Application Note

Three-Phase Hall Sensor BLDC Driver Using The Z8FMC16100 MCU

AN036801-0514

Abstract

This MultiMotor Series application note investigates the closed- and open-loop control of a 3-phase brushless direct current (BLDC) motor using a Z8FMC16100 MCU with Hall sensor feedback. 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, on-the-fly speed/torque and direction control, as well as ease of firmware development for customized applications.

This document further discusses ways in which to implement motor control using a sensored feedback control system, and fault protection. Test results are based on using a MultiMotor Control Module equipped with a Z8FMC16100 MCU, a 3-phase MultiMotor Development Board, and a 3-phase, 24 VDC, 30 W, 3200 RPM BLDC motor.

Note: The source code file associated with this application note, AN0368-SC01, was tested with version 5.0.0 of ZDS II for Z8 Encore! MCUs. Subsequent releases of ZDS II may require you to modify the code supplied with this application.

Features

The power-saving features of this MultiMotor Series application include:

- Hall sensor commutation
- Motor speed measurement
- Motor protection logic
- Closed-loop or open-loop control for precise speed regulation
- Hardware or terminal mode motor control
- UART Interface for PC control
- LED to indicate a fault condition

Discussion

Z8FMC16100 Series Flash microcontrollers are based on Zilog's advanced 8-bit eZ8 CPU core. These Z8FMC16100 devices set a standard of performance and efficiency at 20 MHz. Up to 16 kilobytes of internal Flash memory are accessible by the eZ8 CPU, and as much as 512 bytes of internal RAM provide storage of data, variables and stack operations.

The Z8FMC16100 MCU features a flexible Pulse Width Modulation (PWM) module with three complementary pairs or six independent PWM outputs supporting dead-band 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 pulse-by-pulse or latched fast shutdown of the PWM pins during a fault condition.

Also featured are up to eight single-ended channels of 10-bit analog-to-digital conversion (ADC) with a sample and hold circuit. One operational amplifier performs current sampling, and one comparator performs overcurrent limiting or shutdown. A high-speed ADC enables voltage and current sensing, while dual-edge interrupts and an 8-bit timer for angular period measurements provide a Hall-effect sensor interface.

A full-duplex 9-bit UART provides serial, asynchronous communication and supports an option for the Local Interconnect Network (LIN) serial communications protocol. The LIN bus is a cost-efficient single master/multiple slave organization that supports speeds up to 20kbps.

The Z8FMC16100 MCU offers a rich set of peripherals and other features, such as an SPI, an I^2C master/slave for serial communication, and an internal 5.5MHz precision oscillator.

The single-pin debugger and programming interface simplifies code development and allows easy in-circuit programming.

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

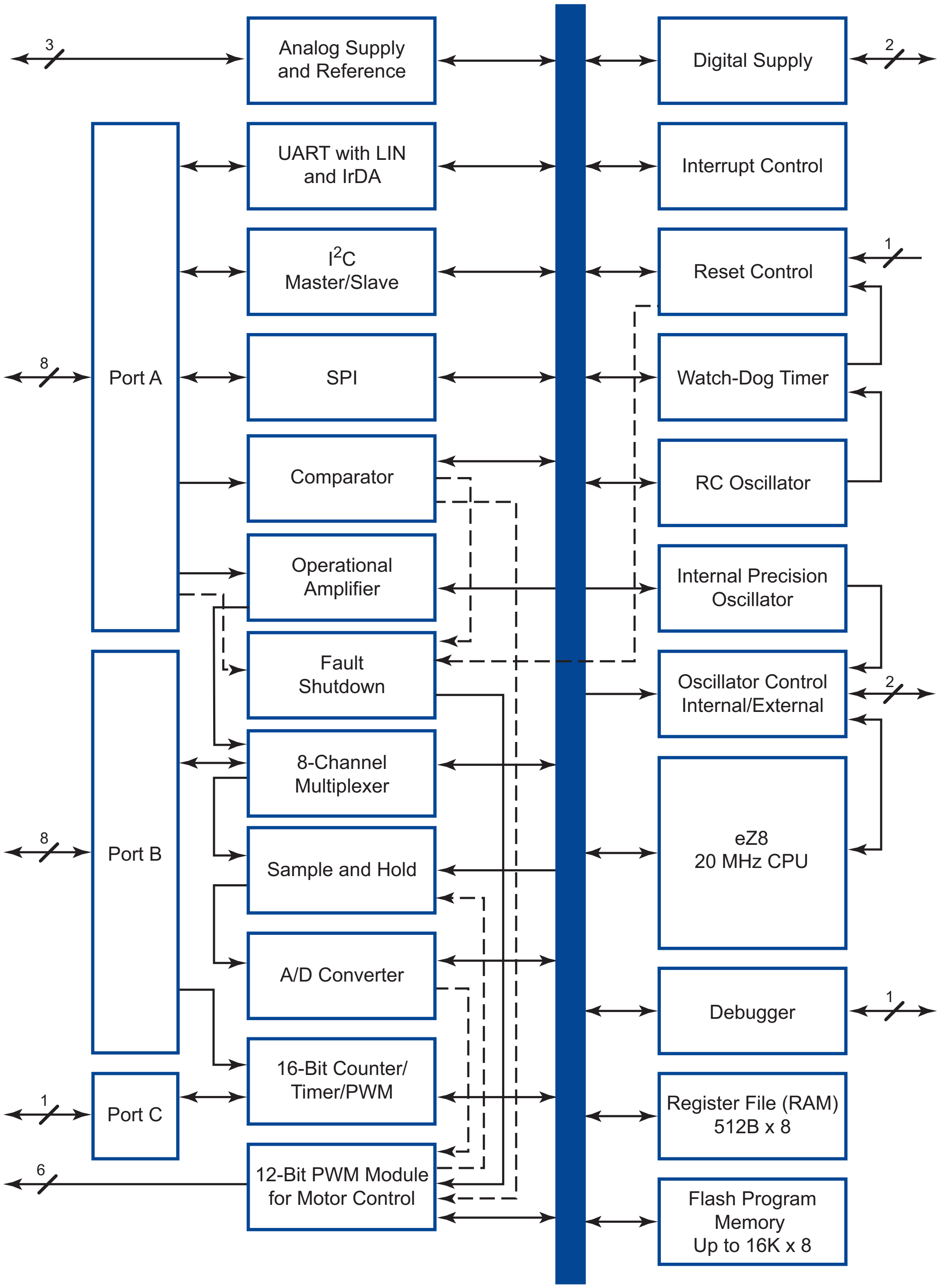

Figure 1. Z8FMC16100 MCU Block Diagram

Hardware Architecture

In a Brushed DC motor, commutation is controlled by brush position. In a BLDC motor, however, commutation is controlled by the supporting circuitry. The rotor's position must therefore be fed back to the supporting circuitry to enable proper commutation.

Two different techniques can be used to determine rotor position:

Hall Sensor-Based Commutation. In the Hall sensor technique, three Hall sensors are placed inside the motor, spaced 120 degrees apart. Each Hall sensor provides either a High or Low output based on the polarity of magnetic pole close to it. Rotor position is determined by analyzing the outputs of all three Hall sensors. Based on the output from hall sensors, the voltages to the motor's three phases are switched.

The advantage of Hall sensor-based commutation is that the control algorithm is simple and easy to understand. Hall sensor-based commutation can also be used to run the motor at very low speeds. The disadvantages are that its implementation requires both separate Hall sensors inside the motor housing and additional hardware for sensor interface.

Sensorless Commutation. In the sensorless commutation technique, the back-EMF induced in the idle phase is used to determine the moment of commutation. When the induced idle-phase back-EMF equals one-half of the DC bus voltage, commutation is complete.

The advantage of sensorless commutation is that it makes the hardware design simpler. No sensors or associated interface circuitry are required. The disadvantages are that it requires a relatively complex control algorithm and, when the speed of the motor is low, the induced BEMF is also low and no longer providing reliable zero-cross detection for commutation.

When a BLDC motor application requires high torque, or when the motor is moving from a standstill, the Hall sensor commutation technique is an appropriate choice. A motor used in an electric bicycle application, for example, requires high initial torque and is a perfect application for Hall sensor commutation.

Furthermore, two voltage application techniques can be applied, based on the configuration of the supply-to-motor windings:

Sinusoidal. Sinusoidal voltage is continuously applied to the three phases. Sinusoidal voltage provides a smooth motor rotation, with less current and torque ripple.

Trapezoidal. DC voltage is applied to two phases at a time, and the third phase remains idle. Trapezoidal voltage is less complex to implement. The idle phase is generating the BEMF from the rotating magnet that passes the nonenergized idle phase and provides the BEMF zero-crossing data.

How Hall Sensor Commutation Works

To better understand how Hall sensor commutation works, let's look at how it's implemented with a two-pole motor. Six different commutation states are required to turn the rotor one revolution. The motor’s commutation states are shown in Figure 2.

Table 1 indicates the relationship between the Hall sensor output and phase switching operations shown in Figure 2.

Table 1. Relationship Between Hall Sensor Output and Phase Switching

State	Hall A	Hall B	Hall C	Phase A	Phase B	Phase C
5	1	0	1	$-V_{DC}$	$+V_{DC}$	0
1	0	0	1	$-V_{DC}$	0	$+V_{DC}$
3	0	1	1	0	$-V_{DC}$	$+V_{DC}$
2	0	1	0	$+V_{DC}$	$-V_{DC}$	0
6	1	1	0	$+V_{DC}$	0	$-V_{DC}$
4	1	0	0	0	$+V_{DC}$	$-V_{DC}$

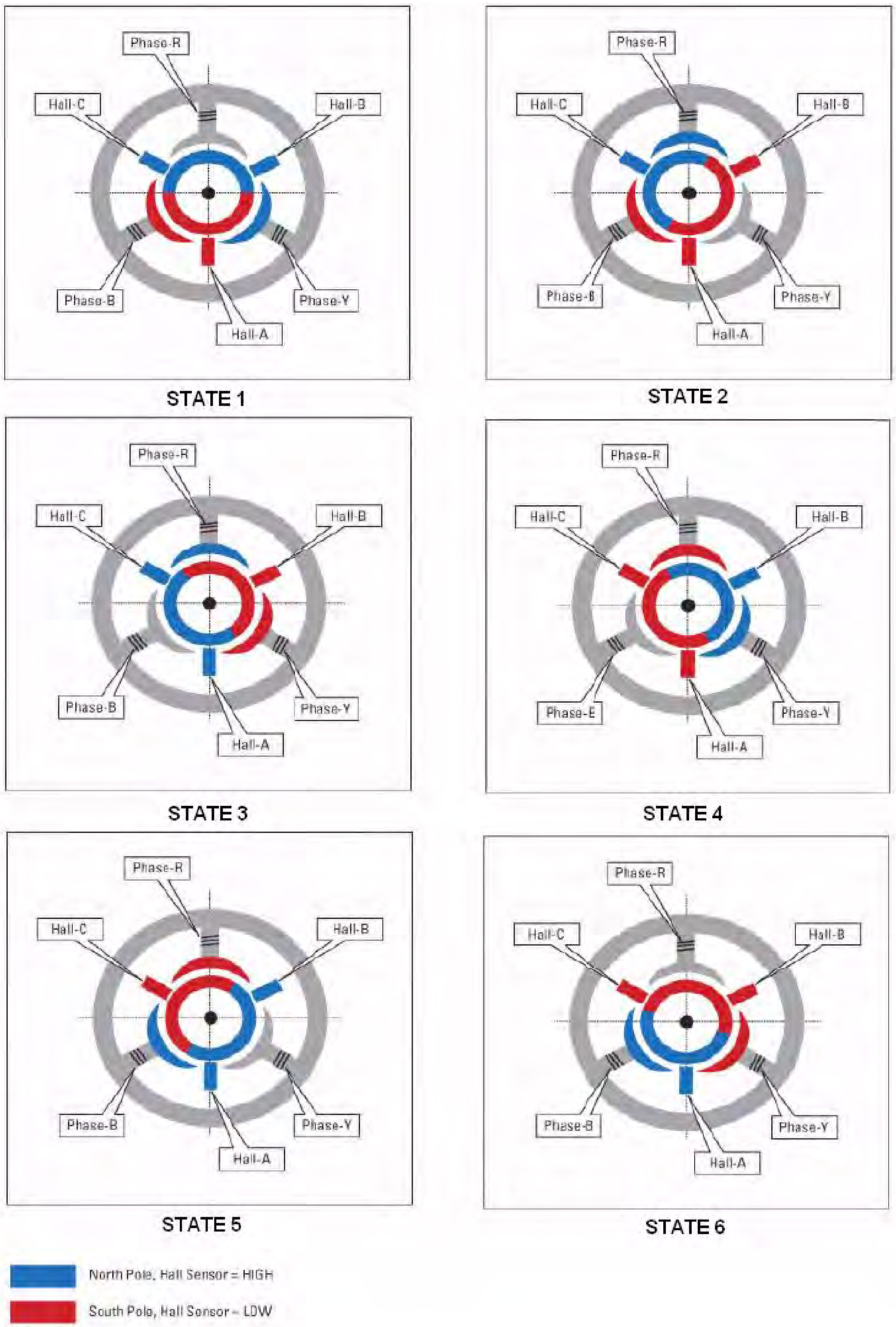

Figure 2. Hall Sensor Commutation States for a 2-Pole Motor

Using the Z8FMC16100 MCU with a 3-Phase Hall Sensor BLDC Motor Controller

Figure 3 offers a visual overview of the 3-phase Hall sensor BLDC motor controller. For more details about hardware connections, see Appendix A. Schematic Diagrams on page 15.

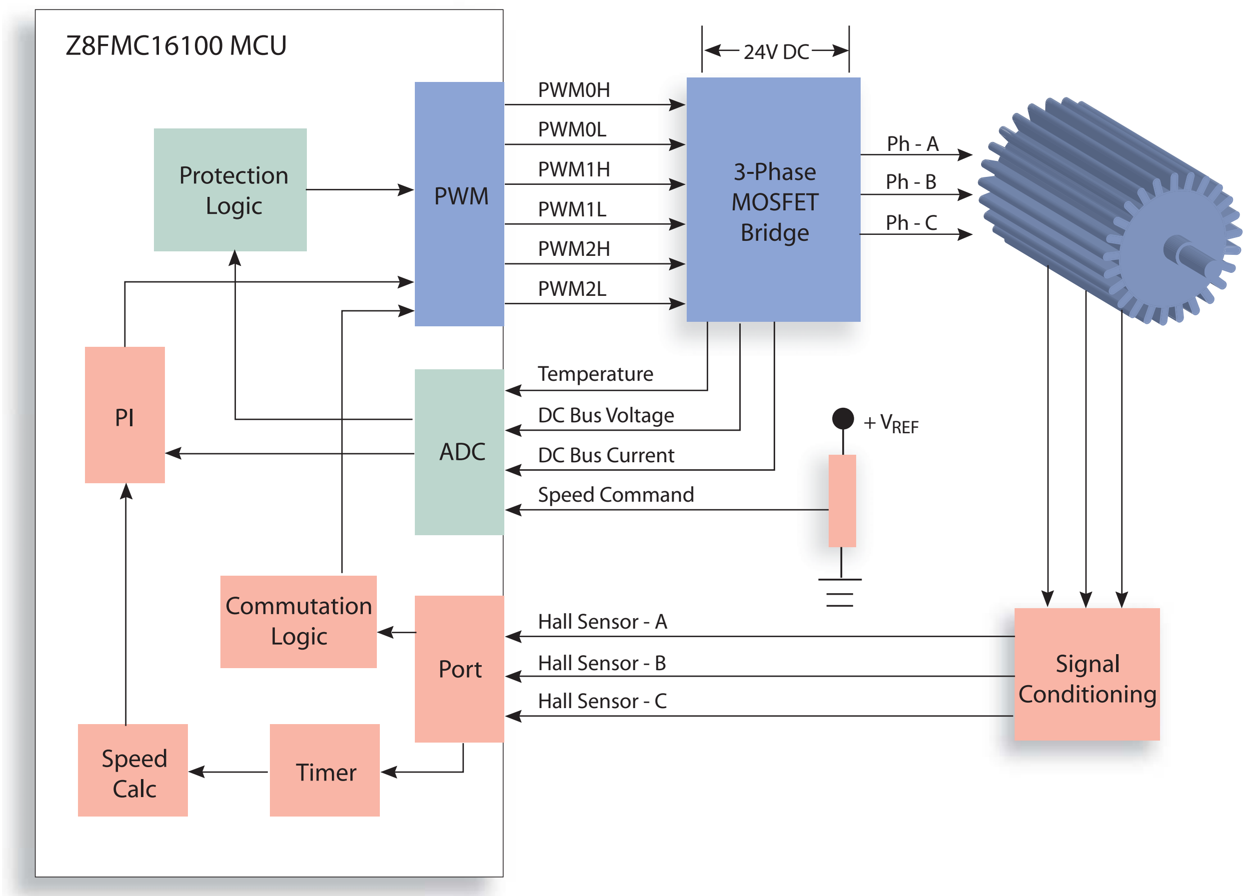

Figure 3. 3-Phase Hall Sensor BLDC Motor Controller Block Diagram

Hardware Design

This design operates a BLDC motor in a closed loop or an open loop, with speed as set by a potentiometer. As shown in the architecture diagram, the design generates PWM voltage via the Z8FMC16100 MCU's PWM module to run the BLDC motor.

After the motor is running, the states of the three Hall sensors change based on the rotor position. Voltage to each of the three motor phases is switched based on the state of the sensors (commutation). Hall sensor interrupts capture timer ticks every sixty degrees to measure the rotor speed of the motor. Other peripheral functions can be used to protect the system in case of current overload, under- or overvoltage, and overtemperature.

The hardware is described in the following sections.

Three-Phase Bridge MOSFET

The three-phase bridge MOSFET consists of six MOSFETs connected in bridge fashion used to drive the three phases of the BLDC motor. The DC bus is maintained at 24 V, which is same as the voltage rating of the BLDC motor. A separate Hi-Lo gate driver is used for each high- and low-side MOSFET phase pair, making the hardware design simpler and robust. The high-side MOSFET is driven by charging the bootstrap capacitor, which is connected to the high- and low-side drivers.

PWM Module

The Z8FMC16100 MCU contains a six-channel, 12-bit PWM module configured in this application to run in Complementary Mode. The switching frequency is set to 20KHz. The PWM outputs are controlled according to the inputs from the Hall sensors.

The inputs from the Hall sensors determine the sequence in which the three phases of the motor are energized. The duty cycle of the PWM is directly proportional to the accelerator potentiometer input. The change in the duty cycle controls the current through the motor winding, thereby controlling motor torque.

Commutation Logic

The Hall sensors are connected to ports PB0, PB1, and PB2 on the Z8FMC16100 MCU. An interrupt is generated when the input state on any pin changes. An interrupt service routine checks the state of all three pins and accordingly switches the voltage for the three phases of the motor.

Trapezoidal commutation is used for this application to make implementation simple. In this process of commutation, any two phases are connected across the DC bus by switching the top MOSFET of one phase and bottom MOSFET of another phase ON. The third phase is left unenergized (both top and bottom MOSFET of that phase are switched OFF), as shown in Table 1 on page 5.

Speed Measurement

One out of the three Hall sensors is used to capture the Timer0 ticks, which represent the actual Hall period for closed loop calculations.

Closed Loop Speed Control

Closed-loop speed control is implemented using a PI loop, which works by reducing the error between the speed set by the potentiometer and actual motor speed. The output of this PI loop changes the duty cycle of the PWM module, thereby changing the average voltage to the motor, and ultimately changing the current or voltage to maintain the speed and, therefore, maintaining the power. The PI loop adjusts the speed at the same rate as the Hall frequency from one of three Hall sensors.

Over-Current Hardware Protection

The Z8FMC16100 MCU has a built-in comparator that is used to shut down the PWM for over-current protection. When the current exceeds the set threshold, a PWM Comparator Fault is generated to turn OFF the PWM Module.

Software Implementation

During implementation of the software, the following actions are performed:

Initialization. Hardware modules are initialized for the following functions:

- Switch from an internal to an external oscillator for system operation
- Enable alternate functions on the respective pins for the ADC, Comparator, and UART, and to drive the LEDs
- Configure Timer0 to run in Continuous Mode to capture the Hall period timing
- Configure the comparator to shut down the PWM module when an overcurrent results
- Enable the op amp to measure the DC bus current flowing to the motor
- Configure the ADC to read values from the op amp and the speed potentiometer
- Configure the PWM module for the individual mode of operation with a 20kHz switching frequency, control output depending on the values in the PWMOUT Register, and drive the PWMOUT as defaulted to a low off state at Power-On Reset and at any other Reset

Interrupt. The Port B interrupt controls commutation. The Hall sensor output is read on pins PB0:2 in the Hall interrupt service routine and determines the switching sequence of the motor phases. The baud rate generator timer interrupt is used to time periodically occurring tasks and for the background loop to read analog values from different channels and average these values, update the LED indicator status, and update the read parameters on the UART.

For a visual representation of the application, see Appendix B. Flowcharts on page 19.

Testing

This section describes how to run the code and demonstrate this sensorless brushless motor application including its setup, implementation and configuration, and the results of testing.

Equipment Used

The following equipment allows the MultiMotor Series Development Kit to demonstrate the sensored trapezoidal PWM modulation technique.

- Z8FMC16100 MultiMotor Control Module equipped with a Z8FMC16100 MCU (98C1395-001G)
- MultiMotor Development Board (99C1358-001G)

- Opto-isolated USB SmartCable (99C0968)
- Opto-isolated UART-to-USB adapter (99C1359-001G)
- LINIX 3-phase 24 VDC, 30 W, 3200 RPM BLDC motor (45ZWN24-30)
- 24 V AC/DC power supply
- Digital oscilloscope

Hardware Setup

Figure 4 shows the application hardware connections.

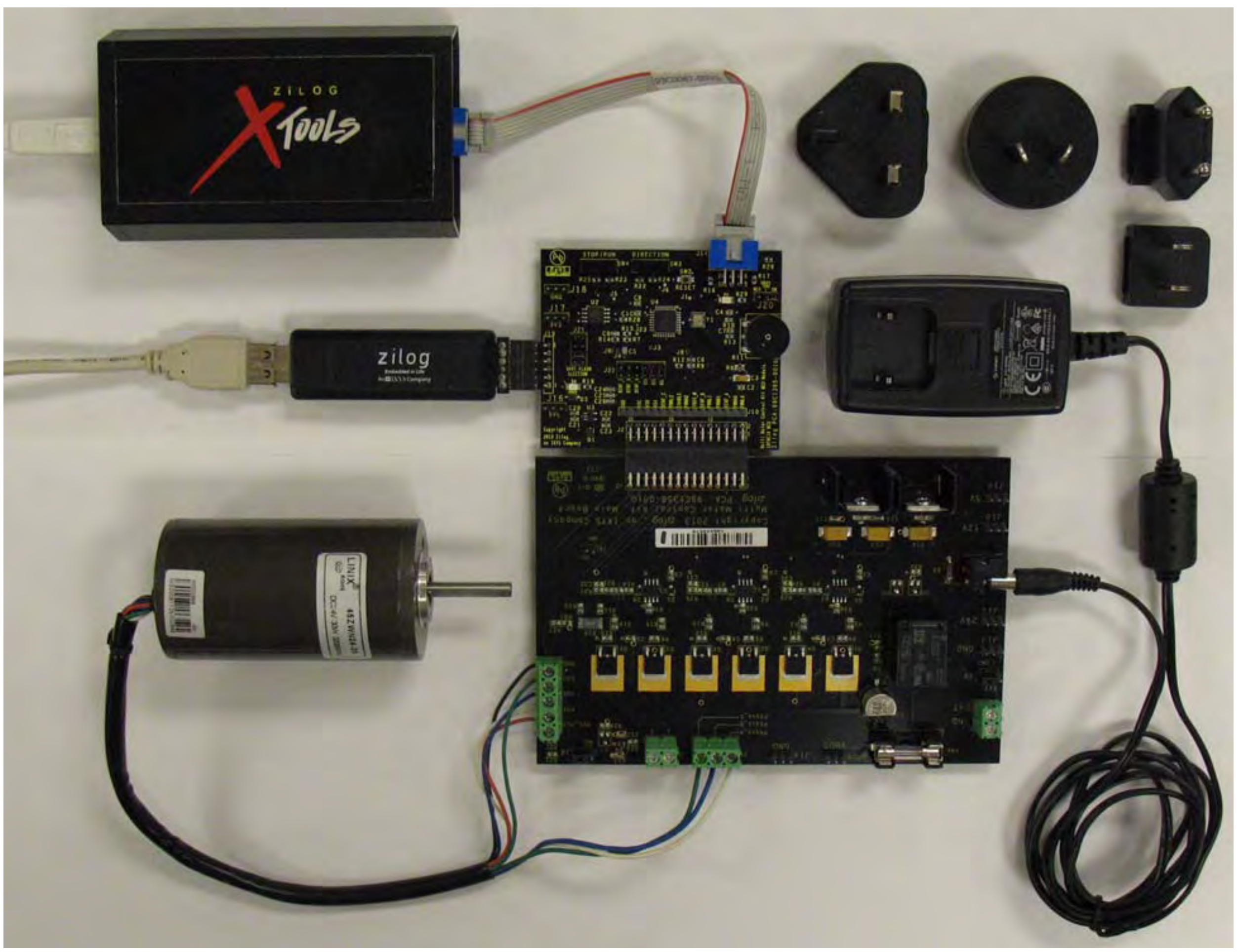

Figure 4. MultiMotor Series Development Kit and Linix BLDC Motor

Testing Procedure

Observe the following procedure to test 3-Phase Sensored trapezoidal PWM modulation on the Z8FMC16100 MCU Module.

1. Download ZDS II for Z8 Encore! 5.0.0 (or newer) from the Zilog Store and install it onto your PC.
2. Download the AN0368-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 4.
   a. Verify that the Z8FMC16100 MCU Module (99C1395) jumpers are configured properly, as follows:
      - J20: Set this jumper to the ON position to activate the V_{BUS} relay on the main board
      - J21: Two jumpers are in positions 3-4 and 7-8 to allow the UART to function properly
      - J22: Three jumpers are in the HSx positions to allow proper sensored 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 the MultiMotor Series Development Board using the 24V DC 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 ZDS II for Z8 Encore! and choose **Open Project** from the **File** menu. Browse to the directory on your PC into which you downloaded the AN0368-SC01 source code. Locate the `AN0368_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 ZDS II, 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 5 should appear. As a result, commands can be entered using the console to change the motor's operation.

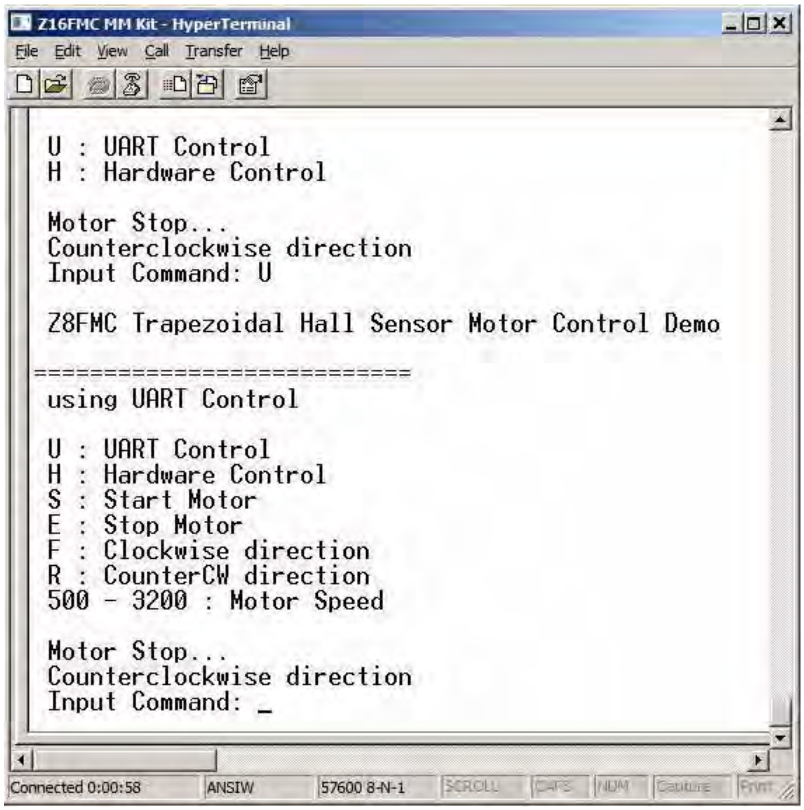

Figure 5. GUI Terminal Showing the UART Control

11. At the `Input Command:` prompt, enter the letter `H` to reestablish hardware control; see Figure 6.

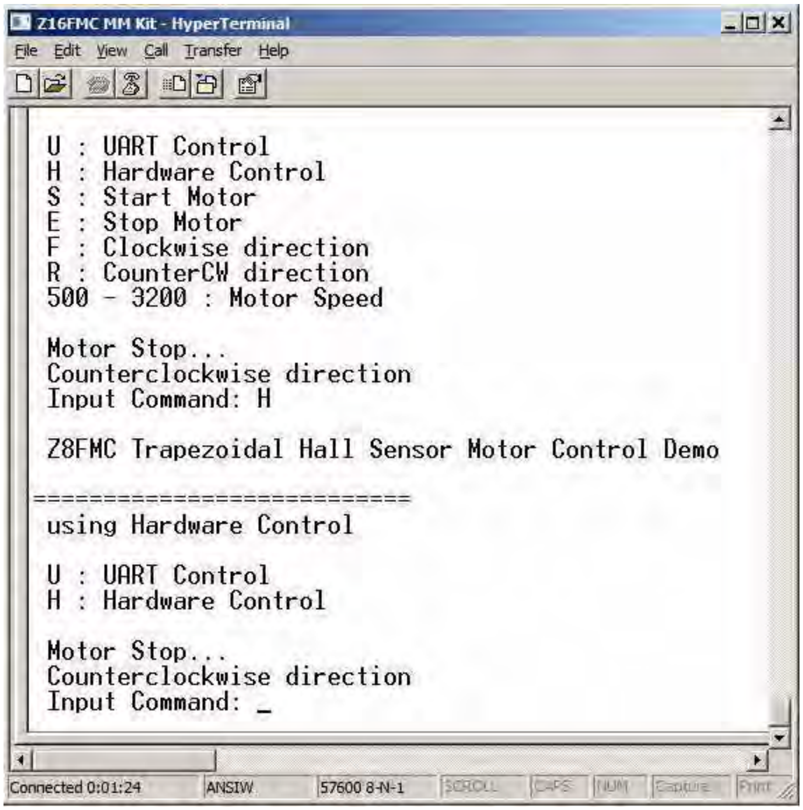

Figure 6. GUI Terminal Showing Hardware Control

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 Control Module to free the Reset pin and apply a power cycle to reset the MCU from Debug Mode.

Results

This three phase, sensored, brushless motor control application was tested with a 3-phase BLDC motor connected to Zilog's MultiMotor Development Board. Testing of the Z8FMC16100 MultiMotor Control Module confirms a seamless start-up of the motor from an idle mode to full operational speed, plus on-the-fly reversal of the direction of rotation, an extremely fast fault-detection cycle, and a lower total solution cost.

- Minimum motor speed: 600RPM

- Maximum motor speed: 3200 RPM
- The motor can be controlled using two methods:
  - Manually using the Stop/Run & Direction switches and the speed pot on the MultiMotor Control Module
  - Using menu-driven commands on a PC terminal emulator connected to the MultiMotor Control Module through the UART connections
- The Red LED illuminates when the motor is stopped or there is a fault detected

References

The following documents are associated with the Z8FMC16100 Series of Motor Control MCUs; each is available for download on www.zilog.com.

- 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)
- BLDC Motor Control Using Sensored Sinusoidal PWM Modulation with the Z8FMC16100 MCU Application Note (AN0367)
- 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)

Appendix A. Schematic Diagrams

Figures 7 and 8 show basic block and MCU schematics, respectively, for the Z8FMC16100 MultiMotor Control Module.

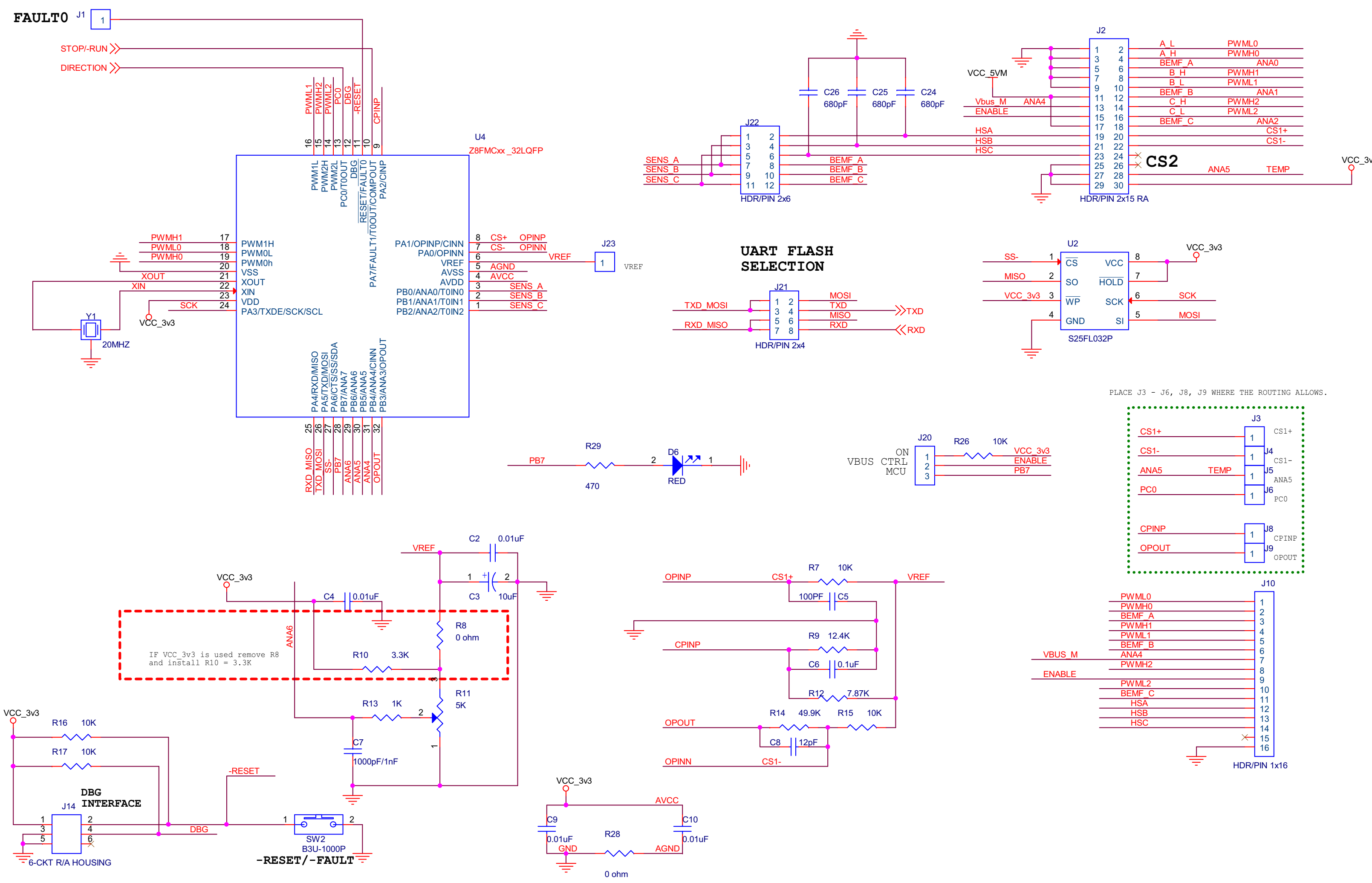

Figure 7. Z8FMC16100 MultiMotor Control Module, #1 of 2

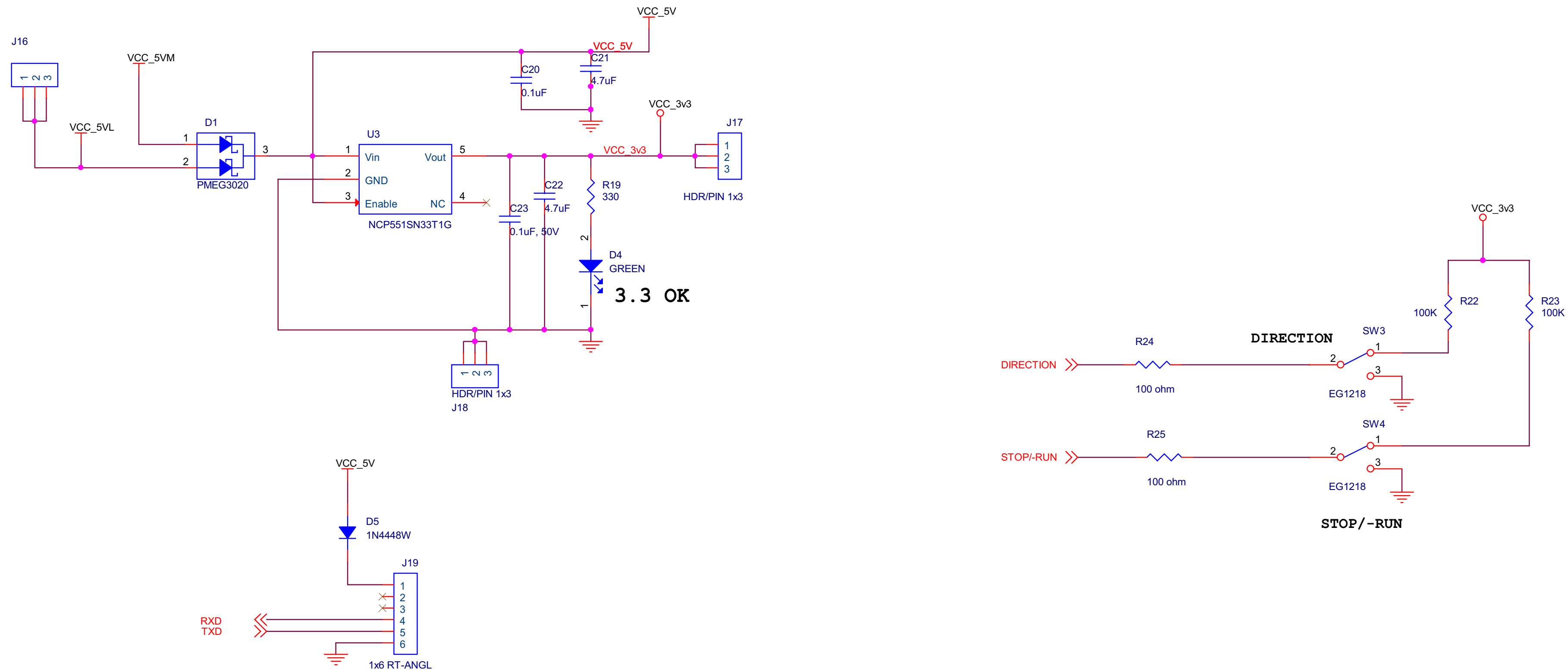

Figure 8. Z8FMC16100 MultiMotor Control Module, #2 of 2

Figure 9 shows the schematics for the Z8FMC16100 MultiMotor Control Module's power and serial interfaces.

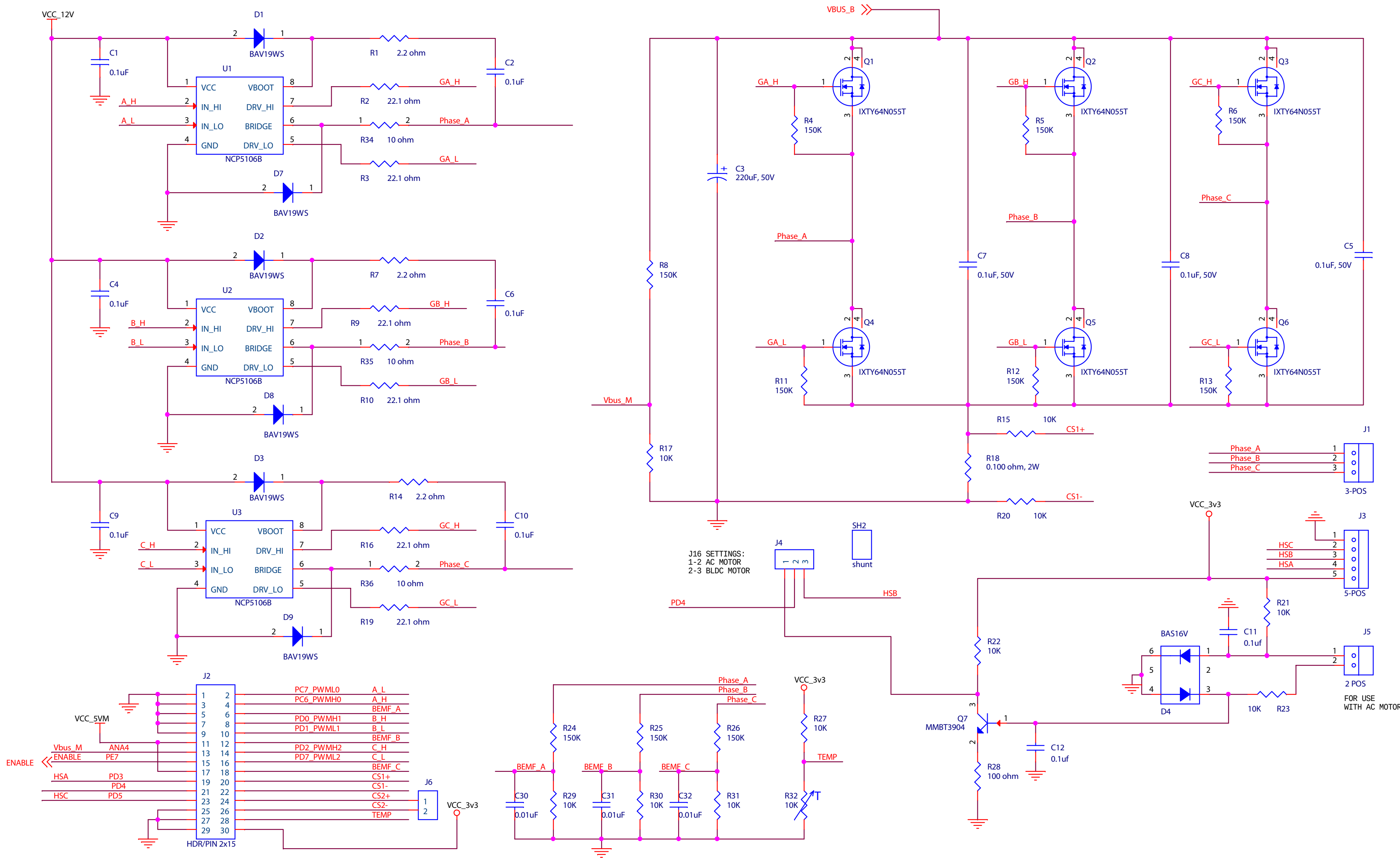

Figure 9. MultiMotor Development Board, #1 of 2

Figure 10 shows Z8FMC16100 MultiMotor Control Module interface schematics.

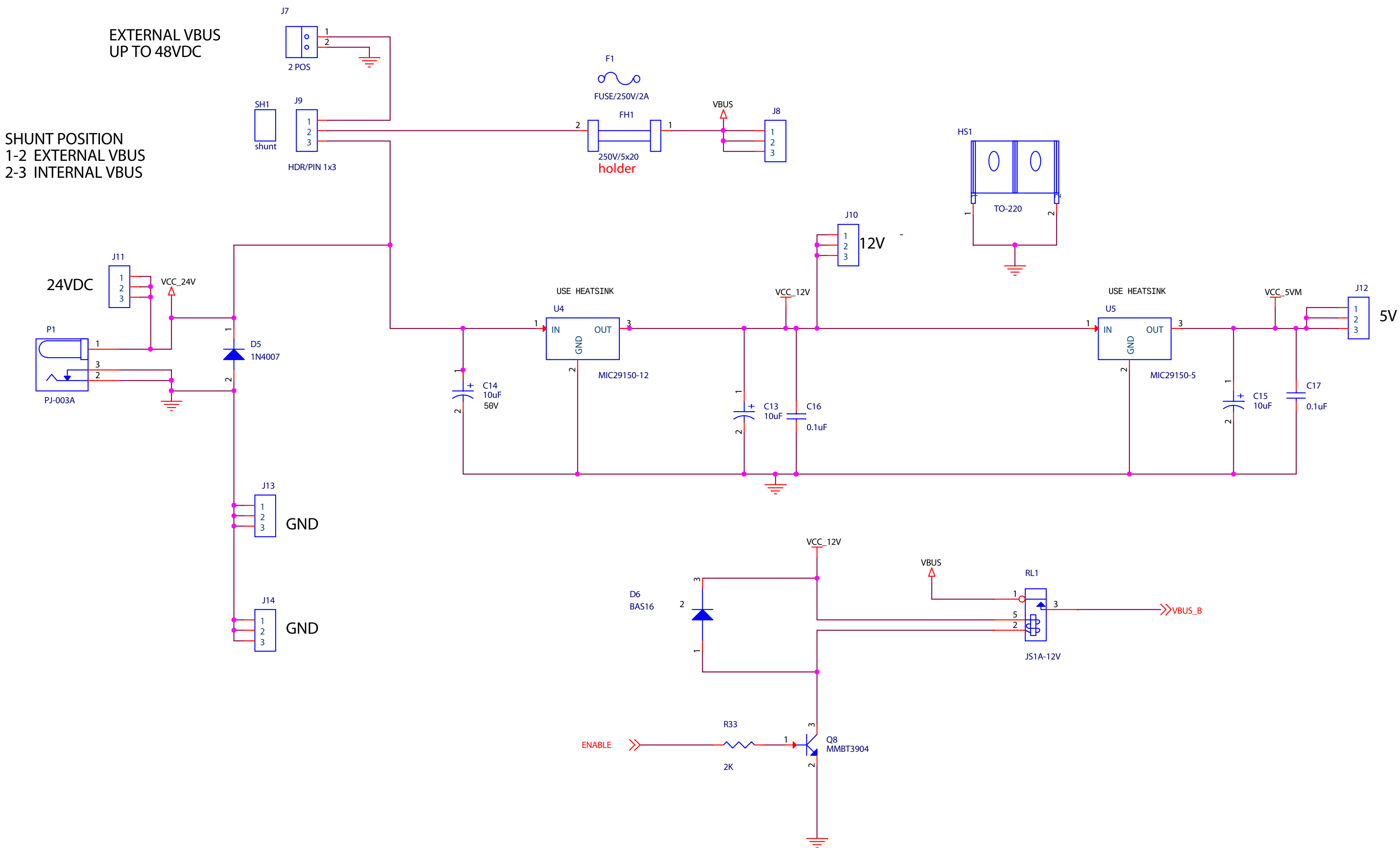

Figure 10. MultiMotor Development Board, #2 of 2

Appendix B. Flowcharts

Figure 11 presents a simple flow chart of the main, timer interrupt and Port D interrupt routines for a 3-phase Hall sensor BLDC motor control application.

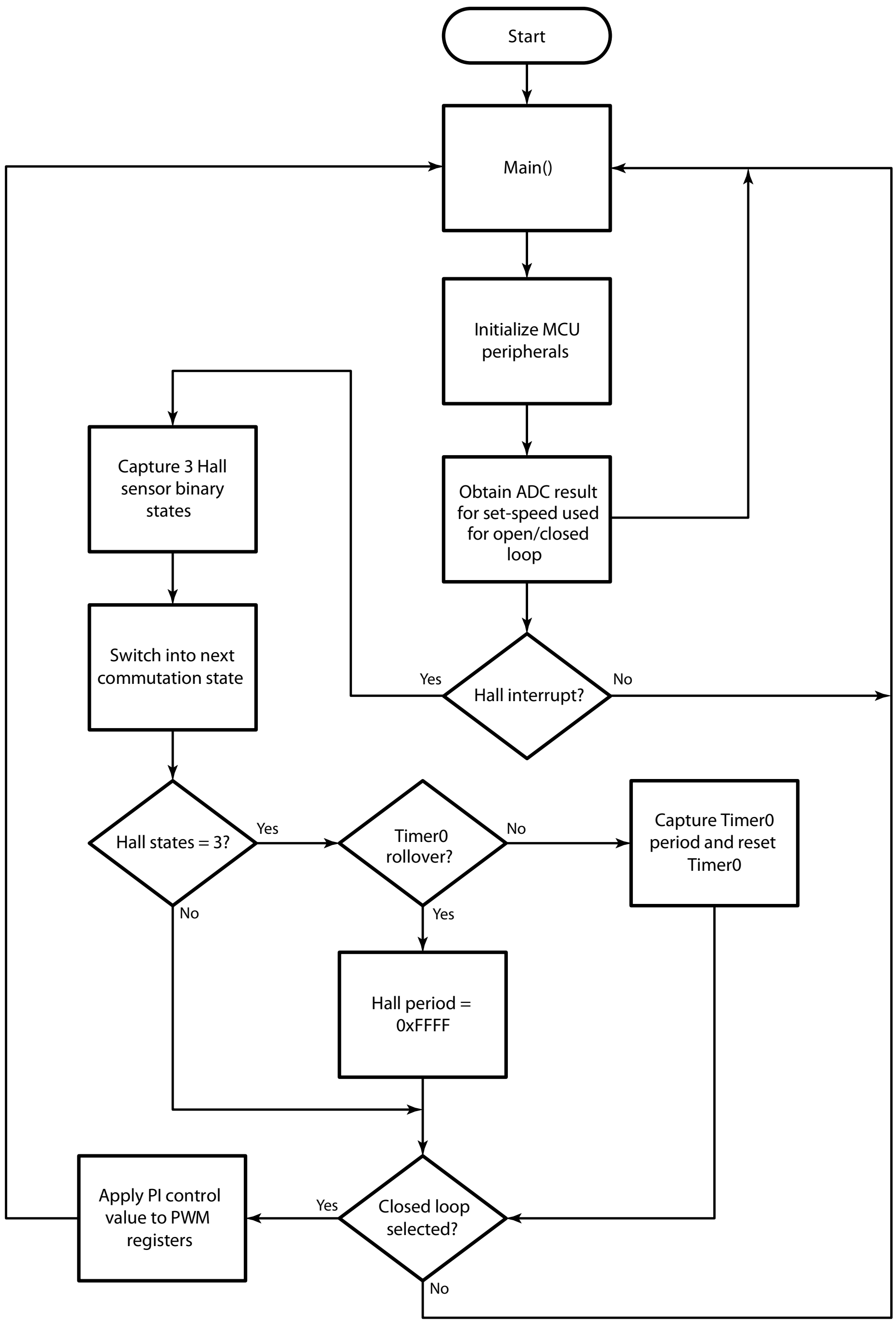

Figure 11. 3-Phase Hall Sensor BLDC Motor Control Application Flowchart

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