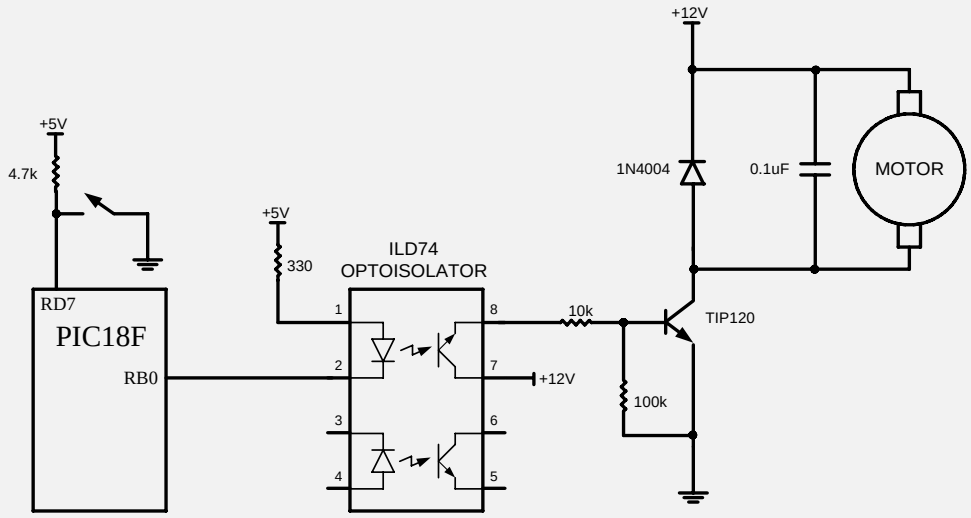
Example 17-7

Refer to the figure in this example. Write a program to monitor the status of the switch and perform the following:

(a) If PORTD.7 = 1, the DC motor moves with 25% duty cycle pulse.
(b) If PORTD.7 = 0, the DC motor moves with 50% duty cycle pulse.

Solution:

```
            BCF TRISB,RB0          ;PORTB.0 as output
            BSF TRISD,RD7          ;PORTD.7 as input
            BCF PORTB,RB0          ;turn off motor
CHK
            BTFSS PORTD,RD7
            BRA   PWM_50
            BSF PORTB,RB0          ;high portion of pulse
            CALL DELAY
            BCF PORTB,RB0          ;low portion of pulse
            CALL DELAY
            CALL DELAY
            CALL DELAY
            BRA  CHK
PWM_50
            BSF PORTB,RB0          ;high portion of pulse
            CALL DELAY
            CALL DELAY
            BCF PORTB,RB0          ;low portion of pulse
            CALL DELAY
            CALL DELAY
            BRA CHK
```



DC motor control and PWM using C

Examples 17-8 through 17-10 show the PIC18 C version of the earlier programs controlling the DC motor.

Example 17-8

Refer to Figure 17-18 for connection of the motor. A switch is connected to pin RD7. Write a C program to monitor the status of SW and perform the following:

(a) If SW = 0, the DC motor moves clockwise.
(b) If SW = 1, the DC motor moves counterclockwise.

Solution:

```
#include <p18f458.h>

#define SW PORTDbits.RD7
#define ENABLE PORTBbits.RB0
#define MTR_1 PORTBbits.RB1
#define MTR_2 PORTBbits.RB2

void main()
  {
  TRISD=0x80;    //make RD7 input pin
  TRISB=0x0;     //make PORTB output
  SW = 1;
  ENABLE = 0;
  MTR_1 = 0;
  MTR_2 = 0;

  while(1)
    {
      ENABLE = 1;
      if(SW == 1)
        {
          MTR_1 = 1;
          MTR_2 = 0;
        }
      else
        {
          MTR_1 = 0;
          MTR_2 = 1;
        }
    }
  }
```

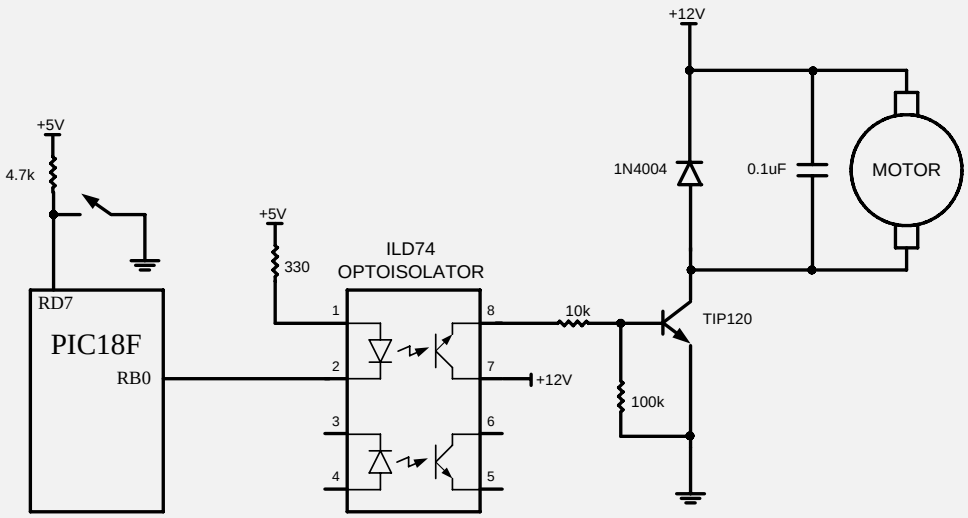
Example 17-9

Refer to the figure in this example. Write a C program to monitor the status of SW and perform the following:

(a) If SW = 0, the DC motor moves with 50% duty cycle pulse.
(b) If SW = 1, the DC motor moves with 25% duty cycle pulse.

Solution:

```
#include <p18f458.h>
#define SW PORTDbits.RD7
#define MTR  PORTBbits.RB1
void MSDelay(unsigned int value);
void main()
  {
  TRISD=0x80;         //make RD7 input pin
  TRISB=0xFD;         //make RB1 output pin
  while(1)
    {
      if(SW == 1)
        {
          MTR = 1;
          MSDelay(25);
          MTR = 0;
          MSDelay(75);
        }
      else
        {
          MTR = 1;
          MSDelay(50);
          MTR = 0;
          MSDelay(50);
        }
    }
  }
void MSDelay(unsigned int value)
  {
    unsigned char x, y;
    for(x=0; x<1275; x++)
      for(y=0; y<value; y++);
  }
```



Example 17-10

Refer to Figure 17-20 for connection to the motor. Two switches are connected to pins RD0 and RD1. Write a C program to monitor the status of both switches and perform the following:

SW2 (RD1)	SW1 (RD0)	
0	0	DC motor moves slowly (25% duty cycle).
0	1	DC motor moves moderately (50% duty cycle).
1	0	DC motor moves fast (75% duty cycle).
1	1	DC motor moves very fast (100% duty cycle).

Solution:

```
#include <p18f458.h>
#define MTR PORTBbits.RB1
void MSDelay(unsigned int value);

void main()
  {
  unsigned int duty;
  TRISB = 0xFD;
  TRISD = 0xFF;
  while(1)
    {
     duty = PORTD&0x03;
     duty++;
     duty *= 25;
     MTR = 1;
     MSDelay(duty);
     MTR = 0;
     MSDelay(100-duty);
    }
  }
```

Review Questions

1. True or false. The permanent magnet field DC motor has only two leads for + and – voltages.
2. True or false. Just like a stepper motor, one can control the exact angle of a DC motor's move.
3. Why do we put a driver between the microcontroller and the DC motor?
4. How do we change a DC motor's rotation direction?
5. What is stall in a DC motor?
6. True or false. PWM allows the control of a DC motor with the same phase, but different amplitude pulses.
7. The RPM rating given for the DC motor is for _____ (no-load, loaded).

SECTION 17.4: PWM MOTOR CONTROL WITH CCP

We examined the CCP (Compare Capture Pulse-Width-Modulation) part of the PIC452/458 in Chapter 15. One of the features of the CCP is the pulse width modulation (PWM) as we saw in Section 15.4 of Chapter 15. In this section we use the PWM feature of the CCP to control DC motors. Review the programming of the PWM in Section 15.4 before embarking on this section.

DC motor control with CCP

Recall from Section 15.4 that the PWM part of the CCP is programmed by using the PR2 and Timer2 registers. Program 17-2 is the rewrite of Example 17-7 using the PWM feature of the CCP1. Notice that Program 17-2 is the modified version of Program 15-5 in Chapter 15. Program 17-2C is the C version of Program 17-2. In Program 17-2 (and 17-2C), an input switch is being monitored. If the switch is low, the PIC18 creates a 50% duty cycle PWM using the CCP1 module. If the switch is high, a 25% duty cycle PWM is created. Recall from Chapter 15 that we must use PR2 and Timer2 registers for creating PWM pulses.

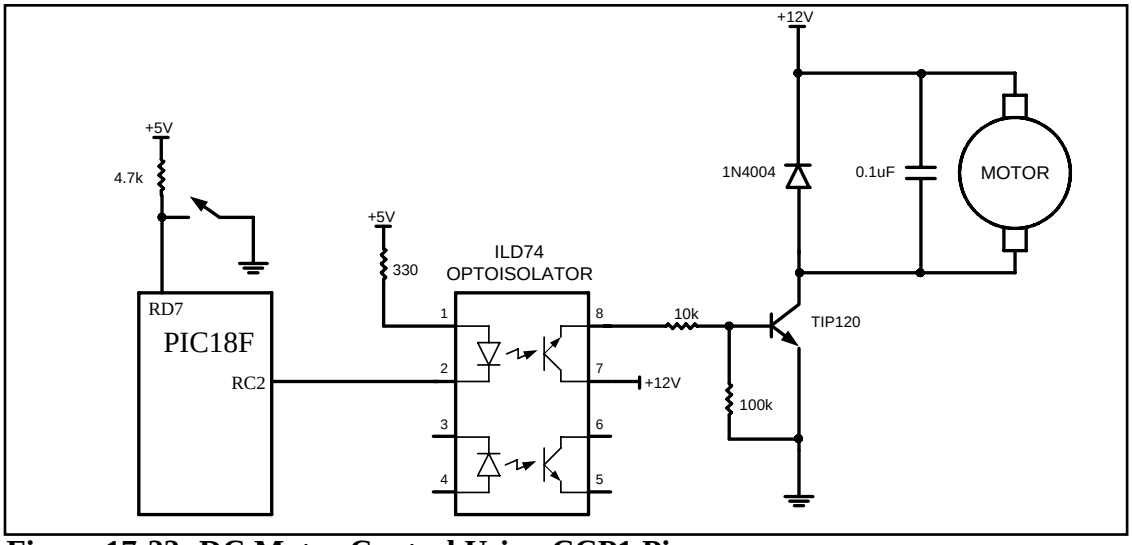


Figure 17-22: DC Motor Control Using CCP1 Pin

```
;Program 17-2
      BCF   TRISC,CCP1       ;make PWM output pin
      BSF   TRISD,RD7        ;make RD7 input pin
      MOVLW 0x3C             ;PWM MODE, 11 for DC1B1:B0
      MOVWF CCP1CON
      MOVLW D'100'           ;set period to 100 * Fosc/4
      MOVWF PR2
      MOVLW 0x01       ;Timer2, 4 prescale, no postscaler
      MOVWF T2CON
AGAIN BTFSS PORTD,RD7        ;Is the switch high?
      BRA T2DUTY             ;no, then 50%
      MOVLW D'25'            ;25% duty cycle
      BRA LOAD
T2DUTY MOVLW D'50'           ;50% duty cycle
```

```
      BRA LOAD
LOAD  MOVWF CCPR1L          ;load duty cycle
      CLRF   TMR2           ;clear Timer2
      BSF    T2CON,TMR2ON   ;turn on Timer2
      BCF    PIR1,TMR2IF    ;clear Timer2 flag
OVER  BTFSS PIR1,TMR2IF     ;wait for end of period
      BRA    OVER
      GOTO   AGAIN          ;continue
```

The following is the C version of the above program.

```
//Program 17-2C
#include <p18f458.h>
void main()
  {
  TRISC = 0xFB;             //make CCP1 output pin
  TRISD = 0x80;             //make RD7 input pin
  CCP1CON = 0x3C;           //PWM MODE, 11 for DC1B1:B0
  PR2=100;                  //set period to 100 * 16/Fosc
  T2CON=0x01;               //4 prescaler, no postscaler
  while(1)
    {
    if(PORTDbits.RD7==1)
      CCPR1L = 25;          //25% duty cycle
    else
      CCPR1L = 50;          //50% duty cycle
    TMR2=0x0;               //clear Timer2
    PIR1bits.TMR2IF=0;      //clear Timer2 flag
    T2CONbits.TMR2ON=1;     //start Timer2
    while(PIR1bits.TMR2IF==0);//wait for end of period
    }
  }
```

Review Questions

1. True or false. For standard CCP1, we use the RC2 pin for PWM.
2. True or false. For standard CCP1, the CCP1 pin must be configured as output.
3. In standard CCP1, we use _____ to set the period for PWM.
4. In standard CCP1, we use _____ to set the duty cycle for PWM.
5. True or false. In standard CCP1, we must use Timer1 for PWM.

SECTION 17.5: DC MOTOR CONTROL WITH ECCP

The PIC18F452/458 (or 4520/4580) comes with one standard CCP and one enhanced CCP (ECCP). Indeed, in recent years the CCP module has been de-emphasized while the ECCP is becoming more prominent in the PIC18 family. The reason is that ECCP allows the implementation of the H-Bridge for bidirectional control of the DC motor in addition to the capture/compare mode present in the standard CCP. In this section, we use the ECCP feature of the PIC18 to control the DC motor. Before embarking on this section, the basic concept of ECCP programming in Chapter 15 needs to be reviewed.

Bidirectional DC motor control with ECCP

ECCP allows the implementation of the H-Bridge for bidirectional movement of the DC motor because it uses 4 pins instead of a single pin as is used in standard CCP. As we saw in Section 17.3 of this chapter, the bidirectional DC movement needs some kind of H-Bridge circuitry. The ECCP module of the PIC18 implements the entire H-Bridge circuitry internally. It uses RD7–RD4 (PORTD.7–PORTD.4) for this purpose as shown in Figures 17-23 through 17-26.

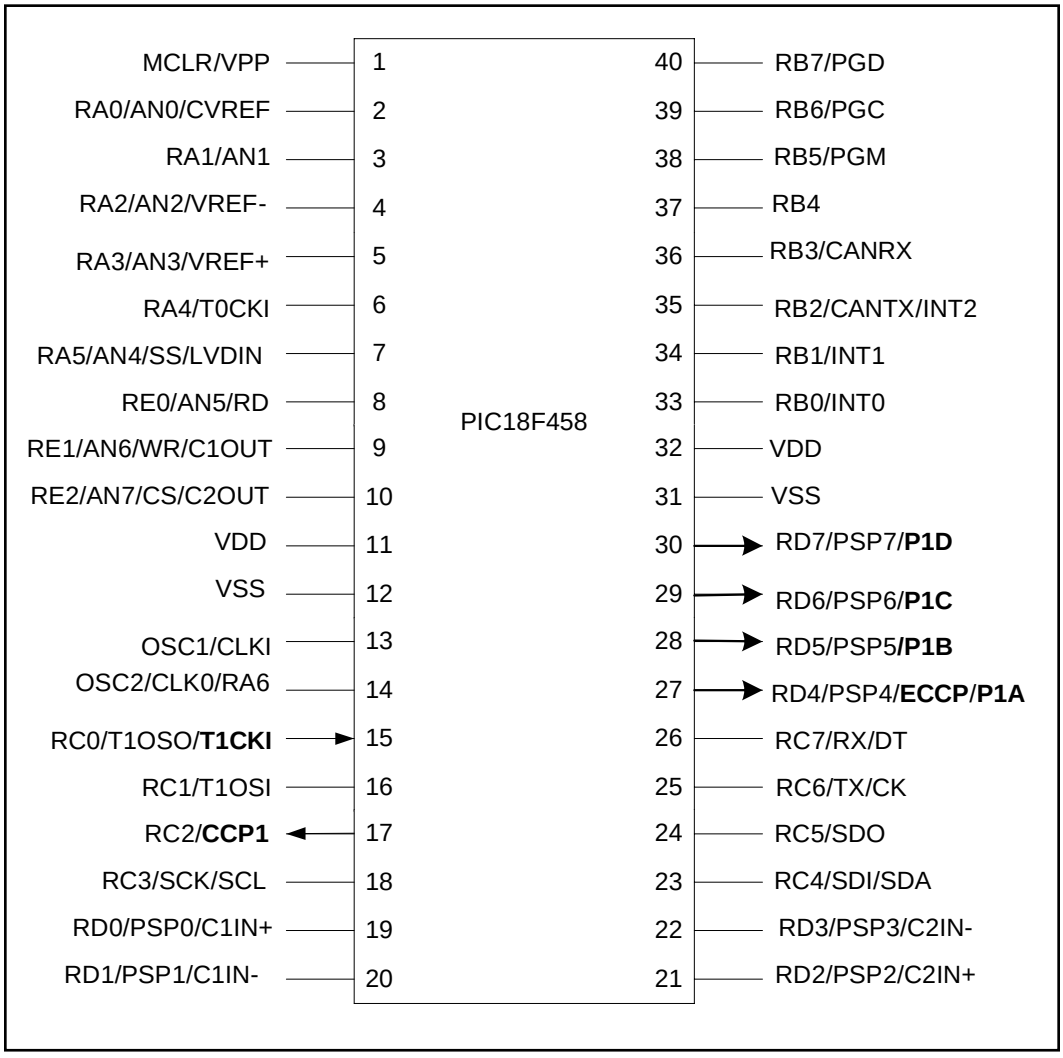


Figure 17-23. ECCP Pins for PWM in PIC18F458/4580 (452/4520)

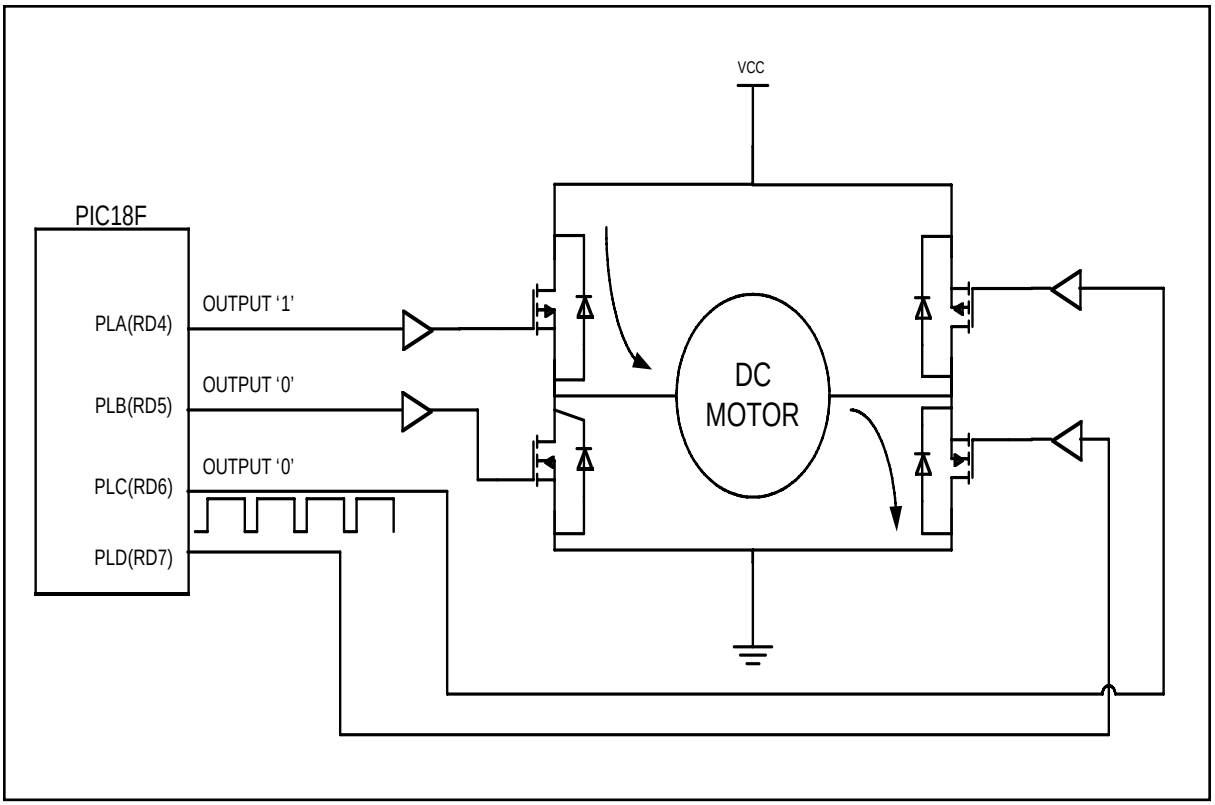


Figure 17-24. Forward Current Flow Using ECCP (from Microchip)

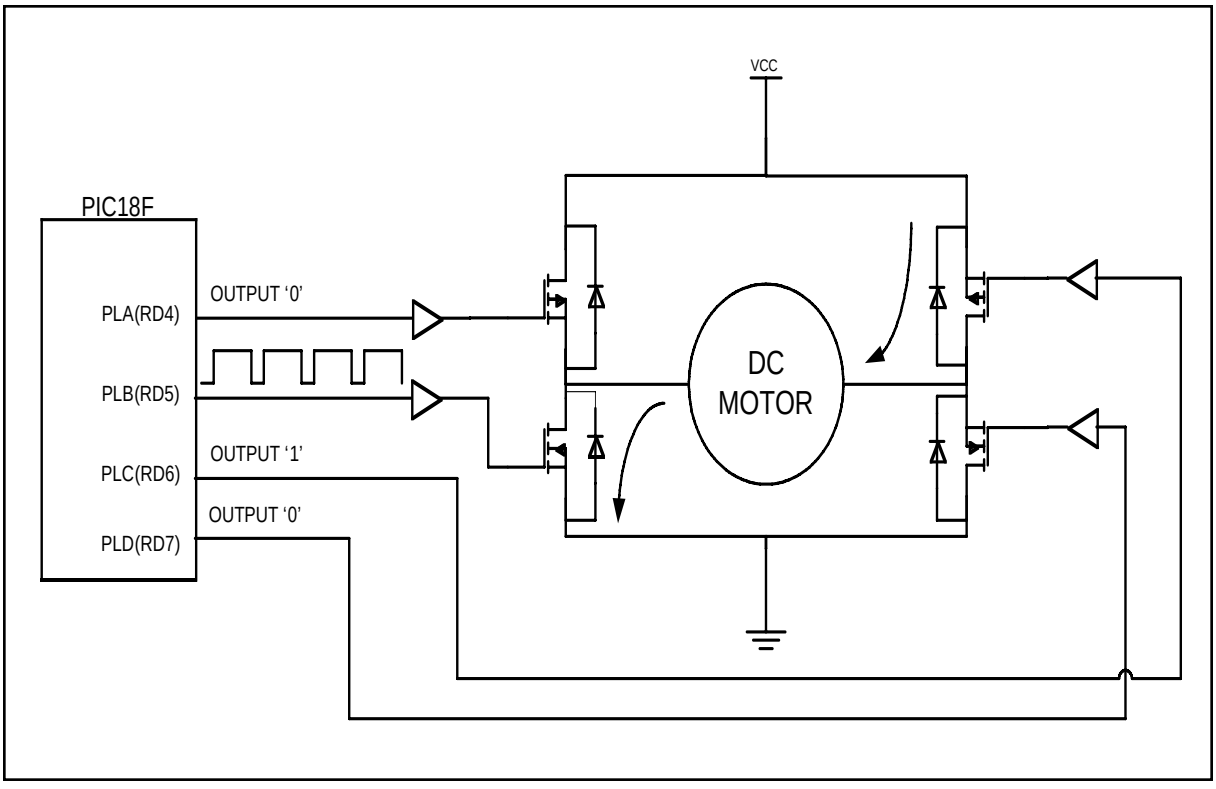


Figure 17-25. Reverse Current Flow Using ECCP (from Microchip)

EPWM1M1	EPWM1M0	EDC1B1	EDC1B0	ECCP1M3	ECCP1M2	ECCP1M1	ECCP1M0
D7							D0

EPWM1M1:EPWM1M0 PWM output pin configuration. It allows the use of a single pin for the capture/compare mode, or four pins for the PWM.
In compare/capture mode, only pin P1A (RD4) is used. In that case, there is no selection for these two bits.
In the PWM mode the options for these two bits are as follows:

00 P1A is used as a modulated output. P1B, P1C, and P1D are used as I/O.
01 Full-Bridge output forward. P1D modulated, P1A active. P1B and P1C inactive.

10 Half-Bridge output. P1A and P1D modulated with deadband control, P1C and P1D used as I/O.
11 Full-Bridge output reverse. P1B modulated, P1C active. P1A and P1D inactive.

EDC1B10:EDC1B1 PWM Duty Cycle least-significant bits. Used in PWM only.
The least-significant bits (Bit 1 and Bit 0) of the 10-bit duty cycle register are used in PWM. The ECCPR1L register is used as Bit 2 to Bit 9 of the 10-bit duty cycle register.

ECCP1M3–ECC1M0 ECCP1 Mode Select

0 0 0 0	ECCP1 is off
0 0 0 1	Reserved
0 0 1 0	Compare Mode. Toggle ECCP1 output pin on match. (ECCP1IF bit is set.)
0 0 1 1	Reserved
0 1 0 0	Capture mode, every falling edge
0 1 0 1	Capture mode, every rising edge
0 1 1 0	Capture mode, every 4th rising edge
0 1 1 1	Capture mode, every 16th rising edge
1 0 0 0	Compare mode. Initialize ECCP1 pin low; on compare match, force CCP1 pin HIGH. (ECCP1IF is set.)
1 0 0 1	Compare mode. Initialize CCP1 pin HIGH; on compare match, force CCP1 pin LOW. (ECCP1IF is set.)
1 0 1 0	Compare mode. Generate software interrupt on compare match. (ECCP1IF bit is set, ECCP1 pin is unaffected.)
1 0 1 1	Compare mode. Trigger special event. (ECCP1IF bit is set, and Timer1 or Timer3 is reset to zero.)
1 1 0 0	PWM Mode; P1A, P1C active-HIGH; P1B and P1D active-HIGH
1 1 0 1	PWM Mode; P1A, P1C active-HIGH; P1B and P1D active-LOW
1 1 1 0	PWM Mode; P1A, P1C active-LOW; P1B and P1D active-HIGH
1 1 1 1	PWM Mode; P1A, P1C active-LOW; P1B and P1D active-LOW

Figure 17-26. ECCP1 Control Register. (This register selects one of the operation modes of Capture, Compare, or PWM of EECP1)

Program 17-3 shows Full-Bridge implementation of the PWM for ECCP module. For the implementation of Half-Bridge and other applications of PWM using the ECCP module, see the PIC18 manual.

```
;Program 17-3
      CLRF TRISD            ;make PORTD output
      MOVLW D'100'
      MOVWF PR2             ;period = 100 * 16/Fosc
      MOVLW D'50'
      MOVWF ECCPR1L         ;duty = 50%
      MOVLW 0xCF
      MOVWF ECCP1CON        ;reverse full-bridge PWM
      MOVLW 0x24
      MOVWF T2CON           ;4 postscaler, turn on Timer2
AGAIN CLRF TMR2             ;start pulse
      BCF   PIR1,TMR2IF     ;clear flag
WAIT  BTFSS PIR1,TMR2IF     ;wait for period
      BRA   WAIT
      BRA   AGAIN           ;do it again
```

The following is the C version of the above program.

```
//Program 17-3C
#include <p18f458.h>

void main()
  {
      TRISD=0;              //make PORTD output
      PR2=100;              //period = 100 * 16/Fosc
      ECCPR1L=50;           //duty = 50%
      ECCP1CON=0xCF;        //reverse full-bridge PWM
      T2CON=0x24;           //4 postscaler,turn on Timer2
while(1)
      {
      TMR2=0;               //start pulse
      PIR1bits.TMR2IF=0;          //clear flag
      while(PIR1bits.TMR2IF==0); //wait for period
      }
  }
```

Review Questions

1. True or false. For ECCP1, we use the RD3–RD0 pins for Full-Bridge.
2. True or false. For ECCP1, the P1A to P1D pins must be configured as output.
3. In ECCP1, we use _____ to set the period for PWM.
4. In ECCP1, we use _____ to set the duty cycle for PWM.
5. True or false. In ECCP1, we must use Timer2 for PWM.

SUMMARY

This chapter continued showing how to interface the PIC18 with real-world devices. Devices covered in this chapter were the relay, optoisolator, stepper motor, and DC motor.

First, the basic operation of relays and optoisolators was defined, along with key terms used in describing and controlling their operations. Then the PIC18 was interfaced with a stepper motor. The stepper motor was then controlled via an optoisolator using PIC18 Assembly and C programming languages.

The PIC18 was interfaced with DC motors. A typical DC motor will take electronic pulses and convert them to mechanical motion. This chapter showed how to interface the PIC18 with a DC motor. Then, simple Assembly and C programs were written to show the concept of PWM.

Control systems that require motors must be evaluated for the type of motor needed. For example, you would not want to use a stepper in a high-velocity application or a DC motor for a low-speed, high-torque situation. The stepper motor is ideal in an open-loop positional system and a DC motor is better for a high-speed conveyer belt application. DC motors can be modified to operate in a closed-loop system by adding a shaft encoder, then using a microcontroller to monitor the exact position and velocity of the motor. In the last two sections, we showed how to use CCP and ECCP features of PIC18 to control DC motors.

PROBLEMS

SECTION 17.1: RELAYS AND OPTOISOLATORS

1. True or false. The minimum voltage needed to energize a relay is the same for all relays.
2. True or false. The minimum current needed to energize a relay depends on the coil resistance.
3 Give the advantages of a solid-state relay over an EM relay.
4. True or false. In relays, the energizing voltage is the same as the contact voltage.
5. Find the current needed to energize a relay if the coil resistance is 1,200 ohms and the coil voltage is 5 V.
6. Give two applications for an optoisolator.
7 Give the advantages of an optoisolator over an EM relay.
8. Of the EM relay and solid-state relay, which has the problem of back EMF?
9. True or false. The greater the coil resistance, the worse the back EMF voltage.
10. True or false. We should use the same voltage sources for both the coil voltage and contact voltage.

SECTION 17.2: STEPPER MOTOR INTERFACING

11. If a motor takes 90 steps to make one complete revolution, what is the step angle for this motor?
12. Calculate the number of steps per revolution for a step angle of 7.5 degrees.

13. Finish the normal four-step sequence clockwise if the first step is 0011 (binary).
14. Finish the normal four-step sequence clockwise if the first step is 1100 (binary).
15. Finish the normal four-step sequence counterclockwise if the first step is 1001 (binary).
16. Finish the normal four-step sequence counterclockwise if the first step is 0110 (binary).
17. What is the purpose of the ULN2003 placed between the PIC18 and the stepper motor? Can we use that for 3A motors?
18. Which of the following cannot be a sequence in the normal four-step sequence for a stepper motor?
    (a) CCH (b) DDH (c) 99H (d) 33H
19. What is the effect of a time delay between issuing each step?
20. In Question 19, how can we make a stepper motor go faster?

SECTION 17.3: DC MOTOR INTERFACING AND PWM

21. Which motor is best for moving a wheel exactly 90 degrees?
22. True or false. Current dissipation of a DC motor is proportional to the load.
23. True or false. The rpm of a DC motor is the same for no-load and loaded.
24. The rpm given in data sheets is for _____ (no-load, loaded).
25. What is the advantage of DC motors over AC motors?
26. What is the advantage of stepper motors over DC motors?
27. True or false. Higher load on a DC motor slows it down if the current and voltage supplied to the motor are fixed.
28. What is PWM, and how is it used in DC motor control?
29. A DC motor is moving a load. How do we keep the rpm constant?
30. What is the advantage of placing an optoisolator between the motor and the microcontroller?

ANSWERS TO REVIEW QUESTIONS

SECTION 17.1: RELAYS AND OPTOISOLATORS

1. With a relay we can use a 5 V digital system to control 12 V–120 V devices such as horns and appliances.
2. Because microcontroller/digital outputs lack sufficient current to energize the relay, we need a driver.
3. When the coil is not energized, the contact is closed.
4. When current flows through the coil, a magnetic field is created around the coil, which causes the armature to be attracted to the coil.
5. It is faster and needs less current to get energized.
6. It is smaller and can be connected to the microcontroller directly without a driver.

SECTION 17.2: STEPPER MOTOR INTERFACING

1. 0110, 0011, 1001, 1100 for clockwise; and 0110, 1100, 1001, 0011 for counterclockwise
2. 72
3. Because the microcontroller pins do not provide sufficient current to drive the stepper motor

SECTION 17.3: DC MOTOR INTERFACING AND PWM

1. True
2. False
3. Because microcontroller/digital outputs lack sufficient current to drive the DC motor, we need a driver.
4. By reversing the polarity of voltages connected to the leads
5. The DC motor is stalled if the load is beyond what it can handle.
6. False
7. No-load

SECTION 17.4: PWM MOTOR CONTROL WITH CCP

1. True
2. True
3. PR2
4. CCPR1L
5. False

SECTION 17.5: DC MOTOR CONTROL WITH ECCP

1. False
2. True
3. PR2
4. CCPR1L
5. True