



Electric Bike BLDC Hub Motor Control Using the Z8FMC1600 MCU

AN026002-0608



Abstract

This application note describes a controller for a 200 W, 24 V Brushless DC (BLDC) motor used to power an electric bike. The design uses Zilog’s Z8 Encore! MC™ Z8FMC16100 Microcontroller unit (MCU) and associated circuitry to implement motoring control, regenerative braking, and fault protection.

► **Note:** *The source code associated with this application note is available in the under Z8 Encore! MC Applications Code Library section of the Application Sample Libraries on www.zilog.com.*

Features

The main features of the high-torque motor control reference design include:

- Hall sensor commutation
- Motor speed measurement
- Potentiometer-adjustable motor speed
- Closed-loop speed control for precise speed regulation
- Protection logic for over-voltage, over-current, and thermal protection.

Discussion

The Z8FMC16100 Series Flash 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 fault condition.

A chip architectural block diagram is displayed in [Figure 1](#).

12-Bit PWM Module for Motor Control	16-Bit Timer Capture/Compare/PWM	Operational Amplifier
Up to 16 KB Flash	20 MHz eZ8 CPU	8-Channel 10-Bit ADC
512 B SRAM		VBO/POR and Reset Control
I ² C, SPI, and UART with LIN		
Watchdog Timer	Single-Pin Debugger	Internal Precision Oscillator
Comparator		Interrupt Controller
17 General Purpose I/O Pins		

Figure 1. Z8FMC16100 Block Diagram

The Z8FMC16100 Series MCU features up to eight single-ended channels of 10-bit analog-to-digital conversion (ADC), with a sample and hold circuit. It also features one operational amplifier for current sampling and one comparator for over-current limiting or shutdown.

A high-speed ADC enables voltage, current, and back-EMF sensing, while dual-edge interrupts and a 16-bit timer provide a Hall-effect sensor interface.

A full-duplex 9-bit UART provides serial, asynchronous communication and supports the Local Interconnect Network (LIN) serial communications protocol. The LIN bus is a cost-efficient single Master, multiple Slave organization that supports speed up to 20 kbps.

The Z8FMC16100 Series MCU has a rich set of peripherals and other features such as: additional 16-bit timer with capture/compare/PWM capability, SPI, or I²C Master/ Slave for serial communication, and an internal precision oscillator.

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

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 magnitude of induced back-EMF is low, it does not support low motor speeds.

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

- **Sinusoidal**—Sinusoidal voltage is applied to the three-phase winding. Sinusoidal voltage provides a smooth motor rotation and fewer ripples.
- **Trapezoidal**—Here DC is applied to two phases at a time and the third phase is left idle. Trapezoidal voltage is simpler to implement and less complex.

When a BLDC motor application requires high torque when the motor is running at low speed, 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.

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 operation is displayed in [Figure 2](#).

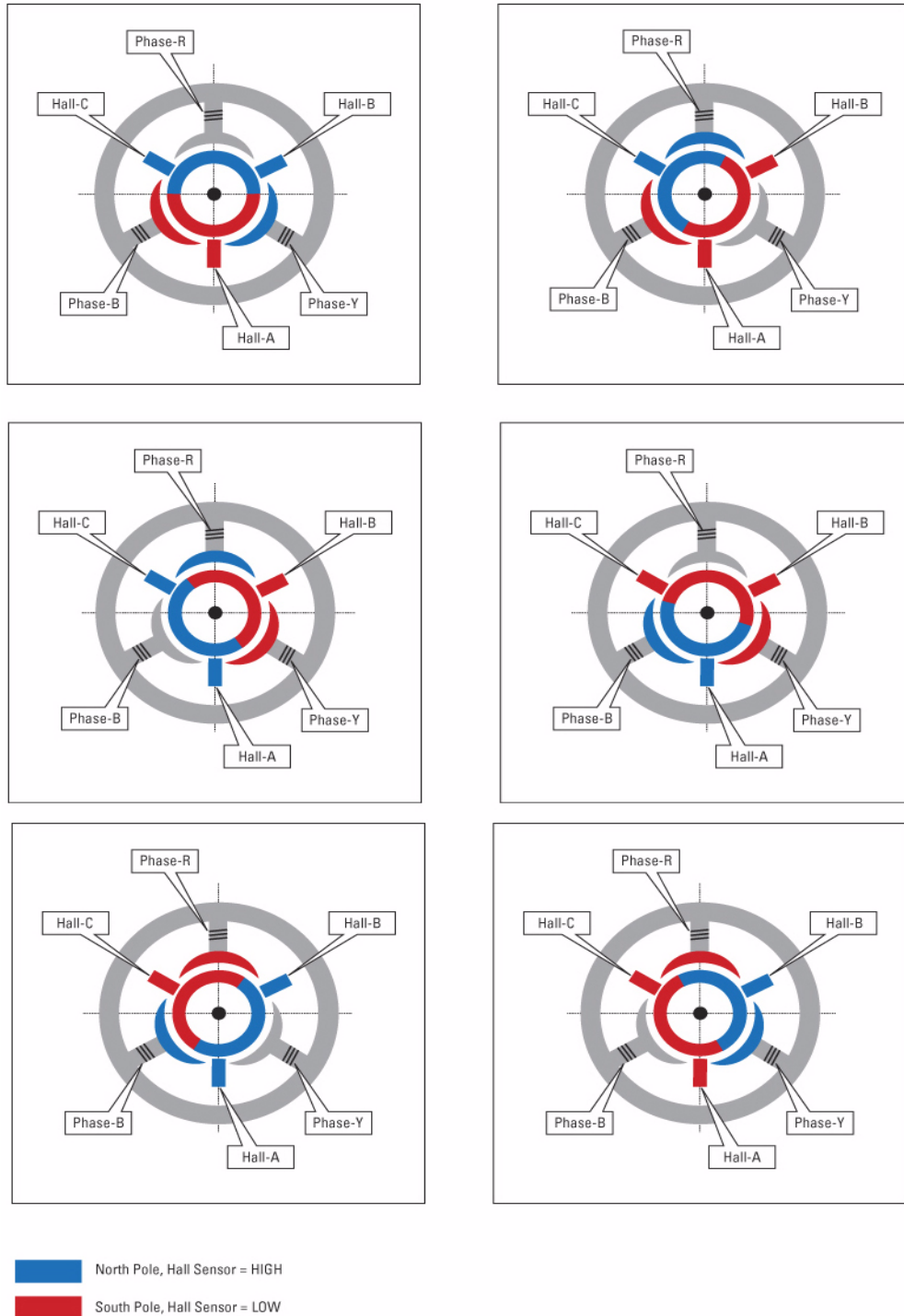


Figure 2. Hall Sensor Commutation in a 2-Pole Motor

Table 1 lists the relation between Hall sensor output and phase switching displayed in Figure 2.

Table 1. Relationship Between Hall Sensor Output and Phase Switching

State	Hall - A	Hall - B	Hall - C	Phase - R	Phase - Y	Phase - B
0	0	1	1	0	+Vdc	-Vdc
1	0	0	1	+Vdc	0	-Vdc
2	1	0	1	+Vdc	-Vdc	0
3	1	0	0	0	-Vdc	+Vdc
4	1	1	0	-Vdc	0	+Vdc
5	0	1	0	-Vdc	+Vdc	0

Table 2 lists the rating of the motor used in the application.

Table 2. Motor Rating for Electric Bike BLDC Motor Control Application

Type of Motor	BLDC
Power Rating	200 W
Speed	400 rpm
Number of poles	32
Voltage	24 V

Table 3 lists the specifications for the battery used in the application.

Table 3. Battery Specifications for Electric Bike BLDC Motor Control Application

Type of Battery	Sealed Lead Acid
Number of Batteries	Two connected in series
Voltage	24 V (12 V each)
Amp-Hour Rating	7 Ah
Charge Termination	When battery charge reaches 29.4 V
Standby Battery Voltage	25.8 V

The fuse used in the application is a 10 A HRC.

Using the Z8FMC16100 in an Electric Bike BLDC Motor Controller

The block diagram in Figure 3 displays an overview of the electric bike BLDC motor controller. For more details on hardware connections, see Appendix A—Schematics on page 10.

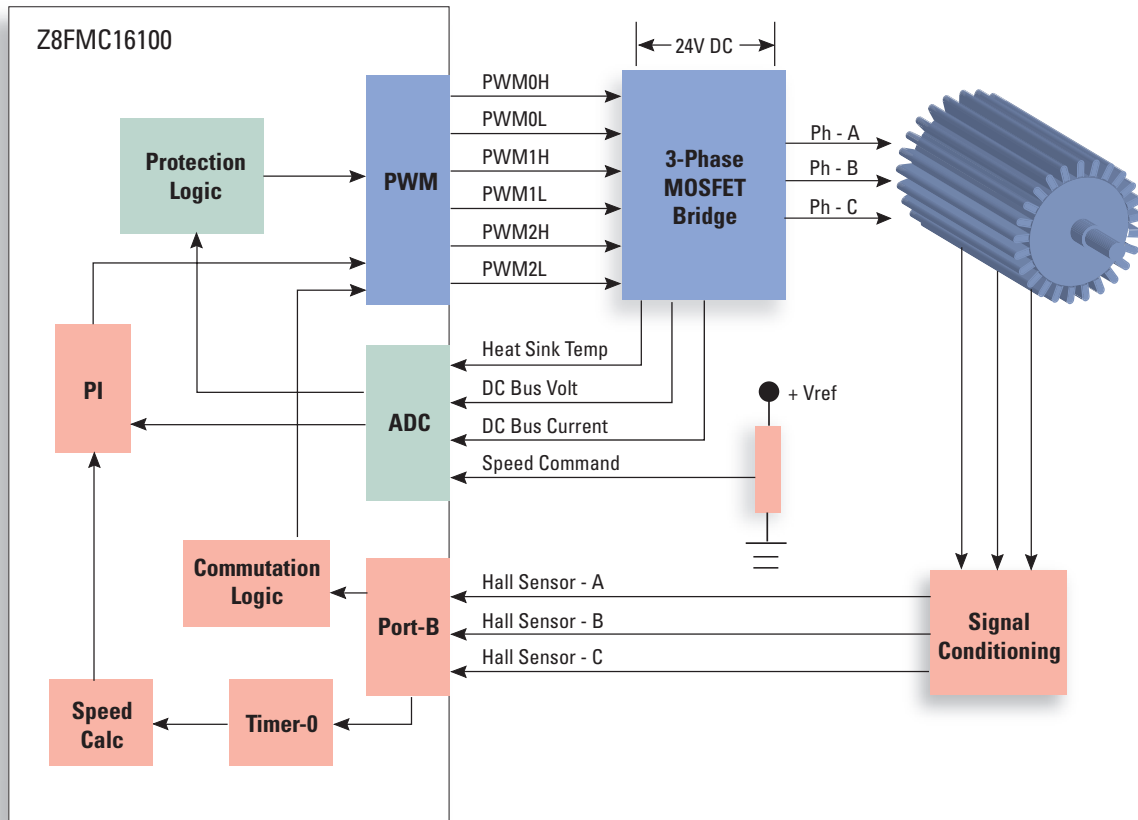


Figure 3. Electric Bike BLDC Motor Controller Block Diagram

Hardware Architecture

The design involves running the BLDC motor in a closed loop, with speed as set by a potentiometer. As displayed in the architecture diagram, the design generates PWM voltage via the Z8FMC16100 PWM module to run the BLDC motor.

Once the motor is running, the state of the three Hall sensors changes 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 are counted to measure the motor speed. Other peripheral functions are used to protect the system in case of overload, under-voltage, and over-temperature.

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 voltage rating of 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.

The DC bus voltage is monitored by reducing it to suitable value using a potential divider. The DC

bus current is monitored by putting a shunt in the DC return path. An NTC-type temperature sensor is mounted on MOSFET heatsink, providing analog voltage output proportional to temperature.

PWM Module

The Z8FMC16100 contains a six-channel, 12-bit PWM module configured in this application to run in Independent mode. The switching frequency is set to 10 KHz. The output on the individual channels is controlled according to the inputs from the Hall sensors.

The inputs from the Hall sensors determine the sequence in which the three-phase bridge MOSFET is switched. 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 port B pin PB0, PB1, and PB2 on the Z8FMC16100. 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 un-energized (both top and bottom MOSFET of that phase are switched OFF).

Speed Measurement

The Hall sensor outputs are connected to port B bits 0, 1, and 2. Interrupts generated on port B bits 0, 1, and 2 are counted every second. The one-second time interval reference is provided by Timer0. With an interrupt occurring every 1 ms, 1000

counts are required to complete a one-second interval.

Closed Loop Speed Control

The 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 PI loop changes the duty cycle of the PWM module, thereby changing the average voltage to the motor and ultimately changing the power input. The PI loop is periodically timed at 128 ms by Timer0 interrupt.

Protection Logic

The ADC module periodically checks DC bus voltage, DC bus current, and heat sink temperature. If these values go beyond the set limits, the motor is shut down. These checks are timed by Timer0 interrupt.

Over-Current Hardware Protection

The Z8FMC16100 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

The software implementation consists of the following procedure:

- **Initialization**—Hardware modules are initialized for the following functions:
 - Switch from internal to external oscillator for system operation.
 - Enable alternate function on respective pins for ADC, Comparator, UART, PA6 as GPIO configured to drive LED.
 - Timer0 configured to run in continuous mode and generate interrupt every one millisecond.
 - Comparator configured to shut down the PWM module when over current results.

- Op-Amp to measure the DC bus current flowing to the motor.
- ADC configured to read Analog values like DC bus voltage, Current, Temperature, and acceleration potentiometer (only one channel at a time).
- PWM module configured for individual mode of operation, with 10 KHz switching frequency and control output depending on the values in PWMOUT register.
- **Interrupt**—Port B interrupt controls commutation. The Hall sensor output is read on pins PB0:2, software filtered and the switching sequence of the MOSFET is determined. Timer0 interrupt is used to time the periodically occurring tasks.
- **Background loop**—Read analog values from different channels and average these values, update the LED indicator status, update the read parameters on UART.

For conceptual design details, see flowchart in [Appendix B—Flowcharts](#) on page 15.

Testing/Demonstrating the Application

A conceptual test setup for the reference design is displayed in [Figure 4](#) on page 8. A photograph of a typical setup is provided in [Figure 5](#) on page 8.

Equipment Used

The following equipment are used for testing:

- Tektronics Digital Phosphor Oscilloscope
- Fluke Multimeter
- 200 W BLDC Hub motor
- 24 V 7 Ah battery
- Dynamometer setup

System Configuration

The system requirements on your PC are as follows:

- System running Windows XP SP2.
- ZDS II version 4.10.0 installed.
- Optically isolated USB smart cable for program download and debugging.

Procedure

Follow the steps below to test the BLDC motor:

1. Connect the CRO across the motor terminals.
2. Connect the motor control board to the 24 V power supply.
3. Build the code on ZDS II v4.10.0 and download the code through USB smart cable.
4. Measure the performance of motor at different loads, for each speed setting of the potentiometer.
5. Record the readings and carry out the process for each step in the test sequence.

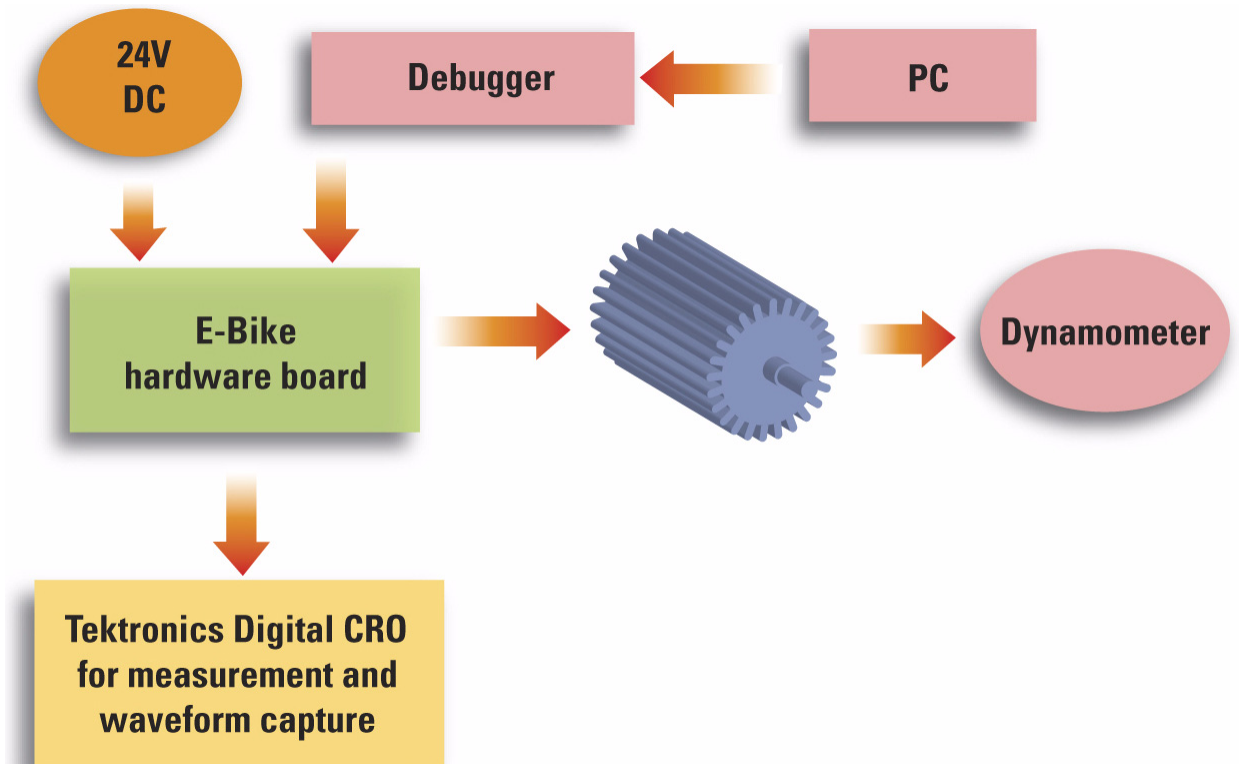


Figure 4. Test Setup for Electric Bike BLDC Motor Controller Application

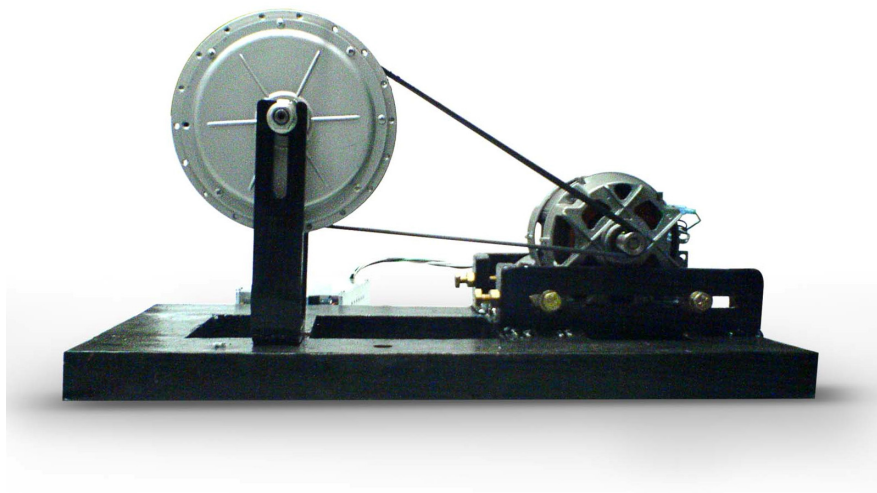


Figure 5. Typical Test Setup for Electric Bike BLDC Motor Controller

Test Results

Laboratory performance test of BLDC motor is as follows:

1. Minimum motor speed: 30 RPM
2. Maximum motor speed: 383 RPM
3. No Load power consumption: 16.8 W (at 200 RPM)
4. Regenerative Current at 200 RPM: 350 mA

- Sensorless Brushless DC Motor Control with Z8 Encore! MC Microcontrollers (AN0226)
- Z8 Encore! XP[®] Based BLDC Fan Control Reference Design Application Note (AN0228)

Future Implementation

The reference design provided in this application note covers the motoring and regenerative braking features for a BLDC hub motor used in an electric bike. Further improvements can be made to the design by adding the following features:

- Controlled charging of SLA batteries by plugging to the AC Mains adaptor.
- Implementing ‘Torque-boost’ functionality (through a push-switch), which will give a boost to motor performance.
- Utilizing LIN/UART communication to create a dashboard display of measured parameters (speed, Battery voltage, Current, and Fault conditions).

References

The documents associated with Z8 Encore![®], Z8 Encore! XP[®], Z8 Encore! MC[™], and eZ8 available on www.zilog.com are provided below:

- eZ8 CPU User Manual (UM0128)
- Z8FMC16100 Series Product Specification (PS0246)
- PID Motor Control with the Z8PE003 Application Note (AN0030)
- Z8 Encore!-Based SLA Battery Charger Application Note (AN0223)

Appendix A—Schematics

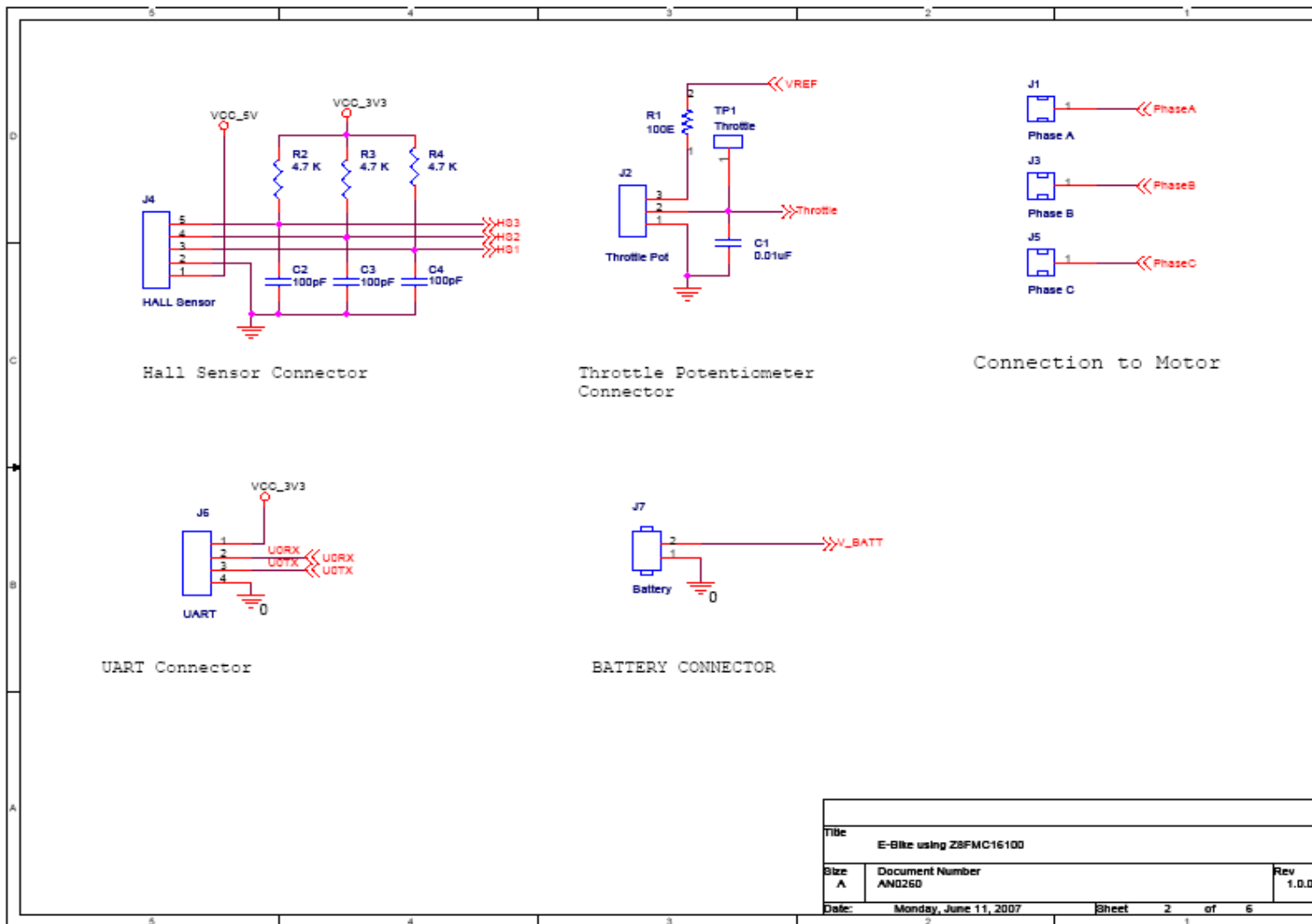


Figure 6. Electric Bike BLDC Motor Controller Application Schematic (1 of 5)

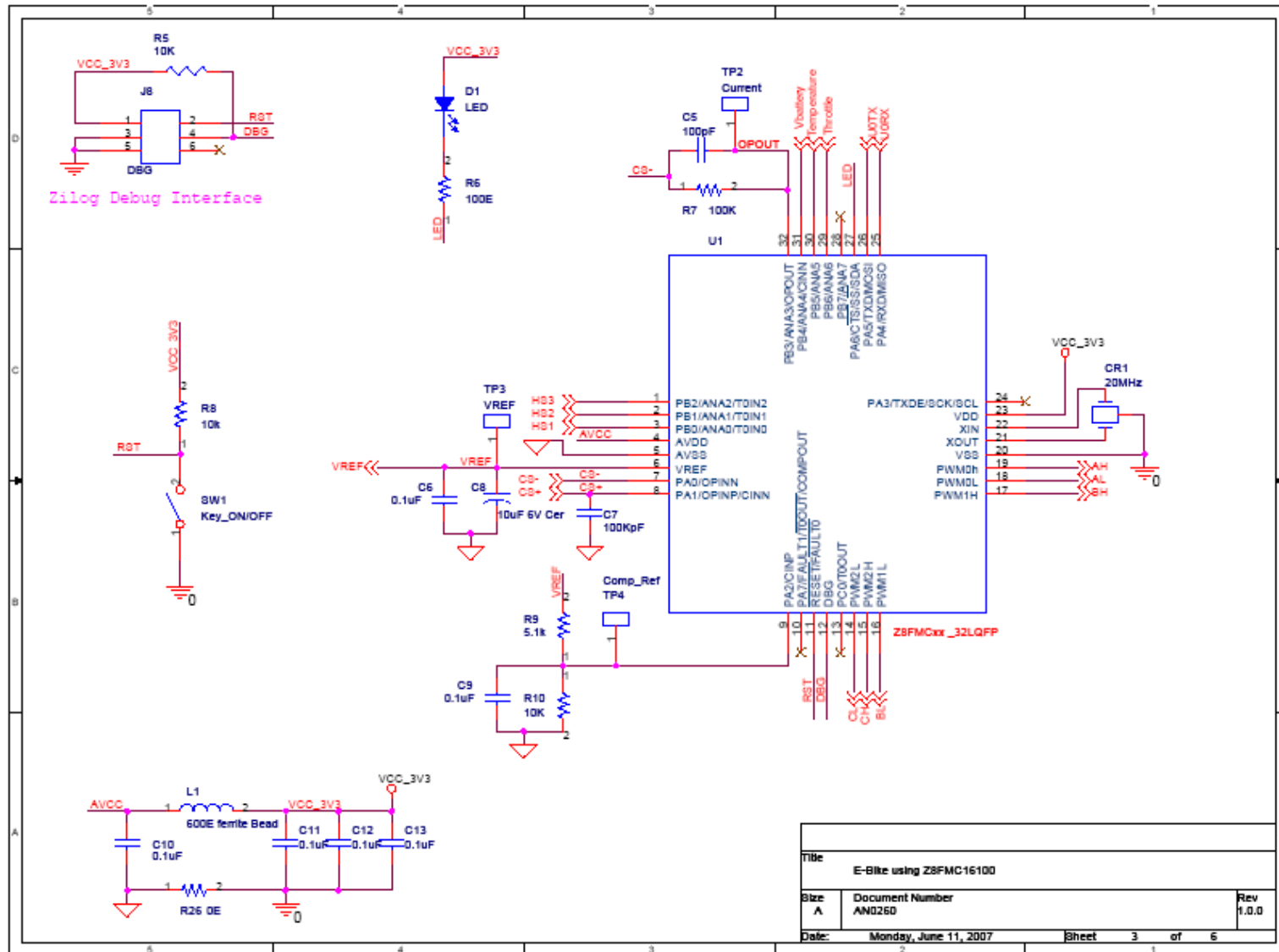


Figure 7. Electric Bike BLDC Motor Controller Application Schematic (2 of 5)

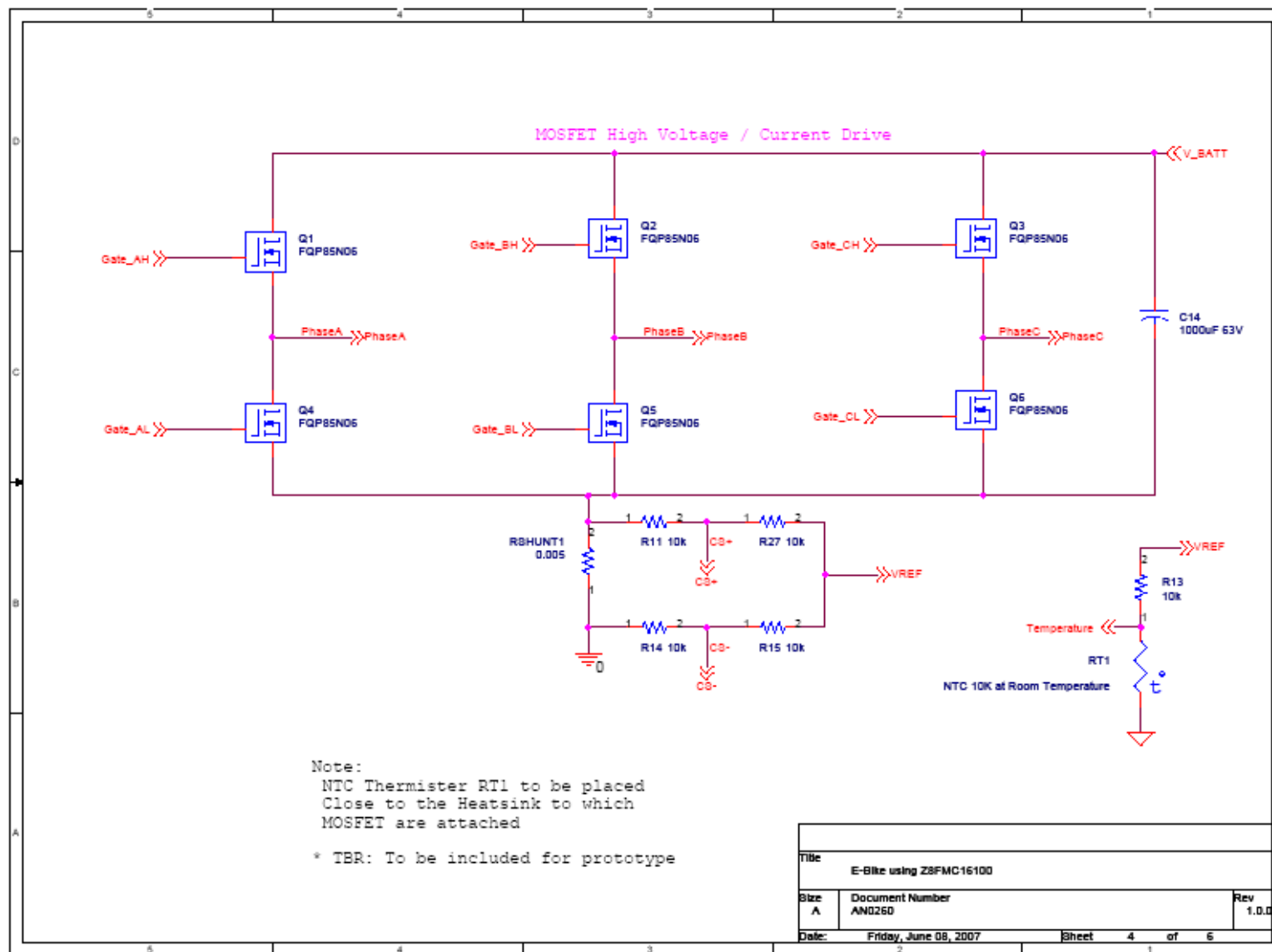


Figure 8. Electric Bike BLDC Motor Controller Application Schematic (3 of 5)

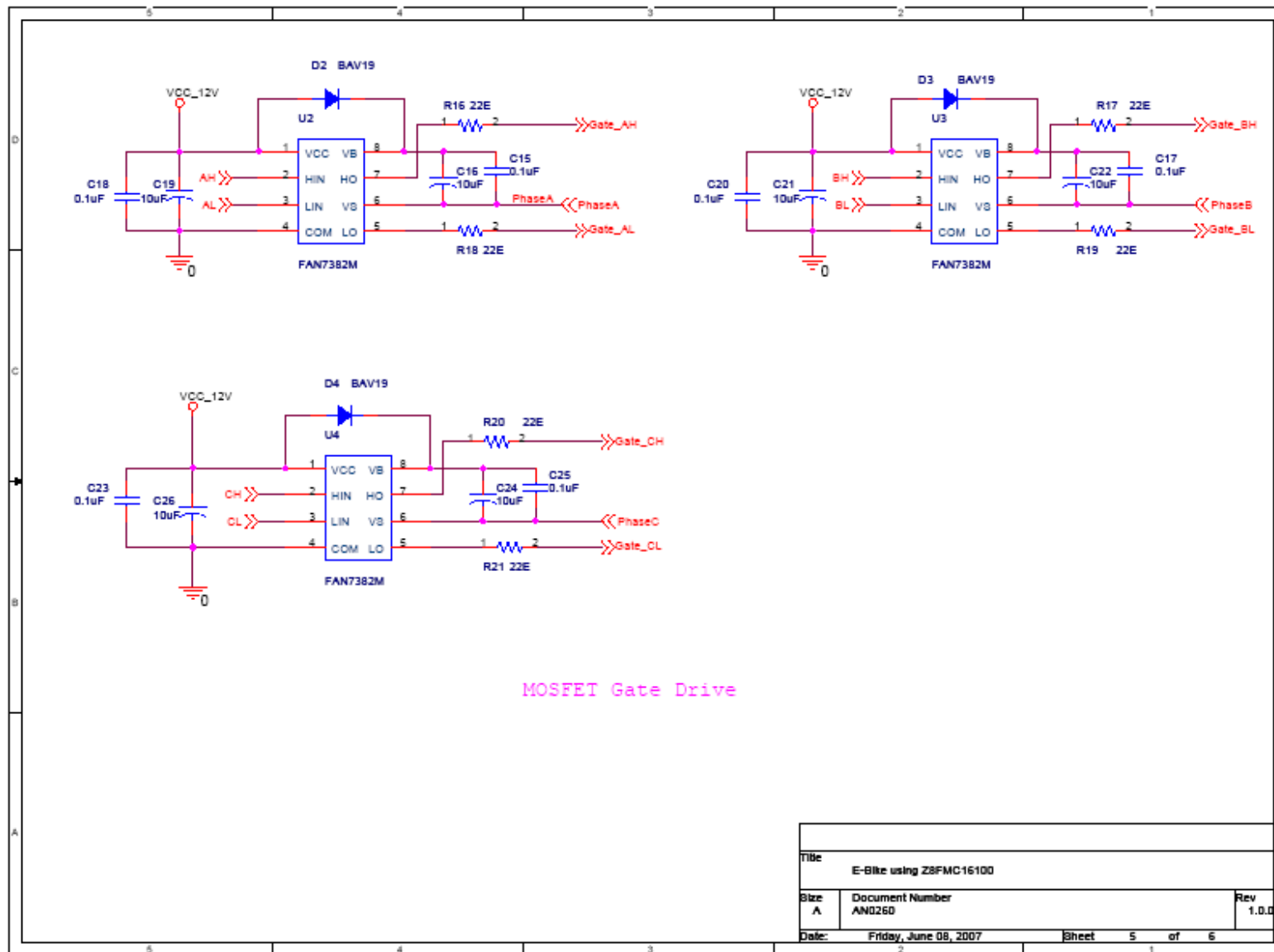


Figure 9. Electric Bike BLDC Motor Controller Application Schematic (4 of 5)

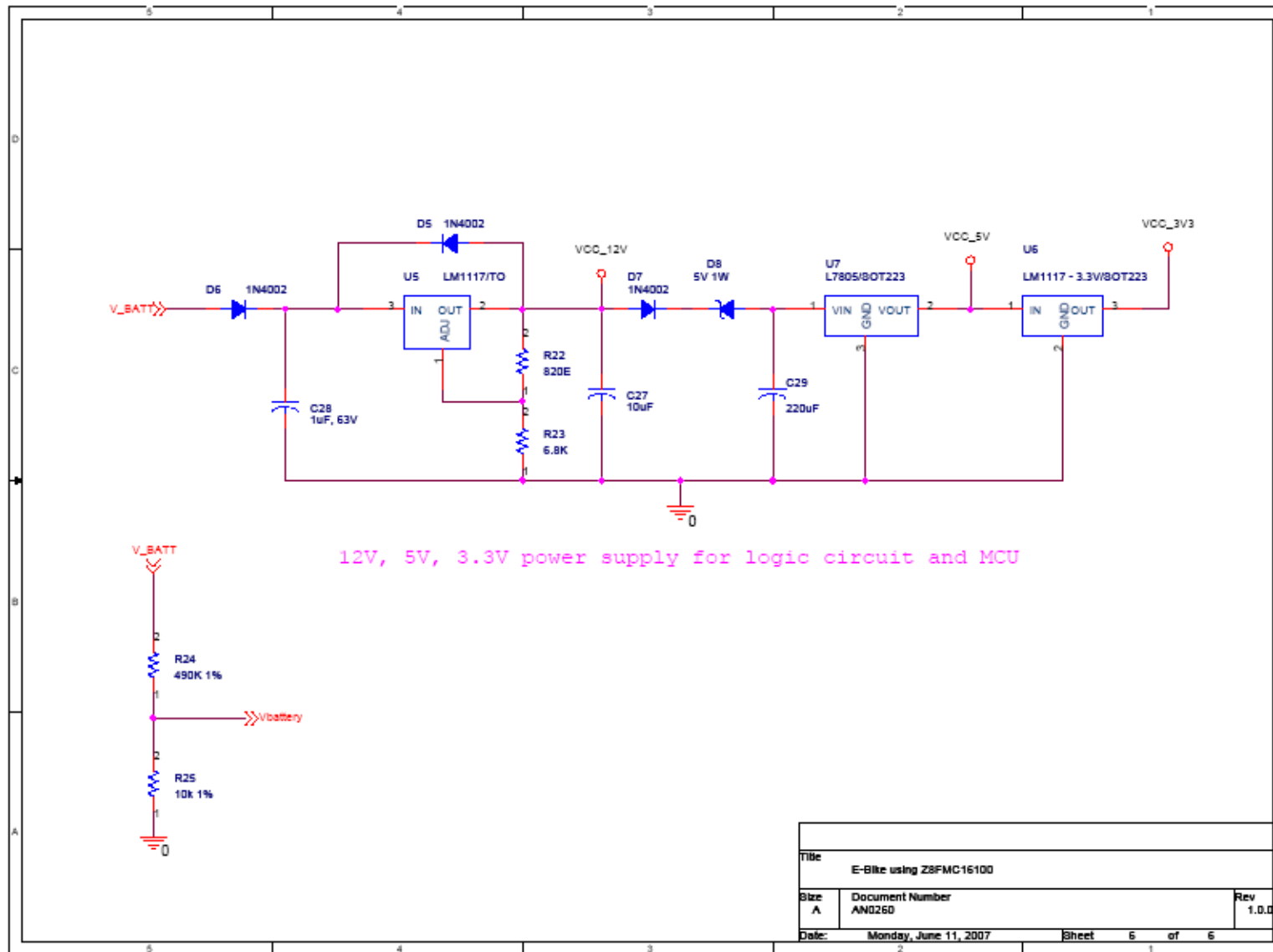


Figure 10. Electric Bike BLDC Motor Controller Application Schematic (5 of 5)

Appendix B—Flowcharts

This Appendix displays the flowcharts for the electric bike BLDC motor controller application.

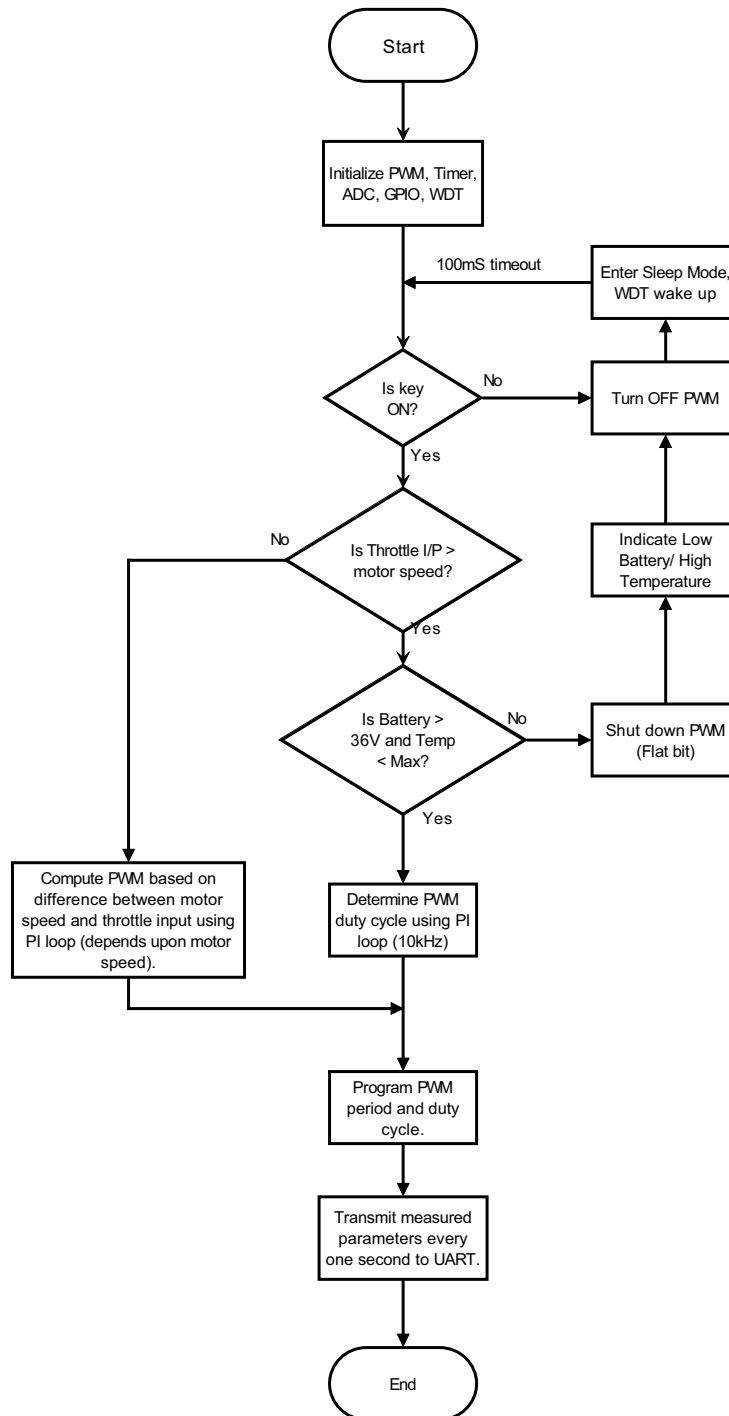


Figure 11. Electric Bike BLDC Motor Controller Application Flowchart - Main

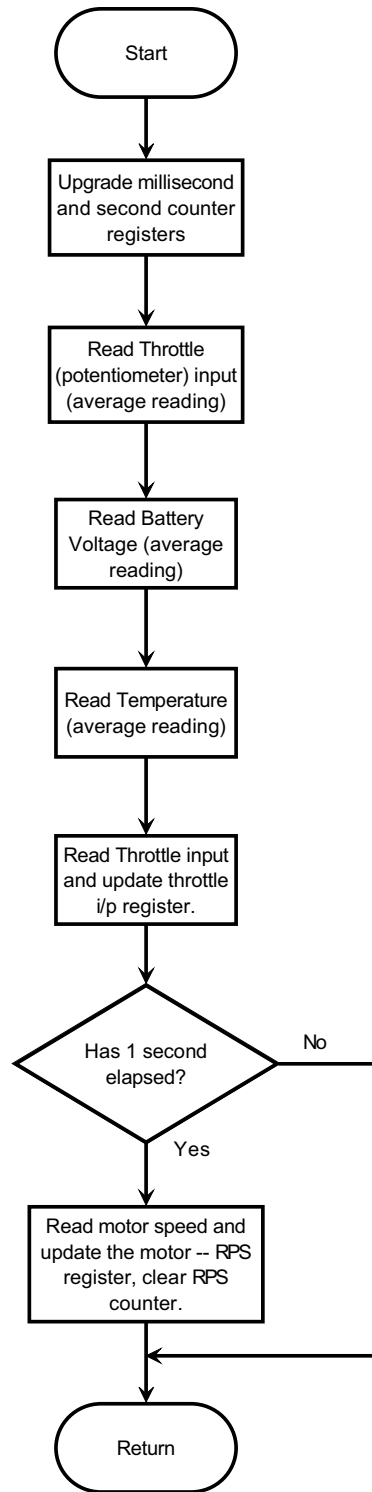


Figure 12. Electric Bike BLDC Motor Controller Application Flowchart – Timer Interrupt

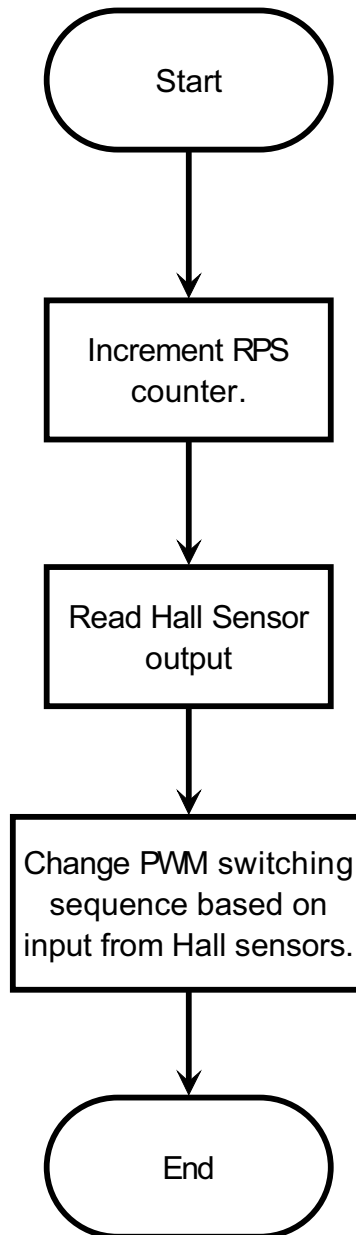


Figure 13. Electric Bike BLDC Motor Controller Application Flowchart – Port B Interrupt



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