CHAPTER 16

PWM PROGRAMMING AND DC MOTOR CONTROL IN AVR

OBJECTIVES

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

>> Describe the basic operation of a DC motor
>> Code AVR programs to control and operate a DC motor
>> Describe how PWM is used to control motor speed
>> Generate waves with different duty cycles using 8-bit and 16-bit timers
>> Code PWM programs to control and operate a DC motor

This chapter discusses the topic of PWM (pulse width modulation) and shows AVR interfacing with DC motors. The characteristics of DC motors are discussed along with their interfacing to the AVR. We use both Assembly and C programming examples to create PWM pulses.

SECTION 16.1: 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 AVR. 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 a 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, the small fans used in many motherboards to cool the CPU are run by DC motors. When the leads are connected 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 with 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 datasheet 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 consumption 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 16-1 shows the DC motor rotation for clockwise (CW) and counterclockwise (CCW) rotations. See Table 16-1 for selected DC motors.

Bidirectional control

With the help of relays or some specially designed chips we can change the direction of the DC motor rotation. Figures 16-2 through 16-4 show the basic concepts of H-bridge control of DC motors.

Table 16-1: 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

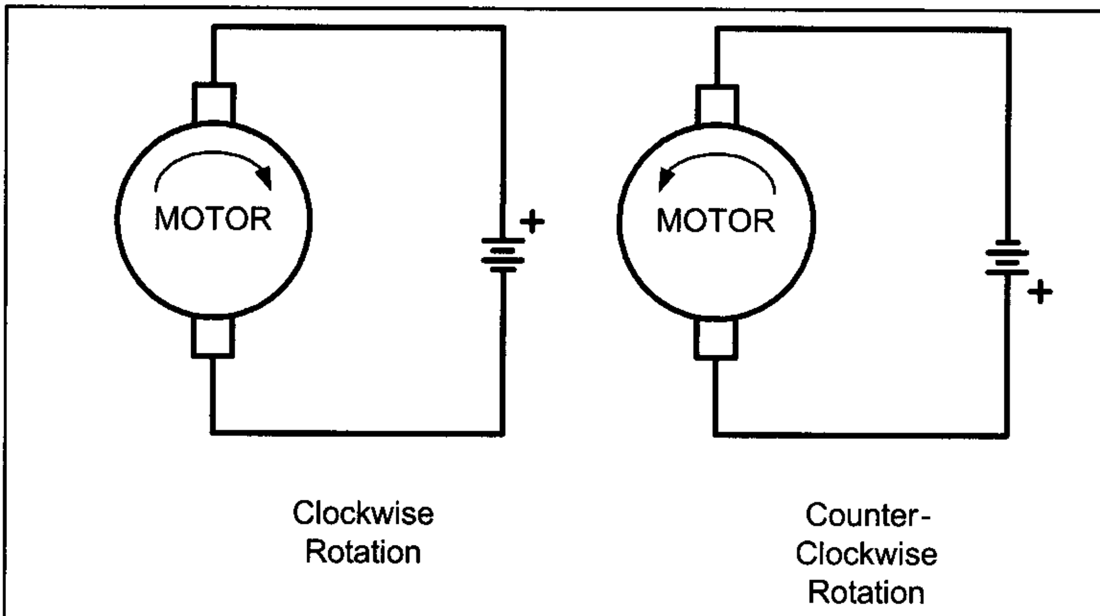


Figure 16-1. DC Motor Rotation (Permanent Magnet Field)

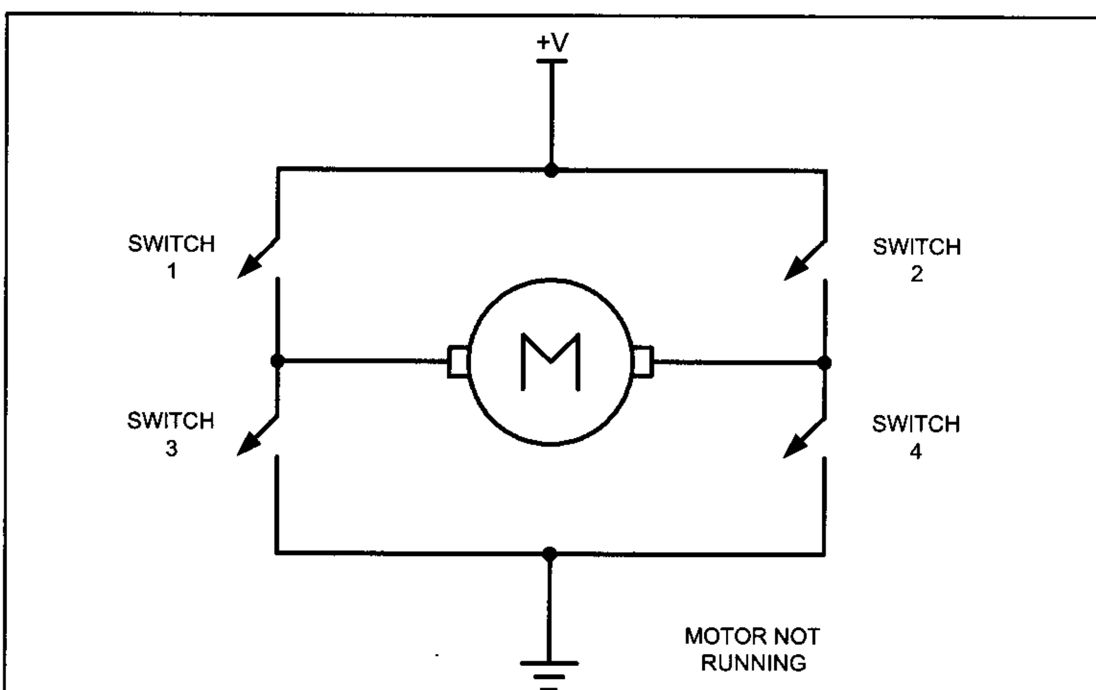


Figure 16-2. H-Bridge Motor Configuration

Figure 16-2 shows the connection of an H-bridge using simple switches. All the switches are open, which does not allow the motor to turn.

Figure 16-3 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 16-4 shows the switch configuration for turning the motor in the opposite direction from the configuration of Figure 16-3. When switches 2 and 3 are closed, current is allowed to pass through the motor.

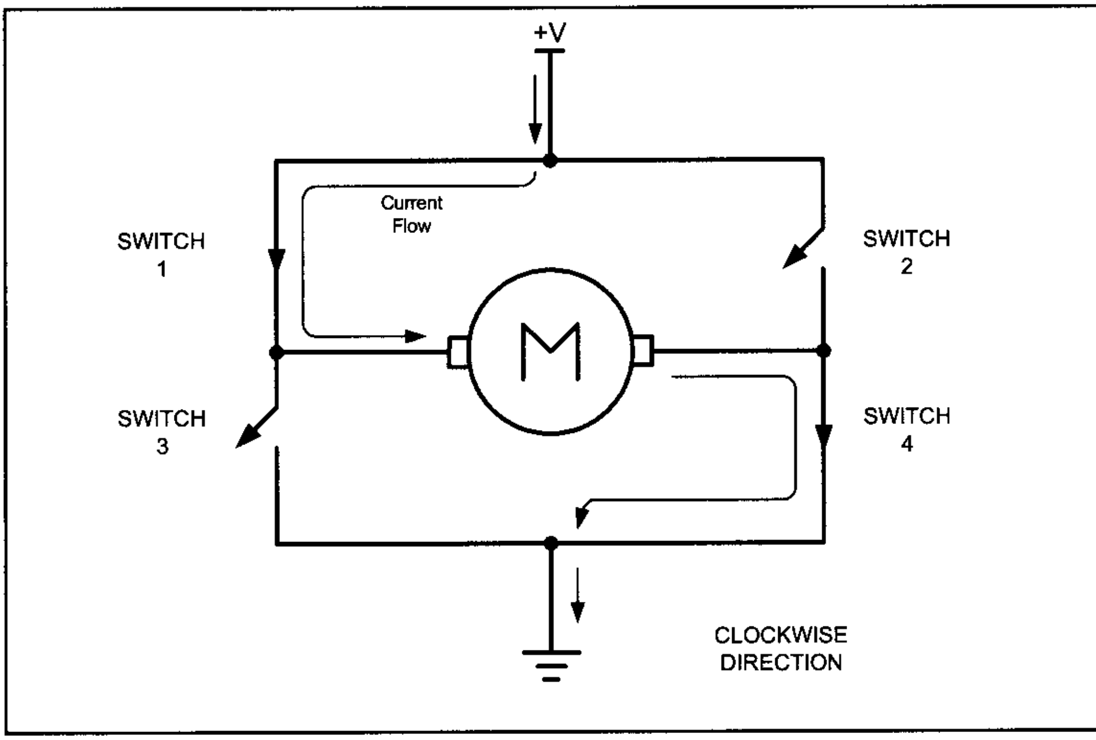


Figure 16-3. H-Bridge Motor Clockwise Configuration

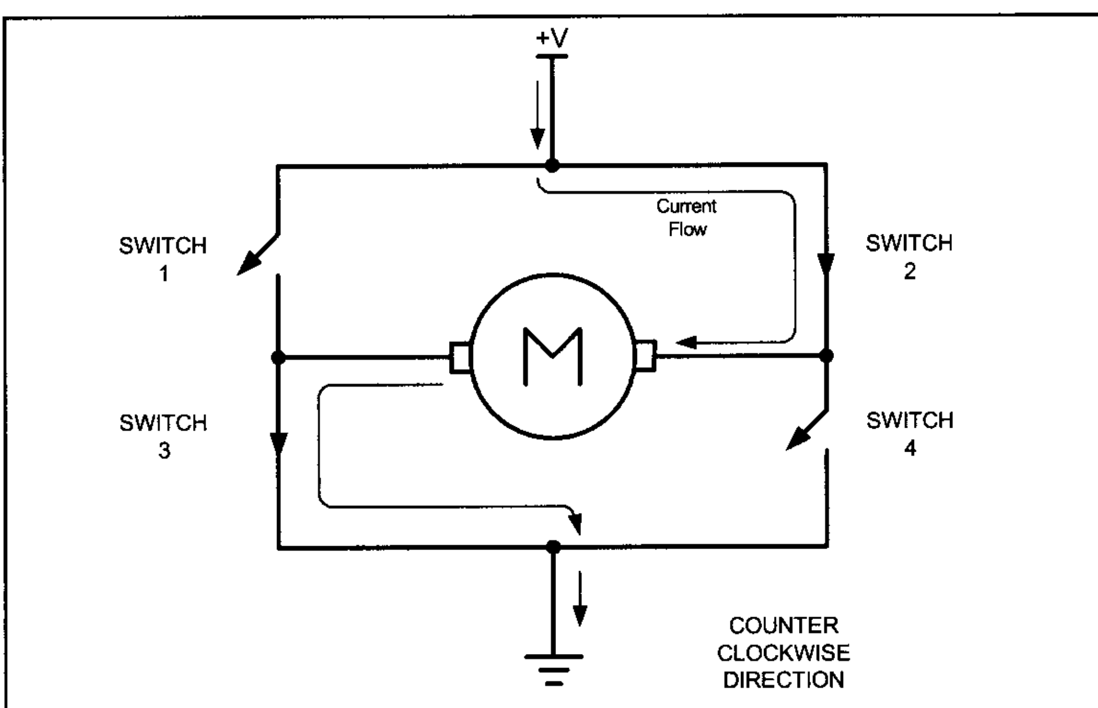


Figure 16-4. H-Bridge Motor Counterclockwise Configuration

Figure 16-5 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.

Table 16-2: Some H-Bridge Logic Configurations for Figure 16-2

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

Table 16-2 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 L298. When using relays and transistors, you must ensure that invalid configurations do not occur.

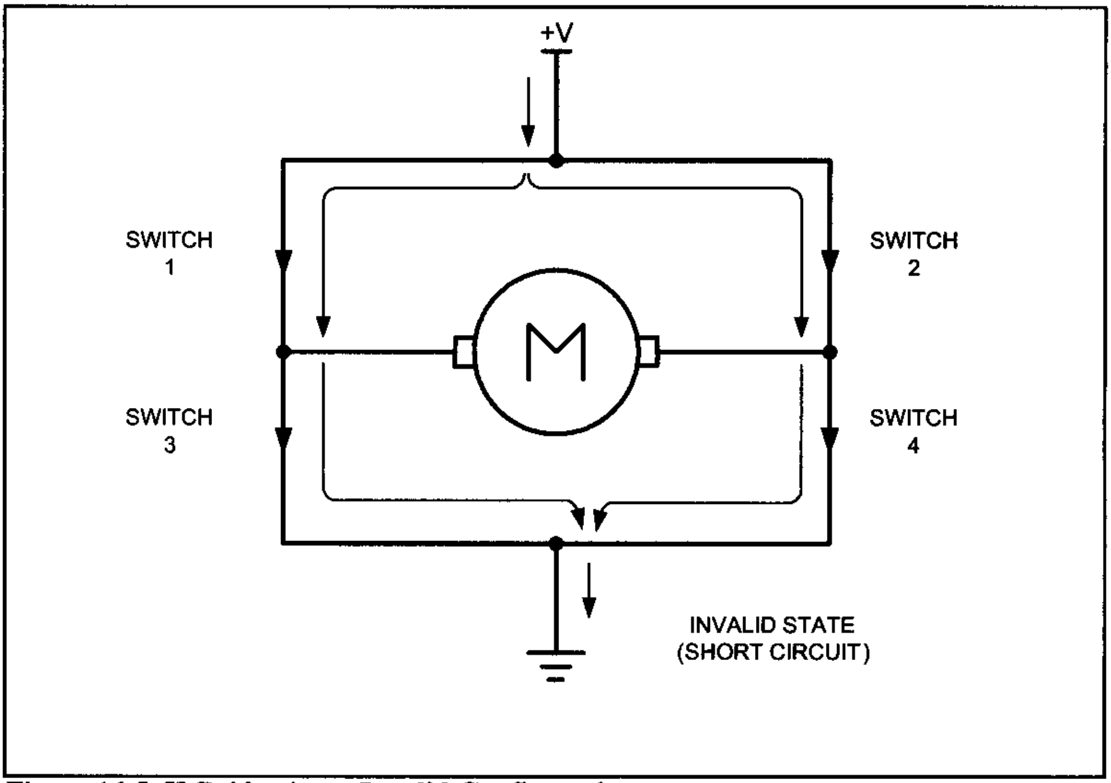


Figure 16-5. H-Bridge in an Invalid Configuration

Although we do not show the relay control of an H-bridge, Example 16-1 shows a simple program to operate a basic H-bridge.

Figure 16-6 shows the connection of the L298 to an AVR. Be aware that the L298 will generate heat during operation. For sustained operation of the motor, use a heat sink. Example 16-2 shows control of the L298.

Example 16-1

A switch is connected to pin PA7 (PORTA.7). Using a simulator, write a program to simulate the H-bridge in Table 16-2. We must perform the following:
(a) If PA7 = 0, the DC motor moves clockwise.
(b) If PA7 = 1, the DC motor moves counterclockwise.

Solution:

```
.INCLUDE "M32DEF.INC"
          SBI  DDRB,0       ;make PB0 an output (switch1)
          SBI  DDRB,1       ;make PB1 an output (switch2)
          SBI  DDRB,2       ;make PB2 an output (switch3)
          SBI  DDRB,3       ;make PB3 an output (switch4)
          CBI  DDRA,7       ;make PA7 an input
MONITOR:  SBIS PINA,7       ;skip next if PINA.7 is set
          RJMP CLKWISE      ;if PA7 = 0 go to CLKWISE
          CBI  DDRB,1       ;switch2 = 0
          CBI  DDRB,2       ;switch3 = 0
          SBI  DDRB,0       ;switch1 = 1
          SBI  DDRB,3       ;switch4 = 1
          JMP  MONITOR
CLKWISE:  CBI  DDRB,0       ;switch1 = 0
          CBI  DDRB,3       ;switch4 = 0
          SBI  DDRB,1       ;switch2 = 1
          SBI  DDRB,2       ;switch3 = 1
          JMP  MONITOR
```

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

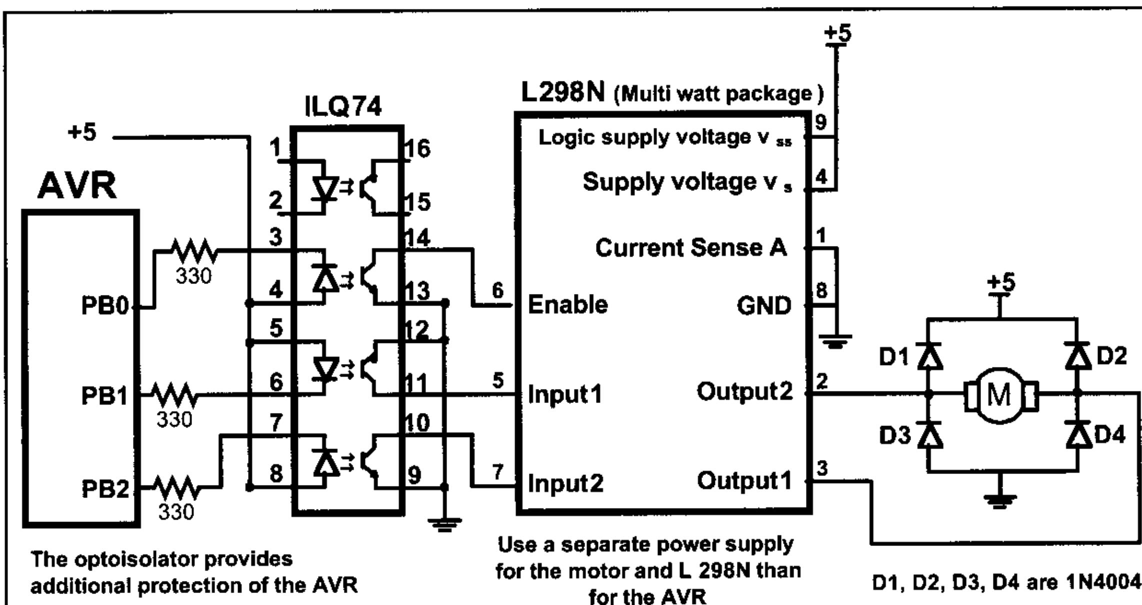


Figure 16-6. Bidirectional Motor Control Using an L298 Chip

DC motor control with optoisolator

As we discussed in Chapter 14, the optoisolator is indispensable in many motor control applications. Figures 16-6 through 16-8 show the connections to a

Example 16-2

Figure 16-6 shows the connection of an L298. Add a switch to pin PA7 (PORTA.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:

```
.INCLUDE "M32DEF.INC"
            SBI   DDRB,0           ;make PB0 an output (Enable)
            SBI   DDRB,1           ;make PB1 an output (clock)
            SBI   DDRB,2           ;make PB2 an output (counter)
            SBI   PORTB,0          ;Enable = 1
            CBI   DDRA,7           ;make PA7 an input
            SBI   PORTA,7
MONITOR:    SBIS  PINA,7           ;skip next if PINA.7 is set
            RJMP  CLKWISE          ;if PA7 = 0 go to CLKWISE
            CBI   PORTB,1          ;switch1 = 0
            SBI   PORTB,2          ;switch2 = 1
            JMP   MONITOR
CLKWISE:    SBI   PORTB,1          ;switch1 = 0
            CBI   PORTB,2          ;switch2 = 1
            JMP   MONITOR
```

simple DC motor using an optoisolator. Notice that the AVR is protected from EMI created by motor brushes by using an optoisolator and a separate power supply.

Figures 16-7 and 16-8 show optoisolators for 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 circuit.

Figure 16-7 shows the connection of a bipolar transistor to a motor. Protection of the control circuit is provided by the optoisolator. The motor and

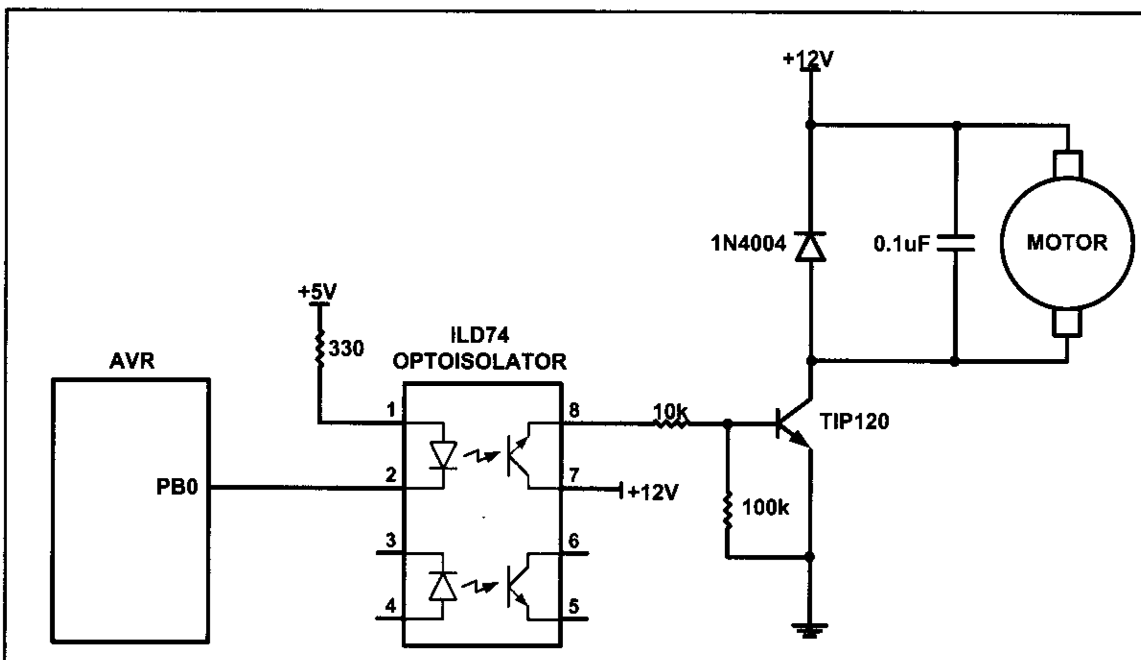


Figure 16-7. DC Motor Connection Using a Darlington Transistor

AVR 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 PB0.

Figure 16-8 shows the connection of a MOSFET transistor. The optoisolator protects the AVR from EMI. The zener diode is required for the transistor to reduce gate voltage below the rated maximum value. See Example 16-3.

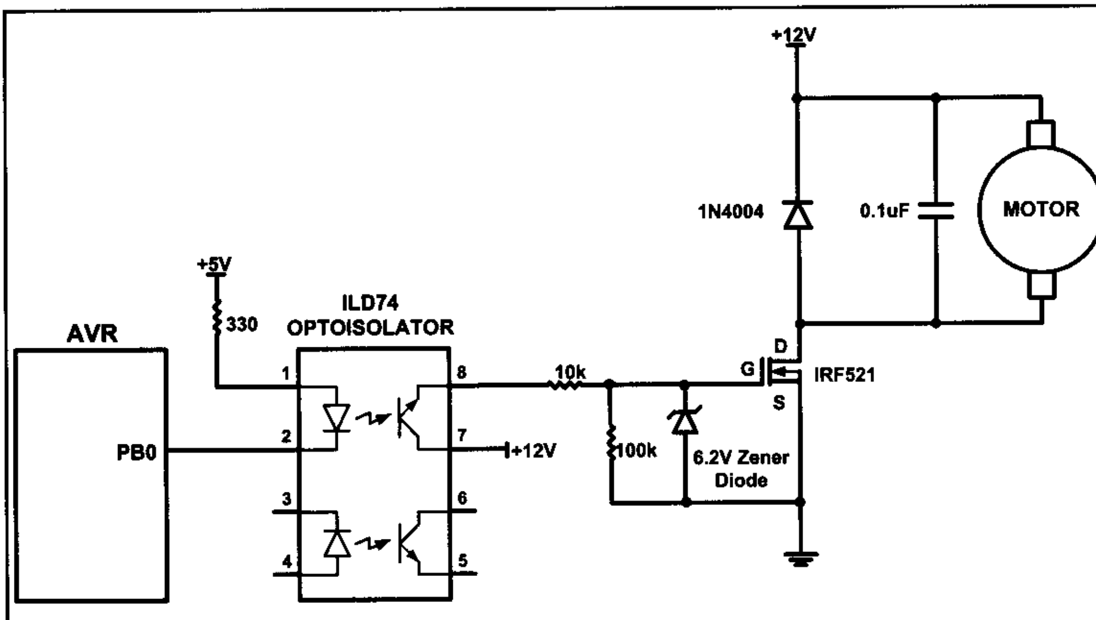


Figure 16-8. DC Motor Connection Using a MOSFET Transistor

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 often preferred 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. See Figure 16-9 for PWM comparisons.

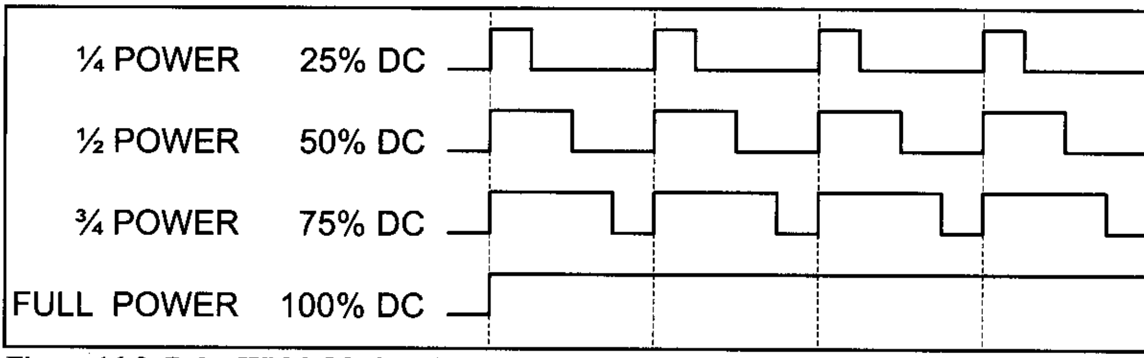
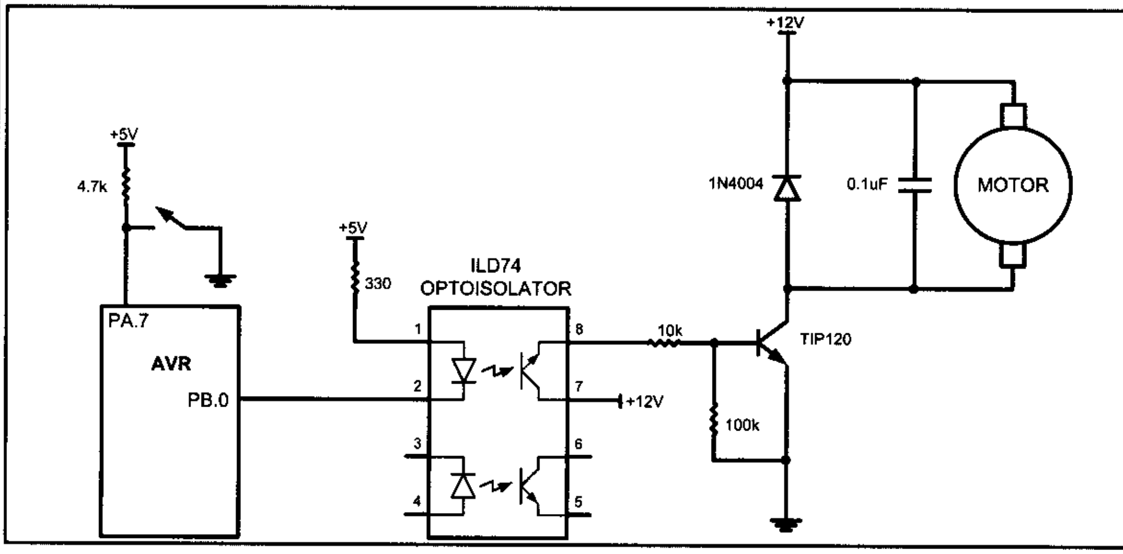


Figure 16-9. Pulse Width Modulation Comparisons

Example 16-3

Refer to the figure in this example. Write a program to monitor the status of the switch and perform the following:
(a) If PORTA.7 = 1, the DC motor moves with 25% duty cycle pulse.
(b) If PORTA.7 = 0, the DC motor moves with 50% duty cycle pulse.



Solution:

```
.INCLUDE "M32DEF.INC"
      LDI   R16,HIGH(RAMEND)
      OUT   SPH,R16
      LDI   R16,LOW(RAMEND)
      OUT   SPL,R16          ;initialize stack pointer
      SBI   DDRB,0           ;PORTB.0 as output
      CBI   DDRA,7           ;PORTA.7 as input
      SBI   PORTA,7          ;enable pull-up
      CBI   PORTB,0          ;turn off motor
CHK:  SBIC  PINA,7
      RJMP  P50
      SBI   PORTB,0          ;high portion of pulse
      RCALL DELAY
      RCALL DELAY
      RCALL DELAY
      CBI   PORTB,0          ;low portion of pulse
      RCALL DELAY
      RJMP  CHK
```

Example 16-3 (Cont.)

```
P50: SBI   PORTB,0        ;high portion of pulse
     RCALL DELAY
     RCALL DELAY
     CBI   PORTB,0        ;low portion of pulse
     RCALL DELAY
     RCALL DELAY
     RJMP  CHK
```

DC motor control and PWM using C

Examples 16-4 through 16-5 show the C versions of the earlier programs controlling the DC motor.

Example 16-4 (C version of Example 16-2)

Refer to Figure 16-6 for connection of the motor. A switch is connected to pin PA7. 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 "avr/io.h"

#define ENABLE 0
#define MTR_1 1
#define MTR_2 2
#define SW (PINA&0x80)
int main ( )
{
     DDRA = 0x7F;      //make PA7 input pin
     DDRB = 0xFF;      //make PORTB output pin
     PORTB = PORTB & (~(1<<ENABLE));
     PORTB = PORTB & (~(1<<MTR_1));
     PORTB = PORTB & (~(1<<MTR_2));

     while (1)
     {
          PORTB = PORTB | (1<<ENABLE);

          if(SW == 1)
          {
               PORTB = PORTB | (1<<MTR_1);       //MTR_1 = 1
               PORTB = PORTB & (~(1<<MTR_2));    //MTR_2 = 0
          }
          else{
               PORTB = PORTB & (~(1<<MTR_1));  //MTR_1 = 0
               PORTB = PORTB | (1<<MTR_2);     //MTR_2 = 1
          }
     }
     return 0;
}
```

Example 16-5 (C version of Example 16-3)

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

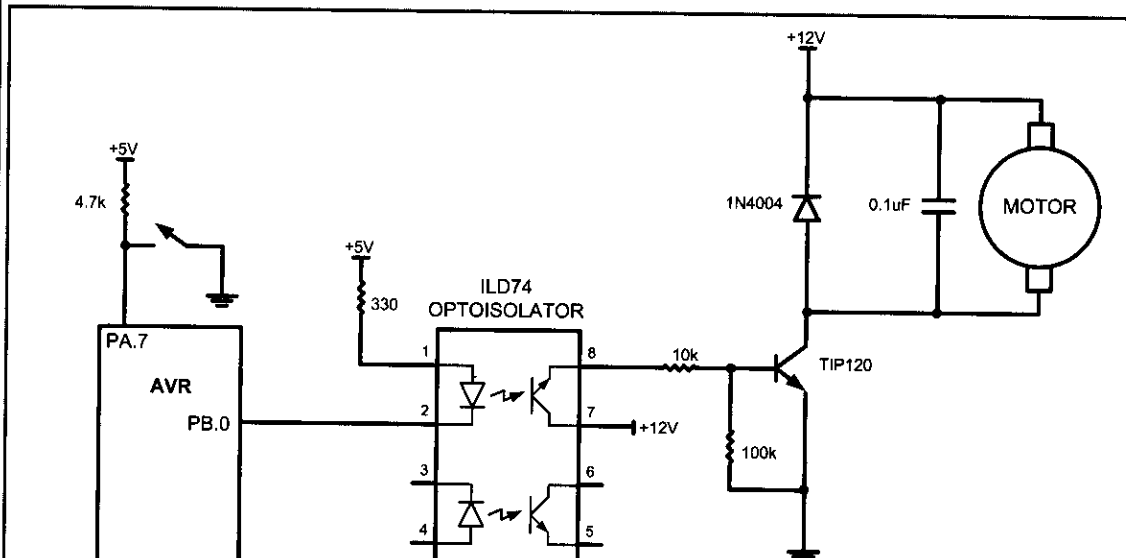
(a) If SW = 0, the DC motor moves with 50% duty cycle pulse.
(b) If SW = 1, the DC motor moves with 25% duty cycle pulse.

Solution:

```
#define F_CPU    8000000UL      //XTAL = 8 MHz
#define SW       (PORTA&(1<<7))

#include "avr/io.h"
#include "util/delay.h"

void main()
{
    DDRA=0x7F;          //make PA7 input pin
    DDRB=0x01;          //make PB0 output pin
    while(1)
    {
        if(SW == 1)
        {
            PORTB = PORTB | (1<<0);
            _delay_ms(75);
            PORTB = PORTB & (~(1<<0));
            _delay_ms(25);
        }
        else
        {
            PORTB = PORTB | (1<<0);
            _delay_ms(50);
            PORTB = PORTB & (~(1<<0));
            _delay_ms(50);
        }
    }
}
```



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. The RPM rating given for the DC motor is for __________ (no-load, loaded).

SECTION 16.2: PWM MODES IN 8-BIT TIMERS

This section and the next section discuss the PWM feature of the AVR. The ATmega32 comes with three timers, which can be used as wave generators, as shown in Figure 16-10. In the first section of this chapter we showed how to use the

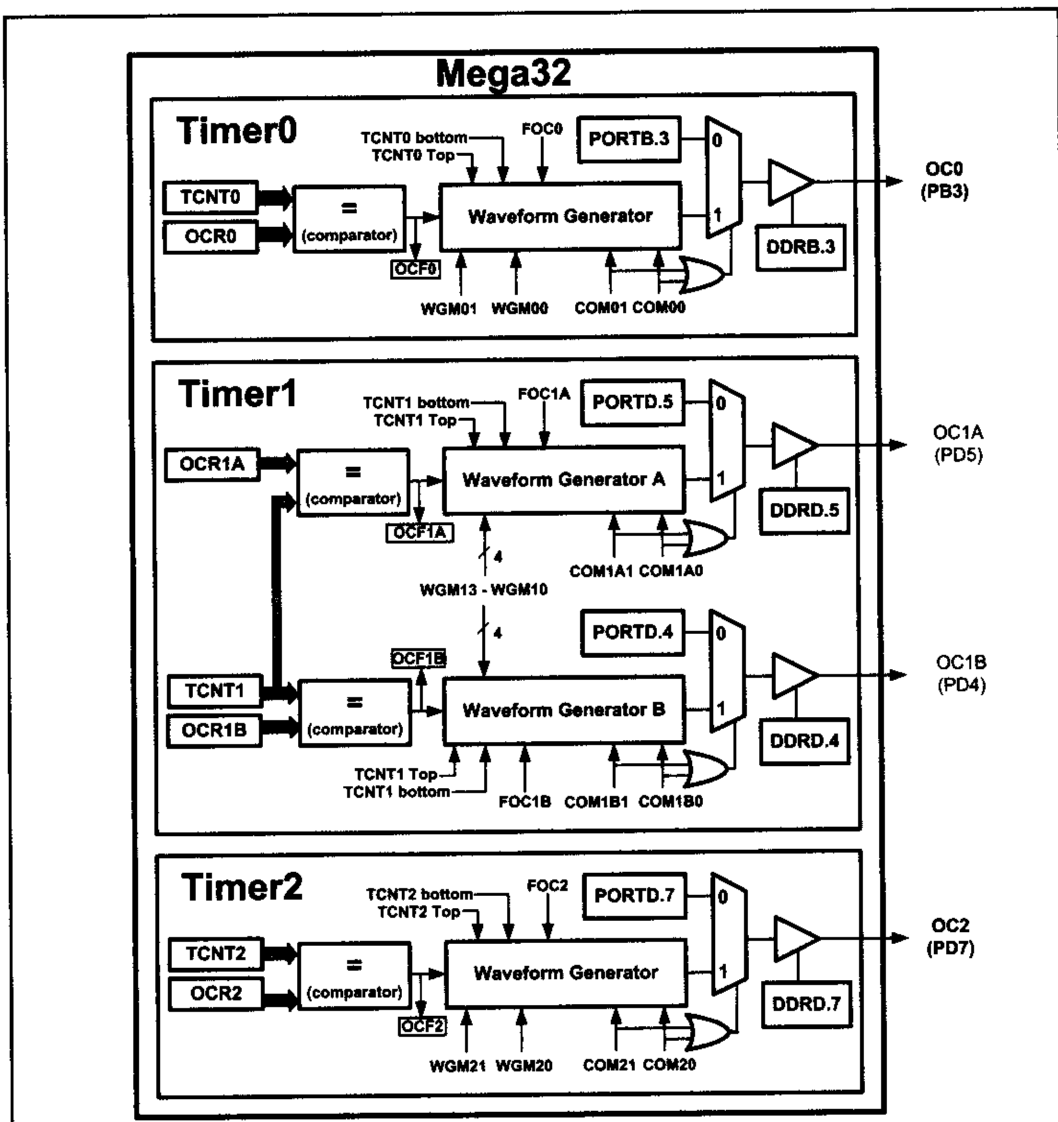


Figure 16-10. Waveform Generator

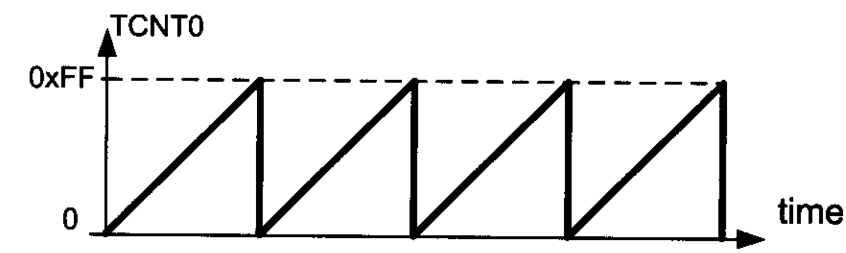


Figure 16-11. Timer/Counter 0 Fast PWM mode

CPU itself to create the equivalent of PWM outputs. The advantage of using the built-in PWM feature of the AVR is that it gives us the option of programming the period and duty cycle, therefore relieving the CPU to do other important things.

Fast PWM mode

In the Fast PWM, the counter counts like it does in the Normal mode. After the timer is started, it starts to count up. It counts up until it reaches its limit of 0xFF. When it rolls over from 0xFF to 00, it sets HIGH the TOV0 flag. See Figure 16-11.

In Figure 16-12 you see the reaction of the waveform generator when compare match occurs while the timer is in Fast PWM mode.

Bit	7	6	5	4	3	2	1	0
	FOC0	WGM00	COM01	COM00	WGM01	CS02	CS01	CS00
Read/Write	W	RW	RW	RW	RW	RW	RW	RW
Initial Value	0	0	0	0	0	0	0	0

FOC0 D7 Force compare match: it is a write-only bit, which can be used while generating a wave. Writing 1 to it causes the wave generator to act as if a compare match has occurred (see Chapter 15).

WGM01:00 D3D6 Timer0 mode selector bit

0	0	Normal
0	1	PWM, Phase correct
1	0	CTC (Clear Timer on Compare match)
1	1	Fast PWM

COM01:00 D5 D4 Compare Output Mode when Timer0 is in Fast PWM mode

COM01	COM00	Mode Name	Description
0	0	Disconnected	Normal port operation, OC0 disconnected
0	1	Reserved	Reserved
1	0	Non-inverted	Clear OC0 on compare match, set OC0 at TOP
1	1	Inverted PWM	Set OC0 on compare match, clear OC0 at TOP

CS02:00 D2D1D0 Timer0 clock selector

0	0	0	No clock source (Timer/Counter stopped)
0	0	1	clk (no prescaling)
0	1	0	clk / 8
0	1	1	clk / 64
1	0	0	clk / 256
1	0	1	clk / 1024
1	1	0	External clock source on T0 pin. Clock on falling edge
1	1	1	External clock source on T0 pin. Clock on rising edge

Figure 16-12. TCCR0 (Timer/Counter Control Register) Register

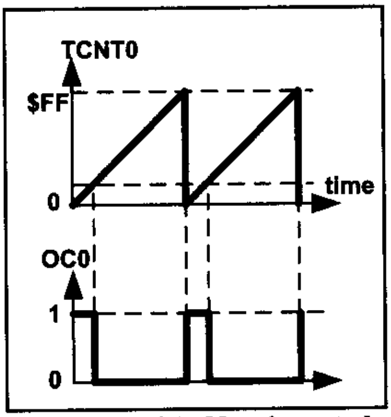


Figure 16-13A. Non-inverted

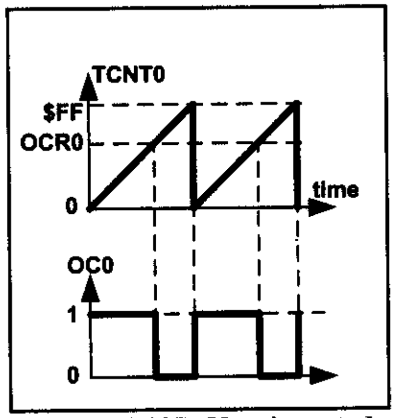


Figure 16-13B. Non-inverted

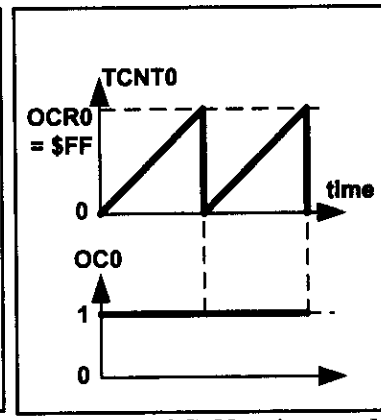


Figure 16-13C. Non-inverted

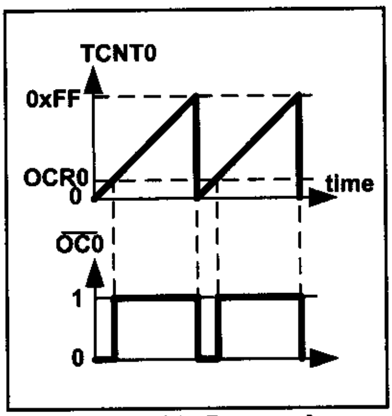


Figure 16-14A. Inverted

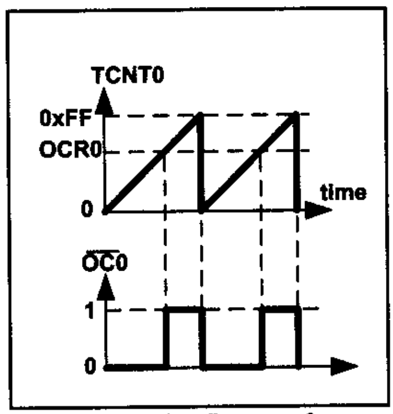


Figure 16-14B. Inverted

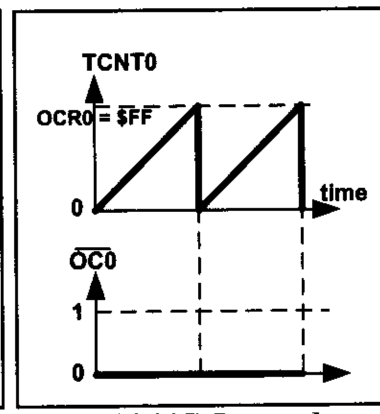


Figure 16-14C. Inverted

When COM01:00 = 00 the OC0 pin operates as an I/O port. When COM01:00 = 10, the waveform generator clears the OC0 pin whenever compare match occurs, and sets it at top. This mode is called *non-inverted PWM.* See Figures 16-13A through 16-13C. As you see from these figures, in the non-inverted PWM, the duty cycle of the generated wave increases when the value of OCR0 increases.

When COM01:00 = 11, the waveform generator sets the OC0 pin whenever compare match occurs, and clears it at top. This mode is referred as inverted PWM mode. See Figures 16-14A through 16-14C. As you see, in the inverted PWM mode when the value of OCR0 increases, the duty cycle of the generated wave decreases.

Frequency of the generated wave in Fast PWM mode

In Fast PWM mode, the timer counts from 0 to top (0xFF in 8-bit counters) and then rolls over. So, the frequency of the generated wave is 1/256 of the frequency of timer clock. As you saw in Section 9-1, the frequency of the timer clock can be selected using the prescaler. So, in 8-bit timers the frequency of the generated wave can be calculated as follows (N is determined by the prescaler):

$$\left.\begin{aligned} F_{\text{generated wave}} &= \frac{F_{\text{timer clock}}}{256} \\ F_{\text{timer clock}} &= \frac{F_{\text{oscillator}}}{N} \end{aligned}\right\} \Longrightarrow F_{\text{generated wave}} = \frac{F_{\text{oscillator}}}{256 \times N}$$

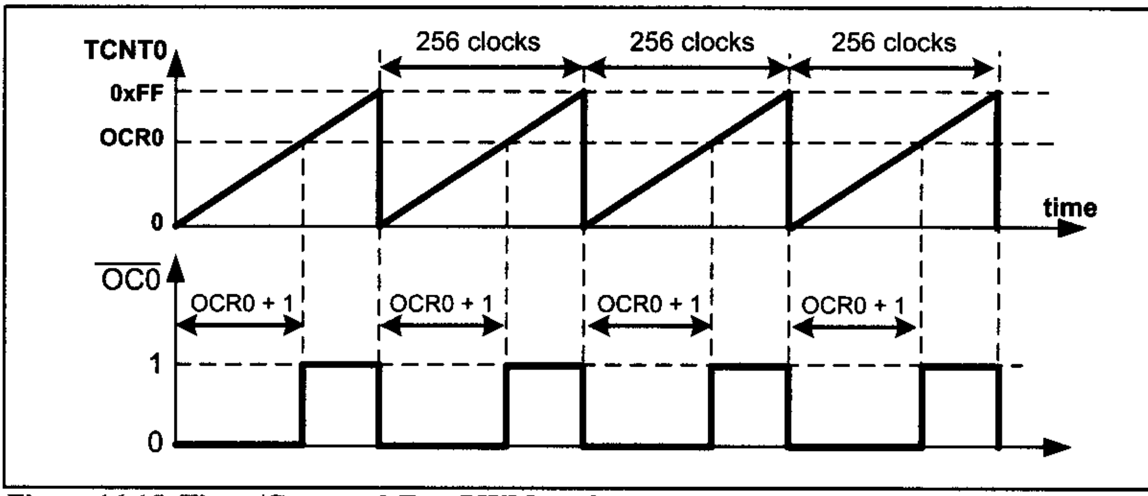


Figure 16-15. Timer/Counter 0 Fast PWM mode

Duty cycle of the generated wave in Fast PWM mode

The duty cycle of the generated mode can be determined using the OCR0 register. When COM01:00 = 10 (in non-inverted mode), the bigger OCR0 value results in a bigger duty cycle; When OCR0 = 255, the OC0 is 256 clocks out of 256 clocks, which means always high (duty cycle = 100%). Generally speaking, the OC0 is high, for a total of OCR0 + 1 clocks. See Figure 16-15. So, the duty cycle can be calculated using the following formula in non-inverted mode:

$$\text{Duty Cycle} = \frac{\text{OCR0} + 1}{256} \times 100$$

Similarly, the duty cycle formula for inverted mode is as follows:

$$\text{Duty Cycle} = \frac{255 - \text{OCR0}}{256} \times 100$$

Examine Figures 16-13 and 16-14 once again, and then examine Examples 16-6 through 16-10.

Example 16-6

To generate a wave with duty cycle of 75% in non-inverted mode, calculate the OCR0.

Solution:

75 = (OCR0 + 1) × 100 / 256 ➔ OCR0 + 1 = 75 × 256 / 100 = 192 ➔ OCR0 = 191

Example 16-7

Find the value for TCCR0 to initialize Timer0 for Fast PWM mode, non-inverted PWM wave generator, and no prescaler.

Solution:

WGM01:00 = 11 = Fast PWM mode
COM01:00 = 10 = Non-inverted PWM
CS02:00 = 001 = No prescaler

TCCR0 =

FOC0	WGM00	COM01	COM00	WGM01	CS02	CS01	CS00
0	1	1	0	1	0	0	1

Example 16-8

Assuming XTAL = 8 MHz, using non-inverted mode, write a program that generates a wave with frequency of 31,250 Hz and duty cycle of 75%.

Solution:

31,250 = 8M / (256 × N) ➔ N = 8M / (31,250 × 256) = 1 ➔ N = 1 ➔ No prescaler

```
.INCLUDE "M32DEF.INC"
      SBI   DDRB,3
      LDI   R20,191     ;from Example 16-6
      OUT   OCR0,R20    ;OCR0 = 191
      LDI   R20,0x69    ;from Example 16-7
      OUT   TCCR0,R20   ;Fast PWM, no prescaler, non-inverted
HERE: RJMP  HERE        ;infinite loop
```

Notice that instead of the infinite loop we can use the CPU to perform other things.

Example 16-9

Assuming XTAL = 8 MHz, using non-inverted mode, write a program that generates a wave with frequency of 3906.25 Hz and duty cycle of 37.5%.

Solution:

3906.25 = 8M / (256 × N) ➔ N = 8M / (3906.25 × 256) = 8 ➔ the prescaler value = 8
37.5 = 100 × (OCR0 + 1) / 256 ➔ OCR0 + 1 = (256 × 37.5) / 100 = 96 ➔ OCR0 = 95

```
.INCLUDE "M32DEF.INC"
      SBI   DDRB,3
      LDI   R20,95
      OUT   OCR0,R20    ;OCR0 = 95
      LDI   R20,0x6A
      OUT   TCCR0,R20   ;Fast PWM, N = 8, non-inverted
HERE: RJMP  HERE
```

Example 16-10

Rewrite Example 16-9 using inverted mode.

Solution:

37.5 = 100 × (255 – OCR0)/256 ➔ 255 – OCR0 = (256 × 37.5)/100 = 96 ➔ OCR0 = 159

```
.INCLUDE "M32DEF.INC"
      SBI   DDRB,3
      LDI   R20,159
      OUT   OCR0,R20    ;OCR0 = 159
      LDI   R20,0x7A
      OUT   TCCR0,R20   ;Fast PWM, N = 8, inverted
HERE: RJMP  HERE
```

Loading values into the OCRx register in PWM modes

In the non-PWM modes (CTC mode and Normal mode), when we load a value into the OCR0 register, the value will be loaded instantly into the OCR0 register, but in the PWM modes (Fast PWM and Phase correct PWM), there is a buffer between us and the OCR0 register. When we read/write a value from/into the OCR0 we are dealing with the buffer. The contents of the buffer will be loaded into the OCR0 register only when the TCNT0 reaches to its topmost value. The top value is 0xFF in the 8-bit timers. See Figure 16-16 and Example 16-11.

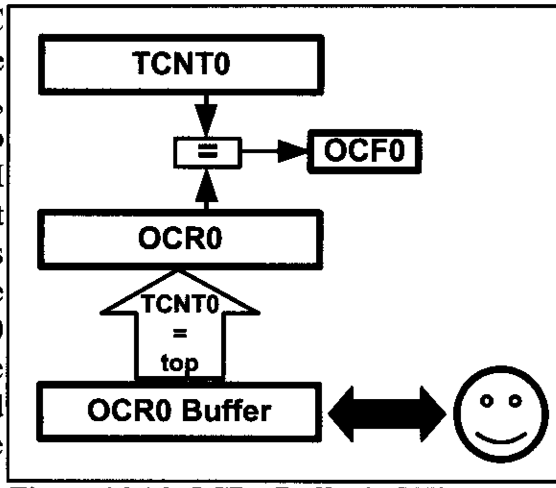


Figure 16-16. OCRn Buffer in PWM Modes

Example 16-11

Draw the wave generated by the following program. Assume XTAL = 1 MHz.

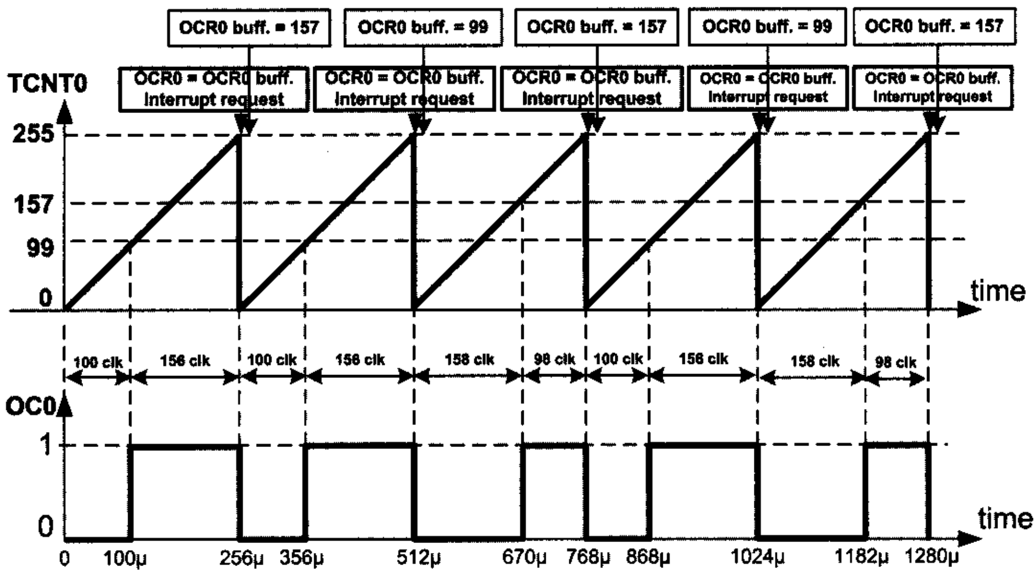
```
      .INCLUDE "M32DEF.INC"
      RJMP  MAIN
      .ORG  0x16              ;Timer0 overflow interrupt vector
      NEG   R20               ;Negative R20
      OUT   OCR0,R20          ;OCR0 = R20
      RETI                    ;return interrupt
MAIN:
      LDI   R16,HIGH(RAMEND)
      OUT   SPH,R16
      LDI   R16,LOW(RAMEND)
      OUT   SPL,R16           ;initialize stack
      SBI   DDRB,3            ;OC0 as output
      LDI   R20,99            ;R20 = 99
      OUT   OCR0,R20          ;OCR0 = 99
      LDI   R16,0x69     ;Fast PWM mode, non-inverted, no prescaler
      OUT   TCCR0,R16
      OUT   OCR0,R20          ;OCR0 buffer = 99
      LDI   R16,(1<<TOIE0)    ;enable overflow interrupt
      OUT   TIMSK,R16
      SEI                     ;enable interrupt
HERE: RJMP  HERE              ;wait here
```

Solution:

The wave generator is in non-inverted Fast PWM mode, which means that on compare match the OC0 pin will be set high. The OCR0 register is loaded with 99; so compare match occurs when TCNT0 reaches 99. When the timer reaches the top value and overflows, the interrupt request occurs, and the OCR0 buffer is loaded with 157 (the two's

Example 16-11 (Cont.)

complement of 99). The next time that the timer reaches the top value, the contents of the OCR0 buffer (157) will be loaded into the OCR0 register. Then the second interrupt occurs and the OCR0 buffer will be loaded with 99 (the two's complement of 157).



Phase correct PWM mode programming of Timer0

In the Phase correct PWM, the TCNT0 goes up and down like a yo-yo! First it counts up until it reaches the top value. Then it counts down until it reaches zero. The TOV0 flag is set whenever it reaches zero. See Figure 16-17.

Phase correct PWM mode

In Figure 16-18 you see the reaction of the waveform generator when compare match occurs in Phase correct PWM mode. When COM01:00 = 00 the OC0 pin operates as an I/O port. When COM01:00 = 10, the waveform generator clears the OC0 pin on compare match when counting up, and sets it on compare match when counting down. This mode is called *non-inverted Phase correct PWM*. See Figures 16-19A through 16-19C.

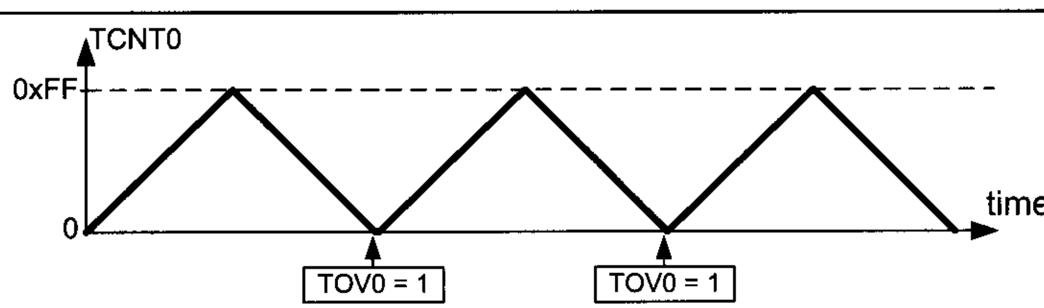


Figure 16-17. Timer/Counter 0 Phase Correct PWM Mode

Bit	7	6	5	4	3	2	1	0
	FOC0	WGM00	COM01	COM00	WGM01	CS02	CS01	CS00
Read/Write	W	RW	RW	RW	RW	RW	RW	RW
Initial Value	0	0	0	0	0	0	0	0

FOC0 D7 Force compare match: This is a write-only bit, which can be used while generating a wave. Writing 1 to it causes the wave generator to act as if a compare match had occurred (Chapter 11).

WGM01:00 D3D6 Timer0 mode selector bit

0 0	Normal
0 1	PWM, Phase correct
1 0	CTC (Clear Timer on Compare match)
1 1	Fast PWM

COM01:00 D5 D4 Compare Output Mode when Timer0 is in Phase correct PWM mode:

COM01	COM00	Description
0	0	Normal port operation, OC0 disconnected
0	1	Reserved
1	0	Clear OC0 on compare match when up-counting. Set OC0 on compare match when down-counting.
1	1	Set OC0 on compare match when up-counting. Clear OC0 on compare match when down-counting.

CS02:00 D2D1D0 Timer0 clock selector

0 0 0	No clock source (Timer/Counter stopped)
0 0 1	clk (no prescaling)
0 1 0	clk / 8
0 1 1	clk / 64
1 0 0	clk / 256
1 0 1	clk / 1024
1 1 0	External clock source on T0 pin. Clock on falling edge
1 1 1	External clock source on T0 pin. Clock on rising edge

Figure 16-18. TCCR0 (Timer/Counter Control Register) Register

When COM01:00 = 11, the waveform generator sets the OC0 pin on compare match when counting up, and clears it on compare match when counting down. This mode is referred as *inverted Phase correct PWM mode*. See Figures 16-20A through 16-20C.

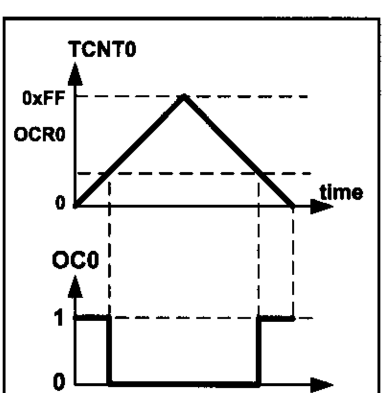


Figure 16-19A. Non-inverted

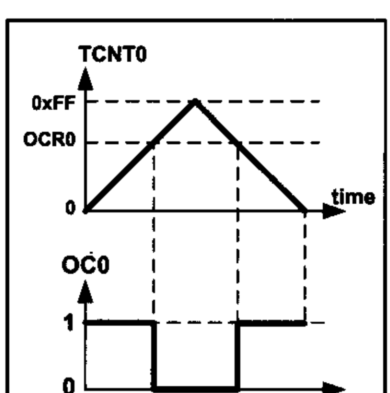


Figure 16-19B. Non-inverted

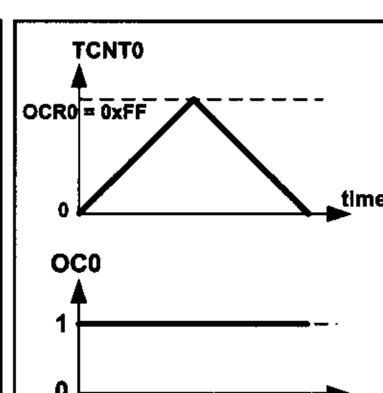


Figure 16-19C. Non-inverted

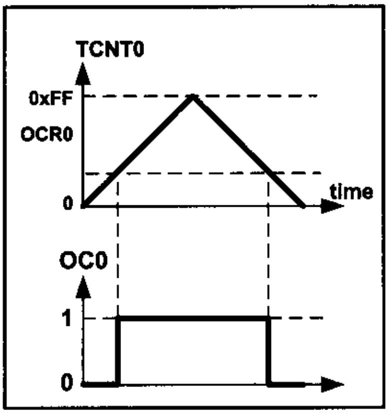


Figure 16-20A. Inverted

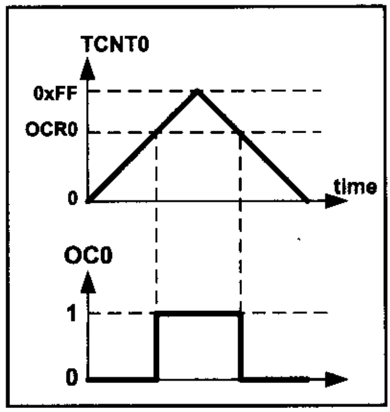


Figure 16-20B. Inverted

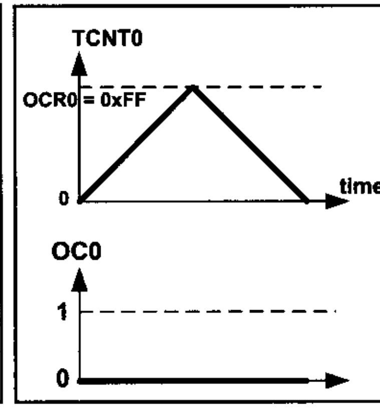


Figure 16-20C. Inverted

Frequency of the generated wave in Phase correct PWM mode

As you see in Figure 16-21, the frequency of the generated wave is 1/510 of the frequency of timer clock. As you saw in Section 9-1, the frequency of timer clock can be selected using the prescaler. So, in 8-bit timers the frequency of the generated wave can be calculated as follows:

$$\left.\begin{array}{l} F_{\text{generated wave}} = \dfrac{F_{\text{timer clock}}}{510} \\[2ex] F_{\text{timer clock}} = \dfrac{F_{\text{oscillator}}}{N} \end{array}\right\} \Longrightarrow F_{\text{generated wave}} = \frac{F_{\text{oscillator}}}{510 \times N}$$

Duty cycle of the generated wave in Phase correct PWM mode

The duty cycle of the generated mode can be determined using the OCR0 register. When COM01:00 = 10 (in non-inverted mode), the bigger OCR0 value results in a bigger duty cycle. When OCR0 = 255, the OC0 is high, 510 clocks out of 510 clocks, which means always (duty cycle = 100%). Generally speaking, the OC0 is high for a total of 2 × OCR0 clocks. See Figure 16-21. So, the duty cycle

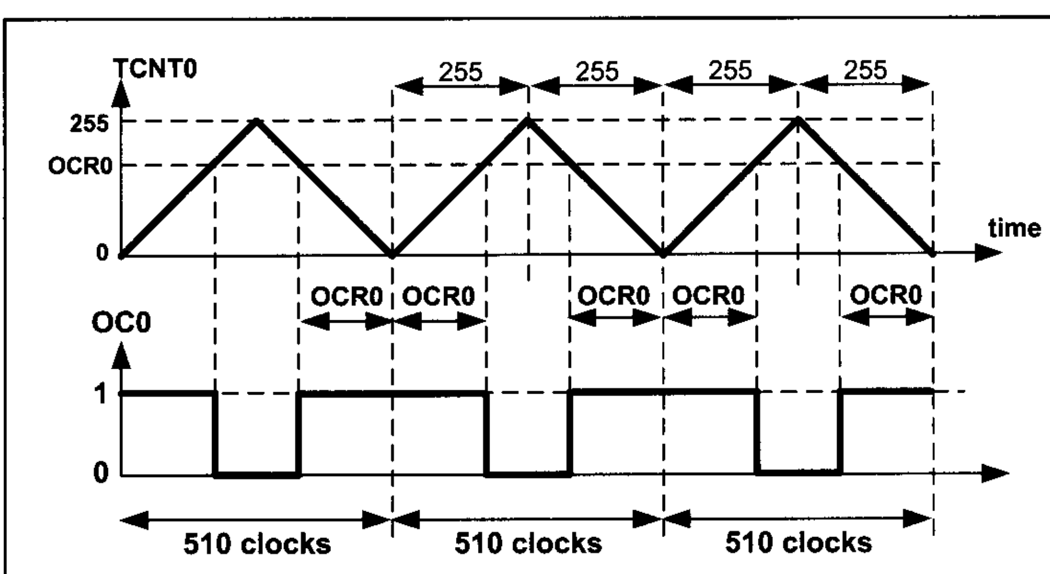


Figure 16-21. Phase Correct PWM

can be calculated using the following formula in non-inverted mode:

$$\text{Duty Cycle} = \frac{2 \times \text{OCR0}}{510} \times 100 \Longrightarrow \text{Duty Cycle} = \frac{\text{OCR0}}{255} \times 100$$

Similarly, the duty cycle formula for inverted mode is as follows:

$$\text{Duty Cycle} = \frac{510 - 2 \times \text{OCR0}}{510} \times 100 \Longrightarrow \text{Duty Cycle} = \frac{255 - \text{OCR0}}{255} \times 100$$

See Examples 16-12 through 16-15.

Example 16-12

Find the value for TCCR0 for Phase correct PWM, non-inverted PWM wave generator, and no prescaler.

Solution:

WGM01:00 = 01 = Phase correct PWM mode
COM01:00 = 10 = Non-inverted PWM
CS02:00 = 001 = No prescaler

TCCR0 =

FOC0	WGM00	COM01	COM00	WGM01	CS02	CS01	CS00
0	1	1	0	0	0	0	1

Example 16-13

Assuming XTAL = 8 MHz, using non-inverted mode, write a program that generates a wave with frequency of 15,686 Hz and duty cycle of 75%.

Solution:

15,686 = 8M / (510 × N) ➔ N = 8M / (15,626 × 510) = 1 ➔ No prescaler
75 = OCR0 × 100 / 255 ➔ OCR0 = 75 × 255 / 100 = 191 ➔ OCR0 = 191

```
.INCLUDE "M32DEF.INC"
      SBI   DDRB,3
      LDI   R20,191
      OUT   OCR0,R20   ;OCR0 = 191
      LDI   R20,0x61
      OUT   TCCR0,R20  ;Phase c. PWM, no prescaler, non-inverted
HERE: RJMP  HERE
```

Comparing the program with the program in Example 16-8, you see that they are almost the same. The only difference is that the TCCR0 is loaded with 0x61 instead of 0x69.

Example 16-14

Find the value for TCCR0 for Phase correct PWM, inverted PWM wave generator, and prescaler = 256.

Solution:

WGM01:00 = 01 = Phase correct PWM mode
COM01:00 = 11 = Inverted PWM
CS02:00 = 100 = Scale 256

TCCR0 =

0	1	1	1	0	1	0	0
FOC0	WGM00	COM01	COM00	WGM01	CS02	CS01	CS00

Example 16-15

Assuming XTAL = 8 MHz, using inverted mode, write a program that generates a wave with frequency of 61 Hz and duty cycle of 87.5%.

Solution:

$61 = 8M/(510 \times N) \rightarrow N = 8M/(61 \times 510) = 256$
$87.5 = 100 \times (255 - OCR0)/255 \rightarrow 255 - OCR0 = (255 \times 87.5)/100 = 223 \rightarrow OCR0 = 32$

```
.INCLUDE "M32DEF.INC"
      SBI   DDRB,3      ;OC0 as output
      LDI   R20,32
      OUT   OCR0,R20    ;OCR0 = 32
      LDI   R20,0x74    ;from Example 16-14
      OUT   TCCR0,R20   ;Phase c. PWM, N = 256, inverted
HERE: RJMP  HERE
```

Difference between the wave generated by Phase correct PWM and Fast PWM

As you see in Figure 16-22, in Fast PWM, the phase of the wave is different for different duty cycles, while it remains unchanged in the Phase correct PWM as shown in Figure 16-23.

In non-inverted Fast PWM, the duty cycle of the generated wave is (OCR0+1)/256. Becuase the value of OCR0 is between 0 and 255, the duty cycle of the wave can be changed between 1/256 and 256/256. Therefore, in non-inverted Fast PWM the duty cycle of wave cannot be 0% (unless we turn off the waveform generator). Similarly, in inverted Fast PWM, the duty cycle changes between 0/256 and 255/256; thus, the duty cycle cannot be 100%. But in Phase correct PWM, the duty cycle changes between 0/255 and 255/255. Therefore, the wave can change between 0% (completely off) and 100% (completely on).

For driving motors, it is preferable to use Phase correct PWM rather than Fast PWM. In Fast PWM the frequency of the generated wave is twice that of the Phase correct mode. Thus, Fast PWM mode is preferable when we need to generate waves with high frequencies.

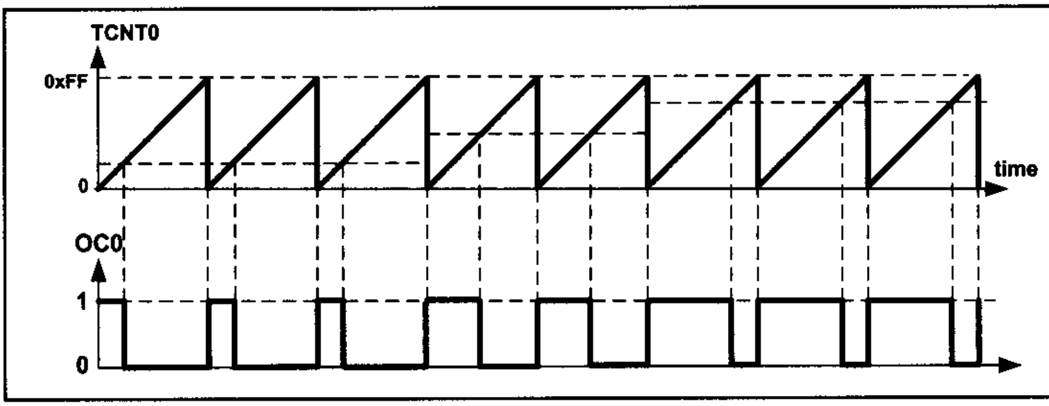


Figure 16-22. Fast PWM

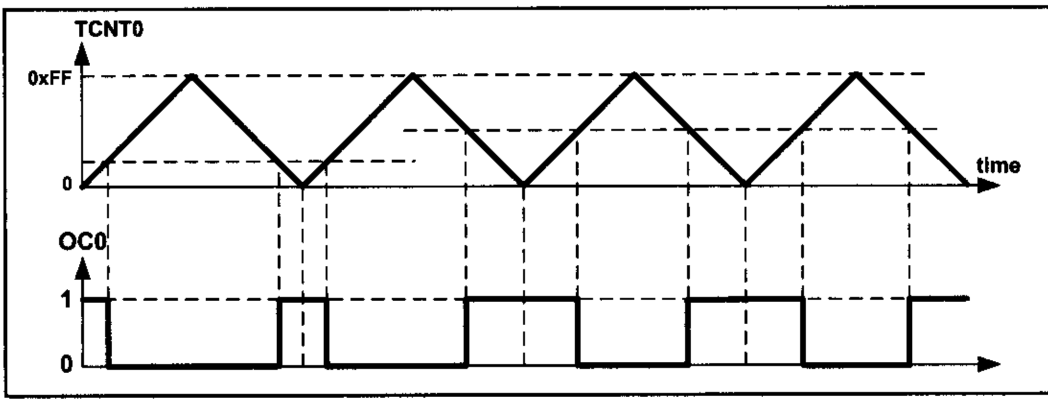


Figure 16-23. Phase Correct PWM

Generating waves using Timer2

Timer2 is an 8-bit timer. Therefore, it works similar to Timer0. The differences are register names, output port, and the prescaler values of TCCRn register. See Example 16-16.

Example 16-16

Rewrite Example 16-15 using Timer2.

Solution:

According to Figure 9-11, the TCCR2 register should be loaded with:

TCCR2 =	FOC2	WGM20	COM21	COM20	WGM21	CS22	CS21	CS20
	0	1	1	1	0	1	1	0

```
.INCLUDE "M32DEF.INC"
      SBI   DDRD,7      ;OC2 (PD7) as output
      LDI   R20,32
      OUT   OCR2,R20    ;OCR2 = 32
      LDI   R20,0x76
      OUT   TCCR2,R20   ;Phase correct PWM, N = 256, inverted
HERE: RJMP  HERE
```

8-bit PWM programming in C

Examples 16-17 through 16-22 show the C versions of the earlier programs creating PWM.

Example 16-17 (C version of Example 16-8)

Rewrite the program of Example 16-8 using C.

Solution:

```
#include "avr/io.h"
int main ()
{
	DDRB |= (1 << 3);
	OCR0 = 191;
	TCCR0 = 0x69; //Fast PWM, no prescaler, non-inverted
	while (1);
	return 0;
}
```

Example 16-18 (C version of Example 16-9)

Rewrite the program of Example 16-9 using C.

Solution:

```
#include "avr/io.h"
int main ()
{
	DDRB |= (1 << 3);
	OCR0 = 95;
	TCCR0 = 0x6A; //Fast PWM, no prescaler, non-inverted
	while (1);
	return 0;
}
```

Example 16-19 (C version of Example 16-10)

Rewrite the program of Example 16-10 using C.

Solution:

```
#include "avr/io.h"
int main ()
{
	DDRB |= (1 << 3);
	OCR0 = 159;
	TCCR0 = 0x7A; //Fast PWM, no prescaler, inverted
	while (1);
	return 0;
}
```

Example 16-20 (C version of Example 16-13)

Rewrite the program of Example 16-13 using C.

Solution:

```
#include "avr/io.h"

int main ()
{
      DDRB |= (1 << 3);
      OCR0 = 191;
      TCCR0 = 0x61; //Phase c. PWM, no prescaler, non-inverted
      while (1);
      return 0;
}
```

Example 16-21 (C version of Example 16-15)

Rewrite the program of Example 16-15 using C.

Solution:

```
#include "avr/io.h"

int main ()
{
      DDRB |= (1 << 3);
      OCR0 = 32;
      TCCR0 = 0x74; //Phase correct PWM, N = 256, inverted
      while (1);
      return 0;
}
```

Example 16-22 (C version of Example 16-16)

Rewrite the program of Example 16-16 using C.

Solution:

```
#include "avr/io.h"

int main ()
{
      DDRD |= (1 << 7);
      OCR2 = 32;
      TCCR2 = 0x76; //Phase correct PWM, N = 256, inverted
      while (1);
      return 0;
}
```

Review Questions

1. True or false. In Fast PWM and Phase correct PWM modes, we can change the duty cycle.
2. True or false. In Fast PWM, we cannot change the frequency of the wave.
3. True or false. For 8-bit timers, in Phase correct PWM mode, the period is 510 clocks.
4. True or false. In Fast PWM, phase does not change when the duty cycle is changed.
5. Which of the PWM modes is preferable for controlling motors?

SECTION 16.3: PWM MODES IN TIMER1

Fast PWM mode

In the Fast PWM, the counter counts like it does in the Normal mode. After the timer is started, it starts to count up. It counts up until it reaches its top limit. See Figure 16-24.

From Figure 16-30 we see that we have five Fast PWM modes in Timer1: modes 5, 6, 7, 14, and 15. In modes 5, 6, and 7 the top value is fixed at 0xFF, 0x1FF, and 0x3FF; while in modes 14 and 15, the ICR1 and OCR1A registers represent the top value, respectively. See Figures 16-25 through 16-29.

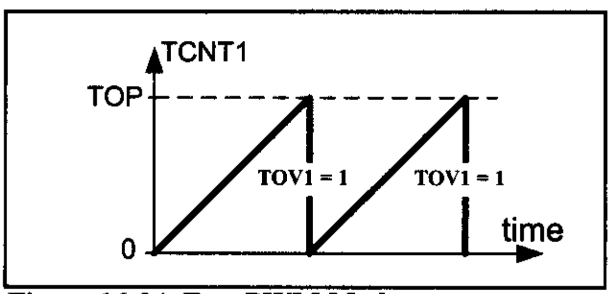


Figure 16-24. Fast PWM Mode

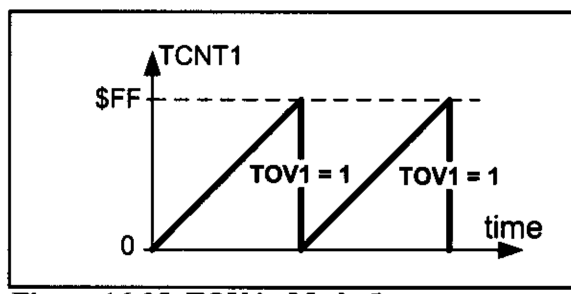


Figure 16-25. TOV in Mode 5

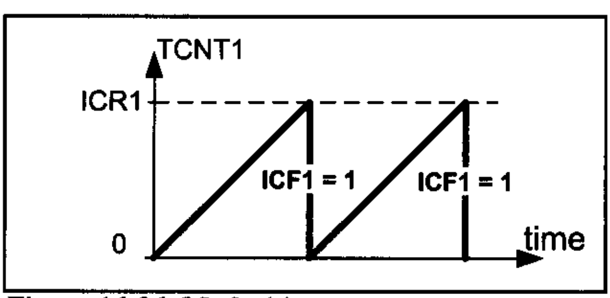


Figure 16-26. Mode 14

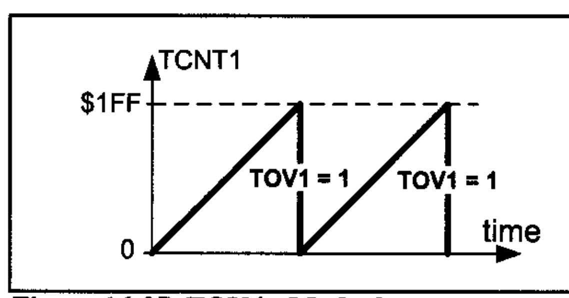


Figure 16-27. TOV in Mode 6

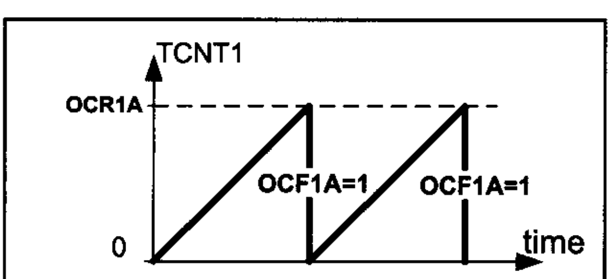


Figure 16-28. Mode 15

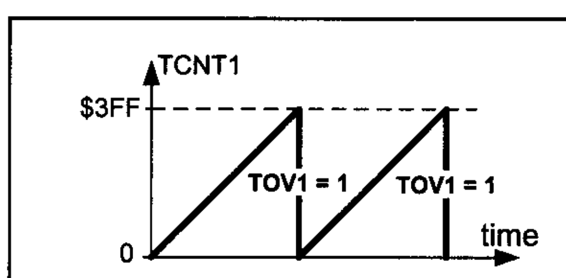


Figure 16-29. TOV in Mode 7

Bit	7	6	5	4	3	2	1	0	
	ICNC1	ICES1	–	WGM13	WGM12	CS12	CS11	CS10	**TCCR1B**
Read/Write	R/W	R/W	R	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

ICNC1 D7 Input Capture Noise Canceler
0 = Input Capture Noise Canceler is disabled.
1 = Input Capture Noise Canceler is enabled.

ICES1 D6 Input Capture Edge Select
0 = Capture on the falling (negative) edge
1 = Capture on the rising (positive) edge

D5 Not used

WGM13:WGM12 D4 D3 Timer1 mode

Mode	WGM13	WGM12	WGM11	WGM10	Timer/Counter Mode of Operation	Top	Update of OCR1x	TOV1 Flag Set on
0	0	0	0	0	Normal	0xFFFF	Immediate	MAX
1	0	0	0	1	PWM, Phase Correct, 8-bit	0x00FF	TOP	BOTTOM
2	0	0	1	0	PWM, Phase Correct, 9-bit	0x01FF	TOP	BOTTOM
3	0	0	1	1	PWM, Phase Correct, 10-bit	0x03FF	TOP	BOTTOM
4	0	1	0	0	CTC	OCR1A	Immediate	MAX
5	0	1	0	1	Fast PWM, 8-bit	0x00FF	TOP	TOP
6	0	1	1	0	Fast PWM, 9-bit	0x01FF	TOP	TOP
7	0	1	1	1	Fast PWM, 10-bit	0x03FF	TOP	TOP
8	1	0	0	0	PWM, Phase and Frequency Correct	ICR1	BOTTOM	BOTTOM
9	1	0	0	1	PWM, Phase and Frequency Correct	OCR1A	BOTTOM	BOTTOM
10	1	0	1	0	PWM, Phase Correct	ICR1	TOP	BOTTOM
11	1	0	1	1	PWM, Phase Correct	OCR1A	TOP	BOTTOM
12	1	1	0	0	CTC	ICR1	Immediate	MAX
13	1	1	0	1	Reserved	–	–	–
14	1	1	1	0	Fast PWM	ICR1	TOP	TOP
15	1	1	1	1	Fast PWM	OCR1A	TOP	TOP

CS12:CS10	D2D1D0	Timer1 clock selector
	0 0 0	No clock source (Timer/Counter stopped)
	0 0 1	clk (no prescaling)
	0 1 0	clk / 8
	0 1 1	clk / 64
	1 0 0	clk / 256
	1 0 1	clk / 1024
	1 1 0	External clock source on T1 pin. Clock on falling edge
	1 1 1	External clock source on T1 pin. Clock on rising edge

Figure 16-30. TCCR1B (Timer1 Control) Register

In Modes 5, 6, and 7, which have fixed top values, the TOV1 flag will be set when the timer rolls over. See Figures 16-25, 16-27, and 16-29.

In Mode 14, whose top value is represented by ICR1, the ICF1 flag will be set when the timer rolls over, as shown in Figure 16-26.

In Mode 15, when the timer rolls over, the OCF1A flag will be set. See Figure 16-28.

Bit	7	6	5	4	3	2	1	0	
	COM1A1	COM1A0	COM1B1	COM1B0	FOC1A	FOC1B	WGM11	WGM10	**TCCR1A**
Read/Write	R/W	R/W	R	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

COM1A1:COM1A0 D7 D6 Compare Output Mode for Channel A

COM1A1	COM1A0	Description
0	0	Normal port operation, OC1A disconnected
0	1	In mode 15, toggle OC1A on compare match. In other modes OC1A disconnected (Normal I/O port)
1	0	Clear OC1A on compare match. Set OC1A at Top.
1	1	Set OC1A on compare match. Clear OC1A at Top.

COM1B1:COM1B0 D5 D4 Compare Output Mode for Channel B

COM1B1	COM1B0	Description
0	0	Normal port operation, OC1B disconnected
0	1	Normal port operation, OC1B disconnected
1	0	Clear OC1B on compare match. Set OC1B at Top.
1	1	Set OC1B on compare match. Clear OC1B at Top.

FOC1A D3 Force Output Compare for Channel A

FOC1B D2 Force Output Compare for Channel B

WGM11:10 D1 D0 Timer1 mode (discussed in Figure 16-30)

Figure 16-31. TCCR1A (Timer1 Control) Register

In Figure 16-31 you see the reaction of the waveform generator when compare match occurs while the timer is in Fast PWM mode. When COM1A1:0 = 00 the OC1A pin operates as an I/O port. When COM1A1:0 = 10, the waveform generator clears the OC1A pin whenever compare match occurs, and sets it at the top value. This mode is called *non-inverted PWM.* See Figures 16-32A through 16-32C. As you see, in non-inverted PWM, the duty cycle of the generated wave increases when the value of OCR1A increases.

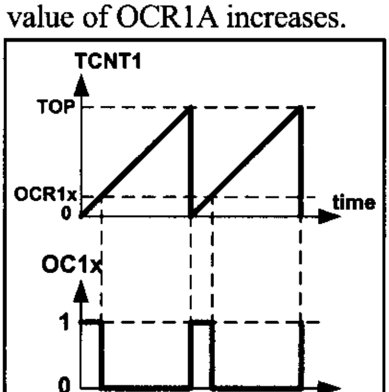


Figure 16-32A. Non-inverted

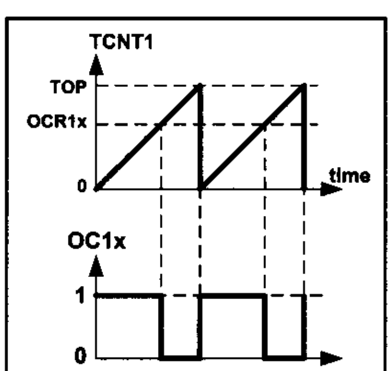


Figure 16-32B. Non-inverted

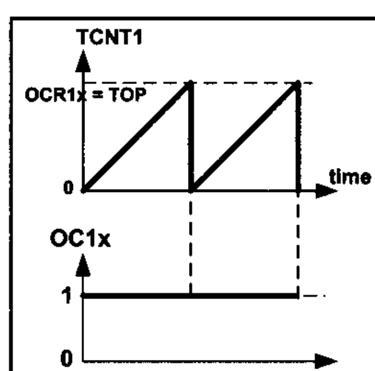


Figure 16-32C. Non-inverted

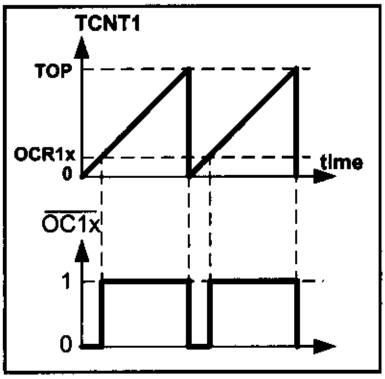


Figure 16-33A. Inverted

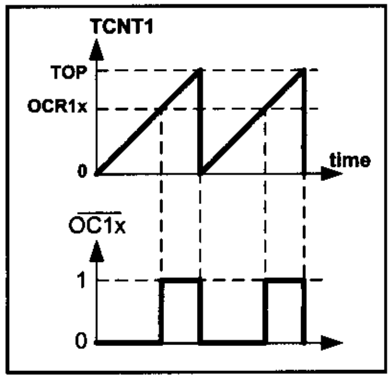


Figure 16-33B. Inverted

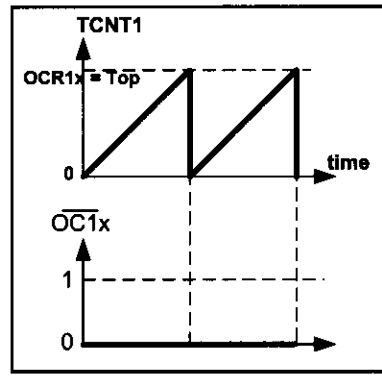


Figure 16-33C. Inverted

When COM1A1:0 = 11, the waveform generator sets the OC1A pin whenever compare match occurs, and clears it at the top value. This mode is referred to as *inverted PWM mode*. See Figures 16-33A through 16-33C. As you see, in inverted PWM, the duty cycle of the generated wave decreases when the value of OCR1A increases.

The same thing is true about the OCR1B register and COM1B1:10 bits.

Frequency of the generated wave in Fast PWM mode

In Fast PWM mode, timer counts from 0 to top value and then rolls over. Thus, the frequency of the generated wave is 1/(Top + 1) of the frequency of timer clock. As you saw in Section 9-1, the frequency of the timer clock can be selected using the prescaler. Therefore, the frequency of the generated wave can be calculated as follows (N is determined by the prescaler):

$$\left.\begin{aligned} F_{\text{generated wave}} &= \frac{F_{\text{timer clock}}}{\text{Top} + 1} \\ F_{\text{timer clock}} &= \frac{F_{\text{oscillator}}}{N} \end{aligned}\right\} \Longrightarrow F_{\text{generated wave}} = \frac{F_{\text{oscillator}}}{(\text{Top} + 1) \times N}$$

Duty cycle of the generated wave in Fast PWM mode

The duty cycle of the generated mode can be determined using the OCR1x register. When COM1x1:0 = 10 (in non-inverted mode), the bigger OCR1x value results in a bigger duty cycle. When OCR1x = Top, the OC1 is always high (duty cycle = 100%). Generally speaking, the OC1x is high for a total of OCR1x + 1 clocks. So, the duty cycle can be calculated using the following formula in non-inverted mode:

$$\text{Duty Cycle} = \frac{\text{OCR1x} + 1}{\text{Top} + 1} \times 100$$

In inverted mode, the duty cycle can be calculated using the following formula:

$$\text{Duty Cycle} = \frac{\text{Top} - \text{OCR1x}}{\text{Top} + 1} \times 100$$

See Examples 16-23 through 16-28.

Example 16-23

Calculate the value for the OCR1B register to generate a wave with duty cycle of 75% for each of the following modes:

(a) Mode 5, non-inverted mode
(b) Mode 7, inverted mode
(c) Mode 6, non-inverted mode
(d) Mode 5, inverted mode
(e) Mode 7, non-inverted mode

Solution:

(a) In mode 5, Top = 0xFF= 255. Thus,
75 = (OCR1x + 1) × 100 / (Top + 1) ➔ OCR1x + 1 = 75 × 256 / 100 = 192
➔ OCR1B = 191

(b) In mode 7, Top = 0x3FF = 1023. Thus,
75 = (Top – OCR1x) × 100 / (Top + 1) ➔ 1023 – OCR1x = 75 × 1024 / 100 = 768
➔ OCR1B = 255

(c) In mode 6, Top = 0x1FF = 511. Thus,
75 = (OCR1x + 1) × 100 /(Top + 1) ➔ OCR1x + 1 = 75 × 512 / 100 = 384
➔ OCR1A = 383

(d) In mode 5, Top = 0xFF = 255. Thus,
75 = (Top – OCR1x) × 100 / (Top + 1) ➔ 75 = (255 – OCR1x) × 100 / 256
➔ 255 – OCR1x = 75 × 256 / 100 = 192 ➔ OCR1B = 255 – 192 = 63

(e) In mode 7, Top = 0x3FF = 1023. Thus,
75 = (OCR1x + 1) × 100 / (Top + 1) ➔ OCR1x + 1 = 75 × 1024 / 100 = 768
➔ OCR1B = 767

Example 16-24

Find the values for TCCR1A and TCCR1B to initialize Timer1 for mode 5 (Fast PWM mode, top = 0xFF), non-inverted PWM wave generator, and no prescaler, using waveform generator A.

Solution:

WGM13:10 = 0101 = Fast PWM mode
CS02:00 = 001 = No prescaler
COM01:00 = 10 = Non-inverted PWM

TCCR1A =

COM1A1	COM1A0	COM1B1	COM1B0	FOC1A	FOC1B	WGM11	WGM10
1	0	0	0	0	0	0	1

TCCR1B =

ICNC1	ICES1	–	WGM13	WGM12	CS12	CS11	CS10
0	0	0	0	1	0	0	1

Example 16-25

Assuming XTAL = 8 MHz, using non-inverted mode, and mode 5, write a program that generates a wave with frequency of 31,250 Hz and duty cycle of 75%.

Solution:

31,250 = 8M / (256 × N) ➔ N = 8M / (31,250 × 256) = 1 ➔ No prescaler

```
.INCLUDE "M32DEF.INC"
      SBI   DDRD,5            ;PD5 = output
      LDI   R16,HIGH(191)     ;from Example 16-23
      OUT   OCR1AH,R16        ;Temp = 0x00
      LDI   R16,LOW(191)      ;R16 = 191
      OUT   OCR1AL,R16        ;OCR1A = 191
      LDI   R16,0x81          ;from Example 16-24
      OUT   TCCR1A,R16        ;COM1A = non-inverted
      LDI   R16,0x09
      OUT   TCCR1B,R16        ;WGM = mode 5, clock = no scaler
HERE: RJMP  HERE
```

Example 16-26

Assuming XTAL = 8 MHz, using non-inverted mode and mode 7, write a program that generates a wave with frequency of 7812.5 Hz and duty cycle of 75%.

Solution:

7812.5 = 8M/(1024 × N) ➔ N = 8M/(7812.5 × 1024) = 1 ➔ No prescaler

```
.INCLUDE "M32DEF.INC"
      SBI   DDRD,5            ;PD5 = output
      LDI   R16,HIGH(767)     ;R16 = the high byte
      OUT   OCR1AH,R16
      LDI   R16,LOW(767)      ;R16 = the low byte
      OUT   OCR1AL,R16        ;OCR1A = 767 (from Example 16-23)
      LDI   R16,0x83
      OUT   TCCR1A,R16        ;COM1A = non-inverted
      LDI   R16,0x09
      OUT   TCCR1B,R16        ;WGM = mode 7, clock = no scaler
HERE: RJMP  HERE              ;wait here forever
```

Example 16-27

Assuming XTAL = 8 MHz, using non-inverted mode and mode 6, write a program that generates a wave with frequency of 1,953 Hz and duty cycle of 60%.

Solution:

In mode 6, Top = 0x1FF= 511. Thus,

60 = (OCR1x + 1) × 100 / (Top + 1) ➔ OCR1x + 1 = 60 × 512 / 100 = 307

➔ OCR1B = **306**

1953 = 8M / (512 × N) ➔ N = 8M / (1953 × 512) = 8 ➔ prescaler = 1:8 ➔ CS12:0 = 010

TCCR1A =

COM1A1	COM1A0	COM1B1	COM1B0	FOC1A	FOC1B	WGM11	WGM10
1	0	0	0	0	0	1	0

TCCR1B =

ICNC1	ICES1	–	WGM13	WGM12	CS12	CS11	CS10
0	0	0	0	1	0	1	0

```
.INCLUDE "M32DEF.INC"
      SBI   DDRD,5          ;PD5 = output
      LDI   R16,HIGH(306)   ;R16 = the high byte
      OUT   OCR1AH,R16      ;Temp = R16
      LDI   R16,LOW(306)    ;R16 = the low byte
      OUT   OCR1AL,R16      ;OCR1A = 306
      LDI   R16,0x82
      OUT   TCCR1A,R16      ;COM1A = non-inverted.
      LDI   R16,0x0A
      OUT   TCCR1B,R16      ;WGM = mode 6, clock = no scaler
HERE: RJMP  HERE            ;wait here forever
```

Example 16-28

Rewrite Example 16-27 using inverted mode.

Solution:

60 = (Top – OCR1x) × 100 / (Top + 1) ➔ 511 – OCR1x = 60 × 512 / 100 = 307

➔ OCR1B = 511 – 307 = **204**

TCCR1A =

COM1A1	COM1A0	COM1B1	COM1B0	FOC1A	FOC1B	WGM11	WGM10
1	1	0	0	0	0	1	0

TCCR1B =

ICNC1	ICES1	–	WGM13	WGM12	CS12	CS11	CS10
0	0	0	0	1	0	1	0

```
.INCLUDE "M32DEF.INC"
      SBI   DDRD,5          ;PD5 = output
      LDI   R16,HIGH(204)
      OUT   OCR1AH,R16      ;Temp = the high byte
      LDI   R16,LOW(204)
      OUT   OCR1AL,R16      ;OCR1A = 204
      LDI   R16,0xB2
      OUT   TCCR1A,R16      ;COM1A = inverted
      LDI   R16,0x0A
      OUT   TCCR1B,R16      ;WGM = mode 6, clock = no scaler
HERE: RJMP  HERE            ;wait here forever
```

Loading values into the OCR1A and OCR1B registers in PWM modes

In the non-PWM modes (CTC mode and Normal mode), when we load a value into the OCR1x register, the value will be loaded instantly, but in the PWM modes (Fast PWM, Phase correct PWM, and phase and frequency correct PWM mode), there is a buffer between us and the OCR1A and OCR1B registers. When we read/write a value from/into the OCR1A or OCR1B register we are dealing with the buffer. The contents of the buffer will be loaded into the OCR1A/OCR1B registers only when the TCNT1 reaches its topmost value. See Figure 16-34 and Example 16-29.

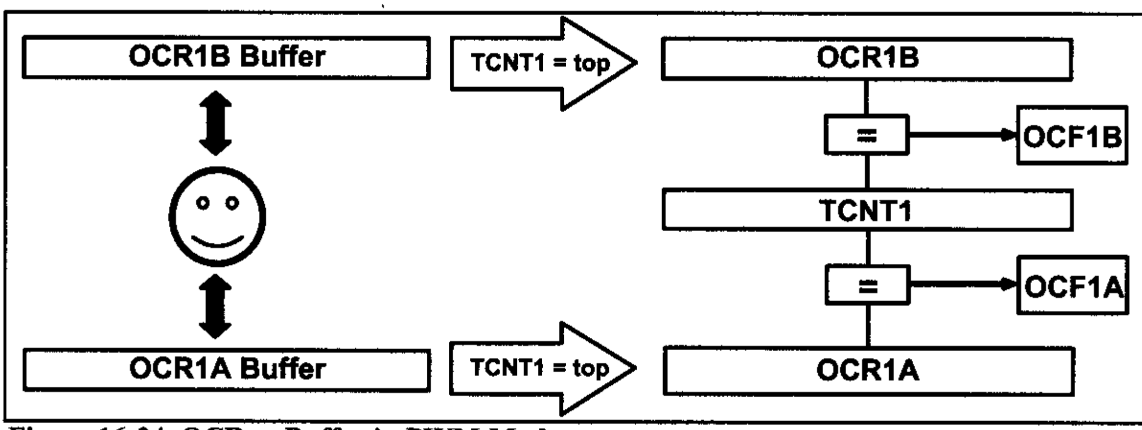


Figure 16-34. OCRnx Buffer in PWM Modes

Example 16-29

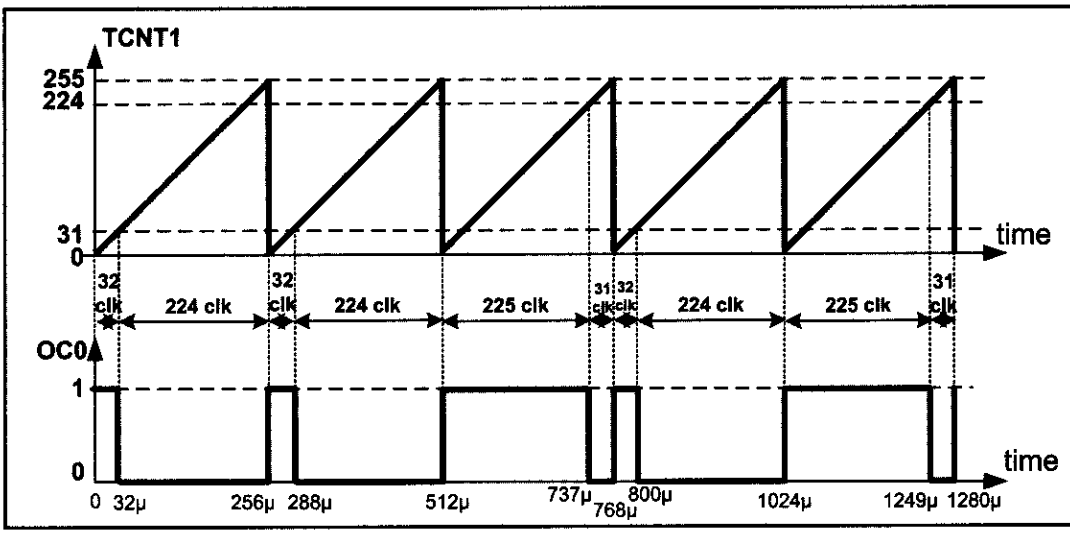
Draw the wave generated by the following program. Assume XTAL = 1 MHz.

```
.INCLUDE   "M32DEF.INC"
      RJMP MAIN
.ORG  0x12                    ;Timer1 overflow interrupt vector
      OUT  OCR1AH,R19         ;OCR1AH = R19 = 0
      NEG  R20
      OUT  OCR1AL,R20         ;OCR1A = R20
      RETI                    ;return from interrupt
MAIN: LDI  R16,LOW(RAMEND)
      OUT  SPL,R16
      LDI  R16,HIGH(RAMEND)
      OUT  SPH,R16            ;initialize stack pointer
      SBI  DDRD,5             ;PD5 = output
      LDI  R19,0
      OUT  OCR1AH,R19         ;Temp = 0x00
      LDI  R20,31
      OUT  OCR1AL,R20         ;OCR1A = 31
      LDI  R16,0x81
      OUT  TCCR1A,R16         ;COM1A = non-inverted.
      LDI  R16,0x0A
      OUT  TCCR1B,R16         ;WGM = mode 5, clock = no scaler
      LDI  R16,(1<<TOIE1)
      OUT  TIMSK,R16          ;enable timer interrupt
      SEI
HERE: RJMP HERE               ;wait here forever
```

Example 16-29 (Cont.)

Solution:

The wave generator is in non-inverted Fast PWM mode, which means that on compare match the OC1A pin will be set high. The OCR1A register is loaded with 31, so compare match occurs when TCNT1 reaches 31. When the timer reaches top and overflows, the interrupt request occurs, and OCR1A buffer is loaded with 224 (the two's complement of 31). The next time that the timer reaches the top value the contents of the OCR1A buffer (224) will be loaded into the OCR1A register. Then the second interrupt occurs and OCR1A buffer will be loaded with 31 (the two's complement of 224).



Generating waves with different frequencies (case study)

As we mentioned earlier, the frequency of the generated wave is equal to $F_{Oscillator}/[N \times (Top + 1)]$. In modes 5, 6, and 7, the Top value is fixed. Therefore, in these modes the only way to change the frequency of the generated wave is to change N (the prescaler). In Figure 16-35, you see the different frequencies that can be generated using modes 5, 6, and 7.

Prescaler	1	1:8	1:64	1:256	1:1024
Mode = 5	$\frac{F_{oscillator}}{1\times256}$	$\frac{F_{oscillator}}{8\times256}$	$\frac{F_{oscillator}}{64\times256}$	$\frac{F_{oscillator}}{256\times256}$	$\frac{F_{oscillator}}{1024\times256}$
Mode = 6	$\frac{F_{oscillator}}{1\times512}$	$\frac{F_{oscillator}}{8\times512}$	$\frac{F_{oscillator}}{64\times512}$	$\frac{F_{oscillator}}{256\times512}$	$\frac{F_{oscillator}}{1024\times512}$
Mode = 7	$\frac{F_{oscillator}}{1\times1024}$	$\frac{F_{oscillator}}{8\times1024}$	$\frac{F_{oscillator}}{64\times1024}$	$\frac{F_{oscillator}}{256\times1024}$	$\frac{F_{oscillator}}{1024\times1024}$

Figure 16-35. Different Frequencies Can Be Made Using Modes 5, 6, and 7

Thus, in these modes we can make a very limited number of frequencies. What if we want to make some other frequencies? In modes 14 and 15, the Top value can be specified by ICR1 and the OCR1A registers. Thus, we can change the frequency by loading proper values to ICR1 and OCR1A. See Examples 16-30 through 16-32.

Example 16-30

Assuming XTAL = 8 MHz, find TCCR1A and TCCR1B to generate a wave with frequency of 80 kHz using mode 14.

Solution:

$80K = 8M / [N \times (Top + 1)] \rightarrow N \times (Top + 1) = 8M / 80K = 100$
$\rightarrow N \times (Top + 1) = 100 \rightarrow N = 1; Top + 1 = 100$
$Top = 99 \rightarrow ICR1 = 99$
$N = 1 \rightarrow CS12:0 = 001$

TCCR1A =

COM1A1	COM1A0	COM1B1	COM1B0	FOC1A	FOC1B	WGM11	WGM10
1	0	0	0	0	0	1	0

TCCR1B =

ICNC1	ICES1	–	WGM13	WGM12	CS12	CS11	CS10
0	0	0	1	1	0	0	1

Example 16-31

Calculate the OCR1B to generate a wave with duty cycle of 20% in each of the following modes:
(a) mode 14, inverted mode, ICR1 = 45, (b) mode 15, non-inverted mode, OCR1A = 124, and (c) mode 14, non-inverted mode, ICR1 = 99.

Solution:

(a) In mode 14, Top = ICR1 = 45. Thus,
$20 = (Top - OCR1x) \times 100 / (Top + 1) \rightarrow 45 - OCR1x = 20 \times 46 / 100 = 9 \rightarrow OCR1A = 36$

(b) In mode 15, Top = OCR1A = 124. Thus,
$20 = (OCR1x + 1) \times 100 / (124 + 1) \rightarrow OCR1x + 1 = 20 \times 125 / 100 = 25 \rightarrow OCR1x = 24$

(c) In mode 14, Top = ICR1 = 99. Therefore,
$20 = (OCR1x + 1) \times 100 / (99 + 1) \rightarrow OCR1x + 1 = 20 \rightarrow OCR1x = 19$

Example 16-32

Assume XTAL = 8 MHz. Using mode 14 write a program that generates a wave with duty cycle of 20% and frequency of 80 kHz.

Solution:

```
.INCLUDE "M32DEF.INC"
      LDI   R16,LOW(RAMEND)
      OUT   SPL,R16
      LDI   R16,HIGH(RAMEND)
      OUT   SPH,R16          ;initialize stack pointer
      SBI   DDRD,5           ;PD5 = output
      LDI   R16,HIGH(99)
      OUT   ICR1H,R16        ;Temp = 0
      LDI   R16,LOW(99)
      OUT   ICR1L,R16        ;ICR1 = 99
      LDI   R16,HIGH(19)
      OUT   OCR1AH,R16       ;Temp = 0
      LDI   R16,LOW(19)
      OUT   OCR1AL,R16       ;OCR1A = 19 (from Example 16-31)
      LDI   R16,0x82         ;from Example 16-30
      OUT   TCCR1A,R16       ;COM1A = non-inverted
      LDI   R16,0x19         ;from Example 16-30
      OUT   TCCR1B,R16       ;WGM = mode 14, clock = no scaler
HERE: RJMP  HERE             ;wait here forever
```

If we use mode 15 instead of mode 14, OCR1A is buffered, and the contents of the buffer will be loaded into OCR1A when the timer reaches its top value. In mode 15 we can only use the OC1B wave generator and not the OC1A wave generator since the OCR1A register is used for defining the top value. See Examples 16-33 and 16-34.

Example 16-33

Assuming XTAL = 8 MHz, find TCCR1A and TCCR1B to generate a wave with frequency of 64 kHz using mode 15.

Solution:

$64k = 8M / [N \times (Top + 1)] \rightarrow N \times (Top + 1) = 8M / 64k = 125 \rightarrow N = 1; Top + 1 = 125$
$\rightarrow Top = 124 \rightarrow OCR1A = 124$
$N = 1 \rightarrow CS12{:}0 = 001$

TCCR1A =

COM1A1	COM1A0	COM1B1	COM1B0	FOC1A	FOC1B	WGM11	WGM10
0	0	1	0	0	0	1	1

TCCR1B =

ICNC1	ICES1	–	WGM13	WGM12	CS12	CS11	CS10
0	0	0	1	1	0	0	1

Example 16-34

Assume XTAL = 8 MHz. Using mode 15 write a program that generates a wave with duty cycle of 20% and frequency of 64 kHz.

Solution:

```
.INCLUDE "M32DEF.INC"
      LDI   R16,LOW(RAMEND)
      OUT   SPL,R16
      LDI   R16,HIGH(RAMEND)
      OUT   SPH,R16           ;initialize stack pointer

      SBI   DDRD,4            ;PD4 = output
      LDI   R16,HIGH(124)     ;R16 = the high byte
      OUT   OCR1AH,R16
      LDI   R16,LOW(124)      ;R16 = the low byte
      OUT   OCR1AL,R16        ;OCR1A = 124

      LDI   R16,HIGH(24)      ;R16 = the high byte
      OUT   OCR1BH,R16
      LDI   R16,LOW(24)       ;R16 = the low byte
      OUT   OCR1BL,R16        ;OCR1B = 24

      LDI   R16,0x23          ;from Example 16-33
      OUT   TCCR1A,R16        ;COM1B = non-inverted
      LDI   R16,0x19          ;from Example 16-33
      OUT   TCCR1B,R16        ;WGM = mode 15, clock = no scaler
HERE: RJMP  HERE              ;wait here forever
```

Phase correct PWM mode

In the Phase correct PWM, the timer counts up until it reaches the top value then counts down until it reaches zero. The TOV1 flag will be set when the timer returns to zero, as shown in Figure 16-36.

There are five Phase correct PWM modes: modes 1, 2, 3, 10, and 11. See Figure 16-37.

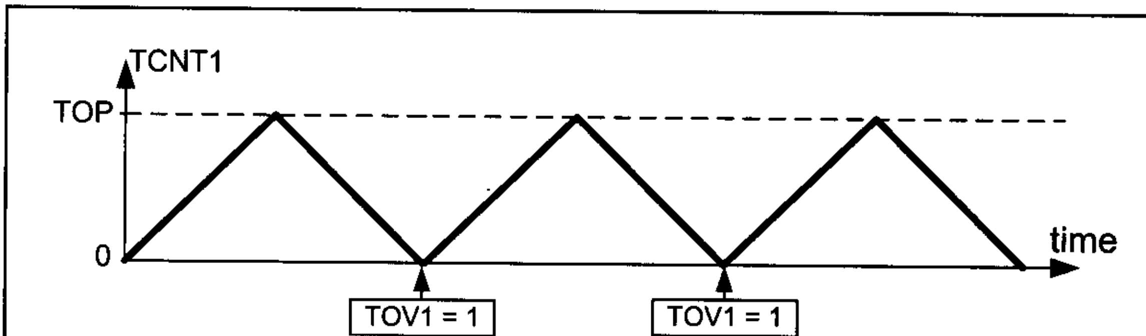


Figure 16-36. Timer/Counter 1 Phase Correct PWM Mode

Bit	7	6	5	4	3	2	1	0	
	ICNC1	ICES1	–	WGM13	WGM12	CS12	CS11	CS10	TCCR1B
Read/Write	R/W	R/W	R	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

ICNC1 D7 Input Capture Noise Canceler
0 = Input Capture is disabled.
1 = Input Capture is enabled.

ICES1 D6 Input Capture Edge Select
0 = Capture on the falling (negative) edge
1 = Capture on the rising (positive) edge

WGM13:WGM12 D4 D3 Timer1 mode

Mode	WGM13	WGM12	WGM11	WGM10	Timer/Counter Mode of Operation	Top	Update of OCR1x	TOV1 Flag Set on
0	0	0	0	0	Normal	0xFFFF	Immediate	MAX
1	0	0	0	1	PWM, Phase Correct, 8-bit	0x00FF	TOP	BOTTOM
2	0	0	1	0	PWM, Phase Correct, 9-bit	0x01FF	TOP	BOTTOM
3	0	0	1	1	PWM, Phase Correct, 10-bit	0x03FF	TOP	BOTTOM
4	0	1	0	0	CTC	OCR1A	Immediate	MAX
5	0	1	0	1	Fast PWM, 8-bit	0x00FF	TOP	TOP
6	0	1	1	0	Fast PWM, 9-bit	0x01FF	TOP	TOP
7	0	1	1	1	Fast PWM, 10-bit	0x03FF	TOP	TOP
8	1	0	0	0	PWM, Phase and Frequency Correct	ICR1	BOTTOM	BOTTOM
9	1	0	0	1	PWM, Phase and Frequency Correct	OCR1A	BOTTOM	BOTTOM
10	1	0	1	0	PWM, Phase Correct	ICR1	TOP	BOTTOM
11	1	0	1	1	PWM, Phase Correct	OCR1A	TOP	BOTTOM
12	1	1	0	0	CTC	ICR1	Immediate	MAX
13	1	1	0	1	Reserved	–	–	–
14	1	1	1	0	Fast PWM	ICR1	TOP	TOP
15	1	1	1	1	Fast PWM	OCR1A	TOP	TOP

CS12:CS10 D2D1D0 Timer1 clock selector

D2	D1	D0	
0	0	0	No clock source (Timer/Counter stopped)
0	0	1	clk (no prescaling)
0	1	0	clk / 8
0	1	1	clk / 64
1	0	0	clk / 256
1	0	1	clk / 1024
1	1	0	External clock source on T1 pin. Clock on falling edge
1	1	1	External clock source on T1 pin. Clock on rising edge

Figure 16-37. TCCR1B (Timer1 Control) Register

In modes 1, 2, and 3 the top value are 0xFF, 0x1FF, and 0x3FF, respectively. In mode 10, the top value is defined by the ICR1 register; and in mode 11, the OCR1A register represents the top value. See Figures 16-38 through 16-42.

In Figure 16-43 you see the reaction of the waveform generator when compare match occurs in Phase correct PWM mode.

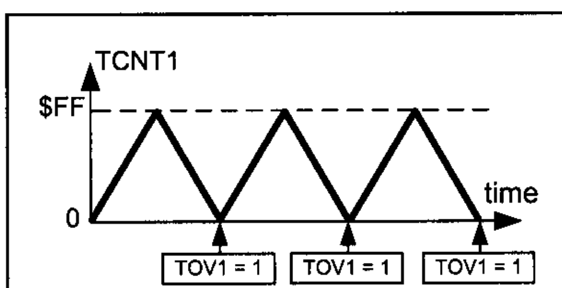


Figure 16-38. Mode 1

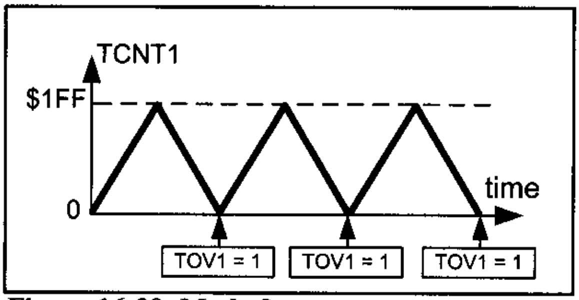


Figure 16-39. Mode 2

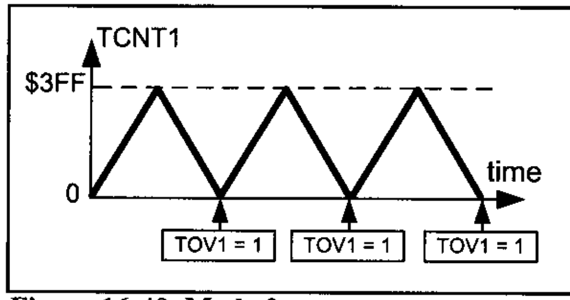


Figure 16-40. Mode 3

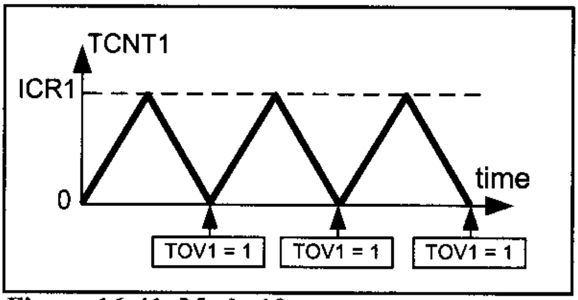


Figure 16-41. Mode 10

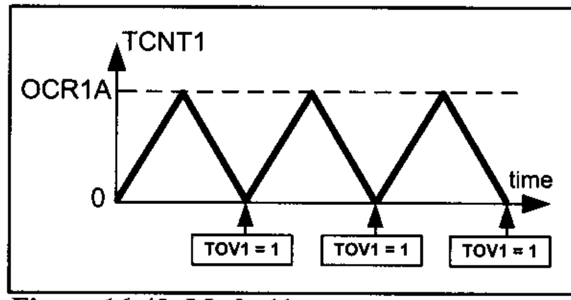


Figure 16-42. Mode 11

Bit	7	6	5	4	3	2	1	0	
	COM1A1	COM1A0	COM1B1	COM1B0	FOC1A	FOC1B	WGM11	WGM10	TCCR1A
Read/Write	R/W	R/W	R	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

COM1A1:COM1A0 D7 D6 Compare Output Mode for Channel A

COM1A1	COM1A0	Description
0	0	Normal port operation, OC1A disconnected
0	1	In mode 9 or 14 toggles on compare match. In other modes OC1A is disconnected (Normal I/O port).
1	0	Clear OC1A on compare match when up-counting. Set OC1A on compare match when down-counting.
1	1	Set OC1A on compare match when up-counting. Clear OC1A on compare match when down-counting.

COM1B1:COM1B0 D5 D4 Compare Output Mode for Channel B

COM1B1	COM1B0	Description
0	0	Normal port operation, OC1B disconnected
0	1	Normal port operation, OC1B disconnected
1	0	Clear OC1B on compare match when up-counting. Set OC1B on compare match when down-counting.
1	1	Set OC1B on compare match when up-counting. Clear OC1B on compare match when down-counting.

FOC1A	D3	Force Output Compare for Channel A
FOC1B	D2	Force Output Compare for Channel B
WGM11:10	D1 D0	Timer1 mode (discussed in Figure 16-37)

Figure 16-43. TCCR1A (Timer1 Control) Register

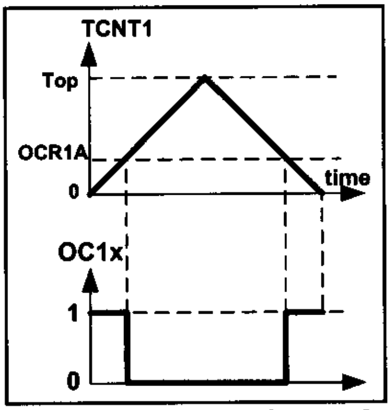


Figure 16-44A. Non-inverted

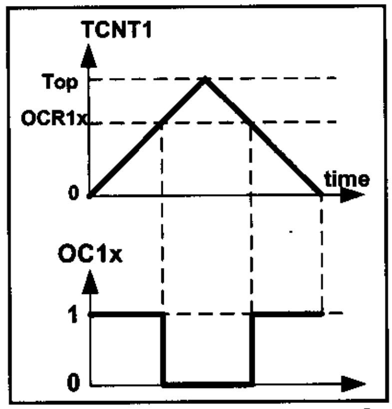


Figure 16-44B. Non-inverted

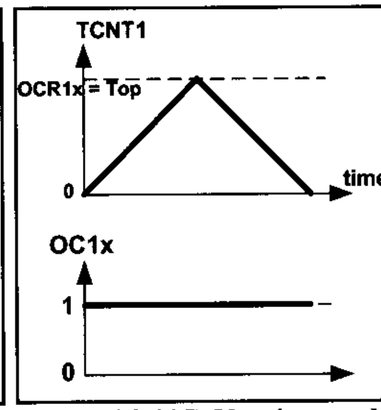


Figure 16-44C. Non-inverted

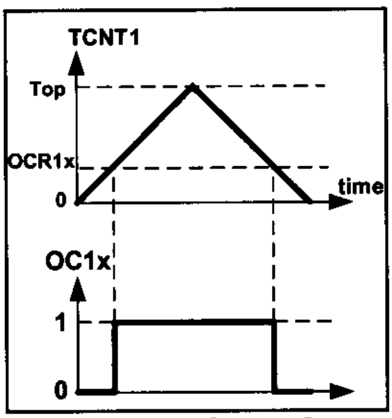


Figure 16-45A. Inverted

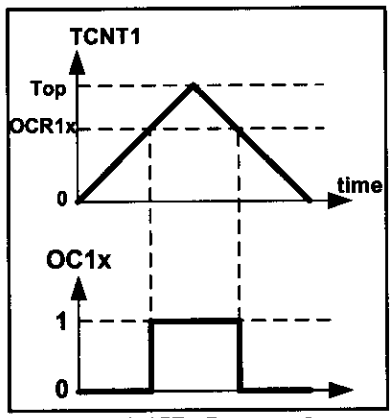


Figure 16-45B. Inverted

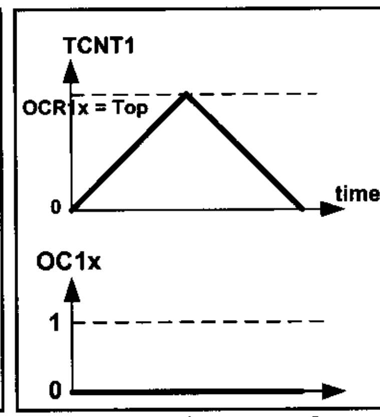


Figure 16-45C. Inverted

When COM1A1:10 = 00 the OC1A pin operates as an I/O port. When COM1A1:00 = 10, the waveform generator clears the OC1A pin on compare match when up-counting, and sets it on compare match when down-counting. This mode is called *non-inverted*.

See Figures 16-44A through 16-44C. As you see, in the non-inverted mode, the duty cycle of the generated wave increases when the value of OCR1A increases.

When COM1A1:00 = 11, the waveform generator sets the OC1A pin on compare match when up-counting, and clears it on compare match when down-counting. This mode is referred to as *inverted mode*. As you can see from Figures 16-45A through 16-45C, in inverted PWM, the duty cycle of the generated wave decreases when the value of OCR1A increases.

The same thing is true about the OCR1B register and COM1B1:10 bits.

Frequency of the generated wave in Phase correct PWM mode

As you see in Figure 16-46, the frequency of the generated wave is 1/2 TOP of the frequency of timer clock. As you saw in Section 9-1, the frequency of the timer clock can be selected using the prescaler. Therefore, in 8-bit timers the frequency of the generated wave can be calculated as follows:

$$\left.\begin{aligned} F_{\text{generated wave}} &= \frac{F_{\text{timer clock}}}{2 \times \text{Top}} \\ F_{\text{timer clock}} &= \frac{F_{\text{oscillator}}}{N} \end{aligned}\right\} \Longrightarrow F_{\text{generated wave}} = \frac{F_{\text{oscillator}}}{2 \times N \times \text{Top}}$$

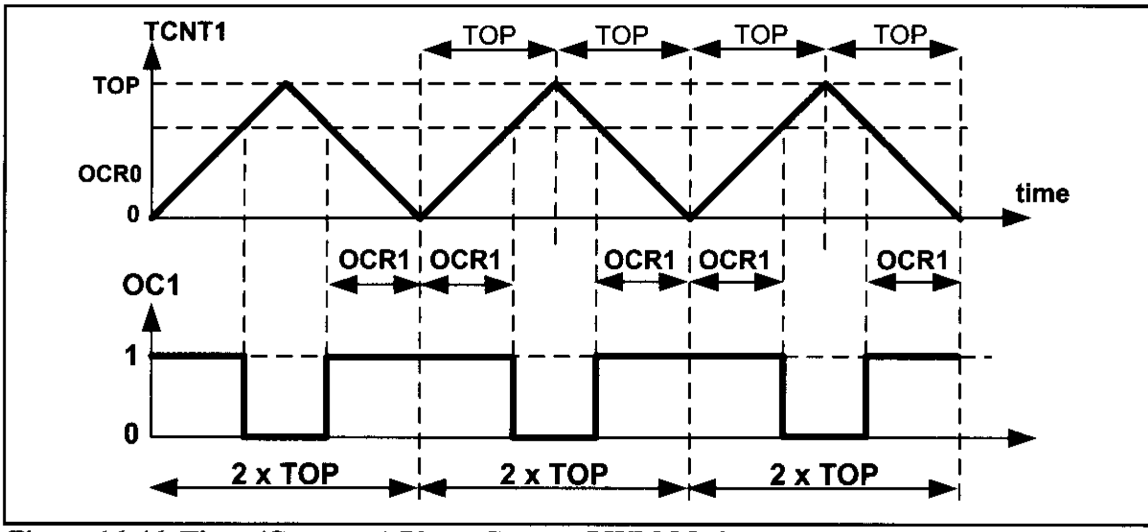


Figure 16-46. Timer/Counter 1 Phase Correct PWM Mode

Duty cycle of the generated wave in Phase correct PWM mode

The duty cycle of the generated mode can be determined using the OCR1x register. When COM1x1:0 = 10 (in non-inverted mode), the bigger OCR1x value results in a bigger duty cycle. When OCR1x = Top, the OC1x is always high (duty cycle = 100%). Generally speaking, OC1x is high for a total of OCR1x clocks. See Figure 16-46. So, the duty cycle can be calculated using the following formula in non-inverted mode:

$$\text{Duty Cycle} = \frac{2 \times \text{OCR1A}}{2 \times \text{Top}} \times 100 \implies \text{Duty Cycle} = \frac{\text{OCR1A}}{\text{Top}} \times 100$$

Similarly, the duty cycle formula for inverted mode is as follows:

$$\text{Duty Cycle} = \frac{2 \times \text{Top} - 2 \times \text{OCR1A}}{2 \times \text{Top}} \times 100 \implies \text{Duty Cycle} = \frac{\text{Top} - \text{OCR1A}}{\text{Top}} \times 100$$

See Examples 16-35 through 16-37.

Example 16-35

Find the values for TCCR1A and TCCR1B to initialize Timer1 for mode 1 (Phase correct PWM mode, top = 0xFF), non-inverted PWM wave generator, and no prescaler.

Solution:

WGM13:10 = 0001 = Phase correct PWM mode   CS02:00 = 001 = No prescaler
COM01:00 = 10 = Non-inverted PWM

TCCR1A =

1	0	0	0	0	0	0	1
COM1A1	COM1A0	COM1B1	COM1B0	FOC1A	FOC1B	WGM11	WGM10

TCCR1B =

0	0	0	0	0	0	0	1
ICNC1	ICES1	–	WGM13	WGM12	CS12	CS11	CS10

Example 16-36

Calculate the OCR1B to generate a wave with duty cycle of 75% in each of the following modes:

(a) Mode 1, non-inverted mode

(b) Mode 3, inverted mode

(c) Mode 2, non-inverted mode

(d) Mode 2, inverted mode

(e) Mode 1, inverted mode

Solution:

(a) In mode 1, Top = 0xFF= 255. So,
$75 = OCR1x \times 100 / Top \rightarrow OCR1x = 75 \times 255 / 100 = 192 \rightarrow OCR1B = 191$

(b) In mode 3, Top = 0x3FF= 1023. So,
$75 = (Top - OCR1x) \times 100 / Top \rightarrow 1023 - OCR1x = 75 \times 1023 / 100 = 767$
$\rightarrow OCR1B = 255$

(c) In mode 2, Top = 0x1FF = 511. So,
$75 = OCR1x \times 100 / Top \rightarrow OCR1x = 75 \times 511 / 100 = 383 \rightarrow OCR1B = 383$

(d) In mode 2, Top = 0x1FF = 511. So,
$75 = (Top - OCR1x) \times 100 / Top \rightarrow 75 = (511 - OCR1x) \times 100 / 511$
$\rightarrow 511 - OCR1x = 75 \times 511 / 100 = 383 \rightarrow OCR1B = 511 - 383 = 128$

(e) In mode 1, Top = 0xFF = 255. So,
$75 = (Top - OCR1x) \times 100 / Top \rightarrow 75 = (255 - OCR1x) \times 100 / 255$
$\rightarrow 255 - OCR1x = 75 \times 255 / 100 = 191 \rightarrow OCR1B = 255 - 191 = 64$

Example 16-37

Assuming XTAL = 8 MHz, using non-inverted mode and mode 1, write a program that generates a wave with frequency of 15,686 Hz and duty cycle of 75%.

Solution:

$15{,}686 = 8M / (510 \times N) \rightarrow N = 8M / (15{,}686 \times 510) = 1 \rightarrow$ No prescaler

```
.INCLUDE "M32DEF.INC"
      SBI   DDRD,5          ;PD5 = output
      LDI   R16,HIGH(191)   ;from Example 16-36
      OUT   OCR1AH,R16      ;Temp = 0x00
      LDI   R16,LOW(191)    ;R16 = 191
      OUT   OCR1AL,R16      ;OCR1A = 191
      LDI   R16,0x81        ;from Example 16-35
      OUT   TCCR1A,R16      ;COM1A = non-inverted
      LDI   R16,0x01
      OUT   TCCR1B,R16      ;WGM = mode 1, clock = no scaler
HERE: RJMP  HERE
```

Generating waves with different frequencies (case study)

As we mentioned earlier, the frequency of the generated wave is equal to $F_{oscillator}/(2N \times Top)$. In modes 1, 2, and 3, the Top value is fixed. Therefore, in these modes the only way to change the frequency of the generated wave is to change N (the prescaler). In Figure 16-47, you see the different frequencies that can be generated using modes 1, 2, and 3.

Prescaler	1	1:8	1:64	1:256	1:1024
Mode = 1	$\frac{F_{oscillator}}{510}$	$\frac{F_{oscillator}}{8*510}$	$\frac{F_{oscillator}}{64*510}$	$\frac{F_{oscillator}}{256*510}$	$\frac{F_{oscillator}}{1024*510}$
Mode = 2	$\frac{F_{oscillator}}{1*1022}$	$\frac{F_{oscillator}}{8*1022}$	$\frac{F_{oscillator}}{64*1022}$	$\frac{F_{oscillator}}{256*1022}$	$\frac{F_{oscillator}}{1024*1022}$
Mode = 3	$\frac{F_{oscillator}}{1*2046}$	$\frac{F_{oscillator}}{8*2046}$	$\frac{F_{oscillator}}{64*2046}$	$\frac{F_{oscillator}}{256*2046}$	$\frac{F_{oscillator}}{1024*2046}$

Figure 16-47. Different Frequencies Can Be Made Using Modes 1, 2, and 3

So, in these modes we can make a very limited number of frequencies. What if we want to make some other frequencies? In modes 10 and 11, the Top value can be specified by ICR1 and the OCR1A registers. Thus, we can change the frequency by loading proper values to ICR1 and OCR1A. See Examples 16-38 through 16-40.

Example 16-38

Assuming XTAL = 8 MHz, find TCCR1A and TCCR1B to generate two waves with frequency of 125 Hz on OC1A and OC1B using mode 10, non-inverted mode, and prescaler = 1:256.

Solution:

125 = 8M / (2N × Top) ➔ 2N × Top = 8M / 125 = 64,000 ➔ Top = 64,000 / 512 = 250
Top = 250 ➔ ICR1 = 250
N = 256 ➔ CS12:0 = 100
Mode = 10 ➔ WGM12:10 = 1010
OC1A in non-inverted mode ➔ COM1A1:COM1A0 = 10
OC1B in non-inverted mode ➔ COM1B1:COM1B0 = 10

TCCR1A =

COM1A1	COM1A0	COM1B1	COM1B0	FOC1A	FOC1B	WGM11	WGM10
1	0	1	0	0	0	1	0

TCCR1B =

ICNC1	ICES1	-	WGM13	WGM12	CS12	CS11	CS10
0	0	0	1	0	1	0	0

Example 16-39

Calculate the OCR1x to generate the following waves in each of the following modes:
(a) Mode 11, inverted mode, OCR1A=50, duty cycle = 30%
(b) Mode 10, non-inverted mode, ICR1 = 250, duty cycle = 30%
(c) Mode 10, non-inverted mode, ICR1 = 250, duty cycle = 60%

Solution:

(a) In mode 11, Top = OCR1A = 50. So,
30 = (Top – OCR1B) × 100 / Top ➔ 50 – OCR1B = 50 × 30 / 100 = 15 ➔ OCR1B = 35

(b) In mode 10, Top = ICR1 = 250. So,
30 = OCR1x × 100 / Top ➔ OCR1x = 30 × 250 / 100 = 75 ➔ OCR1x = 75

(c) In mode 10, Top = ICR1 = 250. So,
60 = OCR1x × 100 / Top ➔ OCR1x = 60 × 250 / 100 ➔ OCR1x = 150

Example 16-40

Assume XTAL = 8 MHz. Using mode 10 write a program that generates waves with duty cycles of 30% and 60% on the OC1A and OC1B pins, respectively. Frequency of the generated waves should be 125 Hz.

Solution:

```
.INCLUDE "M32DEF.INC"
      LDI   R16,LOW(RAMEND)
      OUT   SPL,R16
      LDI   R16,HIGH(RAMEND)
      OUT   SPH,R16          ;initialize stack pointer

      SBI   DDRD,5           ;PD5 (OC1A) = output
      SBI   DDRD,4           ;PD4 (OC1B) = output
      LDI   R16,0
      OUT   OCR1AH,R16       ;Temp = 0
      LDI   R16,75           ;from Example 16-39
      OUT   OCR1AL,R16       ;OCR1AL = 75, OCR1AH = Temp = 0
      LDI   R16,150          ;from Example 16-39
      OUT   OCR1BL,R16       ;OCR1BL = 150, OCR1BH = Temp = 0
      LDI   R16,250
      OUT   ICR1L,R16        ;ICR1L = 250, ICR1H = Temp = 0
      LDI   R16,0xA2         ;from Example 16-38
      OUT   TCCR1A,R16    ;COM1A = non-inverted, COM1B = non-inv.
      LDI   R16,0x14         ;from Example 16-38
      OUT   TCCR1B,R16       ;WGM = mode 10, clock = no scaler

HERE: RJMP  HERE             ;wait here forever
```

If we use mode 11 instead of mode 10, OCR1A is buffered, and the contents of the buffer will be loaded into OCR1A, when the timer reaches its top value. In mode 11 we can only use the OC1B wave generator and we cannot use the OC1A wave generator since the OCR1A register is used for defining the Top value.

16-bit PWM programming in C

Examples 16-41 through 16-49 show the C versions of the earlier programs.

Example 16-41 (C version of Example 16-25)

Assuming XTAL = 8 MHz, using non-inverted mode and mode 5, write a program that generates a wave with frequency of 31,250 Hz and duty cycle of 75%.

Solution:

```
#include "avr/io.h"
int main ( )
{
      DDRD |= (1<<5); //PD5 = output
      OCR1AH = 0;     //Temp = 0
      OCR1AL = 191;   //OCR1A = 191
      TCCR1A = 0x81;  //COM1A = non-inverted
      TCCR1B = 0x09;  //WGM = mode 5, clock = no scaler

      while (1);
      return 0;
}
```

Example 16-42 (C version of Example 16-26)

Assuming XTAL = 8 MHz, using non-inverted mode and mode 7, write a program that generates a wave with frequency of 7812.5 Hz and duty cycle of 75%.

Solution:

```
#include "avr/io.h"
int main ( )
{
      DDRD |= (1<<5); //PD5 = output
      OCR1AH = 767>>8;//OCR1AH = HIGH (767)
      OCR1AL = 767;   //OCR1AL = LOW (767)
      TCCR1A = 0x83;  //COM1A = non-inverted
      TCCR1B = 0x09;  //WGM = mode 7, clock = no scaler
      while (1);
      return 0;
}
```

Example 16-43 (C version of Example 16-27)

Assuming XTAL = 8 MHz, using non-inverted mode and mode 6, write a program that generates a wave with frequency of 1953 Hz and duty cycle of 60%.

Solution:

```
#include "avr/io.h"
int main ( )
{
      DDRD |= (1<<5); //PD5 as output
      OCR1AH = 306>>8;//OCR1AH = HIGH (306)
      OCR1AL = 306;   //OCR1AL = LOW (306)
      TCCR1A = 0x82;  //COM1A = non-inverted
      TCCR1B = 0x0A;  //WGM = mode 6, clock = no prescaler
      while (1);
      return 0;
}
```

Example 16-44 (C version of Example 16-28)

Rewrite Example 16-43 using inverted mode.

Solution:

```
#include "avr/io.h"
int main ( )
{
      DDRD |= (1<<5); //PD5 as output
      OCR1AH = 204>>8;//OCR1AH = HIGH(204) = 0
      OCR1AL = 204;   //OCR1AL = LOW(204) = 204
      TCCR1A = 0xB2;  //COM1A = inverted
      TCCR1B = 0x0A;  //WGM = mode 6, clock = no scaler
      while (1);
      return 0;
}
```

Example 16-45 (C version of Example 16-29)

Rewrite the program of Example 16-29 using C.

Solution:

```
#include "avr/io.h"
#include "avr/interrupt.h"
ISR (TIMER1_OVF_vect)
{
      OCR1AH = 0;
      OCR1AL = ~OCR1AL;
}
int main ( )
{
      DDRD |= (1<<5); //PD5 as output
```

Example 16-45 (Cont.)

```
	OCR1AH = 0;	//Temp = 0
	OCR1AL = 31;	//OCR1A = 31
	TCCR1A = 0x81;	//COM1A = non-inverted
	TCCR1B = 0x0A;	//WGM = mode 5, clock = no scaler
	TIMSK = (1<<TOIE1);
	sei ( );
	while (1);
	return 0;
}
```

Example 16-46 (C version of Example 16-32)

Assume XTAL = 8 MHz. Using mode 14 write a program that generates a wave with duty cycle of 20% and frequency of 80 kHz.

Solution:

```
#include "avr/io.h"
int main ( )
{
	DDRD |= (1<<5);	//PD5 as output
	ICR1H = 0x00;	//Temp = 0x00
	ICR1L = 99;	//ICR1 = 99
	OCR1AH = 0;	//OCR1AH = 0
	OCR1AL = 19;	//OCR1A = 19
	TCCR1A = 0x82;	//COM1A = non-inverted
	TCCR1B = 0x19;	//WGM = mode 14, clock = no scaler
	while (1);
	return 0;
}
```

Example 16-47 (C version of Example 16-34)

Assume XTAL = 8 MHz. Using mode 15 write a program that generates a wave with duty cycle of 20% and frequency of 64 kHz.

Solution:

```
#include "avr/io.h"
int main ( )
{
	DDRD |= (1<<4);	//PD4 as output
	OCR1AH = 0;	//Temp = 0
	OCR1AL = 124;	//OCR1A = 124
	OCR1BH = 0;	//Temp = 0
	OCR1BL = 24;	//OCR1B = 24
	TCCR1A = 0x23;	//COM1B = non-inverted
	TCCR1B = 0x19;	//WGM = mode 15, clock = no scaler
	while (1);
	return 0;
}
```

Example 16-48 (C version of Example 16-37)

Assuming XTAL = 8 MHz, using non-inverted mode and mode 1, write a program that generates a wave with frequency of 15,686 Hz and duty cycle of 75%.

Solution:

```
#include "avr/io.h"
int main ( )
{
      DDRD |= (1<<5); //PD5 as output
      OCR1AH = 0;     //Temp = 0
      OCR1AL = 191;   //OCR1A = 191
      TCCR1A = 0x23;  //COM1A = non-inverted
      TCCR1B = 0x01;  //WGM = mode 1, clock = no prescaler
      while (1);
      return 0;
}
```

Example 16-49 (C version of Example 16-40)

Assume XTAL = 8 MHz. Using mode 10 write a program that generates waves with duty cycles of 30% and 60% on the OC1A and OC1B pins, respectively. The frequency of the generated waves should be 125 Hz.

Solution:

```
#include "avr/io.h"
int main ( )
{
      DDRD = DDRD|(1<<5)|(1<<4); //PD4 and PD5 as output
      OCR1AH = 0x00;  //Temp = 0
      OCR1AL = 75;    //OCR1A = 75
      OCR1BL = 150;   //OCR1B = 150
      ICR1L = 250;    //ICR1 = 250
      TCCR1A = 0xA2;  //COM1A = non-inverted, COM1B = non-inv.
      TCCR1B = 0x14;  //WGM = mode 10, clock = no prescaler
      while (1);
      return 0;
}
```

Review Questions

1. True or false. We can associate each of the pins with each of the waveform generators.
2. True or false. In PWM modes (Fast PWM and Phase correct PWM) we can change the duty cycle of the generated wave.
3. True or false. In inverted Phase correct PWM mode, the duty cycle increases when the OCR1A value increases.

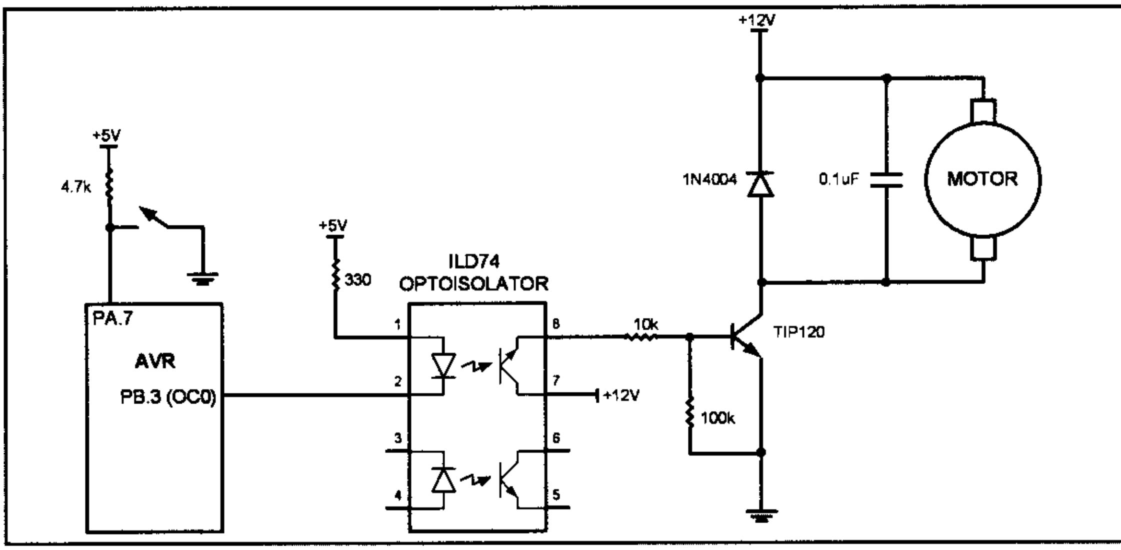
SECTION 16.4: DC MOTOR CONTROL USING PWM

To generate the PWM waves for controlling the DC motor we can use the PWM features of AVR. See Examples 16-50 and 16-51.

Example 16-50 (Example 16-3 using AVR PWM features)

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

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



Solution:

For driving motors it is preferable to use the Phase correct PWM mode.
OCR0 / 255 = duty cycle / 100 ➔ OCR0 = 255 × duty cycle / 100
For duty cycle = 25% ➔ OCR0 = 255 × 25 / 100 = 64
For duty cycle = 50% ➔ OCR0 = 255 × 50 / 100 = 127

In this example we generate waves with frequency of 245 Hz. To do so,
245 = 8M / (510 × N) ➔ N = 8M / (245 × 510) = 64 ➔ Prescaler = 64

TCCR0 =

FOC0	WGM00	COM01	COM00	WGM01	CS02	CS01	CS00
0	1	1	1	0	0	1	1

```
.INCLUDE "M32DEF.INC"
      SBI   DDRB,3       ;make PB3 output
      SBI   PORTA,7      ;activate pull-up of PA7
      LDI   R16,0x73
      OUT   TCCR0,R16    ;N = 64, Phase correct PWM, inverted
L1:   SBIC  PINA,7       ;skip next instruct if PINA.7 is zero
      LDI   R16,64       ;if PINA.7 is one then R16 = 64
      SBIS  PINA,7       ;skip next instruct if PINA.7 is one
      LDI   R16,127      ;if PINA.7 is zero then R16 = 127
      OUT   OCR0,R16     ;OCR0 = R16
      RJMP  L1           ;jump L1
```

Example 16-51

Write a program that gradually changes the speed of a DC motor from 50% to 100%. Use information given in Example 16-50.

Solution:

```
.INCLUDE "M32DEF.INC"
      LDI   R16,HIGH(RAMEND)
      OUT   SPH,R16
      LDI   R16,LOW(RAMEND)
      OUT   SPL,R16     ;initialize stack pointer

      SBI   DDRB,3      ;make PB3 output
      LDI   R16,0x73    ;from Example 16-50
      OUT   TCCR0,R16   ;N = 64, Phase correct PWM, inverted
      LDI   R20,127
L1:   OUT   OCR0,R20    ;OCR0 = R17
      RCALL DELAY
      INC   R20         ;increment R20
      BRNE  L1          ;jump L1 if R20 is not zero
HERE: RJMP  HERE
```

DC motor control and PWM using C

Examples 16-52 and 16-53 show the C versions of the earlier programs.

Example 16-52 (C version of Example 16-50)

Write a program to monitor the status of the switch and perform the following:
(a) If PORTA.7 = 1, the DC motor moves with 25% duty cycle pulse.
(b) If PORTA.7 = 0, the DC motor moves with 50% duty cycle pulse.

Solution:

```
#include "avr/io.h"

int main ( )
{
      DDRB = 0x08;      //PB3 as output
      PORTA = 0x80;     //pull-up resistor
      TCCR0 = 0x73;     //Phase correct PWM, inverted, N = 64

      while (1)
      {
            switch ((PINA&0x80))
            {
                  case 0: OCR0 = 64; break;     //25%
                  case 1: OCR0 = 127; break;    //50%
            }
      }

      return 0;
}
```

Example 16-53 (C version of Example 16-51)

Write a program that gradually changes the speed of a DC motor from 50% to 100%.

Solution:

```
#define  F_CPU  8000000UL  //XTAL = 8 MHz
#include "avr/io.h"
#include "util/delay.h"
int main ( )
{
     unsigned char i;

     DDRB = 0x08;      //PB3 as output
     i = 127;
     OCR0 = 127;       //duty cycle = 50%
     TCCR0 = 0x73;     //Phase correct PWM, inverted, N = 64

     while (i != 0)
     {
          OCR0 = i;
          _delay_ms(25);   //use AVR Studio library delay
          i++;
     }
     while (1);
     return 0;
}
```

SUMMARY

In the first section, The AVR 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 AVR with a DC motor. Then, simple Assembly and C programs were written to show the concept of PWM.

We discussed the PWM features of AVR timers in sections two and three, and in the last section we used the PWM feature of AVR to control DC motors.

PROBLEMS

SECTION 16.1: DC MOTOR INTERFACING AND PWM

1. Which motor is best for moving a wheel exactly 90 degrees?
2. True or false. Current dissipation of a DC motor is proportional to the load.
3. True or false. The RPM of a DC motor is the same for no-load and loaded.
4. The RPM given in data sheets is for ___________ (no-load, loaded).
5. What is the advantage of DC motors over AC motors?
6. What is the advantage of stepper motors over DC motors?
7. True or false. Higher load on a DC motor slows it down if the current and voltage supplied to the motor are fixed.
8. What is PWM, and how is it used in DC motor control?
9. A DC motor is moving a load. How do we keep the RPM constant?
10. What is the advantage of placing an optoisolator between the motor and the microcontroller?

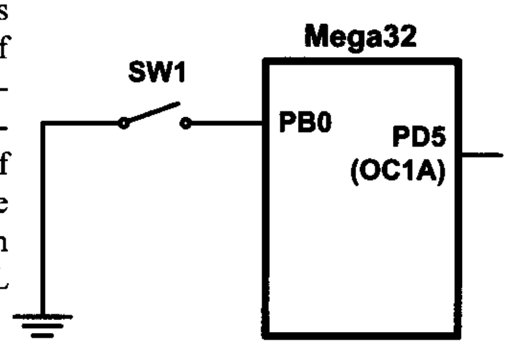
SECTION 16.2: PWM MODES IN 8-BIT TIMERS

11. Using Timer0 and non-inverted Fast PWM mode, write a program that generates a wave with frequency of 62.5 kHz and duty cycle of 60%. Assume XTAL = 16 MHz.
12. Using Timer0 and inverted Fast PWM mode, write a program that generates a wave with frequency of 46.875 kHz and duty cycle of 70%. Assume XTAL = 12 MHz.
13. Using Timer0 and inverted Fast PWM mode, write a program that generates a wave with frequency of 1953 Hz and duty cycle of 20%. Assume XTAL = 4 MHz.
14. Using Timer0 and non-inverted Fast PWM mode, write a program that generates a wave with frequency of 15.25 Hz and duty cycle of 10%. Assume XTAL = 1 MHz.
15. Using Timer0 and inverted Phase correct PWM mode, write a program that generates a wave with frequency of 1960 Hz and duty cycle of 20%. Assume XTAL = 1 MHz.
16. Using Timer0 and inverted Phase correct PWM mode, write a program that generates a wave with frequency of 1.96 kHz and duty cycle of 95%. Assume XTAL = 1 MHz.
17. Using Timer2 and non-inverted Phase correct PWM mode, write a program that generates a wave with frequency of 61.3 Hz and duty cycle of 19%. Assume XTAL = 8 MHz.
18. Using Timer2 and inverted Phase correct PWM mode, write a program that generates a wave with frequency of 245 Hz and duty cycle of 82%. Assume XTAL = 1 MHz.

SECTION 16.3: PWM MODES IN TIMER1

19. Using mode 6 of Timer1 and non-inverted Fast PWM, write a program that generates a wave with frequency of 15,625 Hz and duty cycle of 40%. Assume XTAL = 8 MHz.
20. Using mode 7 of Timer1 and inverted Fast PWM, write a program that generates a wave with frequency of 3906 Hz and duty cycle of 45%. Assume XTAL = 4 MHz.
21. Using mode 7 of Timer1 and inverted Fast PWM, write a program that generates a wave with frequency of 1953 Hz and duty cycle of 35%. Assume XTAL = 16 MHz.
22. Using mode 6 of Timer1 and non-inverted Fast PWM, write a program that generates a wave with frequency of 1953 Hz and duty cycle of 50%. Assume XTAL = 8 MHz.
23. Using mode 1 of Timer1 and inverted Phase correct PWM, write a program that generates a wave with frequency of 976.5 Hz and duty cycle of 35%. Assume XTAL = 4 MHz.
24. Using mode 2 of Timer1 and non-inverted Phase correct PWM, write a program that generates a wave with frequency of 30.5 Hz and duty cycle of 25%. Assume XTAL = 8 MHz.

25. Using mode 1 of Timer1 and non-inverted Phase correct PWM, write a program that generates a wave with frequency of 245 Hz and duty cycle of 19%. Assume XTAL = 8 MHz.
26. As shown in the figure, a switch is connected to PB0. Using mode 2 of Timer1 and non-inverted Phase correct PWM, write a program that generates a wave with frequency of 978 Hz. When the switch is closed the duty cycle is 20%, and when it is open the duty cycle is 85%. Assume XTAL = 8 MHz.



ANSWERS TO REVIEW QUESTIONS

SECTION 16.1: 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. No-load

SECTION 16.2: PWM MODES IN 8-BIT TIMERS

1. True
2. False
3. True
4. False
5. Phase correct PWM

SECTION 16.3: PWM MODES IN TIMER1

1. False
2. True
3. False