Application Note

BLDC Motor Control Using Sensored Sinusoidal PWM Modulation with the Z8FMC16100 MCU

AN036702-1115

Abstract

This application note discusses the control of a 3-phase brushless BLDC motor in Sinusoidal PWM Modulation mode using Zilog's Z8FMC16100 Series of microcontrollers (MCUs). Zilog's Z8FMC16100 Series of microcontrollers is designed specifically for motor control applications and, with this MultiMotor Series, features an on-chip integrated array of application-specific analog and digital modules using the MultiMotor Development Kit. The result is fast and precise fault control, high system efficiency and on-the-fly speed/torque control, as well as ease of firmware development for customized applications.

This document further discusses ways in which to implement sinusoidal PWM modulation and phase-angle synchronization with Hall sensor feedback. The results are based on using a MultiMotor MCU Module equiped with a Z8FMC16100 MCU, a 3-phase MultiMotor Development Board, and a 3-phase, 24VDC, 30W, 3200RPM BLDC motor with internal hall sensors.

Note: The source code file associated with this application note, AN0367-SC01.zip, is available free for download from the Zilog website. This source code has been tested with version 5.0.0 of ZDSII for Z8 Encore! MCUs. Subsequent releases of ZDSII may require you to modify the code supplied with this application note.

Features

The power-saving features of this Z8FMC16100 application code include:

- Smooth motor start-up with reduced starting current
- 3-Hall sensor feedback sinusoidal PWM modulation
- Microcontroller-based overcurrent protection
- Adjustable speed and current (frequency and sine magnitude) in open and closed loops
- Selectable control of motor direction
- UART interface for PC control
- LED to indicate a fault condition

Figure 1 shows a block diagram of the Z8FMC16100 MCU architecture.

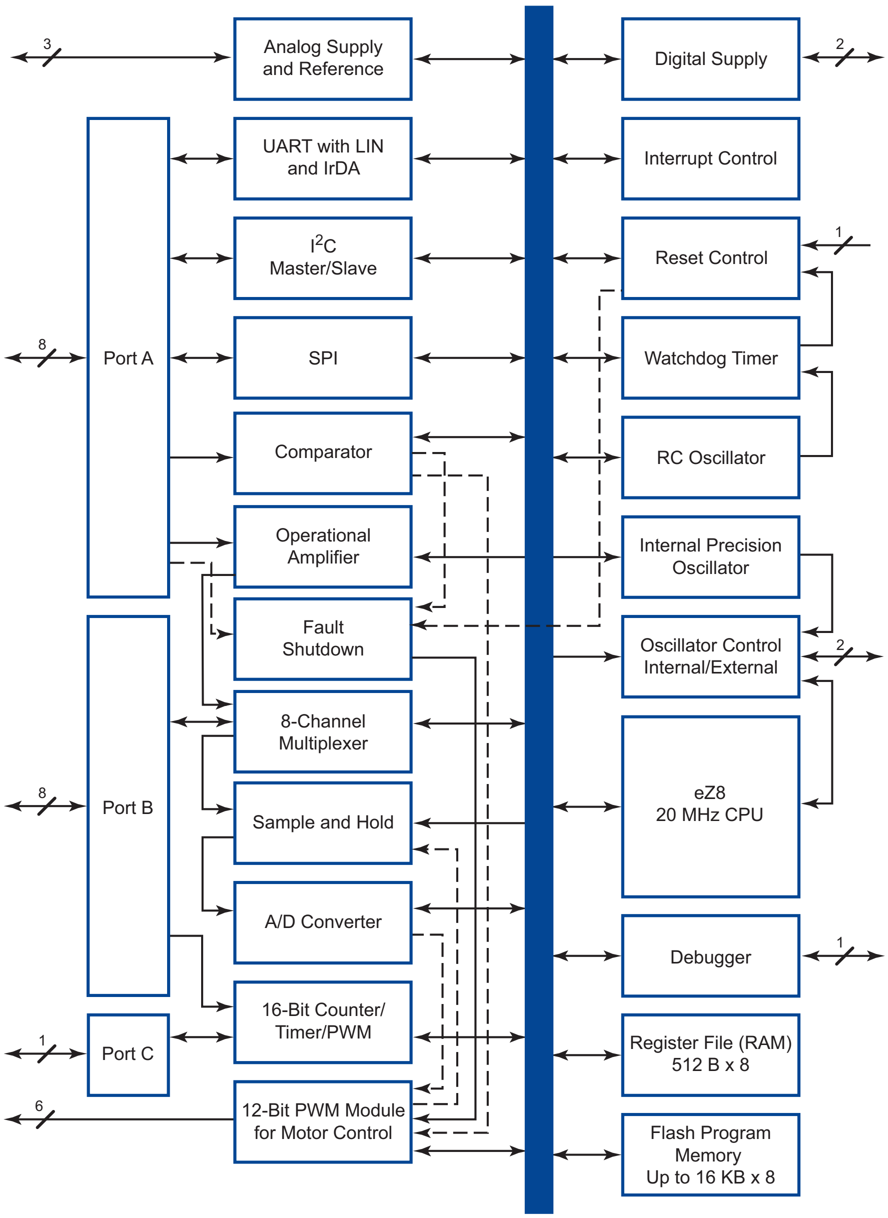

Figure 1. The Z8FMC16100 MCU Architecture

Discussion

The Z8FMC16100 Series Flash microcontrollers upon which this sinusoidal PWM driver has been conceived are based on Zilog's advanced 8-bit eZ8 CPU core, which features a 20 MHz external clock with a minimum of two clock cycles per instruction.

Up to 16KB internal Flash memory is accessible by the CPU. Up to 512bytes of internal RAM provides storage of data, variables, and stack operations.

PWM sinusoidal operation has certain advantages over block-commutated PMSM motor driving approaches, most notably its lower electrical and lower acoustical noise signatures. By comparison, the block commutation method causes harsh current transitions through the PMSM motor coils, essentially turning the phase windings of the motor on and off between commutations. The PWM sinusoidal method does not create these harsh current transitions through the motor coils, because the current and phase voltages are sinusoidal in nature. Motors operating via the sinusoidal PWM method, however, typically run at a higher efficiency than block-commutated motors when the third harmonic-injected sine wave is implemented as described in this document.

Because of the advantages of a PWM sine driver scheme's attributes, PWM sinusoidal operation may be a better option for certain applications in which a smoother torque and the life of ripple capacitors and ball bearings are concerns, in addition to electrical noise.

Sinusoidal PWM driving schemes can be used to drive either PMSM- or BLDC-type motors, however, to take advantage of a sinusoidal driving scheme, a PMSM-type motor is likely to show the best results due to its sinusoidal wound-phase wiring.

In each of the Z8FMC16100 Series products, the novel eZ8 architecture allows for the realization of the following enhanced control features; each is described in this section.

- Time stamp for speed control
- Integrated operational amplifier
- Multichannel PWM timer

Time Stamp for Speed Control

The Capture feature of the 16-bit timers can be used to take a time stamp of the Hall sensor's electrical timing periods. Upon a predefined Hall state, the asynchronously operating timer is read and its value is compared against a calculated speed reference value using PI closed loop control.

Integrated Operational Amplifier

Appliance controllers almost invariably monitor motor speed by sensing current through the motor windings using sensor and sensorless techniques in conjunction with the ADC. Ordinarily, sampling instances by the ADC are synchronized by the MCU. With this process, an external operational amplifier is often used to convert the current signal to a voltage signal; the ADC next samples the voltage signal and outputs the result to the processor. The processor then synthesizes the PWM outputs to control motor speed. In the case of the Z8FMC16100 Series of microcontrollers, an on-chip integrated operational amplifier eliminates the requirement for an external component, thereby reducing overall system cost.

Multichannel PWM Timer

Each Z8FMC16100 MCU features a flexible PWM module with three complementary pairs – or six independent PWM outputs – supporting deadband operation and fault protection trip input. These features provide multiphase control capability for a variety of motor types and ensure safe operation of the motor by providing immediate shutdown of the PWM pins during a fault condition.

Theory of Operation

In a brushless DC motor, the rotor is comprised of permanent magnets, while the stator windings are similar to those in polyphase motors.

Generally, there are two methods for determining motor position and speed: sensored control and sensorless control. In sensor-based control applications, the Hall elements are integrated into the motor and used to detect the position of the rotor for drive and sine wave synchronization. In contrast, sensorless control employs the detection of back-EMF (BEMF) signals, which are generated (induced) by specific phase windings to synchronize the timing of a control loop.

An inverter bridge is used to drive the PWM sine generated currents through the BLDC motor windings, as shown in Figure 2.

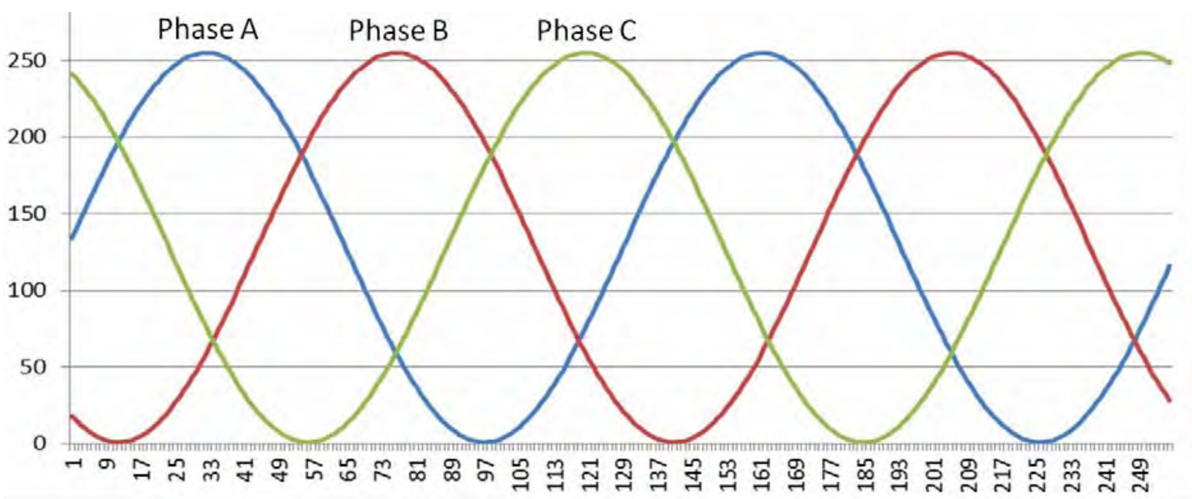

Figure 2. 3-Phase BLDC Motor Control System

The algorithm for Hall sensing is based on an implementation using three I/O ports which are configured for an *interrupt on edge* change of the Hall sensor's signals. One of the advantages of using Hall sensors is that the angular position of the motor is known upon startup of the motor, therefore minimizing erratic start-up behavior. The PWM duty cycle presents the voltage at the motor windings to produce the torque for the motor. The rotating motor generates the Hall signals that vector into a single I/O service interrupt routine, which determines the next commutation state.

Another advantage using Hall sensors as opposed to BEMF sensing is that under sudden and strong load increase, the information of the commutation angle is not in jeopardy of becoming lost. In sensorless feedbacks, an extreme load increase can cause an inductive spike – which results from the stored magnetic energy of the previously turned off phase – to become wide enough to suppress the BEMF information. As a result, the commutation angle information may be lost and could cause the motor to stall.

The Hall sensor's angular position provides the information to energize all three phase voltages at the correct commutation angle. As opposed to trapezoidal or block commutation, in which two of the three phases are energized for each commutation step, the sinusoidal commutation requires all three phases to be energized for each commutation step, as shown in Figure 2.

To save computation time, the firmware implements a look up table in which the sine values are stored. The PWM timer interrupt service routine interrupts every 50 µs and is used to fetch the sine values from the sine table and update the PWM sine frequency for Phase A, Phase B, and Phase C. This method provides very regular time intervals to update the sine frequency and scaling of the sine magnitude for all three phases. Right before exiting the PWM timer interrupt service routine, these three PWM channels are updated with the new PWM modulation values.

For this application, a PWM timer frequency of 20 kHz was chosen to minimize linear switching power losses in the MOSFETs, and to be out of the audible noise range.

PWM Frequency Calculations

Using every value in the 256 sine array, the frequency is:

$$\frac{1}{(\text{PWM period} \times 256)} = \frac{1}{50\,\mu\text{s} \times 256} = 78.125\,\text{Hz}$$

If every second sine value is used instead, then the frequency is effectively doubled and becomes:

$$\frac{1+n}{(\text{PWM period} \times 256)} = \frac{2}{50\,\mu\text{s} \times 256} = 156.25\,\text{Hz}$$

In this second equation, the numerator represents the 1 + nth number of an offset to the array elements; the larger the numerator, the higher the sine frequency. A better way of obtaining a wider sine frequency range and resolution of the sine wave is to use a 16-bit integer-type sine index of which only the upper byte is used to fetch the next PWM sine value from the look-up table. Depending on the frequency demand, the values of the upper byte can change with higher granularity, hitting each sine array value more or less times while the sine index continuously rolls over. Using this method, the lowest period using a 16-bit pointer to a 256-element sine table is:

$$65535 \times 50\,\mu\text{s} = 3.277 \text{ seconds}$$

Assuming the sine frequency is 60 Hz, the offset value for the sine table pointer is:

$$\text{SineIndexOffset} = \frac{60 \times 65536}{20000} \approx 196$$

The resolution of the generated sine wave is a function of the sine frequency.

Sine and Hall Commutation and Frequency Adjustment

Hall sensor interrupts are generated six times – once every sixty degrees – therefore providing data about the rotor position which is used to synchronize the sine wave commutation angle and frequency with the Hall commutation angle and frequency. In other words, the rotor frequency and angular position are synchronized with the stator frequency and angular position. The goal of this synchronization is to maintain 90 degrees between the rotor and stator's angular position.

Figure 2 on page 4 illustrates the generation of three 120-degree shifted sine waves based on values from a look-up table (LUT) which are then reconstructed in the PWM interrupt service routine.

Speed Calculations

The angular period times of the rotor are captured every one-sixth of an electrical commutation, wherein Timer0 represents the number of timer ticks. These timer ticks are then compared against the demand speed coming from a potentiometer – also represented in timer ticks – and processed in a PI closed loop to adjust the look-up table values to change the frequency of the motor. In open or closed loops, the increment value for the sine frequency is a function of the rotor frequency.

The angular speed calculation is:

$$\omega = \frac{d\phi}{dt}$$

In this equation, $d\phi$ is the angular displacement and dt is the time taken for the angular displacement.

The position information is provided by the Hall sensor binary state, and the time between angular positions is measured by Timer0 timer ticks.

The frequency of a sinusoidal operated motor is calculated using the following equation:

$$F(\text{rotor}) = \text{RPM} * \frac{p}{120}$$

The rotor frequency becomes:

$$F(\text{rotor}) = \frac{p/2}{\text{Measured ticks} * \text{timer resolution} * \text{commutation steps} * 60}$$

RPM = (120*f) / N, where N is the number of pole pairs.

Figure 3 illustrates how these calculations can influence a the PWM sine operation of a 3-phase BLDC motor. The hardware used to realize the sinusoidal PWM motor driver approach discussed above is shown in the block diagram in Figure 4.

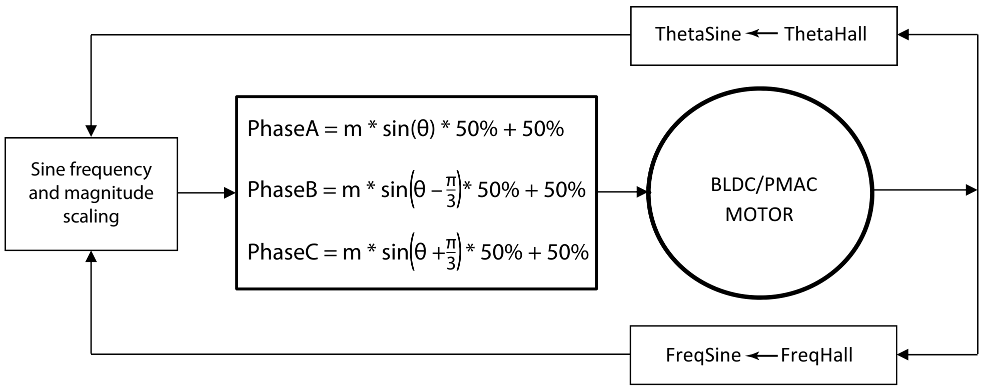

Figure 3. Simplified PWM Sine Operation of a BLDC Motor

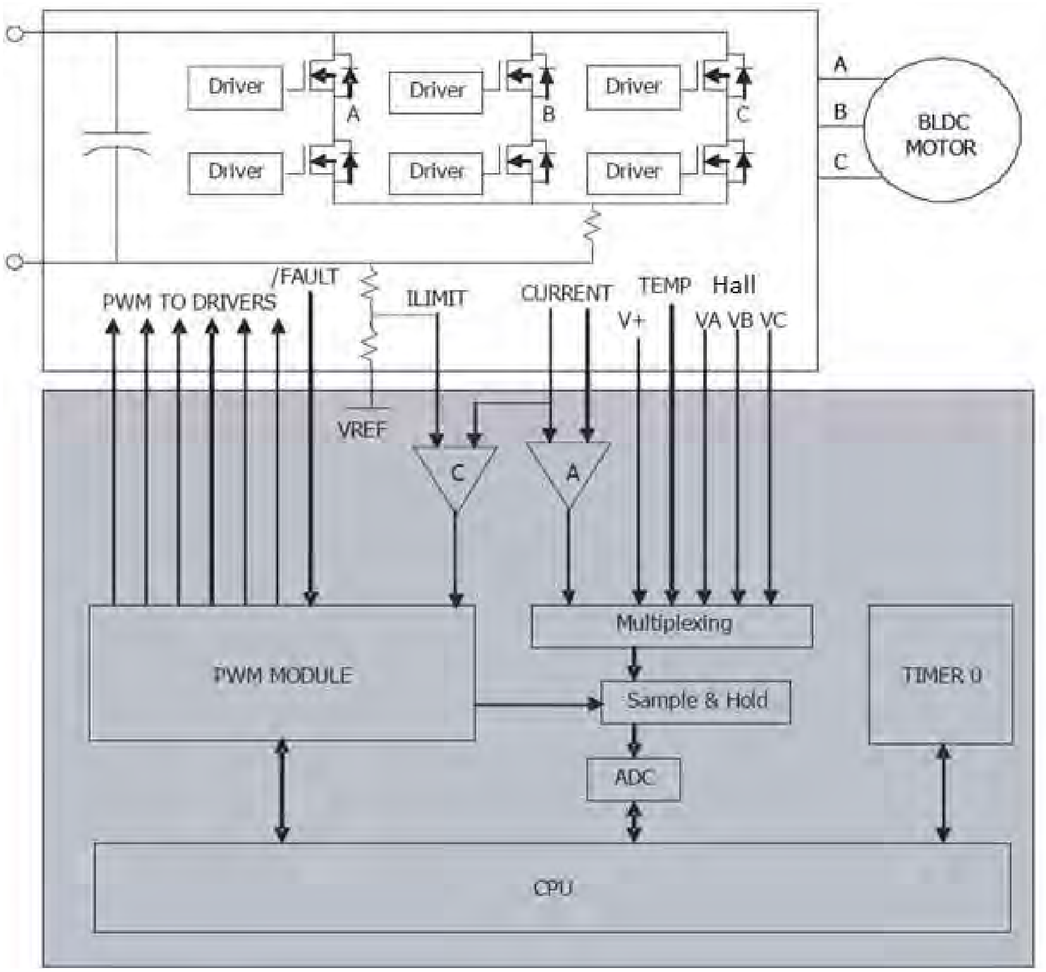

Figure 4. 3-Phase BLDC Motor Control System

Overcurrent Protection

Currents can reach excessive amounts during startup, load changes, or catastrophic failures, for which a motor and electronics must be protected. A key feature of the Z8FMC16100 MCU is the direct coupling of the on-chip integrated comparator to the PWM module to enable a fast, cycle-by-cycle shutdown during an overcurrent event. Oscilloscope-generated waveforms representing this sequence of events are shown in Figure 5.

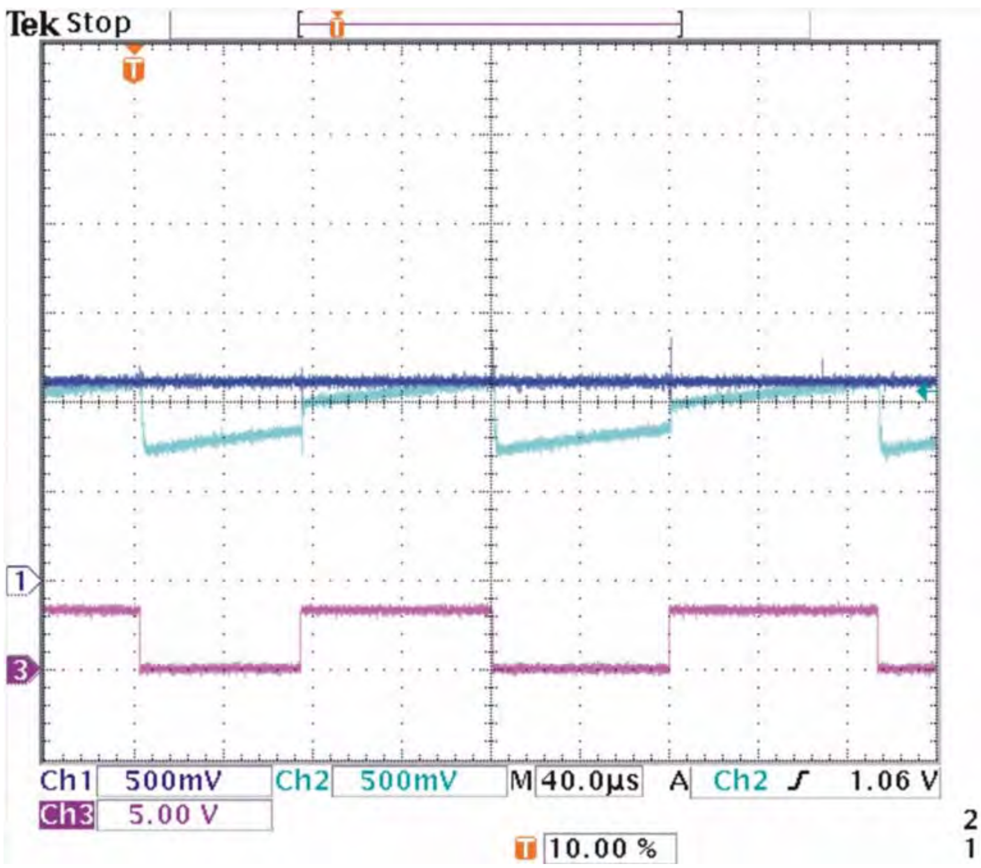

Figure 5. Cycle-by-Cycle Shutdown

Testing

This section describes how to run the code and demonstrate this sensored sinusoidal PWM application including its setup, implementation and configuration, and the results of testing.

Equipment Used

The following equipment is used for the setup; the first four items are contained in the MultiMotor Development Kit (ZMULTIMC100ZCOG).

- MultiMotor Development Board (99C1358-0001G)
- 24V AC/DC power supply
- LINIX 3-phase 24VDC, 30W, 3200RPM BLDC motor (45ZWN24-30)
- Opto-Isolated UART-to-USB adapter (99C1359-001G)
- Z8FMC MultiMotor MCU Module (99C1395-001G) – Order separately
- Opto-Isolated USB SmartCable (99C0968) – Order separately
- Digital Oscilloscope or Logic Analyzer

Hardware Setup

Figure 6 shows the application hardware connections.

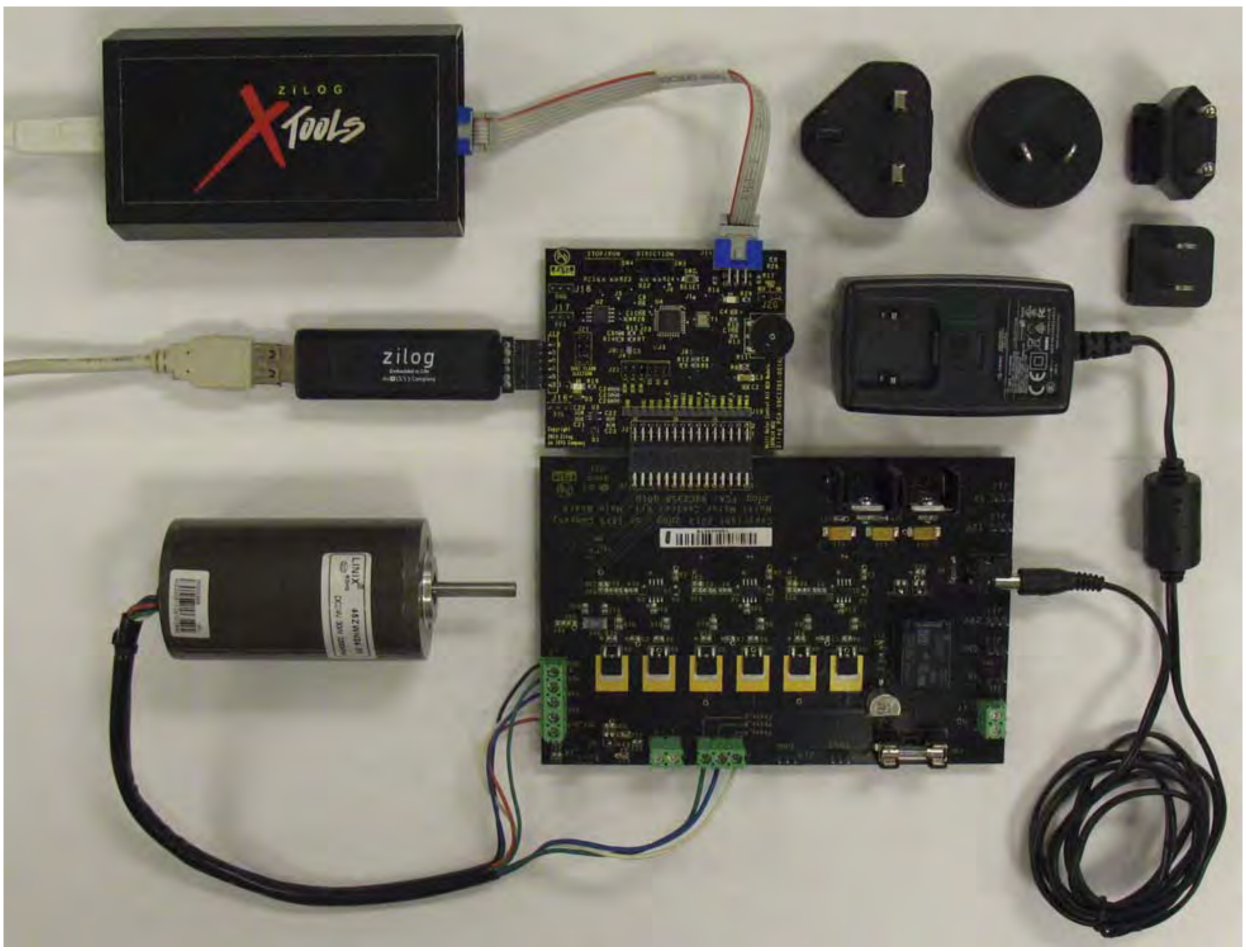

Figure 6. MultiMotor Development Kit with Z8FMC MCU Module and SmartCable

Testing Procedure

Observe the following procedure to test sensored sinusoidal PWM modulation on the Z8FMC16100 MCU Module.

1. Download ZDSII – Z8 Encore! version 5.0.0 (or newer) from the Zilog Store and install it onto your PC.
2. Download the AN0367-SC01.zip source code file from the Zilog website and unzip it to an appropriate location on your PC.
3. Connect the hardware, as shown in Figure 6.
   a. Verify that the Z8FMC16100 MCU Module (99C1395) jumpers are configured properly, as follows:
      - The J20 jumper is in the ON position to activate the VBUS relay on the main board
      - The two J21 jumpers are in positions 3-4 and 7-8 to allow the UART to function properly
      - The three J22 jumpers are in the HSx positions to allow proper sensorless motor control operation
   b. The cables from the opto-isolated USB SmartCable and the UART-to-USB adapter must be connected to two of the PC's USB ports.
   c. Download and install the drivers for the SmartCable and the UART-to-USB adapter, if required. For assistance, refer to the MultiMotor Series Development Kit Quick Start Guide (QS0091).
4. Power up the MultiMotor Development Board using the 24VDC adapter that is included in the Kit.
5. Using a serial terminal emulation program such as HyperTerminal, TeraTerm, or Real-Term, configure the serial port to 57600-8-N-1-N. A console screen should appear on the PC which will show the status of the motor and allow changes to the motor's operation.
6. Launch ZDSII – Z8 Encore! and select **Open Project** from the **File** menu. Browse to the directory on your PC into which you downloaded the AN0367-SC01 source code. Locate the `AN0367_SC01.zdsproj` file, click to highlight it, and select **Open**.
7. Ensure that the RUN/STOP switch on the Z8FMC16100 MCU Module is in the STOP position.
8. In ZDSII, compile and flash the firmware to the Z8FMC16100 MCU Module by selecting **Rebuild All** from the **Build** menu. Next, select **Debug** → **Download code**, followed by **Debug** → **Go**.
9. Set the RUN/STOP switch on the Z8FMC16100 MCU Module to RUN. The motor should begin turning.
10. In the GUI terminal console, enter the letter `U` to switch to UART control; a menu similar to the example shown in Figure 7 should appear. As a result, commands can now be entered using the console to change the motor's operation.

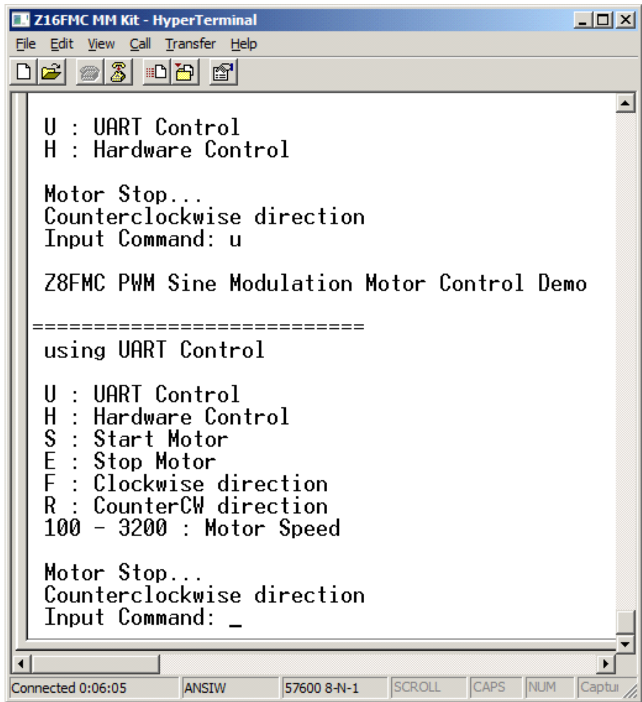

Figure 7. GUI Terminal Showing UART Control

11. At the `Input Command:` prompt, enter the letter `H` to reestablish hardware control; see Figure 8.

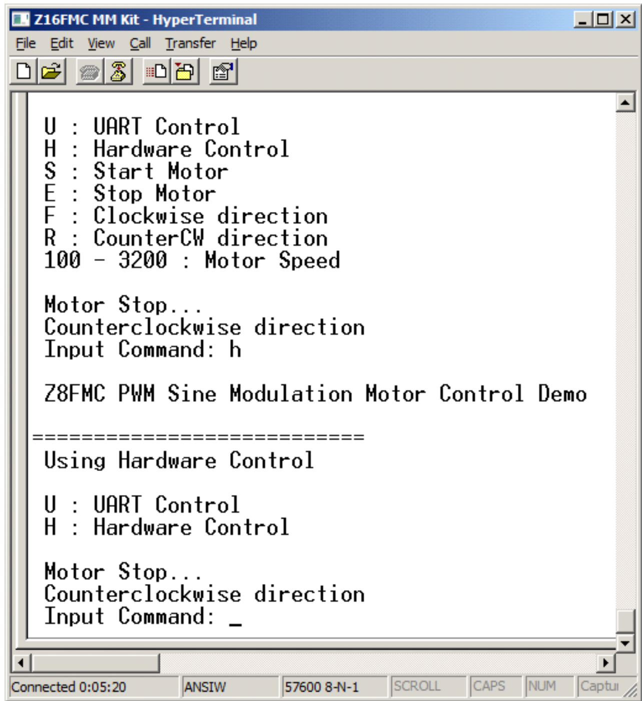

Figure 8. GUI Terminal Showing Hardware Control

You can now add your application software to the main program to experiment with additional functions.

Note: While debugging your code, ensure that the Opto-Isolated USB SmartCable controls the reset pin of the MCU. After debugging and running your code, detach the Opto-Isolated USB SmartCable from J14 of the MultiMotor MCU Module to free the Reset pin and apply a power cycle to reset the MCU from Debug Mode.

Results

Linix BLDC-type and Teknik/Hudson PMSM-type motors were tested to compare their corresponding voltage and current waveforms. During operation of the BLDC motor, three oscilloscope probes were connected to the Hall sensors, and a scope probe was connected to one of the three motor phase BEMF resistor dividers with filters to show the three 120-degree shifted Hall sensors in conjunction with one of three sine wave phase voltages. The scope channel was set to AC so that the positive and negative half of the sine wave modulates with respect to the midpoint. These three voltages and one current waveform are shown for the BLDC and PMSM motors in Figures 9 and 10, respectively.

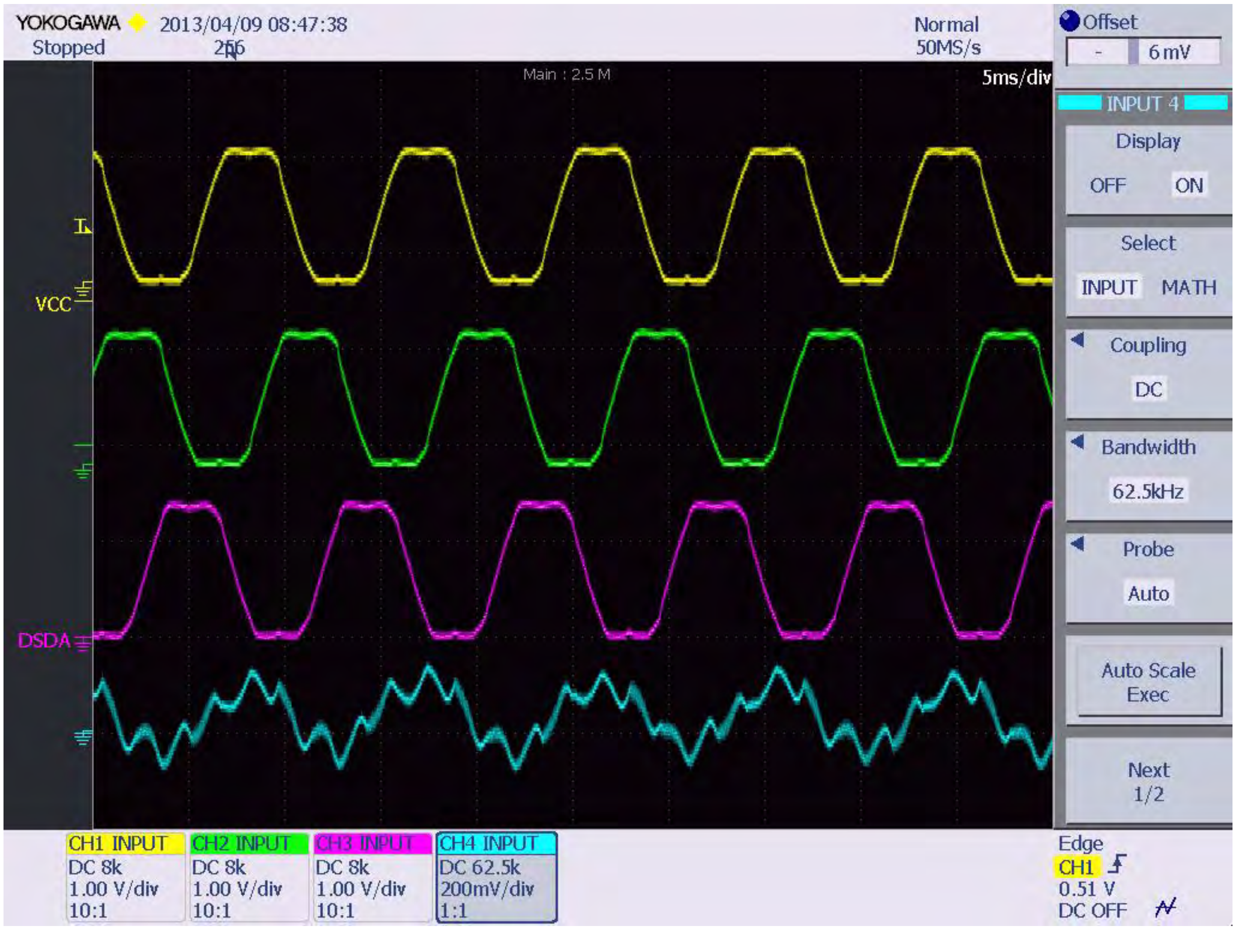

Figure 9. Linix BLDC Motor Phase Voltages and One Current Waveform

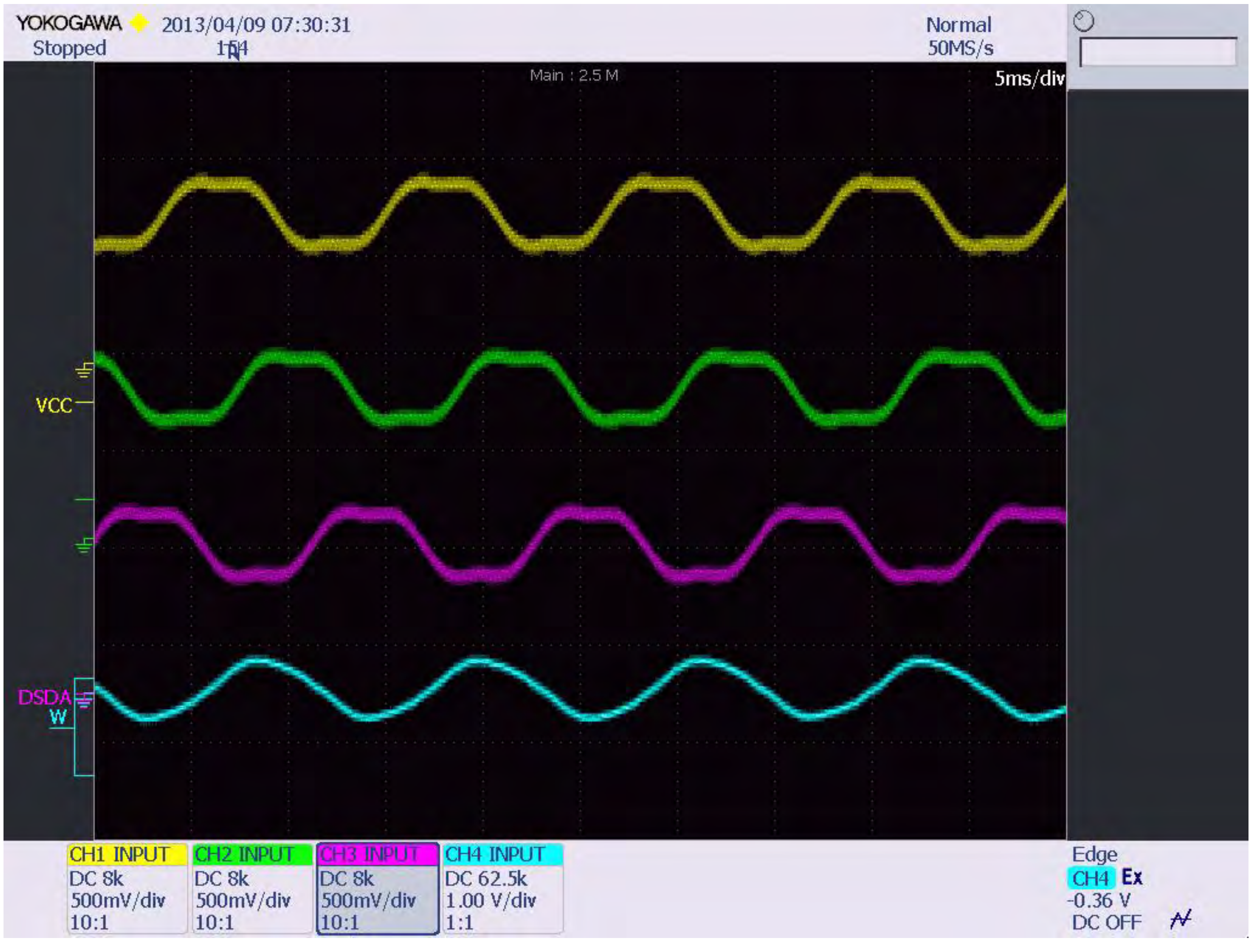

Figure 10. Hudson Teknic PMSM Motor Phase Voltages and One Current Waveform

Speed Control Performance in a Closed Loop

To monitor performance of the speed control function while operating in a closed loop, the motor speed was set to 2000 RPM at a nominal operating voltage of 24 V. As this operating voltage was increased and decreased by plus and minus 4 V, motor speed was observed to remain constant. To test the PI loop under load, the motor load was increased, which caused the PI to quickly ramp up the current to maintain the set speed. PI loop stability was verified by observing the voltage sine wave while loading the running motor, a condition for which the sine wave period time must be maintained constant in both amplitude and frequency.

Speed Control Performance in an Open Loop

To monitor performance of the speed control function while operating in an open loop, the motor speed was set to 2000 RPM at a nominal operating voltage of 24V. As this operating voltage was increased and decreased by plus and minus 4 V, motor speed was observed to vary. Motor load was then increased, which caused the motor current to be increased while its speed slightly dropped.

Summary

The purpose of this application was to demonstrate the operation of a BLDC or PMSM type machine using the sinusoidal PWM technique.

To generate sinusoidal voltages and currents 120 degrees apart for a BLDC machine, a sine look up table (LUT) was implemented to reconstruct the three sine waves and formulas have been shown to calculate the motor frequency. Since the frequency calculations include the PWM period, all sinusoidal wave constructions are executed in the PWM interrupt service routine. The execution time for the sine wave reconstruction in the PWM service interrupt routine takes 20 µs. The execution time of the Hall interrupt service routine takes 30 µs. Both execution times are based on a 20 MHz external clock.

To maintain the 90-degree relationship between the rotor and stator positions, the Hall interrupt service routine captures the binary Hall state upon each interrupt and fetches the corresponding reference angle from a Look Up Table (LUT).

The high byte of the PWM sine Look Up Table index is used to fetch the next value from the Sine Look Up Table (LUT). Any offset value to the high byte of the PWM sine Look Up Table index will change the frequency of the sine wave.

Sinusoidal PWM operation has the advantage of commutating the BLDC or PMSM with less acoustical and electrical noise, because the sine current through the windings has no steep current transitions. As a result, a smoother torque and higher life expectancy can be expected for the ripple current capacitor and ball bearings because the sinusoidal commutation approach causes no torque or current ripple in a PMSM- or BLDC-type motor. In addition to electrical and acoustical noise reduction, the PWM sine approach also increases the efficiency by about 15 percent when a third harmonic is injected into the sine wave, as is the case in this application.

References

The following documents are each associated with the Z8FMC16100 Series of Motor Control MCUs; each is available free for download from the Zilog website.

- Z8FMC16 Series Motor Control Product Specification (PS0246)
- MultiMotor Series Development Kit Quick Start Guide (QS0091)
- MultiMotor Series Development Kit User Manual (UM0262)
- eZ8 CPU Core User Manual (UM0128)
- Zilog Developer Studio II – Z8 Encore! User Manual (UM0130)
- Three-Phase Hall Sensor BLDC Driver Using The Z8FMC16100 MCU Application Note (AN0368)

- Space Vector Modulation of a 3- Phase AC Induction Motor with the Z8FMC16100 MCU Application Note (AN0369)
- Sensorless Brushless DC Motor Control with the Z8FMC16100 MCU Application Note (AN0370)
- Motor Control Electronics Handbook, Richard Valentine; McGraw Hill, 1998

Appendix A. Schematic Diagrams

Figures 11 and 12 show the schematics for the Z8FMC MultiMotor MCU Module.

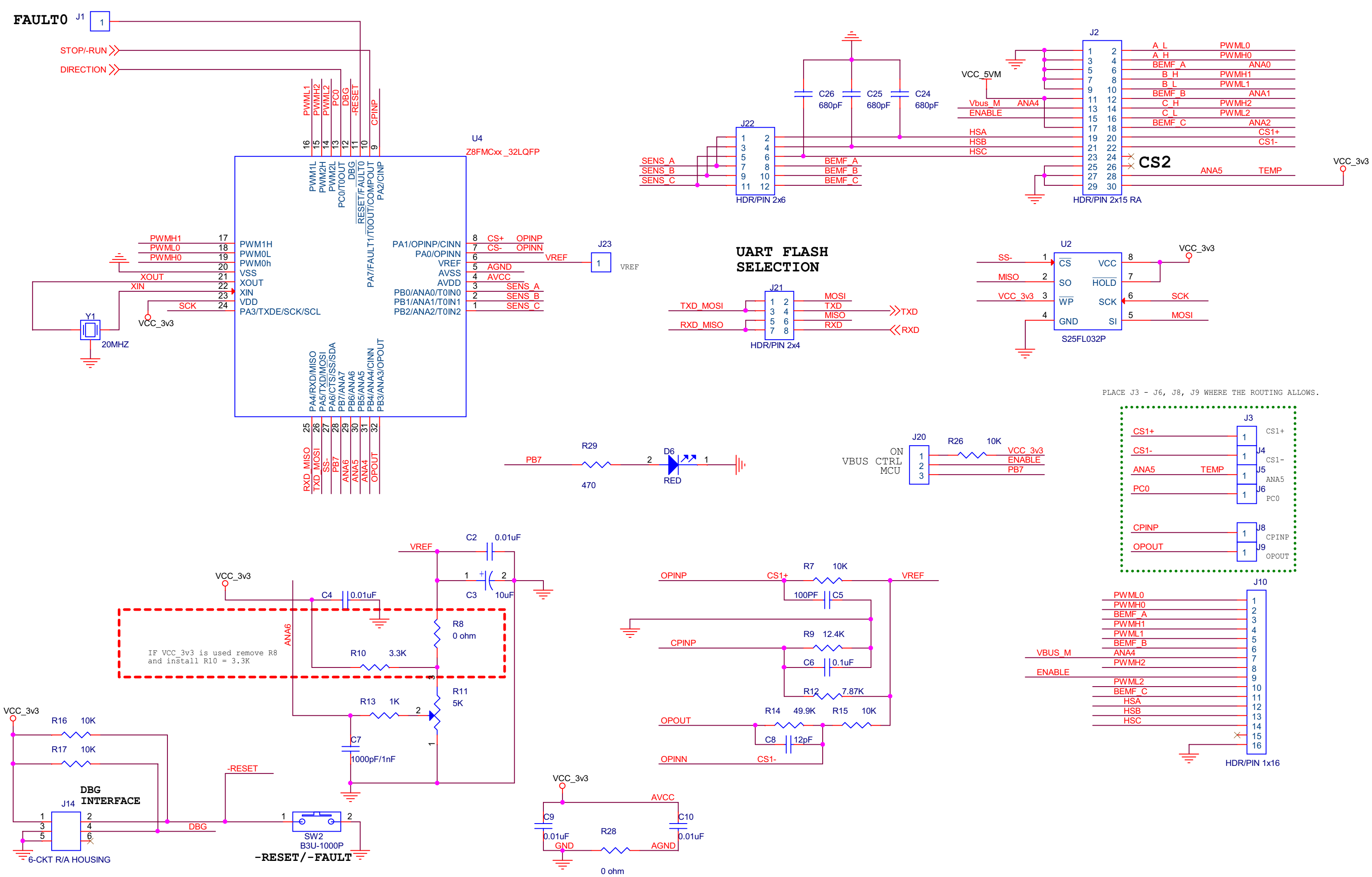

Figure 11. Z8FMC16100 MultiMotor MCU Module, #1 of 2

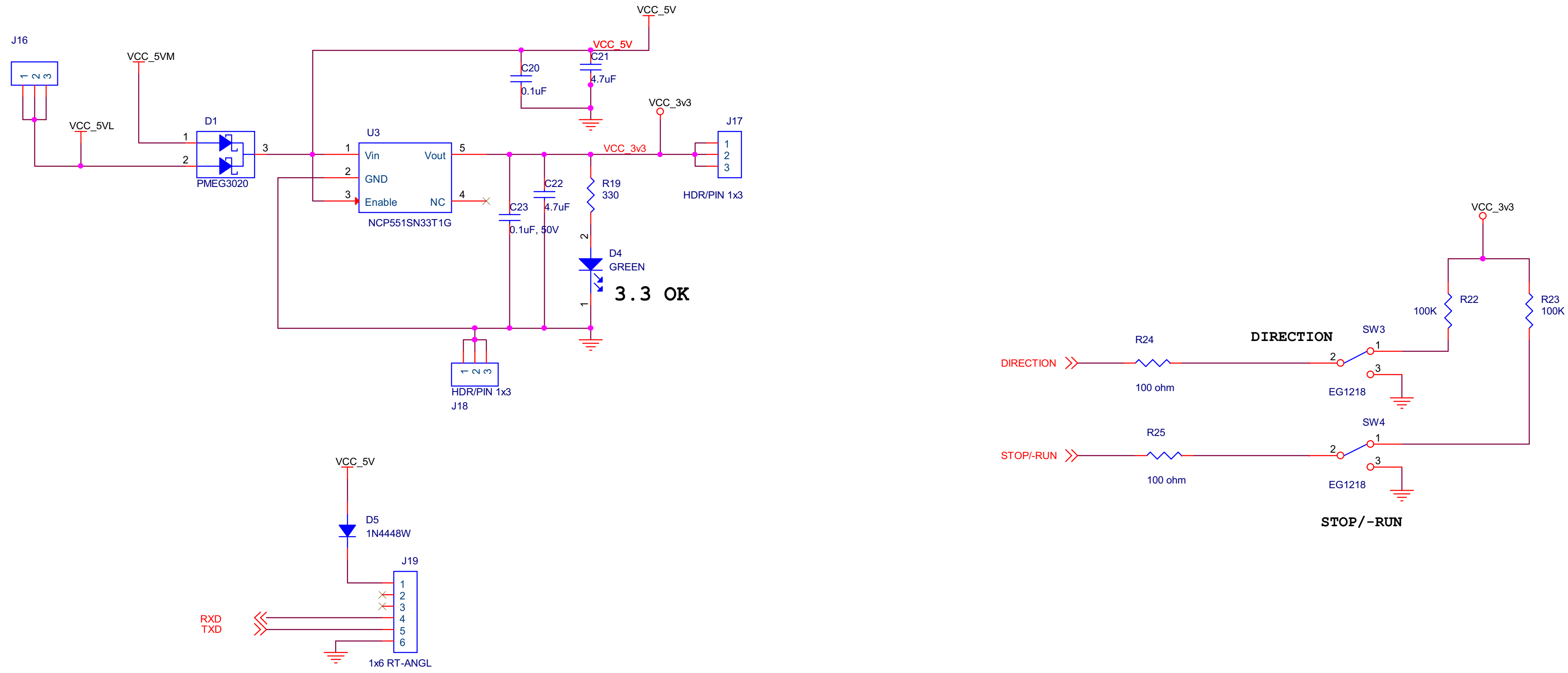

Figure 12. Z8FMC16100 MultiMotor MCU Module, #2 of 2

Figures 13 and 14 show the schematics for the MultiMotor Main Development Board.

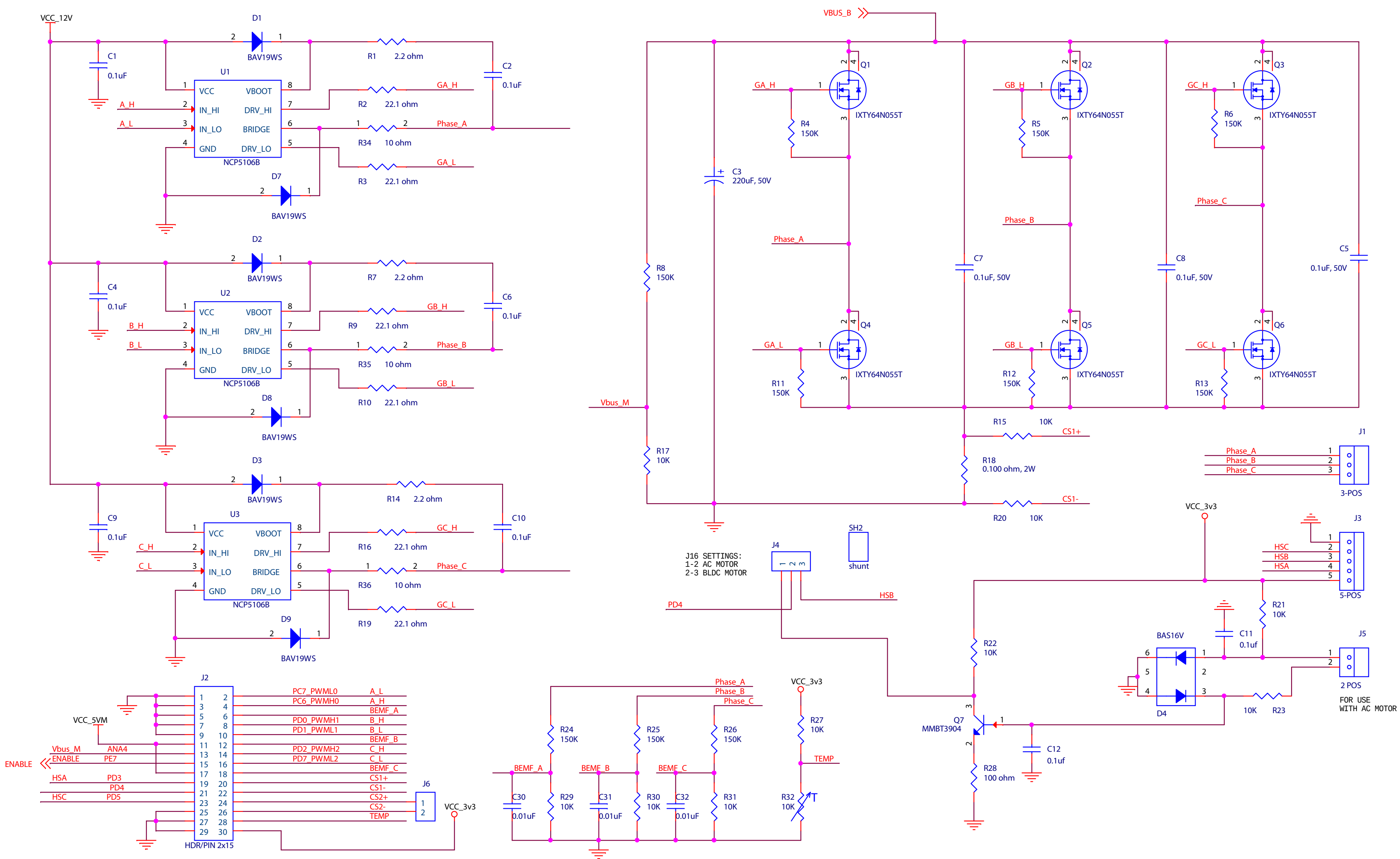

Figure 13. MultiMotor Development Board, #1 of 2

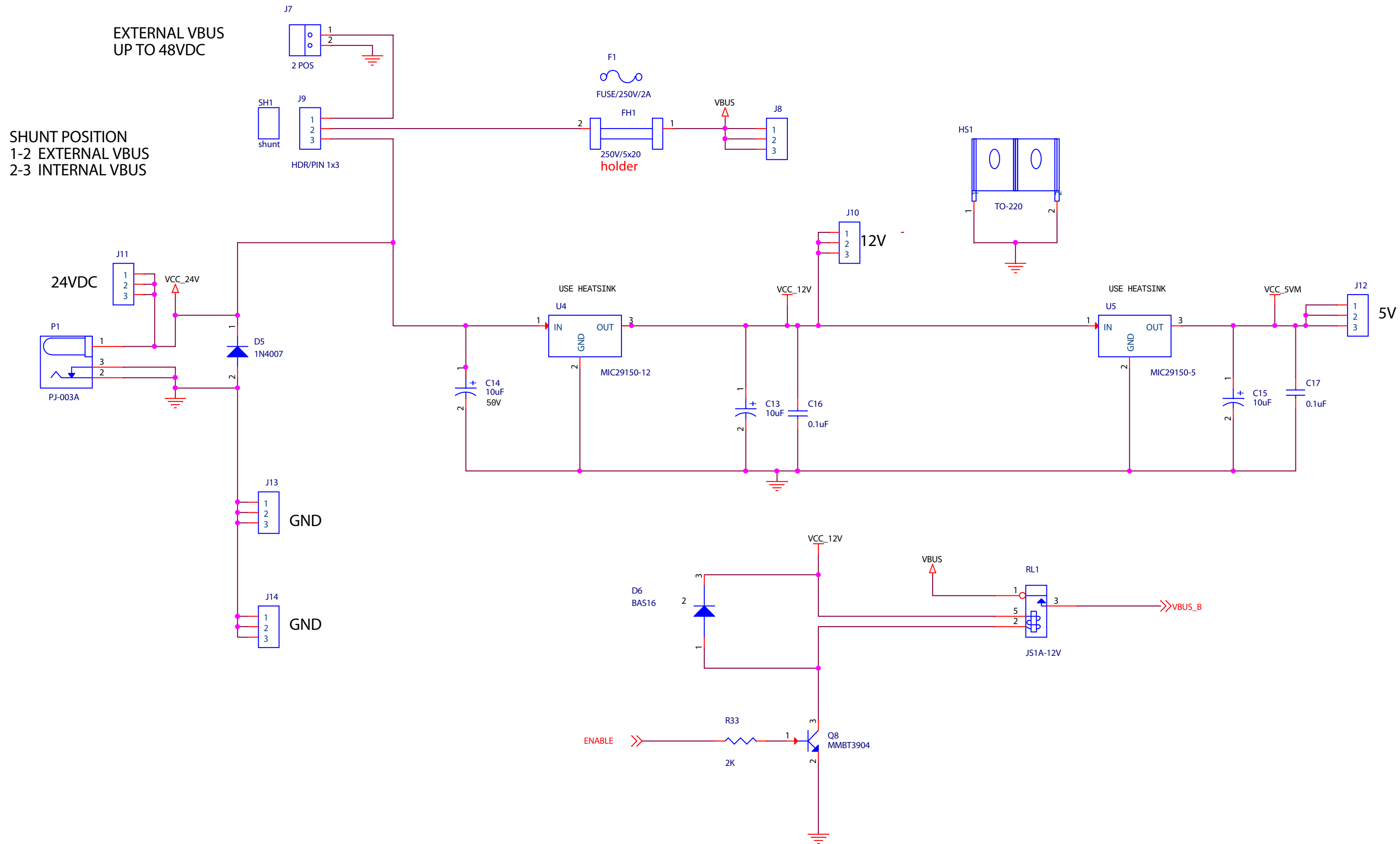

Figure 14. MultiMotor Development Board, #2 of 2

Appendix B. Flow Charts

Figure 15 presents an algorithm by which a 3-phase BLDC motor can be controlled using the Z8FMC16100 MCU.

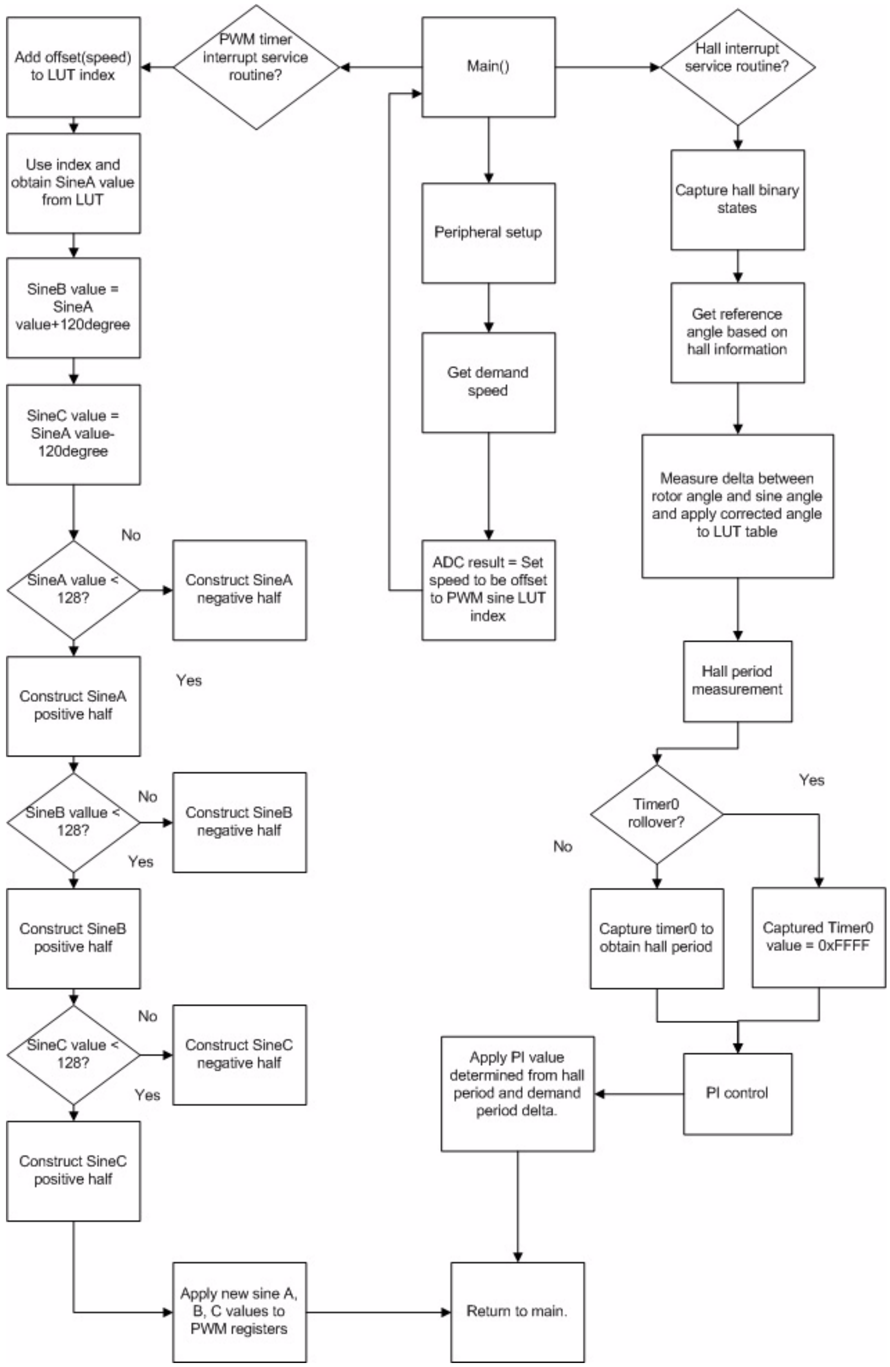

Figure 15. Simplified Control Algorithm

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