
Using the PIC18F2431 for Sensorless BLDC Motor Control

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INTRODUCTION

Brushless Direct Current (BLDC) motors have many advantages over other types of motors available in the industry. Previously, we have discussed the working principles of BLDC motors and the basics of their control in Microchip application note AN885, *Brushless DC (BLDC) Motor Fundamentals*. We have also discussed the use of PIC18FXX31 devices to control a BLDC motor in both open loop and in closed loop using Hall effect sensors and quadrature encoders (Microchip application note AN899, *Brushless DC Motor Control Using PIC18FXX31 Microcontrollers*). This application note describes BLDC motor speed control without the use of sensors.

Those readers interested in additional applications may refer to Microchip application notes AN857, *Brushless DC Motor Control Made Easy* and AN901, *Using the dsPIC30F for Sensorless BLDC Control*, to learn how other PICmicro[®] microcontrollers and dsPIC[®] digital signal controllers can be used for BLDC motor control.

ADVANTAGES AND DISADVANTAGES OF SENSORLESS CONTROL

Sensorless control of a BLDC motor calls for commutation based on the Back Electromotive Force (BEMF) produced in the stator windings. Sensorless control has two distinct advantages: lower system cost and increased reliability.

Hall effect sensors are not required for sensorless control. Some motors may have the Hall sensor magnets mounted on the rotor, in addition to the main rotor magnets. These are used to simplify the process of mounting the Hall sensors onto the stator. The sensor magnets are a scaled-down replica of the rotor; whenever the rotor rotates, they produce the same effect as the main magnets. The Hall sensors are normally mounted on a PC board and are fixed to the enclosure cap on the non-driving end of the motor.

With a sensorless method of commutation, the Hall sensors, the sensor magnets, the sensor wires and the PC board can be eliminated. This simplifies the motor construction and reduces cost. Inherently, systems with fewer components are more reliable. Applications like the compressor control in a refrigerator or in HVAC systems, which generates heat and an elevated temperature, may accelerate Hall sensor failures. Using sensorless control improves the reliability of total system.

There are two disadvantages to sensorless control:

- The motor must be moving at a minimum rate to generate sufficient BEMF to be sensed.
- Abrupt changes to the motor load can cause the BEMF drive loop to go out of lock.

As the BEMF signal is proportional to the speed of rotation at standstill and at low speeds, the amplitude of the BEMF poses a challenge to determine the zero crossover point. In order to overcome this problem, the motor is normally run in open loop during starting and is accelerated to a speed where the BEMF has sufficient amplitude to detect and then synchronize with the zero crossing point. Running the motor in open loop makes it difficult to know the rotor position, when starting from standstill. So, the rotor can rotate in either direction when energized.

Applications which require very low motor speed may be forced to use sensors for control. There are many applications in appliances, automotive, and industrial applications where very low speed is not an issue, and the motor needs variable speeds of about 25% of the rated speed. Sensorless control is ideal for such applications.

Another requirement is that the sensorless control needs extra resources on the control circuit side. Depending upon the method used, it may require a fast A/D converter on the microcontroller, or comparator and filter circuits.

THEORY OF OPERATION

When a BLDC motor rotates, each winding generates BEMF which opposes the main voltage supplied to the windings according to Lenz's Law. The polarity of this BEMF is in the opposite direction of the energizing voltage. BEMF can be calculated as shown in Equation 1, and depends mainly on three factors:

- Angular velocity of the rotor
- Magnetic field generated by rotor magnets
- The number of turns in the stator windings

EQUATION 1:

$$\text{Back EMF} = NlrB\omega$$

where

N = number of winding turns per phase

l = the length of the rotor

r = the internal radius of the rotor

B = the rotor magnetic field density

ω = the motor angular velocity

Once the motor is designed, the rotor's magnetic field and the number of turns in the stator windings remain constant. The only factor that governs back EMF is the angular velocity or speed of the rotor; as the speed increases, back EMF also increases. The motor technical specification gives a parameter called the back EMF constant, which can be used to estimate BEMF for a given speed.

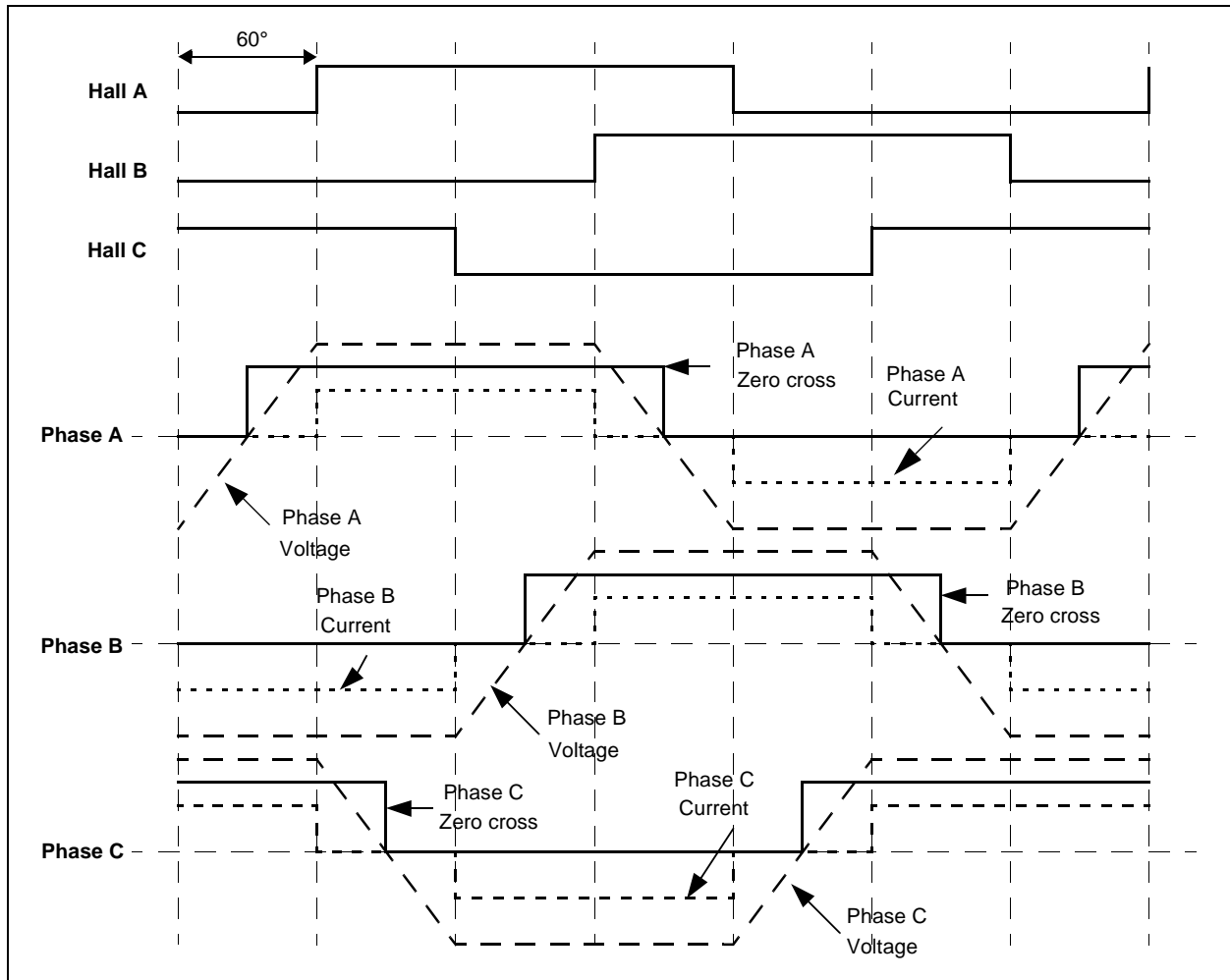
HALL SENSOR SIGNALS VS. BEMF

Figure 1 shows the relationship between the Hall sensor signals and the BEMF signals. Hall sensor signals are out of phase by 120 degrees to each other. At every 60 degrees, one of the Hall sensors makes a transition.

The BEMF generated in the windings are also at 120 degrees out of phase to each other, but they are asynchronous with the Hall sensor signals. In every energizing sequence, two phases are connected across the power supply and the third winding is left open. The BEMF voltage is monitored on the winding that is left open. With this, the BEMF voltage in windings increases when it is connected to power supply and reduces when it is connected to the return path. The transition takes place when the winding is left open in the sequence. The combination of all 3 zero cross over points are used to generate energizing sequence. The phase difference between the hall sensor and the BEMF signal is 30 degrees. This is in the firmware.

Another aspect to be considered is very low-speed operation. Because BEMF is proportional to the rotation speed, it would be at a very low amplitude at very low speeds, making it difficult to detect the zero crossover. In addition, since the commutation itself is derived based on BEMF zero crossovers, it is impossible to start the motor from standstill. To overcome this difficulty, the motor has to be started from standstill in open loop. When sufficient BEMF is built to detect the zero crossover point, control is shifted to the BEMF sensing. The minimum speed at which the BEMF can be sensed is calculated from the BEMF constant of the motor.

FIGURE 1: WAVEFORM OF HALL SENSOR VERSUS BEMF VOLTAGES



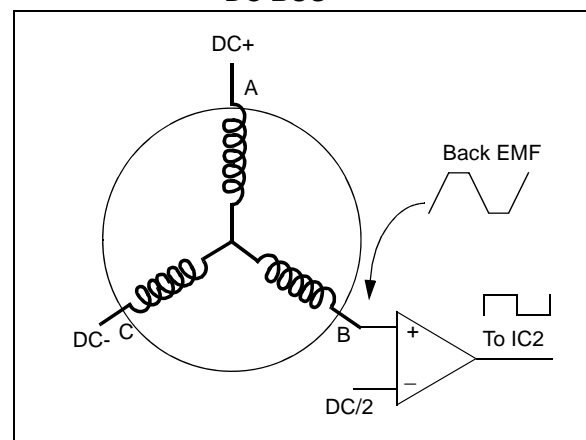
BEMF ZERO CROSSOVER SENSING METHODS

BEMF voltage zero crossing can be detected by different methods. This section gives three different methods of detecting BEMF zero cross point.

The first method is comparing the back EMF voltage to half of the DC bus voltage by using comparators. Figure 2 shows this method. Phase A is connected to the positive side of the power supply (DC+), Phase C is connected to the negative side (or return path DC) of the power supply and Phase B is open. When BEMF is observed on Phase B, it increases and decreases as the power supply (DC+ and DC-) are connected and disconnected to the winding terminals in the energizing sequence. By comparing the BEMF voltage to half of the DC bus, it gives a voltage at the central point of phase A and phase C.

Each phase requires a circuit like that shown in Figure 2 for Phase B. Combinations of these three signals are used to derive the commutation sequence. This scheme is easy to implement with three op amp comparators.

FIGURE 2: BEMF VOLTAGE COMPARED TO HALF OF DC BUS

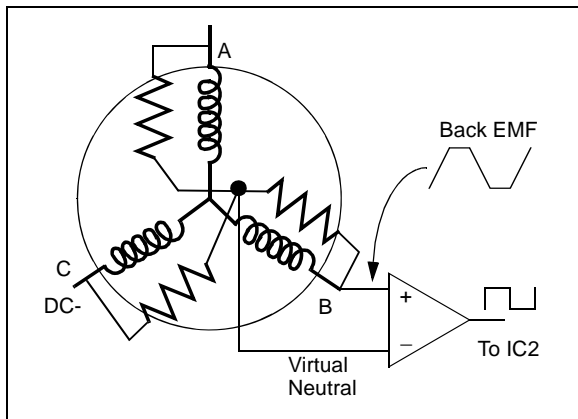


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There are a few drawbacks to this circuit. First, if all three windings do not have identical characteristics, the BEMF measured will have either positive or negative phase shift. This will result in energizing windings at different instances than they should be. This may result in the motor winding drawing excessive current. Another drawback is that if the motor rated voltage is much less than the DC bus voltage, there could be a large difference between the BEMF zero crossover point and half of the DC bus voltage. This could also result in having a phase shift result in either direction.

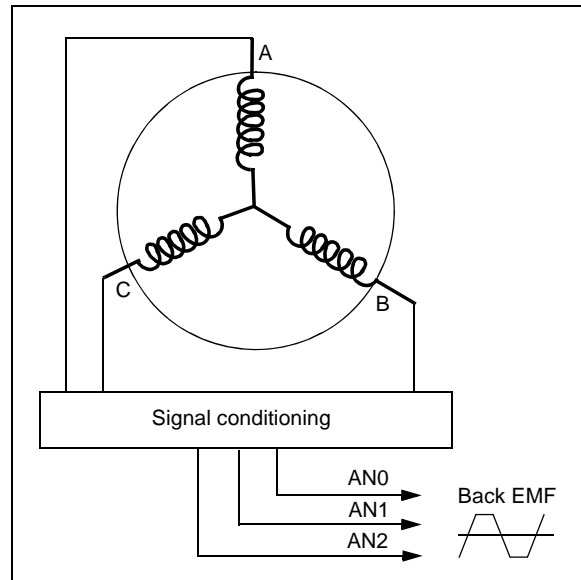
The circuit can be improved upon by generating a virtual neutral point, as shown in Figure 3. The neutral point is generated using a resistor network. Three networks are connected in parallel with the motor windings and connected together to generate a virtual neutral point. This resistive network is assembled on the control board between the 3-phase inverter bridge and the motor terminals. The resistor values should be chosen such that they will have insignificant effect on the motor current. (Refer to **Appendix A: "Motor Control Circuit Schematics"** for the circuit schematic used in this application note.) In this case, the BEMF signal is compared with this virtual neutral point. When the BEMF developed in the winding crosses the zero point towards positive side, the comparator output makes a transition from low-to-high. When the BEMF developed in the winding crosses the zero point towards negative side, the comparator output makes a transition from high-to-low. By having three such comparator circuits, one on each of the phases gives three digital signals corresponding to the BEMF signal in the windings. The combination of these three signals is used to derive the commutation sequence.

FIGURE 3: BEMF VOLTAGE COMPARED TO A VIRTUAL NEUTRAL POINT



A third method of detecting the BEMF zero crossover is using the A/D converter channels, as shown in Figure 4. The PIC18FXX31 microcontrollers have a high-speed A/D converter that can be used for this purpose. Using a potential divider, the BEMF signal is brought down to a level that the microcontroller can measure. This signal is sampled by the A/D, and is continuously compared with a digital value corresponding to the zero point. When the two values match, the commutation sequence is updated. The advantage with this method is that it is more flexible in terms of measurement. When the speed varies, the winding characteristics may fluctuate, resulting in variation of BEMF. In such situations, the microcontroller has complete control over the determination of the zero crossover point. Also, digital filters can be implemented to filter out the high-frequency switching noise components from the BEMF signal.

FIGURE 4: BEMF VOLTAGE MEASURED USING ANALOG-TO-DIGITAL CONVERTERS



HARDWARE

Figure 5 shows the block diagram for the sensorless BLDC control system discussed here; a complete schematic of the prototype board is provided in **Appendix A: "Motor Control Circuit Schematics"**. The board is capable of using either the PIC18F2331/2431 Microcontroller or a dsPIC30F2010 digital signal controller (only the PIC18F2431 is discussed here). Toggle switch S2 is used for changing the rotational direction and switch S1 is used for changing the state between run and stop. A potentiometer (R14) is used to set the speed reference; it is connected to A/D converter channel AN1.

Shunt resistor R26 is connected in the return path of the DC bus. The voltage drop across this resistor varies linearly with respect to motor current. This voltage is amplified by a 1:10 ratio using op amp circuit U10A. This amplified voltage (motor current) is measured using A/D channel AN0. The motor current is compared with a current limit set by another potentiometer (R60). If the motor current exceeds the limit set, the output of U7D will toggle, indicating an overcurrent fault. This Fault is connected to Fault A input pin on PIC18F2431, which is an active-low pin.

A switched-mode block power supply is used to generate 24V (shown in bold lines in Figure 5) from an AC input. Using linear voltage regulators VR1 and VR2, +5V and +15V are generated, respectively. The former powers the microcontroller, all op amps and related logic circuits, while the latter is used to power the MOSFET drivers (U6, U8 and U9).

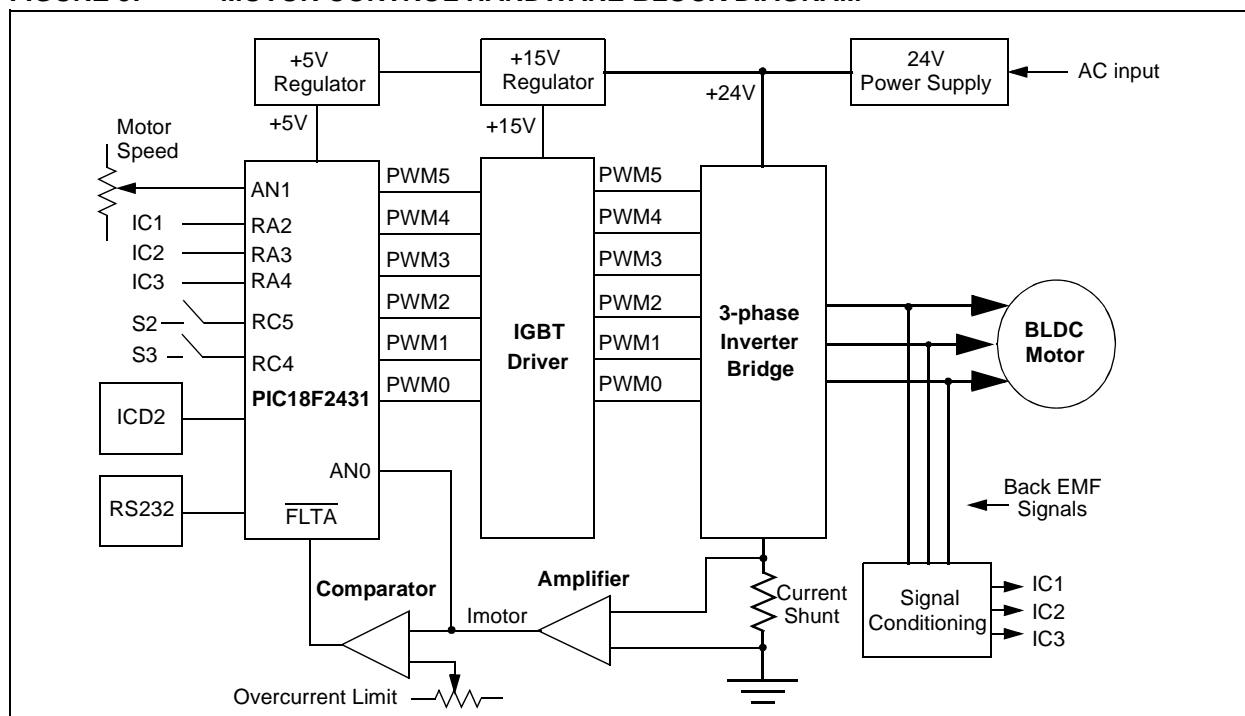
Note: For a complete list of motor control application notes refer to www.microchip.com/motor.

BEMF Sensing Circuit

In this application note, we are following the second method of determining the BEMF zero cross detection shown in Figure 3. As shown in the schematics in the Appendix, low-pass filter circuits and potential divider circuits are implemented on all three motor terminals. The low-pass filter is necessary to filter out the high frequency noise that is generated by the high frequency PWM switching. The potential divider reduces the voltage from high motor voltage to the level MCU can measure. After this, the BEMF signals are connected together using R27, R30 and R40 to form a virtual neutral point. The BEMF signal from each phase is compared with this neutral point using the op amp comparators. In order to use this configuration, jumpers J7, J11 and J13 should be bridged across pins 1 and 2, and jumpers J8, J12 and J14 should be bridged. By doing this, the comparator outputs are connected to the input capture pins IC1, IC2 and IC3 on the PIC18FXX31.

The board also provides the option for connecting the BEMF signals to the A/D channels. The BEMF signal is filtered using the low-pass filters comprised of R34/C17, R41/C19 and R49/C19 on motor terminals M3, M2 and M1, respectively. The potential divider circuits comprised of R34/R36, R41/R44 and R49/R52 on motor terminals M3, M2 and M1 reduce the BEMF voltage to TTL level. To route the BEMF signals to the A/D channels, J7, J11 and J13 should be bridged between pins 2 and 3.

FIGURE 5: MOTOR CONTROL HARDWARE BLOCK DIAGRAM



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Motor Specifications

A Hurst NT dynamo Brushless DC motor is used for the experiments. Its specifications are:

- Rated voltage: 24 VDC
- Rated current: 1.00 A
- Rated speed: 2500 RPM
- Rotor poles: 10 (5 pole pairs)

Software Routines

As discussed in earlier sections, the motor has to be run in open loop during start-up. When the speed reaches a level where the BEMF voltage has sufficient amplitude to measure the zero crossover point, the control is switched to closed loop. The difficult portion is synchronizing the rotor from open loop to closed loop with BEMF zero cross signals.

Motor Start-up

From experimentation, it has been determined that the motor develops sufficient BEMF voltage amplitude at about 900 RPM. At this speed, the BEMF signals are compared with the virtual neutral point; this signal is read using the Input Capture module. This is done in two steps: when the motor is run at approximately 400 RPM, and then accelerated to 900 RPM.

Timer1 is used to time the energizing sequence. The Timer1 reload value is calculated and the new energizing sequence is output on the PWM pins when the reload value expires. This ensures that the motor runs

at one fixed speed. The Timer1 reload value, as shown in Equation 2, depends upon the motor rated speed, number of rotor poles, and the Timer1 prescaler value.

EQUATION 2:

$$\text{Timer1 Time} = \frac{60}{\text{RPM} \times \text{Pole pairs} \times 6}$$

According to Equation 2, in order to run the motor at 400 RPM, Timer1 should expire every 5 ms, or 2.2 ms for 900 RPM. The Timer1 overflow value can be calculated based on the main oscillator frequency and Timer1 prescaler, as shown in Equation 3.

EQUATION 3:

$$\text{Timer1 Reload Value} = \text{FFFFh} - \left(\text{Timer1 time} \times \frac{\text{Fosc}}{4} \right)$$

Upon a Timer1 overflow in the ISR, a new energizing sequence is loaded into the PWM override registers and Timer1 registers are reloaded with the value calculated using Equation 3. The PWM duty cycle corresponding to the speed is calculated and loaded on to the PDC registers. When the motor starts running at 900 RPM, the BEMF zero crossover point signals from the comparators are observed for 16 cycles to synchronize with the energizing sequence.

FIGURE 6: OSCILLOSCOPE WAVEFORM OF BEMF AND HALL SENSOR SIGNALS

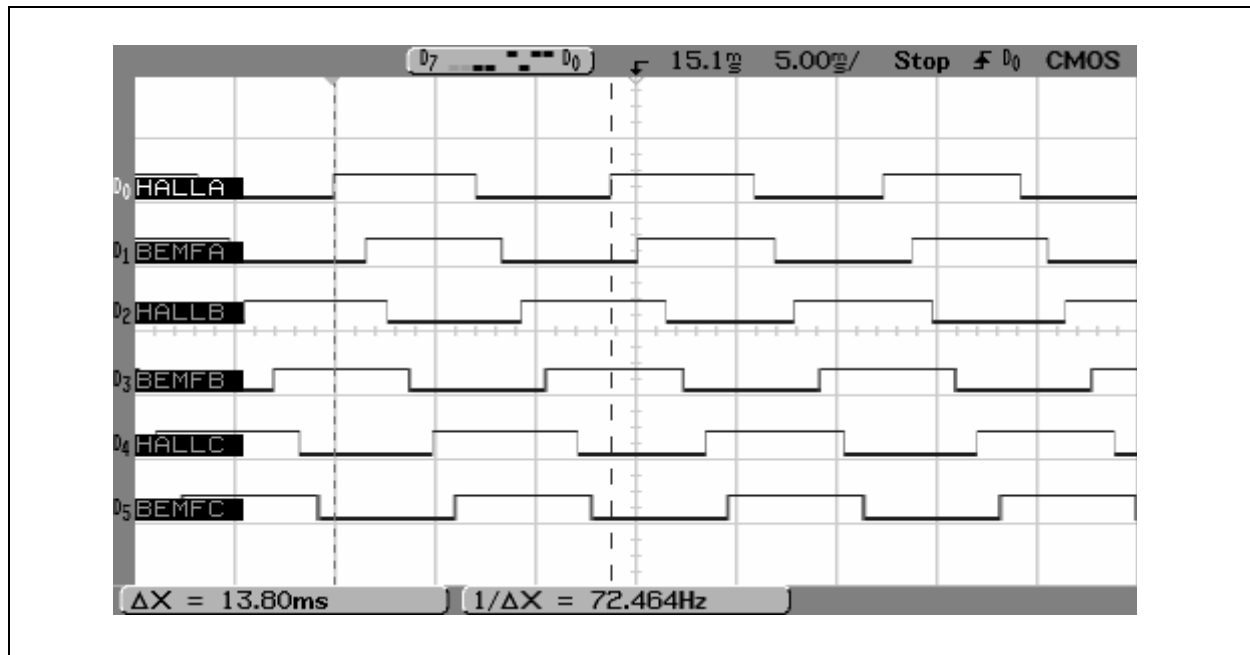
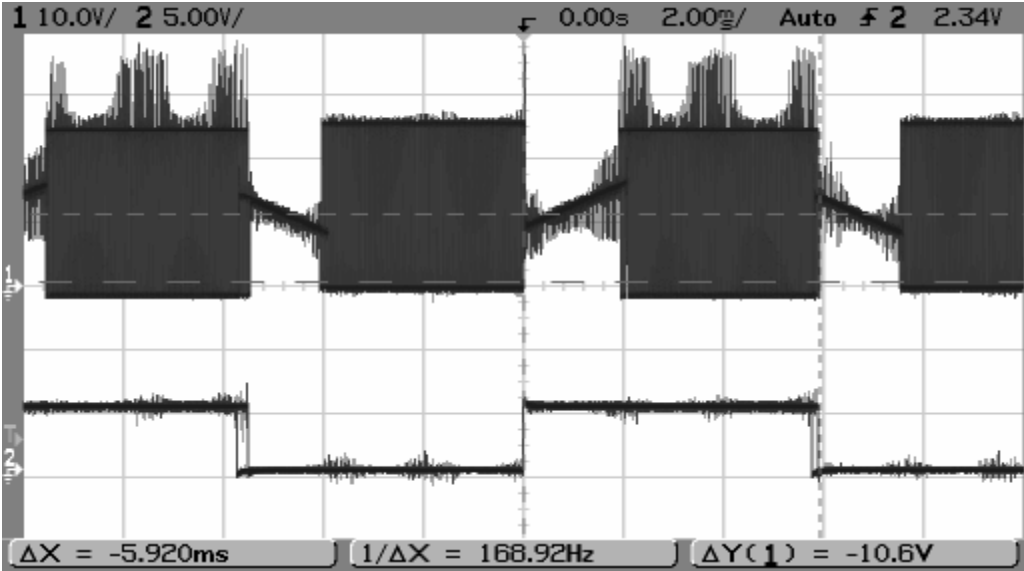
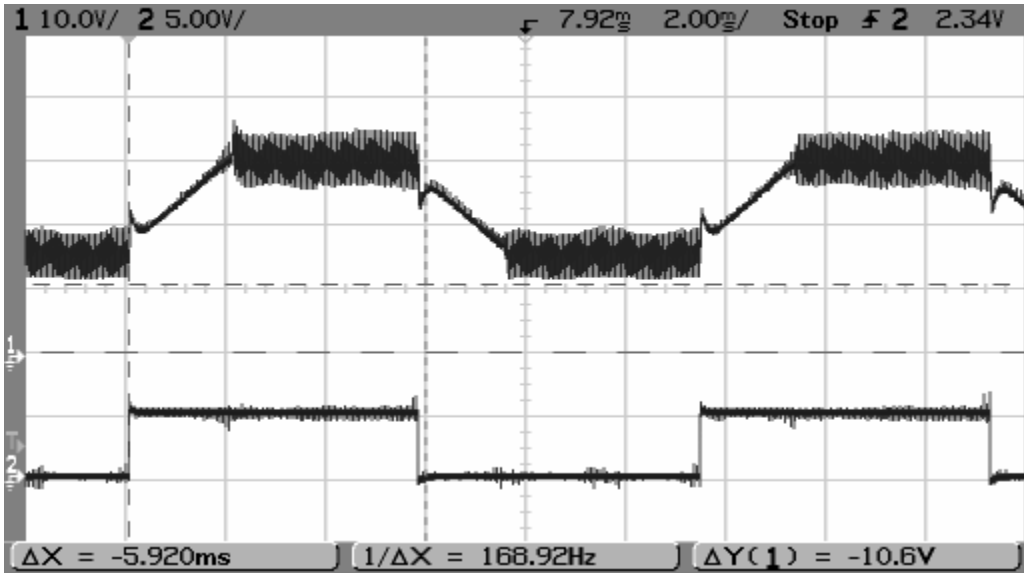


FIGURE 7: BEMF VERSUS ZERO CROSSING



a) Back EMF signal vs. zero crossover point (without filter)



b) Back EMF signal vs. zero crossover point (with filter)

SYNCHRONIZING ZERO CROSSOVER SIGNALS WITH THE ENERGIZING SEQUENCE

When the motor is running at 900 RPM, the BEMF zero crossover (BEMC-ZC) signals, with respect to Hall sensor output, looks like those shown in Figure 6. The phase difference between the actual BEMF-ZC and the Hall sensors is 30 degrees. From the experiments, it's found that the delay between the Hall signals to BEMF-ZC signals connected to input capture pins is 60 degrees throughout the speed range. Keeping this delay in mind, the energizing sequence has to be synchronized with the BEMF-ZC signal. Timer1 is used

to count a 60-degree electrical delay from every BEMF-ZC signal. After the timer expires, the energizing sequence is loaded to the OVDCOND register.

In this version of firmware, IC1 input is used for synchronizing the BEMF-ZC signals twice in an electric cycle. All three input capture inputs are used for determining the energizing sequence for every rotor state.

The Motion Feedback Module (MFM) on the PIC18F2431 has programmable digital filters. These act like low-pass filters with a selectable prescaler. Based on the speed, three levels of filtering is provided in this firmware.

A more detailed overview of the firmware is provided in the flowcharts in Figure 8 through Figure 10.

FIGURE 8: MAIN MOTOR CONTROL SOFTWARE LOOP

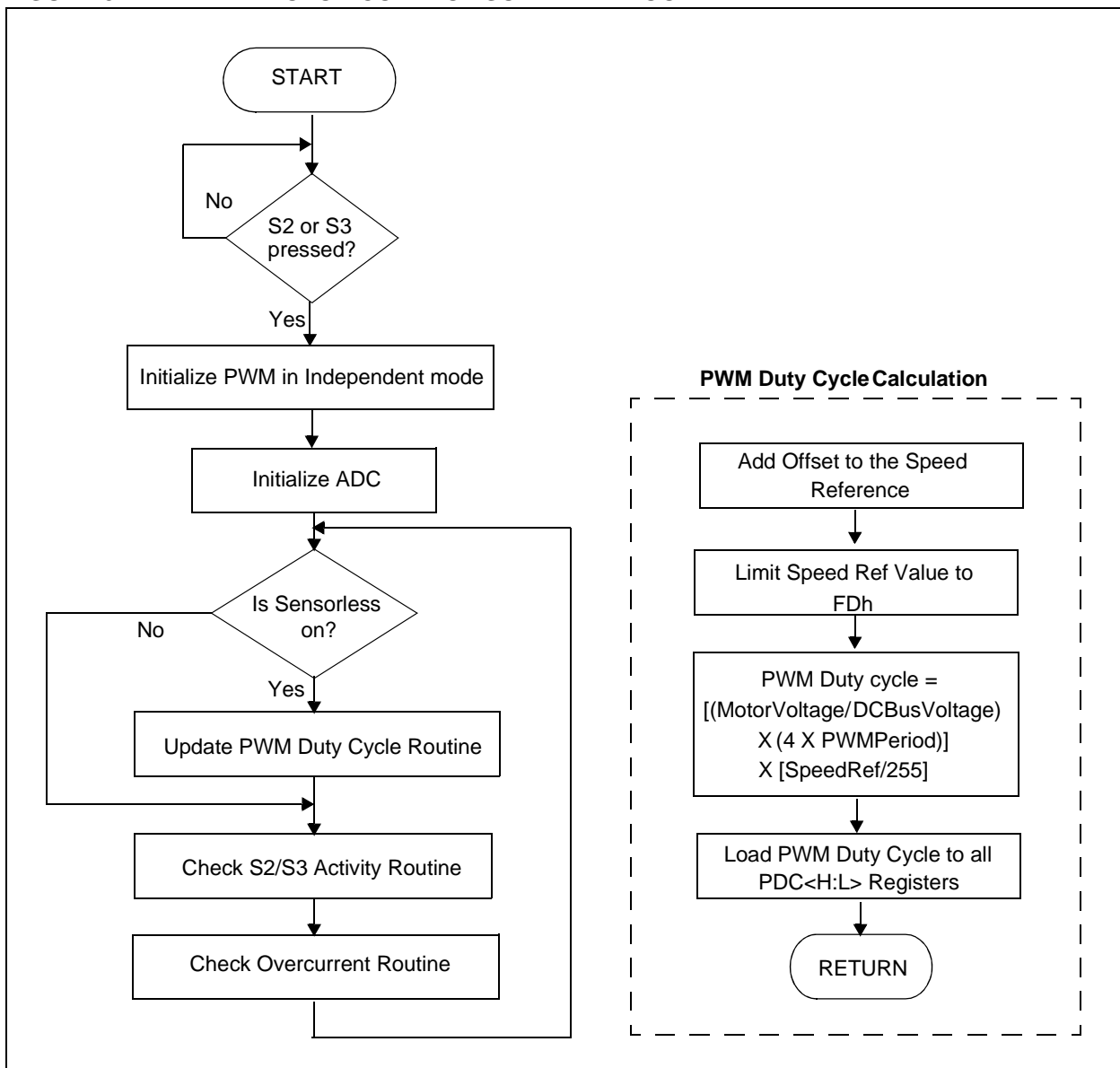


FIGURE 9: ISR FLOWCHART (MAIN ROUTINE AND IC1 SERVICE)

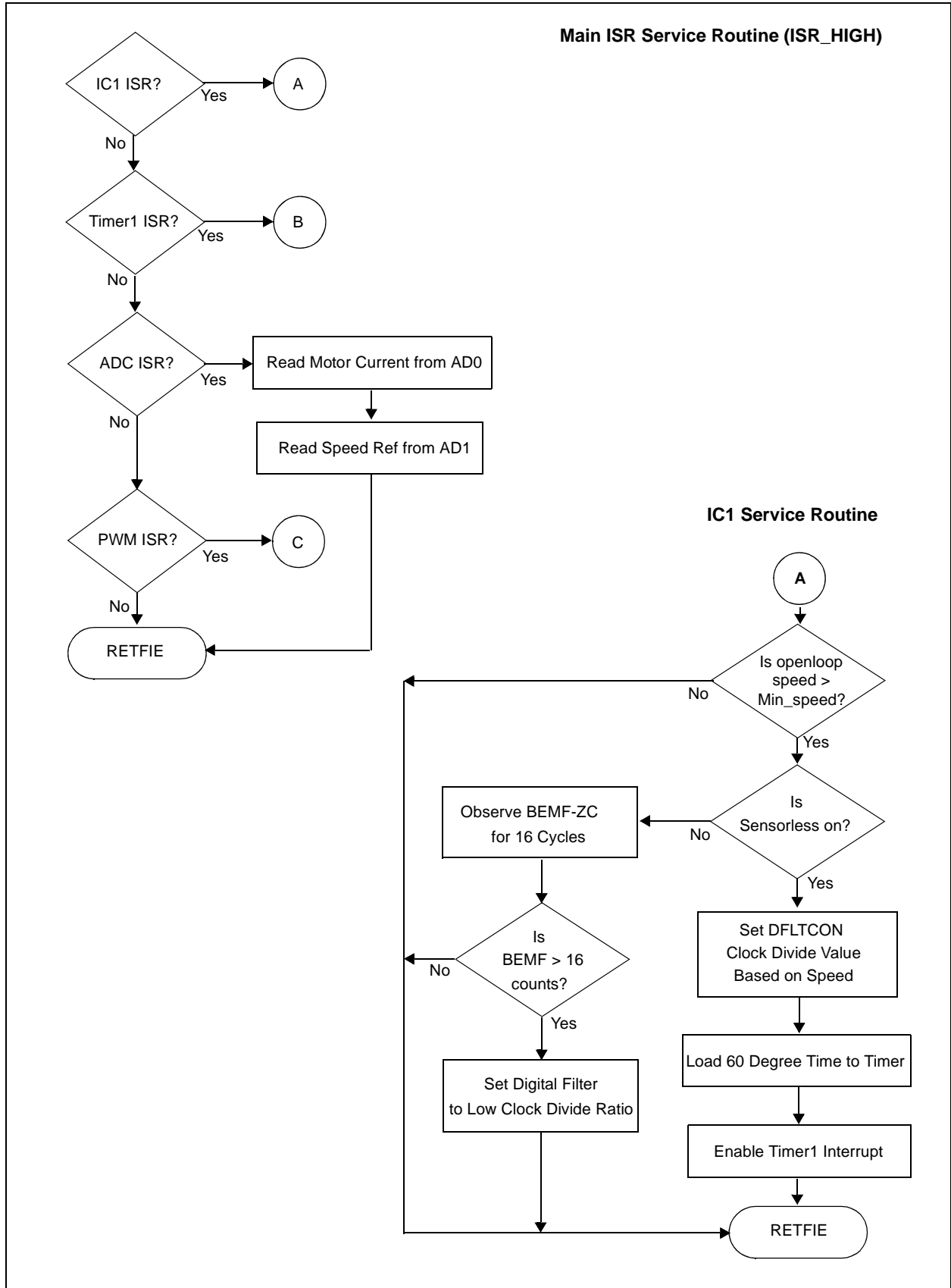
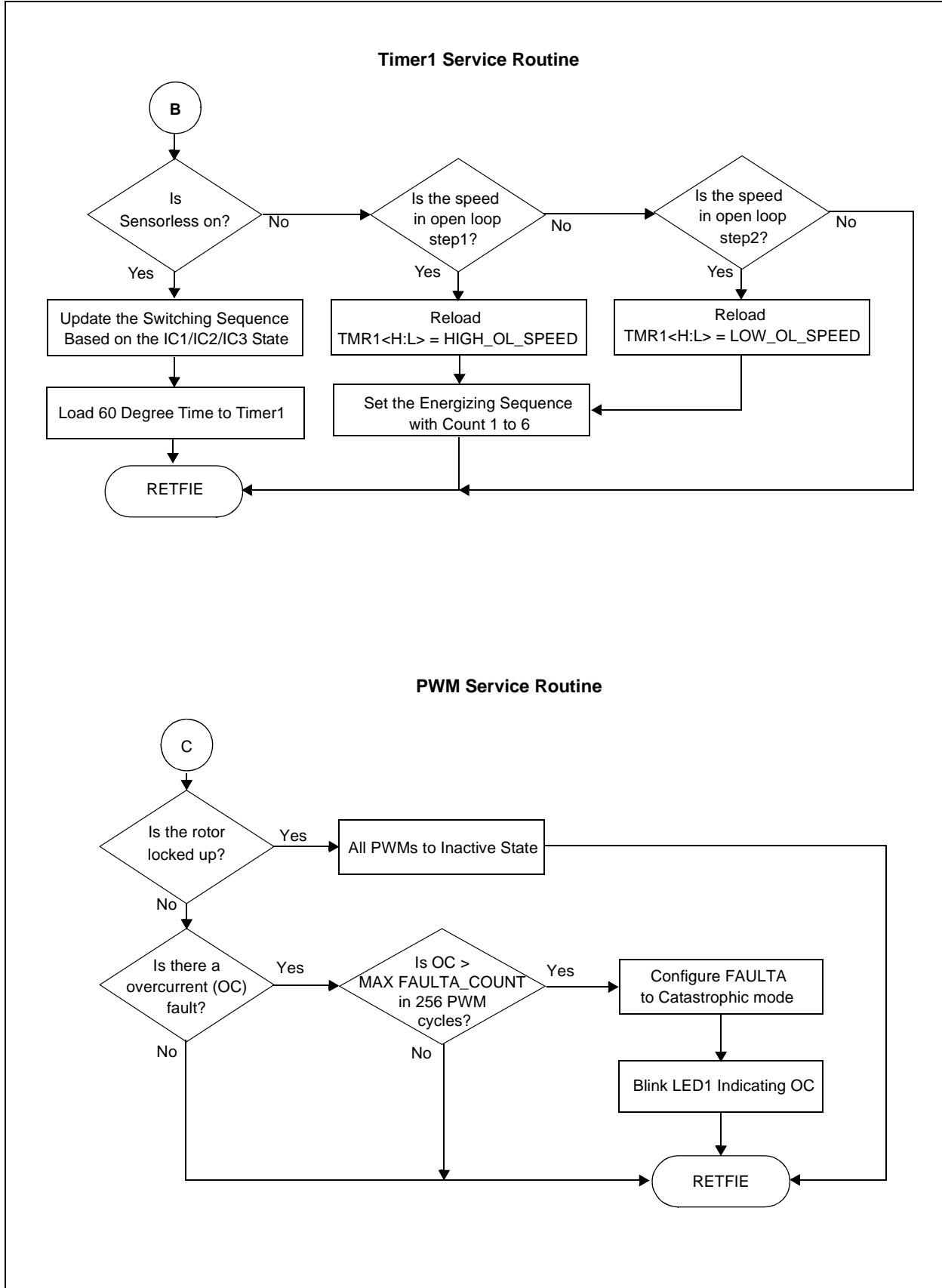


FIGURE 10: ISR ROUTINE (TIMER1 AND PWM SERVICE)



RESOURCE USAGE

The BLDC application consumes CPU resources as shown in Table 1.

TABLE 1: RESOURCES USED IN THE BLDC (USING PIC18F2431)

Resource Type	Used
ROM	800 bytes
RAM	65 bytes
MIPS	4.5 MIPS

CONCLUSION

Sensorless control of BLDC motors has several advantages, such as reduction of total system cost and increased reliability. However, it requires extra resources on the control circuit side. The specialized peripherals on PIC18FXX31 microcontrollers (PCPWM, Motion Feedback Module and the High-Speed A/D converter) can simplify the sensorless control up to a great extent. This application note demonstrates the implementation of sensorless control of a BLDC motor using the 28-pin version of the PIC18FXX31 microcontroller family, the PIC18F2431.

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FIGURE A-2: BOARD SCHEMATIC, PART 2 (BACK EMF SIGNAL CONDITIONING AND CURRENT FAULT DETECTION)

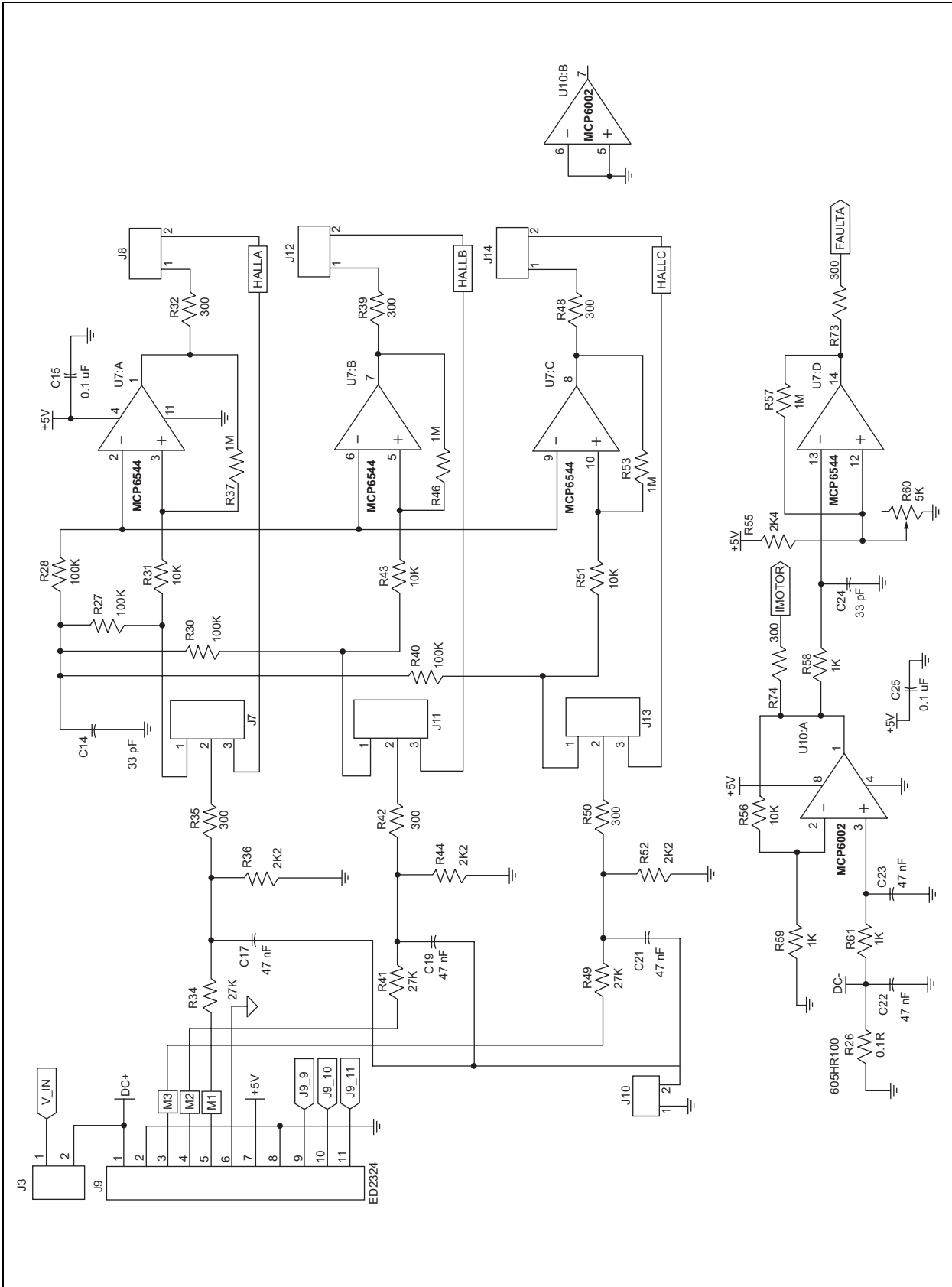
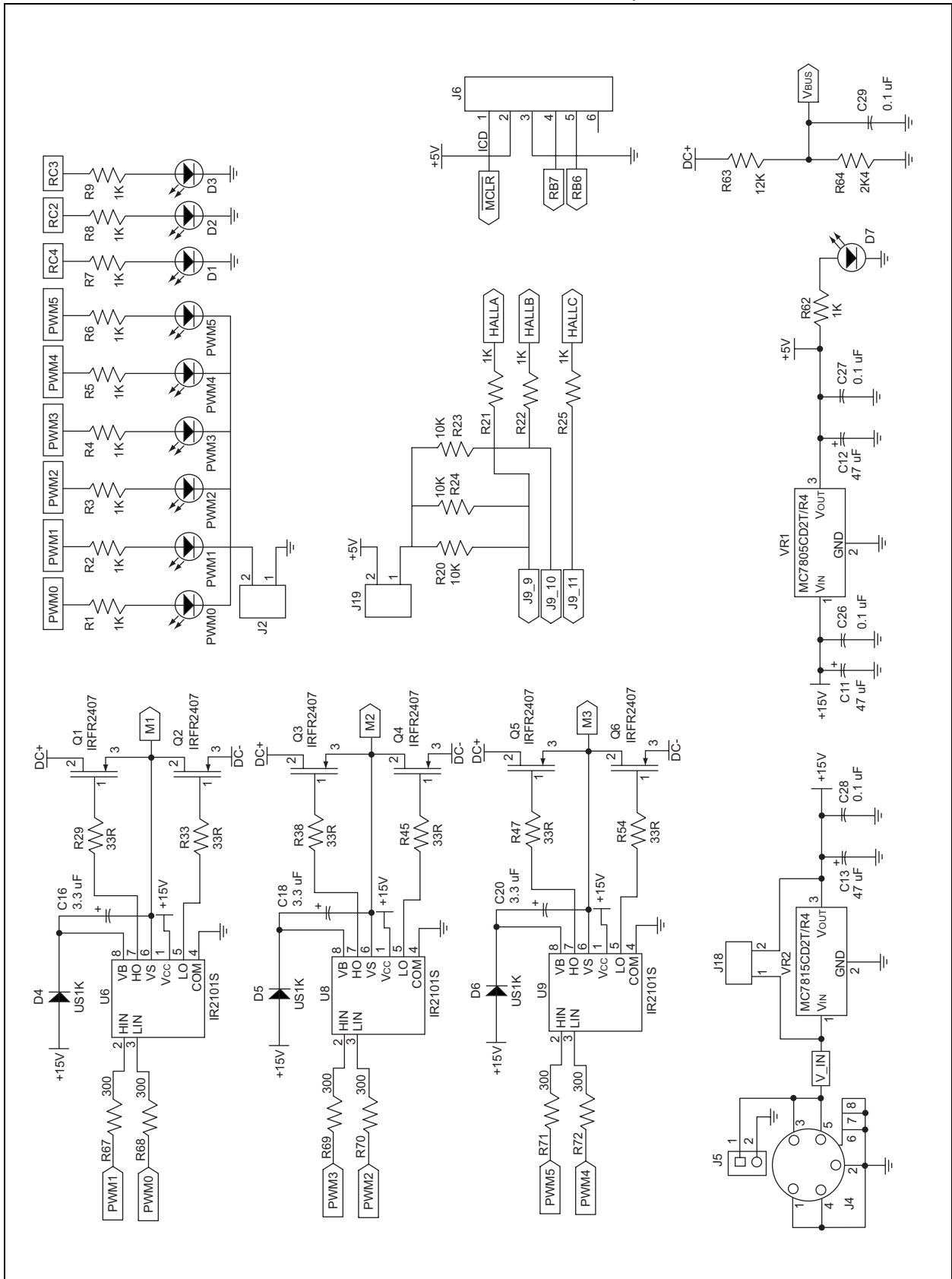


FIGURE A-3: BOARD SCHEMATIC, PART 3 (MOTOR DRIVER BRIDGE, POWER SUPPLY AND REGULATORS, LEDS AND OTHER CONNECTORS)



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NOTES:

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