INTRODUCTION

This application note discusses the steps of developing several controllers for brushless motors. We cover sensored, sensorless, open-loop, and closed-loop design. There is even a controller with independent voltage and speed controls so you can discover your motor’s characteristics empirically.

The code in this application note was developed with the Microchip PIC16F877 PIC® microcontroller, in conjunction with the In-Circuit Debugger (ICD). This combination was chosen because the ICD is inexpensive, and code can be debugged in the prototype hardware without need for an extra programmer or emulator. As the design develops, we program the target device and exercise the code directly from the MPLAB® environment. The final code can then be ported to one of the smaller, less expensive, PIC microcontrollers. The porting takes minimal effort because the instruction set is identical for all PIC 14-bit core devices.

It should also be noted that the code was bench tested and optimized for a Pittman N2311A011 brushless DC motor. Other motors were also tested to assure that the code was generally useful.

Anatomy of a BLDC

Figure 1 is a simplified illustration of BLDC motor construction. A brushless motor is constructed with a permanent magnet rotor and wire wound stator poles. Electrical energy is converted to mechanical energy by the magnetic attractive forces between the permanent magnet rotor and a rotating magnetic field induced in the wound stator poles.

FIGURE 1: SIMPLIFIED BLDC MOTOR DIAGRAMS
In this example there are three electromagnetic circuits connected at a common point. Each electromagnetic circuit is split in the center, thereby permitting the permanent magnet rotor to move in the middle of the induced magnetic field. Most BLDC motors have a three-phase winding topology with star connection. A motor with this topology is driven by energizing two phases at a time. The static alignment shown in Figure 2, is that which would be realized by creating an electric current flow from terminal A to B, noted as path 1 on the schematic in Figure 1. The rotor can be made to rotate clockwise 60 degrees from the A to B alignment by changing the current path to flow from terminal C to B, noted as path 2 on the schematic. The suggested magnetic alignment is used only for illustration purposes because it is easy to visualize. In practice, maximum torque is obtained when the permanent magnet rotor is 90 degrees away from alignment with the stator magnetic field.

The key to BLDC commutation is to sense the rotor position, then energize the phases that will produce the most amount of torque. The rotor travels 60 electrical degrees per commutation step. The appropriate stator current path is activated when the rotor is 120 degrees from alignment with the corresponding stator magnetic field, and then deactivated when the rotor is 60 degrees from alignment, at which time the next circuit is activated and the process repeats. Commutation for the rotor position, shown in Figure 1, would be at the completion of current path 2 and the beginning of current path 3 for clockwise rotation. Commutating the electrical connections through the six possible combinations, numbered 1 through 6, at precisely the right moments will pull the rotor through one electrical revolution.

In the simplified motor of Figure 1, one electrical revolution is the same as one mechanical revolution. In actual practice, BLDC motors have more than one of the electrical circuits shown, wired in parallel to each other, and a corresponding multi-pole permanent magnetic rotor. For two circuits there are two electrical revolutions per mechanical revolution, so for a two-circuit motor, each electrical commutation phase would cover 30 degrees of mechanical rotation.

**Sensored Commutation**

The easiest way to know the correct moment to commutate the winding currents is by means of a position sensor. Many BLDC motor manufacturers supply motors with a three-element Hall effect position sensor. Each sensor element outputs a digital high level for 180 electrical degrees of electrical rotation, and a low level for the other 180 electrical degrees. The three sensors are offset from each other by 60 electrical degrees so that each sensor output is in alignment with one of the electromagnetic circuits. A timing diagram showing the relationship between the sensor outputs and the required motor drive voltages is shown in Figure 2.
The numbers at the top of Figure 2 correspond to the current phases shown in Figure 1. It is apparent from Figure 2 that the three sensor outputs overlap in such a way as to create six unique three-bit codes corresponding to each of the drive phases. The numbers shown around the peripheral of the motor diagram in Figure 1 represent the sensor position code. The north pole of the rotor points to the code that is output at that rotor position. The numbers are the sensor logic levels where the Most Significant bit is sensor C and the Least Significant bit is sensor A.

Each drive phase consists of one motor terminal driven high, one motor terminal driven low, and one motor terminal left floating. A simplified drive circuit is shown in Figure 3. Individual drive controls for the high and low drivers permit high drive, low drive, and floating drive at each motor terminal. One precaution that must be taken with this type of driver circuit is that both high side and low side drivers must never be activated at the same time. Pull-up and pull-down resistors must be placed at the driver inputs to ensure that the drivers are off immediately after a microcontroller Reset, when the microcontroller outputs are configured as high-impedance inputs.

Another precaution against both drivers being active at the same time is called dead-time control. When an output transitions from the high drive state to the low drive state, the proper amount of time for the high side driver to turn off must be allowed to elapse before the low side driver is activated. Drivers take more time to turn off than to turn on, so extra time must be allowed to elapse so that both drivers are not conducting at the same time. Notice in Figure 3 that the high drive period and low drive period of each output, is separated by a floating drive phase period. This dead time is inherent to the three-phase BLDC drive scenario, so special timing for dead-time control is not necessary. The BLDC commutation sequence will never switch the high-side device and the low-side device in a phase, at the same time.

At this point we are ready to start building the motor commutation control code. Commutation consists of linking the input sensor state with the corresponding drive state. This is best accomplished with a state table and a table offset pointer. The sensor inputs will form the table offset pointer, and the list of possible output drive codes will form the state table. Code development will be performed with a PIC16F877 in an ICD. PORTC has arbitrarily been assigned as the motor drive port and PORTE as the sensor input port. PORTC was chosen as the driver port because the ICD demo board also has LED indicators on that port so we can watch the slow speed commutation drive signals without any external test equipment.

Each driver requires two pins, one for high drive and one for low drive, so six pins of PORTC will be used to control the six motor drive MOSFETS. Each sensor requires one pin, so three pins of PORTE will be used to read the current state of the motor’s three-output sensor. The sensor state will be linked to the drive state by using the sensor input code as a binary offset to the drive table index. The sensor states and motor drive states from Figure 2 are tabulated in Table 1.

FIGURE 3: THREE PHASE BRIDGE

![Three Phase Bridge Diagram](image-url)
TABLE 1: CW SENSOR AND DRIVE BITS BY PHASE ORDER

<table>
<thead>
<tr>
<th>Pin</th>
<th>RE2</th>
<th>RE1</th>
<th>RE0</th>
<th>RC5</th>
<th>RC4</th>
<th>RC3</th>
<th>RC2</th>
<th>RC1</th>
<th>RC0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>Sensor C</td>
<td>Sensor B</td>
<td>Sensor A</td>
<td>C High Drive</td>
<td>C Low Drive</td>
<td>B High Drive</td>
<td>B Low Drive</td>
<td>A High Drive</td>
<td>A Low Drive</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
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<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Sorting Table 1 by sensor code binary weight results in Table 2. Activating the motor drivers, according to a state table built from Table 2, will cause the motor of Figure 1 to rotate clockwise.

TABLE 2: CW SENSOR AND DRIVE BITS BY SENSOR ORDER

<table>
<thead>
<tr>
<th>Pin</th>
<th>RE2</th>
<th>RE1</th>
<th>RE0</th>
<th>RC5</th>
<th>RC4</th>
<th>RC3</th>
<th>RC2</th>
<th>RC1</th>
<th>RC0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>Sensor C</td>
<td>Sensor B</td>
<td>Sensor A</td>
<td>C High Drive</td>
<td>C Low Drive</td>
<td>B High Drive</td>
<td>B Low Drive</td>
<td>A High Drive</td>
<td>A Low Drive</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Counter clockwise rotation is accomplished by driving current through the motor coils in the direction opposite of that for clockwise rotation. Table 3 was constructed by swapping all the high and low drives of Table 2. Activating the motor coils, according to a state table built from Table 3, will cause the motor to rotate counter clockwise. Phase numbers in Table 3 are preceded by a slash denoting that the EMF is opposite that of the phases in Table 2.

TABLE 3: CCW SENSOR AND DRIVE BITS

<table>
<thead>
<tr>
<th>Pin</th>
<th>RE2</th>
<th>RE1</th>
<th>RE0</th>
<th>RC5</th>
<th>RC4</th>
<th>RC3</th>
<th>RC2</th>
<th>RC1</th>
<th>RC0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>Sensor C</td>
<td>Sensor B</td>
<td>Sensor A</td>
<td>C High Drive</td>
<td>C Low Drive</td>
<td>B High Drive</td>
<td>B Low Drive</td>
<td>A High Drive</td>
<td>A Low Drive</td>
</tr>
<tr>
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<td>1</td>
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<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

The code segment for determining the appropriate drive word from the sensor inputs is shown in Figure 4.
FIGURE 4: COMMUTATION CODE SEGMENT

<table>
<thead>
<tr>
<th>Define</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DrivePort</td>
<td>PORTC</td>
</tr>
<tr>
<td>SensorMask</td>
<td>B’00000111’</td>
</tr>
<tr>
<td>SensorPort</td>
<td>PORTE</td>
</tr>
<tr>
<td>DirectionBit</td>
<td>PORTA, 1</td>
</tr>
</tbody>
</table>

```assembly
#define DrivePort PORTC
#define SensorMask B'00000111'
#define SensorPort PORTE
#define DirectionBit PORTA, 1

 Commutate

movlw SensorMask ;retain only the sensor bits
andwf SensorPort ;get sensor data
xorwf LastSensor, w ;test if motion sensed
btfsc STATUS, Z ;zero if no change
return ;no change - return

xorwf LastSensor, f ;replace last sensor data with current
btfss DirectionBit ;test direction bit
goto FwdCom ;bit is zero - do forward commutation

movlw HIGH RevTable ;get MS byte to table
movwf PCLATH ;prepare for computed GOTO
movlw LOW RevTable ;get LS byte of table
goto Com2 ;reverse commutation

FwdCom ;forward commutation

movlw HIGH FwdTable ;get MS byte of table
movwf PCLATH ;prepare for computed GOTO
movlw LOW FwdTable ;get LS byte of table

Com2

addwf LastSensor, w ;add sensor offset
btfsc STATUS, C ;page change in table?
icf PCLATH, f ;yes - adjust MS byte
call GetDrive ;get drive word from table
movwf DriveWord ;save as current drive word
return

GetDrive

movwf PCL

FwdTable

retlw B'00000000' ;invalid
retlw B'00001001' ;phase 6
retlw B'00001001' ;phase 4
retlw B'00001100' ;phase 5
retlw B'00010010' ;phase 2
retlw B'00000110' ;phase 1
retlw B'00100001' ;phase 3
retlw B'00000000' ;invalid

RevTable

retlw B'00000000' ;invalid
retlw B'00100001' ;phase /6
retlw B'00000110' ;phase /4
retlw B'00100100' ;phase /5
retlw B'00001100' ;phase /2
retlw B'00001001' ;phase /1
retlw B'00001001' ;phase /3
retlw B'00000000' ;invalid
```
Before we try the commutation code with our motor, let's consider what happens when a voltage is applied to a DC motor. A greatly simplified electrical model of a DC motor is shown in Figure 5.

**FIGURE 5: DC MOTOR EQUIVALENT CIRCUIT**

When the rotor is stationary, the only resistance to current flow is the impedance of the electromagnetic coils. The impedance is comprised of the parasitic resistance of the copper in the windings, and the parasitic inductance of the windings themselves. The resistance and inductance are very small by design, so start-up currents would be very large, if not limited.

When the motor is spinning, the permanent magnet rotor moving past the stator coils induces an electrical potential in the coils called Back Electromotive Force, or BEMF. BEMF is directly proportional to the motor speed and is determined from the motor voltage constant $K_V$.

**EQUATION 1:**

\[
\text{RPM} = K_V \times \text{Volts} \\
\text{BEMF} = \frac{\text{RPM}}{K_V}
\]

In an ideal motor, $R$ and $L$ are zero, and the motor will spin at a rate such that the BEMF exactly equals the applied voltage.

The current that a motor draws is directly proportional to the torque load on the motor shaft. Motor current is determined from the motor torque constant $K_T$.

**EQUATION 2:**

\[
\text{Torque} = K_T \times \text{Amps}
\]

An interesting fact about $K_T$ and $K_V$ is that their product is the same for all motors. Volts and Amps are expressed in MKS units, so if we also express $K_T$ in MKS units, that is $N$-M/Rad/Sec, then the product of $K_V$ and $K_T$ is 1.

**EQUATION 3:**

\[
K_V \times K_T = 1
\]

This is not surprising when you consider that the units of the product are \([1/(V*A)] \times [(N*M)/(Rad/Sec)]\), which is the same as mechanical power divided by electrical power.

If voltage were to be applied to an ideal motor from an ideal voltage source, it would draw an infinite amount of current and accelerate instantly to the speed dictated by the applied voltage and $K_V$. Of course no motor is ideal, and the start-up current will be limited by the parasitic resistance and inductance of the motor windings, as well as the current capacity of the power source. Two detrimental effects of unlimited start-up current and voltage are excessive torque and excessive current. Excessive torque can cause gears to strip, shaft couplings to slip, and other undesirable mechanical problems. Excessive current can cause driver MOSFETs to blow out and circuitry to burn.

We can minimize the effects of excessive current and torque by limiting the applied voltage at start-up with Pulse-Width Modulation (PWM). Pulse-Width Modulation is effective and fairly simple to do. Two things to consider with PWM are, the MOSFET losses due to switching, and the effect that the PWM rate has on the motor. Higher PWM frequencies mean higher switching losses, but too low of a PWM frequency will mean that the current to the motor will be a series of high current pulses instead of the desired average of the voltage waveform. Averaging is easier to attain at lower frequencies if the parasitic motor inductance is relatively high, but high inductance is an undesirable motor characteristic. The ideal frequency is dependent on the characteristics of your motor and power switches. For this application, the PWM frequency will be approximately 10 kHz.
We are using PWM to control start-up current, so why not use it as a speed control also? We will use the Analog-to-Digital Converter (ADC), of the PIC16F877 to read a potentiometer and use the voltage reading as the relative speed control input. Only 8 bits of the ADC are used, so our speed control will have 256 levels. We want the relative speed to correspond to the relative potentiometer position. Motor speed is directly proportional to applied voltage, so varying the PWM duty cycle linearly from 0% to 100% will result in a linear speed control from 0% to 100% of maximum RPM. Pulse width is determined by continuously adding the ADC result to the free running Timer0 count to determine when the drivers should be on or off. If the addition results in an overflow, then the drivers are on, otherwise they are off. An 8-bit timer is used so that the ADC to timer additions need no scaling to cover the full range. To obtain a PWM frequency of 10 kHz Timer0 must be running at 256 times that rate, or 2.56 MHz. The minimum prescale value for Timer0 is 1:2, so we need an input frequency of 5.12 MHz. The input to Timer0 is Fosc/4. This requires an Fosc of 20.48 MHz. That is an odd frequency, and 20 MHz is close enough, so we will use 20 MHz resulting in a PWM frequency of 9.77 kHz.

There are several ways to modulate the motor drivers. We could switch the high and low side drivers together, or just the high or low driver while leaving the other driver on. Some high side MOSFET drivers use a capacitor charge pump to boost the gate drive above the drain voltage. The charge pump charges when the driver is off and discharges into the MOSFET gate when the driver is on. It makes sense then to switch the high side driver to keep the charge pump refreshed. Even though this application does not use the charge pump type drivers, we will modulate the high side driver while leaving the low side driver on. There are three high side drivers, any one of which could be active depending on the position of the rotor. The motor drive word is 6-bits wide, so if we logically AND the drive word with zeros in the high driver bit positions, and 1's in the low driver bit positions, we will turn off the active high driver regardless which one of the three it is.

We have now identified 4 tasks of the control loop:
- Read the sensor inputs
- Commutate the motor drive connections
- Read the speed control ADC
- PWM the motor drivers using the ADC and Timer0 addition results

At 20 MHz clock rate, control latency, caused by the loop time, is not significant so we will construct a simple polled task loop. The control loop flowchart is shown in Figure 6 and code listings are in Appendix B.
FIGURE 6: SENSORED DRIVE FLOWCHART

Initialize

ADC Ready ?
Yes
Read new ADC
No
Set ADC GO

Add ADRESH to TMR0

Carry?
Yes

Mask Drive Word
No

Output Drive Word

Sensor Change
Yes
Save Sensor Code
No

Commutate
Sensorless Motor Control

It is possible to determine when to commutate the motor drive voltages by sensing the back EMF voltage on an undriven motor terminal during one of the drive phases. The obvious cost advantage of sensorless control is the elimination of the Hall position sensors. There are several disadvantages to sensorless control:

- The motor must be moving at a minimum rate to generate sufficient back EMF to be sensed
- Abrupt changes to the motor load can cause the BEMF drive loop to go out of lock
- The BEMF voltage can be measured only when the motor speed is within a limited range of the ideal commutation rate for the applied voltage
- Commutation at rates faster than the ideal rate will result in a discontinuous motor response

If low cost is a primary concern and low speed motor operation is not a requirement and the motor load is not expected to change rapidly then sensorless control may be the better choice for your application.

Determining the BEMF

The BEMF, relative to the coil common connection point, generated by each of the motor coils, can be expressed as shown in Equation 4 through Equation 6.

**EQUATION 4:**

\[ B_{BEMF} = \sin(\alpha) \]

**EQUATION 5:**

\[ C_{BEMF} = \sin\left(\alpha - \frac{2\pi}{3}\right) \]

**EQUATION 6:**

\[ A_{BEMF} = \sin\left(\alpha - \frac{4\pi}{3}\right) \]

Figure 7 shows the equivalent circuit of the motor with coils B and C driven while coil A is undriven and available for BEMF measurement. At the commutation frequency the L's are negligible. The R's are assumed to be equal. The L and R components are not shown in the A branch since no significant current flows in this part of the circuit so those components can be ignored.
The BEMF generated by the B and C coils in tandem, as shown in Figure 7, can be expressed as shown in Equation 7.

**EQUATION 7:**

\[ \text{BEMF}_{BC} = B_{\text{BEMF}} - C_{\text{BEMF}} \]

The sign reversal of \( C_{\text{BEMF}} \) is due to moving the reference point from the common connection to ground. Recall that there are six drive phases in one electrical revolution. Each drive phase occurs +/- 30 degrees around the peak back EMF of the two motor windings being driven during that phase. At full speed the applied DC voltage is equivalent to the RMS BEMF voltage in that 60 degree range. In terms of the peak BEMF generated by any one winding, the RMS BEMF voltage across two of the windings can be expressed as shown in Equation 8.

**EQUATION 8:**

\[
\begin{align*}
\text{BEMF}_{\text{RMS}} &= \sqrt{\frac{3}{2\pi} \int_{\pi/6}^{\pi/3} \sin(\alpha) - \sin \left( \alpha - \frac{2\pi}{3} \right)^2 d\alpha} \\
\text{BEMF}_{\text{RMS}} &= \sqrt{\frac{3}{2\pi} \left( \frac{\pi}{2} + \frac{3\pi}{4} \right)} \\
\text{BEMF}_{\text{RMS}} &= 1.6554
\end{align*}
\]

We will use this result to normalize the BEMF diagrams presented later, but first let’s consider the expected BEMF at the undriven motor terminal. Since the applied voltage is pulse-width modulated, the drive alternates between on and off throughout the phase time. The BEMF, relative to ground, seen at the A terminal when the drive is on, can be expressed as shown in Equation 9.

**EQUATION 9:**

\[
\begin{align*}
\text{BEMF}_{A} &= \frac{V - (B_{\text{BEMF}} - C_{\text{BEMF}})}{2R} - C_{\text{BEMF}} + A_{\text{BEMF}} \\
\text{BEMF}_{A} &= \frac{V - B_{\text{BEMF}} + C_{\text{BEMF}}}{2} - C_{\text{BEMF}} + A_{\text{BEMF}}
\end{align*}
\]

Notice that the winding resistance cancels out, so resistive voltage drop, due to motor torque load, is not a factor when measuring BEMF. The BEMF, relative to ground, seen at the A terminal when the drive is off can be expressed as shown in Equation 10.

**EQUATION 10:**

\[
\text{BEMF}_{A} = A_{\text{BEMF}} - C_{\text{BEMF}}
\]
Figure 8 is a graphical representation of the BEMF formulas computed over one electrical revolution. To avoid clutter, only the terminal A waveform, as would be observed on an oscilloscope, is displayed and is denoted as BEMF\text{(drive on)}. The terminal A waveform is flattened at the top and bottom because at those points the terminal is connected to the drive voltage or ground. The sinusoidal waveforms are the individual coil BEMFs relative to the coil common connection point. The 60 degree sinusoidal humps are the BEMFs of the driven coil pairs relative to ground. The entire graph has been normalized to the RMS value of the coil pair BEMFs.

**FIGURE 8: BEMF AT 100% DRIVE**

Notice that the BEMF\text{(drive on)} waveform is fairly linear and passes through a voltage that is exactly half of the applied voltage at precisely 60 degrees which coincides with the zero crossing of the coil A BEMF waveform. This implies that we can determine the rotor electrical position by detecting when the open terminal voltage equals half the applied voltage.

What happens when the PWM duty cycle is less than 100%? Figure 9 is a graphical representation of the BEMF formulas computed over one electrical revolution when the effective applied voltage is 50% of that shown in Figure 8. The entire graph has been normalized to the peak applied voltage.
As expected, the BEMF waveforms are all reduced proportionally but notice that the BEMF on the open terminal still equals half the applied voltage midway through the 60 degree drive phase. This occurs only when the drive voltage is on. Figure 10 shows a detail of the open terminal BEMF when the drive voltage is on and when the drive voltage is off. At various duty cycles, notice that the drive on curve always equals half the applied voltage at 60 degrees.
How well do the predictions match an actual motor? Figure 11 shows the waveforms present on terminal A of a Pittman N2311A011 brushless motor at various PWM duty cycle configurations. The large transients, especially prevalent in the 100% duty cycle waveform, are due to flyback currents caused by the motor winding inductance.
FIGURE 11: PITTMAN BEMF WAVEFORMS

The rotor position can be determined by measuring the voltage on the open terminal when the drive voltage is applied and then comparing the result to one half of the applied voltage.

Recall that motor speed is proportional to the applied voltage. The formulas and graphs presented so far represent motor operation when commutation rate coincides with the effective applied voltage. When the commutation rate is too fast then commutation occurs early and the zero crossing point occurs later in the drive phase. When the commutation rate is too slow then commutation occurs late and the zero crossing point occurs earlier in the drive phase. We can sense and use this shift in zero crossing to adjust the commutation rate to keep the motor running at the ideal speed for the applied voltage and load torque.
Open-Loop Speed Control

An interesting property of brushless DC motors is that they will operate synchronously to a certain extent. This means that for a given load, applied voltage, and commutation rate the motor will maintain open-loop lock with the commutation rate provided that these three variables do not deviate from the ideal by a significant amount. The ideal is determined by the motor voltage and torque constants. How does this work? Consider that when the commutation rate is too slow for an applied voltage, the BEMF will be too low resulting in more motor current. The motor will react by accelerating to the next phase position then slow down waiting for the next commutation. In the extreme case the motor will snap to each position like a stepper motor until the next commutation occurs. Since the motor is able to accelerate faster than the commutation rate, rates much slower than the ideal can be tolerated without losing lock but at the expense of excessive current.

Now consider what happens when commutation is too fast. When commutation occurs early the BEMF has not reached peak resulting in more motor current and a greater rate of acceleration to the next phase but it will arrive there too late. The motor tries to keep up with the commutation but at the expense of excessive current. If the commutation arrives so early that the motor can not accelerate fast enough to catch the next commutation, lock is lost and the motor spins down. This happens abruptly not very far from the ideal rate. The abrupt loss of lock looks like a discontinuity in the motor response which makes closed-loop control difficult. An alternative to closed-loop control is to adjust the commutation rate until self locking open-loop control is achieved. This is the method we will use in our application.

When the load on a motor is constant over its operating range then the response curve of motor speed relative to applied voltage is linear. If the supply voltage is well regulated, in addition to a constant torque load, then the motor can be operated open loop over its entire speed range. Consider that with Pulse-Width Modulation the effective voltage is linearly proportional to the PWM duty cycle. An open-loop controller can be made by linking the PWM duty cycle to a table of motor speed values stored as the time of commutation for each drive phase. We need a table because revolutions per unit time is linear, but we need time per revolution which is not linear. Looking up the time values in a table is much faster than computing them repeatedly.

The program that we use to run the motor open loop is the same program we will use to automatically adjust the commutation rate in response to variations in the torque load. The program uses two potentiometers as speed control inputs. One potentiometer, we’ll call it the PWM potentiometer, is directly linked to both the PWM duty cycle and the commutation time look-up table. The second potentiometer, we’ll call this the Offset potentiometer, is used to provide an offset to the PWM duty cycle determined by the PWM potentiometer. An Analog-to-Digital conversion of the PWM potentiometer produces a number between 0 and 255. The PWM duty cycle is generated by adding the PWM potentiometer reading to a free running 8-bit timer. When the addition results in a carry the drive state is on, otherwise it is off. The PWM potentiometer reading is also used to access the 256 location commutation time look-up table. The Offset potentiometer also produces a number between 0 and 255. The Most Significant bit of this number is inverted making it a signed number between -128 and 127. This offset result, when added to the PWM potentiometer, becomes the PWM duty cycle threshold, and controls the drive on and off states described previously.

Closed-Loop Speed Control

Closed-loop speed control is achieved by unlinking the commutation time table index from the PWM duty cycle number. The PWM potentiometer is added to a fixed manual threshold number between 0 and 255. When this addition results in a carry, the mode is switched to automatic. On entering Automatic mode the commutation index is initially set to the PWM potentiometer reading. Thereafter, as long as Automatic mode is still in effect, the commutation table index is automatically adjusted up or down according to voltages read at motor terminal A at specific times. Three voltage readings are taken.

FIGURE 12: BEMF SAMPLE TIMES
The first reading is taken during drive phase 4 when terminal A is actively driven high. This is the applied voltage. The next two readings are taken during drive phase 5 when terminal A is floating. The first reading is taken when \( \frac{1}{4} \) of the commutation time has elapsed and the second reading is taken when \( \frac{3}{4} \) of the commutation time has elapsed. We'll call these readings 1 and 2, respectively. The commutation table index is adjusted according to the following relationship between the applied voltage reading and readings 1 and 2:

- Index is unchanged if Reading 1 > Applied Voltage/2 and Reading 2 < Applied Voltage/2
- Index is increased if Reading 1 < Applied Voltage/2
- Index is decreased if Reading 1 > Applied Voltage/2 and Reading 2 > Applied Voltage/2

The motor rotor and everything it is connected to has a certain amount of inertia. The inertia delays the motor response to changes in voltage load and commutation time. Updates to the commutation time table index are delayed to compensate for the mechanical delay and allow the motor to catch up.

**Acceleration and Deceleration Delay**

The inertia of the motor and what it is driving, tends to delay motor response to changes in the drive voltage. We need to compensate for this delay by adding a matching delay to the control loop. The control loop delay requires two time constants, a relatively slow one for acceleration, and a relatively fast one for deceleration.

Consider what happens in the control loop when the voltage to the motor suddenly rises, or the motor load is suddenly reduced. The control senses that the motor rotation is too slow and attempts to adjust by making the commutation time shorter. Without delay in the control loop, the next speed measurement will be taken before the motor has reacted to the adjustment, and another speed adjustment will be made. Adjustments continue to be made ahead of the motor response until eventually, the commutation time is too short for the applied voltage, and the motor goes out of lock. The acceleration timer delay prevents this runaway condition. Since the motor can tolerate commutation times that are too long, but not commutation times that are too short, the acceleration time delay can be longer than required without serious detrimental effect.

Consider what happens in the control loop when the voltage to the motor suddenly falls, or the motor load is suddenly increased. If the change is sufficiently large, commutation time will immediately be running too short for the motor conditions. The motor cannot tolerate this, and loss of lock will occur. To prevent loss of lock, the loop deceleration timer delay must be short enough for the control loop to track, or precede the changing motor condition. If the time delay is too short, then the control loop will continue to lengthen the commutation time ahead of the motor response resulting in over compensation. The motor will eventually slow to a speed that will indicate to the BEMF sensor that the speed is too slow for the applied voltage. At that point, commutation deceleration will cease, and the commutation change will adjust in the opposite direction governed by the acceleration time delay. Over compensation during deceleration will not result in loss of lock, but will cause increased levels of torque ripple and motor current until the ideal commutation time is eventually reached.

**Determining The Commutation Time Table Values**

The assembler supplied with MPLAB performs all calculations as 32-bit integers. To avoid the rounding errors that would be caused by integer math, we will use a spreadsheet, such as Excel, to compute the table entries then cut and paste the results to an include file. The spreadsheet is setup as shown in Table 4.

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Number or Formula</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phases</td>
<td>12</td>
<td>Number of commutation phase changes in one mechanical revolution.</td>
</tr>
<tr>
<td>Fosc</td>
<td>20 MHz</td>
<td>Microcontroller clock frequency</td>
</tr>
<tr>
<td>Fosc_4</td>
<td>Fosc/4</td>
<td>Microcontroller timers source clock</td>
</tr>
<tr>
<td>Prescale</td>
<td>4</td>
<td>Timer 1 prescale</td>
</tr>
<tr>
<td>MaxRPM</td>
<td>8000</td>
<td>Maximum expected speed of the motor at full applied voltage</td>
</tr>
<tr>
<td>MinRPM</td>
<td>((60\times Fosc_4)/\text{Phases}\times\text{Prescale}\times 65535)+1)</td>
<td>Limitation of 16-bit timer</td>
</tr>
<tr>
<td>Offset</td>
<td>-345</td>
<td>This is the zero voltage intercept on the RPM axis. A property normalized to the 8-bit A to D converter.</td>
</tr>
<tr>
<td>Slope</td>
<td>((\text{MaxRPM-Offset})/255)</td>
<td>Slope of the RPM to voltage input response curve normalized to the 8-bit A to D converter.</td>
</tr>
</tbody>
</table>
The body of the spreadsheet starts arbitrarily at row 13. Row 12 contains the column headings. The body of the spreadsheet is constructed as follows:

- Column A is the commutation table index number \( N \). The numbers in column A are integers from 0 to 255.
- Column B is the RPM that will result by using the counter values at index number \( N \). The formula in column B is: \( =IF(Offset+A13*Slope>MinRPM,Offset+A13*Slope,MinRPM) \).
- Column C is the duration of each commutation phase expressed in seconds. The formula for column C is: \( =60/(Phases*B13) \).
- Column D is the duration of each commutation phase expressed in timer counts. The formula for column D is: \( =C13*FOSC_4/Prescale \).

The range of commutation phase times at a reasonable resolution requires a 16-bit timer. The timer counts from 0 to a compare value then automatically resets to 0. The compare values are stored in the commutation time table. Since the comparison is 16 bits and tables can only handle 8 bits, the commutation times will be stored in two tables accessed by the same index.

- Column E is the Most Significant Byte of the 16-bit timer compare value. The formula for column E is: \( =CONCATENATE("\text{retlw high D'}",\text{INT(D13)},\"\text{"}) \).
- Column F is the Least Significant Byte of the 16-bit timer compare value. The formula for column F is: \( =CONCATENATE("\text{retlw low D'}",\text{INT(D13)},\"\text{"}) \).

When all spreadsheet formulas have been entered in row 13, the formulas can be dragged down to row 268 to expand the table to the required 256 entries. Columns E and F will have the table entries in assembler ready format. An example of the table spreadsheet is shown in Figure 13.
Using Open-Loop Control to Determine Motor Characteristics

You can measure the motor characteristics by operating the motor in Open-Loop mode, and measuring the motor current at several applied voltages. You can then chart the response curve in a spreadsheet, such as Excel, to determine the slope and offset numbers. Finally, plug the maximum RPM and offset numbers back into the table generator spreadsheet to regenerate the RPM tables.

To operate the motor in Open-Loop mode:

- Set the manual threshold number (ManThresh) to 0xFF. This will prevent the Auto mode from taking over.
- When operating the motor in Open-Loop mode, start by adjusting the offset control until the motor starts to move. You may also need to adjust the PWM control slightly above minimum.
- After the motor starts, you can increase the PWM control to increase the motor speed. The RPM and voltage will track, but you will need to adjust the offset frequently to optimize the voltage for the selected RPM.
- Optimize the voltage by adjusting the offset for minimum current.

To obtain the response offset with Excel®, enter the voltage (left column), and RPM (right column) pairs in adjacent columns of the spreadsheet. Use the chart wizard to make an X-Y scatter chart. When the chart is finished, right click on the response curve and select the pop-up menu “add trendline...” option. Choose the linear regression type and, in the Options tab, check the “display equation on chart” option. An example of the spreadsheet is shown in Figure 14.
Constructing The Sensorless Control Code

At this point we have all the pieces required to control a sensorless motor. We can measure BEMF and the applied voltage then compare them to each other to determine rotor position. We can vary the effective applied voltage with PWM and control the speed of the motor by timing the commutation phases. Some measurement events must be precisely timed. Other measurement events need not to interfere with each other. The ADC must be switched from one source to another and allow for sufficient acquisition time. Some events must happen rapidly with minimum latency. These include PWM and commutation.

We can accomplish everything with a short main loop that calls a state table. The main loop will handle PWM and commutation and the state table will schedule reading the two potentiometers, the peak applied voltage and the BEMF voltages at two times when the attached motor terminal is floating. Figure A-1 through Figure A-10, in Appendix A: “Sensorless Control Flowchart”, is the resulting flow chart of sensorless motor control. Code listings are in Appendix C: “Sensored Code” and Appendix D: “Sensorless Code”.
APPENDIX A: SENSORLESS CONTROL FLOWCHART

FIGURE A-1: MAIN LOOP

Sensorless Control
  ↓
  Initialize

  ↓
  Is Timer1 Compare Flag Set?

Yes
  Call Commutate
  ↓
  No

  ↓
  Is Full On Flag Set?

Yes
  Add PWM Threshold to Timer0
  ↓
  No

  ↓
  Carry ?

Yes
  Set Drive-On Flag
  ↓
  No

  ↓
  Clear Drive-On Flag

  ↓
  Call DriveMotor

  ↓
  Call LockTest

  ↓
  CallStateMachine
FIGURE A-2: MOTOR COMMUTATION

1. Commutate
2. Is Timer1 Clear on Compare Enabled?
   - Yes: Commutate
   - No: Decrement PhaseIndex
3. Is PhaseIndex = 0?
   - Yes: Commutate End
   - No: Drive Word = Table Entry@PhaseIndex
4. DriveMotor
5. Commutate End
FIGURE A-3: MOTOR DRIVER CONTROL

DriveMotor

Get Stored DriveWord

Is DriveOnFlag Set?

AND DriveWord with OffMask

Yes

OR DriveWord with SpeedStatus

Output DriveWord to motor drive port

DriveMotor End

No

FIGURE A-4: PHASE DRIVE PERIOD

SetTimer

High byte of Timer1 compare = High byte Table@RPMIndex

Low byte of Timer1 compare = Low byte Table@RPMIndex

SetTimer End
FIGURE A-5: MOTOR SPEED LOCKED WITH COMMUTATION RATE

LockTest

Is PWM cycle start flag set?

Yes

Which half of PWM cycle is longest?

On Cycle

No

Is Drive Active?

No

Off Cycle

Yes

Clear PWM cycle start flag

Decrement RampTimer

Is RampTimer Zero?

No

Is ADCRPM > Manual Threshold?

No

Reset AutoRPM Flag

LT2

Yes

Set AutoRPM Flag

LT3
FIGURE A-6: MOTOR SPEED LOCKED WITH COMMUTATION RATE (CONT.)

- Is BEMF1 < VSupply/2?
  - Yes: SpeedStatus = Speed Too Slow
    - RampTimer = AccelerateDelay
    - AutoRPM?
      - Yes: Increment RPMIndex Limit to maximum
      - No: No
  - No: SpeedStatus = Speed Too Fast
    - RampTimer = DecelerateDelay
    - AutoRPM?
      - Yes: Decrement RPMIndex Limit to minimum
      - No: No

- Is BEMF2 < VSupply/2?
  - Yes: SpeedStatus = Speed Locked
    - RampTimer = DecelerateDelay
    - RPMIndex = ADCRPM
    - LockTest End
  - No: No No

- Increment RPMIndex Limit to maximum
- Decrement RPMIndex Limit to minimum
FIGURE A-7: MOTOR CONTROL STATE MACHINE

StateMachine

State = RPMSetup

Yes

No

Is motor in Phase 1?

Yes

State = RPMSetup

No

State = RPMSetup

Is ADC Done?

Yes

No

ADCRPM = ADC Result

State = OffsetSetup

State = OffsetSetup

Is motor in Phase 2?

Yes

State = OffsetRead

No

State = OffsetRead

Is ADC Done?

Yes

No

ADCOffset = ADC Result

Invert msb of ADC Offset

PWMThreshold = ADCRPM + ADCOffset

Limit PWMThreshold to Max or Min

SM4

SM1

SM2

SM3
FIGURE A-8: MOTOR CONTROL STATE MACHINE (CONT.)

SM4

Is motor in Phase 4?
Yes
Call SetTimer
State = VIdle

No

Is motor drive active?
Yes
Wait for ADC acquisition time
Start ADC
State = VRead

No

State = VIdle

SM1

State = VSetup?
Yes
Is PWMThreshold = 0?
No

Yes
Set FullOnFlag
Clear FullOnFlag
State = VSetup

No

SM2

Is PWMThreshold >0xFD?
Yes
Set ADC input to PWM Pot
State = RPMSetup

No

Clear SpeedStatus

SM3

Is ADC Done?
Yes
VSupply = ADC Result
State = BEMFSetup

No

State = VRead?
Yes

No

State = RPMSetup
FIGURE A-9: MOTOR CONTROL STATE MACHINE (CONT.)

- **SM4**
  - Is motor in Phase 5?
  - Yes: State = BEMFSetup
  - No: Is this the start of the longest PWM half cycle?
    - Yes: Disable Timer1 clear on compare
    - No: Save current compare word (commutation time)
  - Set compare word to 1/4 current commutation time
  - State = BEMFIdle

- **SM5**
  - State = BEMFSetup?
    - Yes: Force motor drive active
    - No: Timer1 compare?
      - Yes: Wait for ADC acquisition time
      - No: Start ADC
  - Set compare word to 3/4 current commutation time
  - State = BEMFRead

- **SM6**
  - State = BEMFRead?
    - Yes: DeltaV1 = VSupply/2 - ADC result
    - No: Is ADC Done?
      - Yes: State = BEMF2Idle
      - No: SM4

- **SM3**

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FIGURE A-10: MOTOR CONTROL STATE MACHINE (CONT.)

- **State = BEMF2Idle**
  - Yes: Force motor drive active
  - No: Timer1 Compare?
    - Yes: State = RPMSetup
      - Start ADC
      - Change ADC input to PWM Pot
      - Set Timer1 compare word to saved commutation time
      - Change compare mode to clear Timer1 on compare
      - State = BEMF2Read
    - No: State = RPMSetup
      - Wait for ADC acquisition time
      - Start ADC
      - Change ADC input to PWM Pot
      - Set Timer1 compare word to saved commutation time
      - Change compare mode to clear Timer1 on compare
      - State = BEMF2Read

- **State = BEMF2Read**
  - Yes: Timer1 Compare?
    - Yes: Invalid State:
      - Set ADC input to PWM Pot
      - State = RPMSetup
    - No: Force motor drive active
  - No: Is ADC Done?
    - Yes: State = RPMSetup
    - No: DeltaV2 = VSupply/2 - ADC result

- **StateMachine End**
APPENDIX C: SENSORED CODE

;******************************************************************************
; * Filename: sensored.asm *
; * Date: 11 Feb. 2002 *
; * File Version: 1.0 *
; * Author: W.R. Brown *
; * Company: Microchip Technology Incorporated *
; *
;******************************************************************************

Files required: p16f877.inc

******************************************************************************

Notes: Sensored brushless motor control Main loop uses 3-bit sensor input as index for drive word output. PWM based on Timer0 controls average motor voltage. PWM level is determined from ADC reading of potentiometer.

******************************************************************************

list p=16f877 ; list directive to define processor
#include <p16f877.inc> ; processor specific variable definitions

__CONFIG _CP_OFF & _WDT_OFF & _BODEN_ON & _PWRTE_ON & _HS_OSC & _WRT_ENABLE_OFF & _LVP_ON & _DEBUG_OFF & _CPD_OFF

******************************************************************************

* Define variable storage
*
CBLOCK 0x20

ADC ; PWM threshold is ADC result
LastSensor ; last read motor sensor data
DriveWord ; six bit motor drive data

ENDC
```c
#define OffMask    B'11010101'
define DrivePort PORTC
#define DrivePortTris TRISC
#define SensorMask  B'00000111'
#define SensorPort  PORTE
#define DirectionBit PORTA,1

;******************************************************************************
;
org     0x000     ; startup vector
clrf    PCLATH    ; required for ICD operation
clrf    DrivePort ; all drivers off
banksel TRISA     ; setup I/O

clf      DrivePortTris ; set motor drivers as outputs
movlw    B'00000011' ; A/D on RA0, Direction on RA1, Motor sensors on RE<2:0>
movwf    TRISA     ;
movlw    B'11010000' ; Timer0: Fosc, 1:2
movwf    OPTION_REG ; Setup ADC (bank1)
movlw    B'00001110' ; ADC left justified, AN0 only
movwf    ADCON1

banksel  ADCON0     ; setup ADC (bank0)
movlw    B'11000001' ; ADC clock from int RC, AN0, ADC on
movwf    ADCON0
bsf      ADCON0,GO ; start ADC
clrf      LastSensor ; initialize last sensor reading
call     Commutate  ; determine present motor position
clf       ADC       ; start speed control threshold at zero until first ADC reading

;******************************************************************************
;
org     0x004     ; interrupt vector location
retfie   ; return from interrupt

;******************************************************************************
;
;* Initialize I/O ports and peripherals
;*

Initialize
clrf    DrivePort ; all drivers off

banksel TRISA
; setup I/O
clrf      DrivePortTris ; set motor drivers as outputs
movlw    B'00000011' ; A/D on RA0, Direction on RA1, Motor sensors on RE<2:0>
movwf    TRISA
;
movlw    B'11010000' ; Timer0: Fosc, 1:2
movwf    OPTION_REG
;
; Setup ADC (bank1)
movlw    B'00001110' ; ADC left justified, AN0 only
movwf    ADCON1

banksel  ADCON0     ; setup ADC (bank0)
movlw    B'11000001' ; ADC clock from int RC, AN0, ADC on
movwf    ADCON0
bsf      ADCON0,GO ; start ADC
clrf      LastSensor ; initialize last sensor reading
call     Commutate  ; determine present motor position
clf       ADC       ; start speed control threshold at zero until first ADC reading

;******************************************************************************
;
;* Main control loop
;*

Loop
    call     ReadADC   ; get the speed control from the ADC
    incfsz   ADC,w    ; if ADC is 0xFF we're at full speed - skip timer add
    goto     PWM       ; add Timer0 to ADC for PWM
    movf     DriveWord,w ; force on condition
    goto     Drive     ; continue
```

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**AN857**

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DS00857B-page 32 © 2002-2011 Microchip Technology Inc.
movf ADC,w ; restore ADC reading
addwf TMRO,w ; add it to current Timer0
movf DriveWord,w ; restore commutation drive data
btfss STATUS,C ; test if ADC + Timer0 resulted in carry
andlw OffMask ; no carry - suppress high drivers

Drive
movwf DrivePort ; enable motor drivers
call Commutate ; test for commutation change
goto Loop ; repeat loop

ReadADC
;**********************************************************************
;* If the ADC is ready then read the speed control potentiometer
;* and start the next reading
;*
btfs ADCON0,NOT_DONE ; is ADC ready?
return ; no - return
movf ADRESH,w ; get ADC result
bsf ADCON0,GO ; restart ADC
movwf ADC ; save result in speed control threshold
return

;**********************************************************************
;* Read the sensor inputs and if a change is sensed then get the
;* corresponding drive word from the drive table
;*
Commutate
movlw SensorMask ; retain only the sensor bits
andwf SensorPort,w ; get sensor data
xorwf LastSensor,w ; test if motion sensed
btfsc STATUS,Z ; zero if no change
return ; no change - back to the PWM loop
xorwf LastSensor,f ; replace last sensor data with current
btfss DirectionBit ; test direction bit
goto FwdCom ; bit is zero - do forward commutation

; reverse commutation
movlw HIGH RevTable ; get MS byte of table
movwf PCLATH ; prepare for computed GOTO
movlw LOW RevTable ; get LS byte of table
goto Com2

FwdCom
movlw HIGH FwdTable ; get MS byte of table
movwf PCLATH ; prepare for computed GOTO
movlw LOW FwdTable ; get LS byte of table

Com2
addwf LastSensor,w ; add sensor offset
btfsc STATUS,C ; page change in table?
icwf PCLATH,f ; yes - adjust MS byte
call GetDrive ; get drive word from table
movwf DriveWord ; save as current drive word
return

GetDrive
movwf PCL
;**********************************************************************
;* The drive tables are built based on the following assumptions:
;* 1) There are six drivers in three pairs of two
;* 2) Each driver pair consists of a high side (+V to motor) and low side (motor to ground) drive
;* 3) A 1 in the drive word will turn the corresponding driver on
;* 4) The three driver pairs correspond to the three motor windings: A, B and C
;* 5) Winding A is driven by bits <1> and <0> where <1> is A's high side drive
;* 6) Winding B is driven by bits <3> and <2> where <3> is B's high side drive
;* 7) Winding C is driven by bits <5> and <4> where <5> is C's high side drive
;* 8) Three sensor bits constitute the address offset to the drive table
;* 9) A sensor bit transitions from a 0 to 1 at the moment that the corresponding
;*    winding's high side forward drive begins.
;* 10) Sensor bit <0> corresponds to winding A
;* 11) Sensor bit <1> corresponds to winding B
;* 12) Sensor bit <2> corresponds to winding C
;*
;* FwdTable
retlw B'00000000' ; invalid
retlw B'00010010' ; phase 6
retlw B'00001001' ; phase 4
retlw B'00011000' ; phase 5
retlw B'00100100' ; phase 2
retlw B'00000110' ; phase 1
retlw B'00000000' ; invalid

RevTable
retlw B'00000000' ; invalid
retlw B'00100001' ; phase /6
retlw B'00010001' ; phase /4
retlw B'00100100' ; phase /5
retlw B'00001100' ; phase /2
retlw B'00000101' ; phase /1
retlw B'00001001' ; phase /3
retlw B'00000000' ; invalid

END ; directive 'end of program'
APPENDIX D: SENSORLESS CODE

;******************************************************************************
; *
; Filename: snsrless.asm *
; Date: 14 Jan. 2002 *
; File Version: 1.0 *
; *
; Author: W.R. Brown *
; Company: Microchip Technology Incorporated *
; *
;******************************************************************************
; *
; Files required: p16f877.inc *
; *
;******************************************************************************
; *
; Notes: Sensorless brushless motor control *
; *
; Closed loop 3 phase brushless DC motor control. *
; Two potentiometers control operation. One potentiometer (A0) *
; controls PWM (voltage) and RPM (from table). The other *
; potentiometer (A1) provides a PWM offset to the PWM derived *
; from A0. Phase A motor terminal is connected via voltage *
; divider to A3. This is read while the drive is on during *
; phase 4. The result is the peak applied voltage (Vsupply). *
; A3 is also read while the drive is on at two times during *
; phase 5. The result is the BEMF voltage. The BEMF voltage is *
; read at the quarter (t1) and mid (t2) points of the phase 5 *
; period. BEMF is compared to VSupply/2. If BEMF is above *
; VSupply/2 at t1 and below VSupply/2w at t2 then no speed *
; adjustment is made. If BEMF is high at both t1 and t2 then *
; the speed is reduced. If BEMF is low at t1 and t2 then the *
; speed is increased. *
; *
;******************************************************************************

list P = PIC16F877
include "p16f877.inc"
__CONFIG _CP_OFF & _WRT_ENABLE_OFF & _HS_OSC & _WDT_OFF & _PWRTE_ON & _BODEN_ON

#define AccelDelay D'100' ; determines full range acceleration time
#define DecelDelay D'10'  ; determines full range deceleration time
#define ManThresh 0x3f    ; Manual threshold is the PWM potentiometer reading above which RPM is adjusted automatically
#define AutoThresh 0x100-ManThresh
OffMask equ B'11010101'   ; PWM off kills the high drives
Invalid equ B'00000000' ; invalid
Phase1 equ B'00100001'  ; phase 1 C high, A low
Phase2 equ B'00100100'  ; phase 2 C high, B low
Phase3 equ B'00000110'  ; phase 3 A high, B low
Phase4 equ B'00010010'  ; phase 4 A high, C low
Phase5 equ B'00001001'  ; phase 5 B high, C low
Phase6 equ B'00010010'  ; phase 6 B high, A low

#define CARRY STATUS,C
#define ZERO STATUS,Z
#define subwl sublw

;*********************************************************************************
;* Define I/O Ports
;*********************************************************************************
#define ReadIndicator PORTB,0       ; diagnostic scope trigger for BEMF readings
#define DrivePort PORTC              ; motor drive and lock status

;*********************************************************************************
;* Define RAM variables
;*********************************************************************************

CBLOCK 0x20
STATE            ; Machine state
PWMThresh        ; PWM threshold
PhaseIndex       ; Current motor phase index
Drive            ; Motor drive word
RPMIndex         ; RPM Index workspace
ADCRPM           ; ADC RPM value
ADCOffset        ; Delta offset to ADC PWM threshold
PresetHi         ; speed control timer compare MS byte
PresetLo         ; speed control timer compare LS byte
Flags            ; general purpose flags
Vsupply          ; Supply voltage ADC reading
DeltaV1          ; Difference between expected and actual BEMF at T/4
DeltaV2          ; Difference between expected and actual BEMF at T/2
CCPSaveH         ; Storage for phase time when finding DeltaV
CCPSaveL         ; Storage for phase time when finding DeltaV
CCPT2H           ; Workspace for determining T/2 and T/4
CCPT2L           ; Workspace for determining T/2 and T/4
RampTimer        ; Timer0 post scaler for accel/decel ramp rate
xCount           ; general purpose counter workspace
Status           ; relative speed indicator status

ENDC
**Define Flags**

```c
#define DriveOnFlag Flags,0 ; Flag for invoking drive disable mask when clear
#define AutoRPM Flags,1 ; RPM timer is adjusted automatically
    ; Flags,3 ; Undefined
#define FullOnFlag Flags,4 ; PWM threshold is set to maximum drive
#define Tmr0Ovf Flags,5 ; Timer0 overflow flag
#define Tmr0Sync Flags,6 ; Second Timer0 overflow flag
    ; Flags,7 ; undefined
#define BEMF1Low DeltaV1,7 ; BEMF1 is low if DeltaV1 is negative
#define BEMF2Low DeltaV2,7 ; BEMF2 is low if DeltaV2 is negative
```

**Define State machine states and index numbers**

```c
sRPMSetup equ D'0' ; Wait for Phase1, Set ADC GO, RA1->ADC
sRPMRead equ sRPMSetup+1 ; Wait for ADC nDONE, Read ADC->RPM
sOffsetSetup equ sRPMRead+1 ; Wait for Phase2, Set ADC GO, RA3->ADC
sOffsetRead equ sOffsetSetup+1 ; Wait for ADC nDONE, Read ADC->ADCOffset
sVSetup equ sOffsetRead+1 ; Wait for Phase4, Drive On, wait 9 uSec, Set ADC GO
sVIdle equ sVSetup+1 ; Wait for Drive On, wait Tacq, set ADC GO
sVRead equ sVIdle+1 ; Wait for ADC nDONE, Read ADC->Vsupply
sBEMFSetup equ sVRead+1 ; Wait for Phase5, set Timer1 compare to half phase time
sBEMFIdle equ sBEMFSetup+1 ; Wait for Timer1 compare, Force Drive on and wait 9 uSec, Set ADC GO, RA0->ADC
sBEMFRead equ sBEMFIdle+1 ; Wait for Timer1 compare, Force Drive on and wait 9 uSec, Set ADC GO, RA0->ADC
sBEMF2Idle equ sBEMFRead+1 ; Wait for Timer1 compare, Force Drive on and wait 9 uSec, Set ADC GO, RA0->ADC
sBEMF2Read equ sBEMF2Idle+1 ; Wait for ADC nDONE, Read ADC->Vbemf
```

**The ADC input is changed depending on the STATE**

```c
;* Each STATE assumes a previous input selection and changes the selection
;* by XORing the control register with the appropriate ADC input change mask
;* defined here:

ADC0to1 equ B'00001000' ; changes ADCON0<5:3> from 000 to 001
ADC1to3 equ B'00010000' ; changes ADCON0<5:3> from 001 to 011
ADC3to0 equ B'00011000' ; changes ADCON0<5:3> from 011 to 000
```

**Program Starts Here**
banksel TRISA
; setup I/O
clr TRISC ; motor drivers on PORTC
movlw B'00001011' ; A/D on RA0 (PWM), RA1 (Speed) and RA3 (BEMF)
movwf TRISA ;
movlw B'11111110' ; RB0 is locked indicator
movwf TRISB
; setup Timer0
movlw B'11010000' ; Timer0: Fosc, 1:2
movwf OPTION_REG
bsf INTCON,T0IE ; enable Timer0 interrupts
; Setup ADC
movlw B'00000100' ; ADC left justified, AN0, AN1
movwf ADCON1
banksel PORTA
movlw B'10000001' ; ADC clk = Fosc/32, AN0, ADC on
movwf ADCON0
; setup Timer 1
movlw B'00100001' ; 1:4 prescale, internal clock, timer on
movwf T1CON
; setup Timer 1 compare
movlw 0xFF ; set compare to maximum count
movwf CCPR1L ; LS compare register
movwf CCPR1H ; MS compare register
movlw B'00001011' ; Timer 1 compare mode, special event - clears timer1
movwf CCP1CON
; initialize RAM
clr PWMThresh
movlw D'6'
movwf PhaseIndx
clr Flags
clr Status ;
clr STATE ; LoopIdle->STATE
bcf INTCON,T0IF ; ensure Timer0 overflow flag is cleared
bsf INTCON,GIE ; enable interrupts

MainLoop
;*****************************************************************
;
; PWM, Commutation, State machine loop
;
;*****************************************************************

btfs PIC1,CCPIIF ; time for phase change?
call Commutate ; yes - change motor drive

PWM
bsf DriveOnFlag ; pre-set flag
btfs PIC1,FullOnFlag ; is PWM level at maximum?
goto PWM02 ; yes - only commutation is necessary
movf PWMThresh,w ; get PWM threshold
addwf TMRO,w ; compare to Timer0
btfs PIC1,CARRY ; drive is on if carry is set
bcf DriveOnFlag ; timer has not reached threshold, disable drive
call DriveMotor ; output drive word

PWM02

call LockTest
call StateMachine ; service state machine
goto MainLoop ; repeat loop
StateMachine
movlw SMTableEnd-SMTable-1 ; STATE table must have 2^n entries
andwf STATE,f ; limit STATE index to state table
movlw high SMTable ; get high byte of table address
movwf PCLATH ; prepare for computed goto
movlw low SMTable ; get low byte of table address
addwf STATE,w ; add STATE index to table root
bfss CARRY ; test for page change in table
incf PCLATH,f ; page change adjust
movwf PCL ; jump into table

SMTable
; number of STATE table entries MUST be evenly divisible by 2

goto RPMSetup ; Wait for Phase1, Set ADC GO, RA1->ADC, clear Timer0 overflow

goto RPMRead ; Wait for ADC nDONE, Read ADC->RPM

goto OffsetSetup ; Wait for Phase2, Set ADC GO, RA3->ADC

goto OffsetRead ; Wait for ADC nDONE, Read ADC->ADCOffset

goto VIdle ; Wait for Drive On, wait Tacq, set ADC GO

goto VRead ; Wait for ADC nDONE, Read ADC->Vsupply

goto BEMFSetup ; Wait for Phase5, set Timer1 compare to half phase time

goto BEMFIdle ; When Timer1 compares force Drive on, Set ADC GO after Tacq,

RA0-->ADC

goto BEMFRead ; Wait for ADC nDONE, Read ADC->Vbemf

goto BEMF2Idle ; When Timer1 compares force Drive on, Set ADC GO after Tacq,

RA0-->ADC

goto BEMF2Read ; Wait for ADC nDONE, Read ADC->Vbemf

; fill out table with InvalidStates to make number of table entries evenly divisible by 2

goto InvalidState ; invalid state - reset state machine

goto InvalidState ; invalid state - reset state machine

goto InvalidState ; invalid state - reset state machine

goto InvalidState ; invalid state - reset state machine

SMTableEnd

;~~~~~~~~~~~~~~~~~~~~~~~~~

RPMSetup
movlw Phase1 ; compare Phase1 word...
xorwf Drive,w ; ...with current drive word
bfss ZERO ; ZERO if equal
return ; not Phase1 - remain in current STATE

bsf ADCON0,GO ; start ADC
movlw ADC0to1 ; prepare to change ADC input
xorwf ADCON0,f ; change from AN0 to AN1
incf STATE,f ; next STATE

bcf Tmr0Sync ; clear Timer0 overflow
return ; back to Main Loop

;~~~~~~~~~~~~~~~~~~~~~~~~~

RPMRead

bfss ADCON0,GO ; is ADC conversion finished?
return ; no - remain in current STATE

movf ADRESH,w ; get ADC result
movwf ADCRPM ; save in RPM
incf STATE,f ; next STATE
return ; back to Main Loop

;~~~~~~~~~~~~~~~~~~~~~~~~~
OffsetSetup ; Wait for Phase2, Set ADC GO, RA3->ADC

movlw  Phase2   ; compare Phase2 word...
xorwf  Drive, w ; ...with current drive word
btfss  ZERO     ; ZERO if equal
return         ; not Phase2 - remain in current STATE
bsf    ADCON0,GO ; start ADC
movlw  ADC1to3  ; prepare to change ADC input
xorwf  ADCON0,f ; change from AN1 to AN3
incf  STATE,f  ; next STATE
return         ; back to Main Loop

;~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
OffsetRead ; Wait for ADC nDONE, Read ADC->ADCOffset

btfsc  ADCON0,GO ; is ADC conversion finished?
return         ; no - remain in current STATE
movf   ADRESH,w ; get ADC result
xorlw  H'80'    ; complement MSB for +/- offset
movwf  ADCOffset ; save in offset
addwf  ADCRPM,w ; add offset to PWM result
btfss  ADCOffset,7 ; is offset a negative number?
goto   OverflowTest ; no - test for overflow
btfss  CARRY ; underflow?
andiw  H'00' ; yes - force minimum
goto   Threshold ;

OverflowTest

btfsc  CARRY ; overflow?
movlw  H'ff' ; yes - force maximum

Threshold

movwf  PWMThresh ; PWM threshold is RPM result plus offset
btfsc  ZERO ; is drive off?
goto   DriveOff ; yes - skip voltage measurements
bcf    FullOnFlag ; pre-clear flag in preparation of compare
sublw  0xFD ; full on threshold
btfss  CARRY ; CY = 0 if PWMThresh > FullOn
bsf    FullOnFlag ; set full on flag
incf  STATE,f  ; next STATE
return         ; back to Main Loop

DriveOff

clrwf  Status ; clear speed indicators
movlw B'11000111' ; reset ADC input to AN0
andwf  ADCON0,f ;
crflw  STATE ; reset state machine
return

;~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
VSetup ; Wait for Phase4

movlw  Phase4   ; compare Phase4 word...
xorwf  Drive, w ; ...with current Phase drive word
btfss  ZERO     ; ZERO if equal
return         ; not Phase4 - remain in current STATE
call   SetTimer ; set timer value from RPM table
incf  STATE,f  ; next STATE
return         ; back to Main Loop
;~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

VIdle ; Wait for Drive On, wait Tacq, set ADC GO
btfss DriveOnFlag ; is Drive active?
return ; no - remain in current STATE
call Tacq ; motor Drive is active - wait ADC Tacq time
bsf ADCON0,GO ; start ADC
incf STATE,f ; next STATE
return ; back to Main Loop

;~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

VRead ; Wait for ADC nDONE, Read ADC->Vsupply
btfsc ADCON0,GO ; is ADC conversion finished?
return ; no - remain in current STATE
movf ADRESH,w ; get ADC result
movwf Vsupply ; save as supply voltage
incf STATE,f ; next STATE
bcf Tmr0Sync ; clear Timer0 overflow
return ; back to Main Loop

;~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

BEMFSetup ; Wait for Phase5, set Timer1 compare to half phase time
movlw Phase5 ; compare Phase5 word...
xorwf Drive,w ; ...with current drive word
btfss ZERO ; ZERO if equal
return ; not Phase5 - remain in current STATE

btfss Tmr0Sync ; synchronize with Timer0
return ;

btfss PWMThresh,7 ; if PWMThresh > 0x80 then ON is longer than OFF
goto BEMS1 ; OFF is longer and motor is currently off - compute now

btfss DriveOnFlag ; ON is longer - wait for drive cycle to start
return ; not started - wait

BEMS1
bcf CCP1CON,0 ; disable special event on compare
movf CCP1H,w ; save current capture compare state
movwf CCPSaveH ;
movwf CCP2H ; save copy in workspace
movf CCP1L,w ; low byte
movwf CCPSaveL ; save
movwf CCP2L ; and save copy
bcf CARRY ; pre-clear carry for rotate
rrf CCPT2H,f ; divide phase time by 2
rrf CCPT2L,f ;
bcf CARRY ; pre-clear carry
rrf CCPT2H,w ; divide phase time by another 2
movwf CCP1H ; first BEMF reading at phase T/4
rrf CCPT2L,w ;
movwf CCP1L ;
incf STATE,f ; next STATE
return ; back to Main Loop

;~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
BEMFIdle ; When Timer1 compares force Drive on, Set ADC GO after Tacq, RA0->ADC

btfss PIR1,CCP1IF ; timer compare?
return ; no - remain in current STATE
bsf DriveOnFlag ; force drive on for BEMF reading
call DriveMotor ; activate motor drive
bsf ReadIndicator ; Diagnostic
call Tacq ; wait ADC acquisition time
bsf ADCON0,GO ; start ADC
bcf ReadIndicator ; Diagnostic

; setup to capture BEMF at phase 3/4 T

movf CCPT2H,w
addwf CCP1H,f ; next compare at phase 3/4 T
movf CCPT2L,w ;
addwf CCP1L,f ; set T/2 lsb
btfsc CARRY ; test for carry into MSb
incf CCP1H,f ; perform carry
bcf PIR1,CCP1IF ; clear timer compare interrupt flag
incf STATE,f ; next STATE
return ; back to Main Loop

;~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

BEMFRead ; Wait for ADC nDONE, Read ADC->Vbemf

btfsc ADCON0,GO ; is ADC conversion finished?
return ; no - remain in current STATE
rrf Vsupply,w ; divide supply voltage by 2
subwf ADRESH,w ; Vbemf - Vsupply/2
movwf DeltaV1 ; save error voltage
incf STATE,f ; next STATE
return ; back to Main Loop

;~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

BEMF2Idle ; When Timer1 compares force Drive on, Set ADC GO after Tacq, RA0->ADC

btfss PIR1,CCP1IF ; timer compare?
return ; no - remain in current STATE
bsf DriveOnFlag ; force drive on for BEMF reading
call DriveMotor ; activate motor drive
bsf ReadIndicator ; Diagnostic
call Tacq ; wait ADC acquisition time
bsf ADCON0,GO ; start ADC
bcf ReadIndicator ; Diagnostic
movlw ADC3to0 ; prepare to change ADC input
xorwf ADCON0,f ; change from AN3 to AN0

; restore Timer1 phase time and special event compare mode

movf CCPSaveH,w
movwf CCP1H ; next compare at phase T
movf CCPSaveL,w ;
movwf CCP1L ; set T lsb
bcf PIR1,CCP1IF ; clear timer compare interrupt flag
bsf CCP1CON,0 ; enable special event on compare
incf STATE,f ; next STATE
return ; back to Main Loop
BEMF2Read ; Wait for ADC nDONE, Read ADC->Vbemf
  btfs C ADCON0,GO ; is ADC conversion finished?
  return ; no - remain in current STATE
  rrf Vsupply, w ; divide supply voltage by 2
  subwf ADRESH, w ; Vbemf - Vsupply/2
  movwf DeltaV2 ; save error voltage
  clrf STATE ; reset state machine to beginning
  return ; back to Main Loop

;~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

InvalidState ; trap for invalid STATE index
  movlw B'11000111' ; reset ADC input to AN0
  andwf ADCON0, f ;
  clrf STATE
  return

;________________________________________________________________________________________________

Tacq
;*******************************************************************************
; Software delay for ADC acquisition time
; Delay time = Tosc*(3+3*xCount)
;*******************************************************************************
  movlw D'14 ; 14 equates to approx 9 uSec delay
  movwf xCount ;
  decfsz xCount, f ;
  goto $-1 ; loop here until time complete
  return

LockTest
;*******************************************************************************
;  T is the commutation phase period. Back EMF is measured on the
;  floating motor terminal at two times during T to determine
;  the approximate zero crossing of the BEMF. BEMF low means that
;  the measured BEMF is below (supply voltage)/2.
;  If BEMF is low at 1/4 T then accelerate.
;  If BEMF is high at 1/4 T and low at 3/4 T then speed is OK.
;  If BEMF is high at 1/4 T and 3/4 T then decelerate.
;  Lock test computation is synchronized to the PWM clock such
;  that the computation is performed during the PWM ON or OFF
;  time whichever is longer.
;*******************************************************************************
  ; synchronize test with start of Timer0
  btfs Tmr0Ovf ; has Timer0 wrapped around?
  return ; no - skip lock test
  btfs PWMThresh, 7 ; if PWMThresh > 0x80 then ON is longer than OFF
  goto LT05 ; OFF is longer and motor is currently off - compute now
  btfs DriveOnFlag ; ON is longer - wait for drive cycle to start
  return ; not started - wait
LT05

bcf Tmr0Ovf ; clear synchronization flag
decfsz RampTimer,f ; RampTimer controls the acceleration/deceleration rate
return

; use lock results to control RPM only if not manual mode
bsf AutoRPM ; preset flag
movf ADRPM,w ; compare RPM potentiometer...
addlw AutoThresh ; ...to the auto control threshold
btfss CARRY ; CARRY is set if RPM is > auto threshold
bcf AutoRPM ; not in auto range - reset flag
btfss BEMF1Low ; is first BEMF below Supply/2
goto LT20 ; no - test second BEMF

LT10

; accelerate if BEMF at 1/4 T is below Supply/2
movlw B'10000000' ; indicate lock test results
movwf Status ; status is OR'd with drive word later
movlw AccelDelay ; set the timer for acceleration delay
movwf RampTimer ;

btfss AutoRPM ; is RPM in auto range?
goto ManControl ; no - skip RPM adjustment
incfsz RPMIndex,f ; increment the RPM table index
return ; return if Index didn't wrap around
decf RPMIndex,f ; top limit is 0xFF
return

LT20

btfsc BEMF2Low ; BEMF1 was high...
goto ShowLocked ; ... and BEMF2 is low - show locked

; decelerate if BEMF at 3/4 T is above Supply/2
movlw B'01000000' ; indicate lock test results
movwf Status ; status is OR'd with drive word later
movlw DecelDelay ; set the timer for deceleration delay
movwf RampTimer ;

btfss AutoRPM ; is RPM in auto range?
goto ManControl ; no - skip RPM adjustment
decfsz RPMIndex,f ; set next lower RPM table index
return ; return if index didn't wrap around
incf RPMIndex,f ; bottom limit is 0x01
return

ShowLocked
movlw B'11000000' ; indicate lock test results
movwf Status ; status is OR'd with drive word later
movlw DecelDelay ; set the timer for deceleration delay
movwf RampTimer ;
btfsc AutoRPM ; was RPM set automatically?
return ; yes - we're done
ManControl

movf ADCRPM, w ; get RPM potentiometer reading...
movwf RPMIndex ; ...and set table index directly
return

Commutate

;******************************************************************************
; Commutation is triggered by PIR1<CCP1IF> flag.
; This flag is set when timer1 equals the compare register.
; When BEMF measurement is active the compare time is not
; cleared automatically (special event trigger is off).
; Ignore the PIR1<CCP1IF> flag when special trigger is off
; because the flag is for BEMF measurement.
; If BEMF measurement is not active then decrement phase table
; index and get the drive word from the table. Save the
; drive word in a global variable and output to motor drivers.
;******************************************************************************

btfss CCP1CON, 0 ; is special event on compare enabled?
return ; no - this is a BEMF measurement, let state machine handle this

bcf PIR1, CCP1IF ; clear interrupt flag

movlw high OnTable ; set upper program counter bits
movwf PCLATH

decfsz PhaseIndx, w ; decrement to next phase
goto $+2 ; skip reset if not zero
movlw D'6' ; phase counts 6 to 1
movwf PhaseIndx ; save the phase index
adlw LOW OnTable
btfsc CARRY ; test for possible page boundary
incf PCLATH, f ; page boundary adjust
call GetDrive
movwf Drive ; save motor drive word

DriveMotor

movf Drive, w ; restore motor drive word
btfss DriveOnFlag ; test drive enable flag
andlw OffMask ; kill high drive if PWM is off
iorwf Status, w ; show speed indicators
movwf DrivePort ; output to motor drivers
return

GetDrive

movwf PCL ; computed goto

OnTable

retlw Invalid
retlw Phase6
retlw Phase5
retlw Phase4
retlw Phase3
retlw Phase2
retlw Phase1
retlw Invalid

SetTimer
This sets the CCP module compare registers for timer 1.

The motor phase period is the time it takes timer 1
to count from 0 to the compare value. The CCP module
is configured to clear timer 1 when the compare occurs.

Get the timer1 compare variable from two lookup tables, one
for the compare high byte and the other for the low byte.

;******************************************************************************
call SetTimerHigh
movwf CCPR1H ; Timer1 High byte preset
call SetTimerLow
movwf CCPR1L ; Timer1 Low byte preset
return

SetTimerHigh
movlw high T1HighTable ; lookup preset values
movwf PCLATH ; high bytes first
movlw low T1HighTable ;
addwf RPMIndex,w ; add table index
btfsc STATUS,C ; test for table page crossing
incf PCLATH,f ;
movwf PCL ; lookup - result returned in W

SetTimerLow
movlw high T1LowTable ; repeat for lower byte
movwf PCLATH ;
movlw low T1LowTable ;
addwf RPMIndex,w ; add table index
btfsc STATUS,C ; test for table page crossing
incf PCLATH,f ;
movwf PCL ; lookup - result returned in W

#include "BLDCapd4.inc"

end
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