Application Note

Control a Cordless Drill Motor and Battery Charger Using Z8 Encore!® F0830 Series MCUs

AN025505-0911

Abstract

Currently, most hand-held electric drilling machines operating on batteries require a separate external battery charger to charge those batteries. This application note describes a motor control implementation for a 350-Watt hand-held electric drill and describes the charging of single-unit nickel-cadmium (NiCd) batteries. This application is based on Zilog's Z8 Encore! F0830 Series of microcontrollers, which efficiently control motor speed, motor current monitoring, fault detection, and the dv/dt charging of a NiCd battery. All functionalities of this design are implemented with minimum hardware.

The on-chip peripherals of the F0830 Series MCUs are used to drive the drill motor at low, medium and high speeds using pulse width modulation (PWM). The battery voltage and the charger input voltage are monitored by an analog-to-digital converter (ADC) and the batteries are charged depending on the voltage read from the batteries and the charger. Light-emitting diodes (LEDs) are provided to indicate motor operation, motor fault, low battery and battery charging status.

Note: The source code file associated with this application note, AN0225-SC01.zip, is available for download on zilog.com. This source code has been tested with version 4.11.0 of ZDS II for Z8 Encore!-powered MCUs. Subsequent releases of ZDS II may require you to modify the code supplied with this application note.

Features

The key features of this application note are:

- Motor control and battery charging in a single unit
- Smooth startup of motor, reducing the starting current of motor
- Three-step speed control of the motor using PWM
- Microcontroller-based overcurrent protection
- Monitoring of battery charger input voltage and battery voltage
- Controlled dv/dt charging of a NiCd battery
- LED indication of motor operation, overload, and fault condition
- LED indication of battery charging status and low battery status
- Three-way switch for Low-Medium-High motor speed selection
- Two-way switch for Forward and Reverse operation of the motor

Discussion

The drill motors used in most of the cordless handheld electric drilling machines are controlled by an electronic circuit. This electronic circuit mainly comprises of a simple square wave generator to control the speed. Usually batteries used in these machines are charged using a separate charging unit. By designing a control circuit based on the F0830 Series of microcontrollers, it is easy to accomplish motor control at different speeds and battery charging as a single unit. This is an added advantage because the battery used to drive the motor is charged in the drilling machine without a separate battery charger.

The functions of the drilling machine like motoring, stop (break), and the steps of speed (High, Medium and Low) can be effectively controlled by changing the duty cycle of the PWM generated by the microcontroller. LEDs are provided for monitoring fault condition like overload, short circuit of motor, and the charging status of the battery. Motor control operation resumes after the overload and short circuit faults are rectified.

The controller circuit based on the F0830 Series MCU can also be used to charge Nickel Metal Hydride (NiMH), NiCd, or Lithium ion batteries. The battery status such as low battery, charging, and charge completed are displayed using LEDs.

This application is implemented with minimum hardware changes to accommodate interfacing motors and batteries rated for different voltage and current ratings.

This application can also be easily ported to an F083A Series microcontroller with a 20MHz internal precision oscillator (IPO) for better operation in terms of processor speed and ADC conversion. The required changes are modifying the setting of the clock source frequency that is defined as a macro in the header files and configuring the ADC Register used in the project.

Theory of Operation

The basic functions of a hand-held drill are classified as forward motoring, reverse motoring, speed control, and torque adjustment. The motors used in these cordless hand-held drills are available at different voltage ratings. Commonly-used DC voltage ratings for the motor are 7.5V, 12V, 14.4V, 18V, 24V and 36V. These motors generate a maximum constant current rating and therefore can be operated at the maximum specified current rating, which in turn specifies torque. Motors used in this application are rated from 300W to 500W. Generally, the no load current consumption of a hand-held drill rotating a 1/4-inch drill bit is in the range of 2A to 2.5A, and the stall current of the motor is in the range of 80A to 100A. The speed of these drilling machines is adjustable from 150rpm to 1200rpm. Speed variation is necessary for different types of work, ranging from the driving of screws to drilling into a metal sheet.

Rechargeable batteries are used to provide power to a drill motor. The most common rechargeable batteries are NiCd, NiMH or Lithium ion. The design uses NiCd cells of 1.2V each that are connected in series to form a 14.4V battery pack. A NiCd battery can be charged with a constant current from an adapter plugged into the drill's drive unit. (See Appendix C. Battery Technology on page 16 for a discussion about NiCd battery charging. Battery charge termination occurs when a zero or negative dv/dt on the battery terminals is reached, or upon termination of a fixed time interval. In this application, charge termination occurs either by zero/negative dv/dt or upon a fixed-interval time-out, whichever occurs first.

Motors

Brushed Universal motors are commonly employed in cordless electric hand-held drives; these motors can be operated using a DC power supply. Brushed DC motors are classified as *permanent magnet* and *temporary magnet* motors. Permanent magnet DC motors are employed in applications in which very low power/torque is required (for example, toys, tape players and instrument-cooling fans). Temporary magnet DC motors are classified based on the type of magnetic field winding used in their construction. Temporary-magnet DC motors can be further classified as three motor types, which are defined as:

Shunt Motor. Employed where constant speed is required.

Series Motor. Employed where high torque is required, but series motors rotate at very high speed when they are not loaded.

Compound Motor. Combine the features of series and shunt motors.

Hand-held drilling machines require high torque to drill objects. Because the maintenance of speed is not a criterion in such drilling applications, series motors are the most suitable type for most of hand-held drills.

Rechargeable Batteries

Batteries can be used to power cordless electric handheld drill motors. Drill motors consume high power during their operation. The no load current consumed by a 350 W motor can be in the range of 2 A to 2.5 A, and motor stall current can be in the range of 80 A to 100 A. The batteries required for this application should have a high charge density to meet the power requirements of the motor. Rechargeable NiCd or NiMH batteries have a moderate charge density, which can be considered suitable to the application. NiMH batteries exhibit higher power density compared to their NiCd counterparts. The voltage per cell of the NiCd battery type is 1.2 V. NiCd batteries are charged using the constant current charging method.

Hardware Architecture

Figure 1 displays a functional block diagram of the F0830 Series MCU hand-held drill motor control.

The block diagram is divided into following functional blocks:

- Battery Charging Block
- Controller Block
- Power Electronic Drive

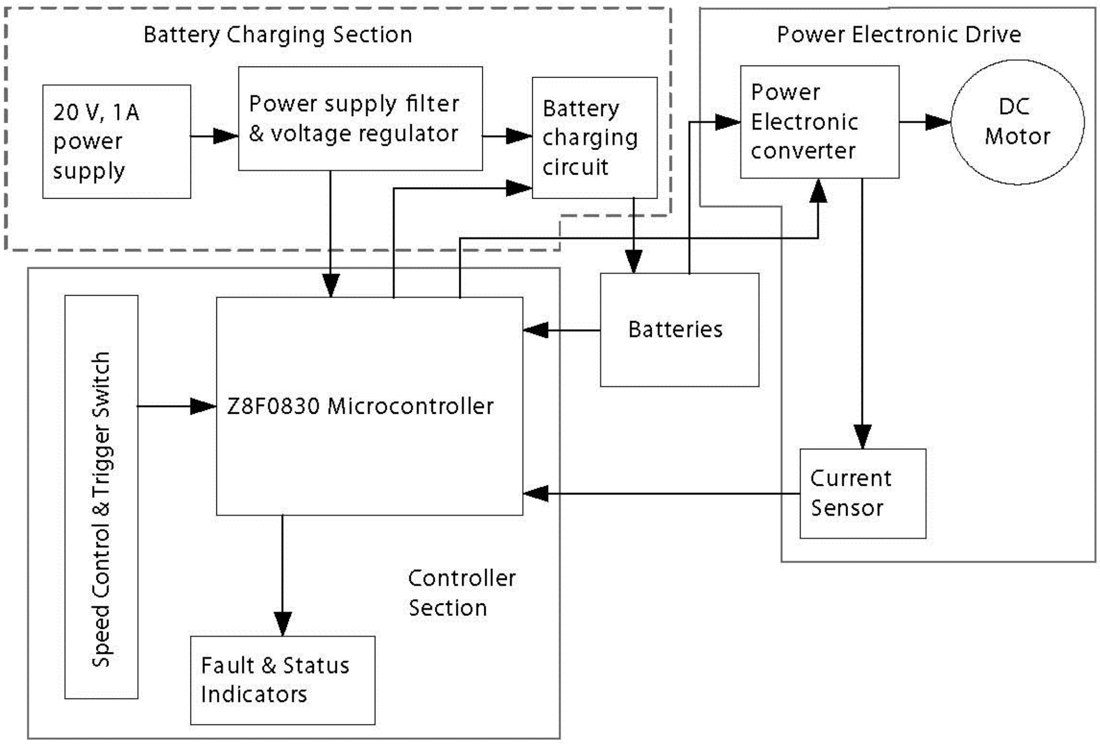

Figure 1. F0830 Series Hand-Held Drill Motor Control Block Diagram

All functional blocks are controlled by F0830 Series MCU operation via the IPO block at 5.5296 MHz. The pins on the F0830 Series 20-pin MCU are used for the functions listed in Table 1.

Table 1. Pin Functions

Pin No.	Pin Function	Function Used	Input/Output/PWR	Function on Board
1	PB1/ANA1	ANA1	Input	Battery charger voltage sensing
2	PB2/ANA2	–	Not Used	–
3	PB3/CLKIN/ANA3	–	Not Used	–
4	V_{DD}	V_{DD}	PWR	3.3V supply
5	PA0/T0IN/T0OUT /XIN	–	Not Used	–
6	PA1/T0OUT/XOUT	–	Not Used	–
7	GND	GND	PWR	GND
8, 9	PA2, PA3	PA2, PA3	Input	Three-level speed setting
10	PA4	PA4	Input	Run/Break switch
11	PA5	PA5	Output	Charger ON/OFF control
12	PA6/T1IN/T1OUT			

Table 1. Pin Functions (Continued)

Pin No.	Pin Function	Function Used	Input/Output/PWR	Function on Board
–	Not Used	–		
13	PA7/T1OUT	T1OUT	Output	Output PWM to drive MOSFET connected to motor
14	RESET /PD0			
RESET	Input	RESET		
15	DBG	DBG	Input/Output	DEBUG
16	PC0/ANA4/CINP/LED	CINP	Input	Current sense input for comparator
17	PC1/ANA5/CINN/LED	–	Not Used	–
18	PC2/ANA6/LED/VREF	PC2	Output	LED
19	PC3/COUT/LED	PC3	Output	LED
20	PB0/ANA0	ANA0	Input	Battery voltage sensing

The descriptions that follow are reflected in the schematics in Appendix A. Schematics on page 11.

Battery Charging Block

The output of a 110/230VAC to 20VDC 1A power adapter is connected to the input of the battery charger block. This battery charging block is comprised of a charging current limiting resistor, a transistor to turn on/off the charging current, a trickle charging resistor, and a 14.4V NiCd battery pack. The resistor across the transistor provides a trickle charging current of C/40 to the battery, where C is the rated battery capacity in Ampere Hours (AH). Transistor switching is controlled by the F0830 Series MCU. The charging input voltage and the battery terminal voltage are attenuated to a voltage level acceptable by the ADC peripheral within the F0830 Series MCU. The attenuated voltage is connected to the respective pins of the microcontroller, which monitors the attenuated charging voltage and battery voltage for charging the battery. The microcontroller measures the voltage slope of the battery every 32 seconds. When the batteries show a negative voltage slope (–dv/dt), the microcontroller turns off the charging transistor by driving the GPIO pin Low.

Note: This design facilitates either battery charging or drill motor control functions in a sequential manner rather than simultaneously. It is not possible to run the motor when the batteries are charging; the reverse is also true.

Controller Block

The controller block is comprised of a F0830 Series MCU operating at 5.5296 MHz via the IPO block. The power supply for the controller is derived from either the battery or the charger input voltage. A battery voltage of 14.4 V and a charger input voltage of 20 V are logically ORed using diodes, and are stepped down to 3.3 V. This stepped-down voltage is achieved using a transistor and zener diode combination. The microcontroller is connected to a three-position switch for DC motor speed control. Based on the switch position, the PWM duty cycle is varied to achieve low-, medium- and high-speed operation of the motor. A trigger switch to turn the drill motor on or off is connected to PA4. The LEDs to indicate battery and motor status are connected to the PC2 and PC3 pins of the microcontroller, respectively. The voltage developed across the current-sensing resistor – when current flows through it – is fed to the positive input of the on-chip comparator. When the voltage on the positive input of the comparator exceeds the on-chip reference voltage connected to the noninverting input of the comparator, PWM operation stops. Every 10 ms, the PWM is initialized to check for faults. If the PWM is not started, the motor status LED blinks to indicate a motor fault/overload.

Power Electronic Drive

The power electronic drive unit consists of transistors to drive a highly-efficient IXYS Trench Gate Metal Oxide Semiconductor Field Effect Transistor (MOSFET), with ultralow Rds, connected to the low side of the supply voltage. The transistor drive stage forms a voltage level converter to drive the gate of the MOSFET with the appropriate voltage. A switching frequency of 100 Hz provides smooth variation in motor speed. The MOSFET is switched at a frequency of 100 Hz. The source pin of the MOSFET is connected to Ground through a current-sense resistor. The voltage drop across this current-sense resistor is the input to the CINP pin of the microcontroller. This CINP pin is the input connected to the positive input of the comparator within the F0830 Series MCU. The negative input of the comparator is connected to the programmable internal reference voltage generated within the F0830 Series MCU.

The user interface consists of switch inputs for starting and stopping the motor, setting motor direction to forward or reverse, and setting the speed of the motor to low-, medium- or high-speed operation. Two LEDs are provided to indicate the status of the motor and battery.

Software Implementation

The procedure for implementing the motor control and battery charging software include the following sequence of tasks:

1. Initialize the comparator, timer 0, timer 1 PWM, ADC, WDT and GPIO upon power-up or external pin reset.
2. Read the battery voltage and update the status flags to reflect the condition of the battery.

3. If the battery voltage is above or below the threshold limit, turn on the battery damage flag and charge the battery for 60 seconds.
4. If the trigger switch is not pressed, skip to Step 8.
5. If the trigger switch is pressed and the battery has sufficient charge, set the speed of the motor to the value set by the settings switch.
6. Continuously monitor for changes in the speed setting switch and trigger the switch release.
7. If the trigger switch is released, or if the battery is completely discharged, turn off the PWM.
8. If the battery is not completely charged and a charger voltage is present, turn on the charger.
9. Continuously monitor battery status and the trigger switch.
10. If the trigger switch is pressed, repeat Steps 5 through 7.
11. If the charger voltage is not present, or if the battery is completely charged, turn off charger and enter STOP Mode.
12. STOP Mode is recovered when the WDT times out or the trigger switch is pressed.

Testing

To connect the test circuit, refer to the Test Procedure section that follows and to Appendix A. Schematics on page 11.

Equipment Used

The equipment used for testing consists of the following items:

- 14.4V DC-operated cordless hand-held drill/screwdriver
- 20V, 1A DC power supply
- Digital multimeter
- Oscilloscope
- Serial/USB Smart Cable
- ZDSII for Z8 Encore! installed on a host PC with a USB/serial port to compile code and download this code to the target

Test Procedure

Observe the following procedure to test the F0830 Series-based cordless drill motor design.

1. Connect the circuit in accordance with the schematic diagrams shown in Appendix A. Schematics on page 11.

2. Connect the 14.4V battery to the circuit.
3. Connect the Serial/USB Smart Cable to the debug connector in the circuit and to the host PC.
4. Open the `Motor_Control.zdsproj` project file, which is located in the source folder of this application installation (see the AN0225-SC01 zip file, available for download from the Zilog website) using the ZDSII Compiler, build the project, and download the code to the target device.
5. Disconnect the Smart Cable from the target device and recycle the power to the application.
6. Connect a multi-meter in series with the battery and the circuit to measure the motor current/battery charging current.
7. Connect an oscilloscope across the terminals of the motor.
8. Press and hold the RUN/STOP switch.
9. Observe the motor speed as it gradually increases up to the maximum speed set by the speed position switch.
10. Observe the waveforms on the oscilloscope.
11. Change the speed settings of the motor by changing the position of the speed setting slide switch.
12. Measure the speed and observe the waveforms for all of the speed settings.

Test Results: Current Values

The results shown in Table 2 reflect RPM and current values obtained at various speed settings of the motor.

Table 2. Motor Speed and Current Values

Trigger Switch Position	Speed Switch Position	No Load Speed (RPM)	Current (A)
Released	–	0	0
Pressed	Low	400	2.00
Pressed	Medium	800	2.90
Pressed	High	1150	3.20

Figure 2 shows the starting and operating current of the motor while operating at minimum speed.

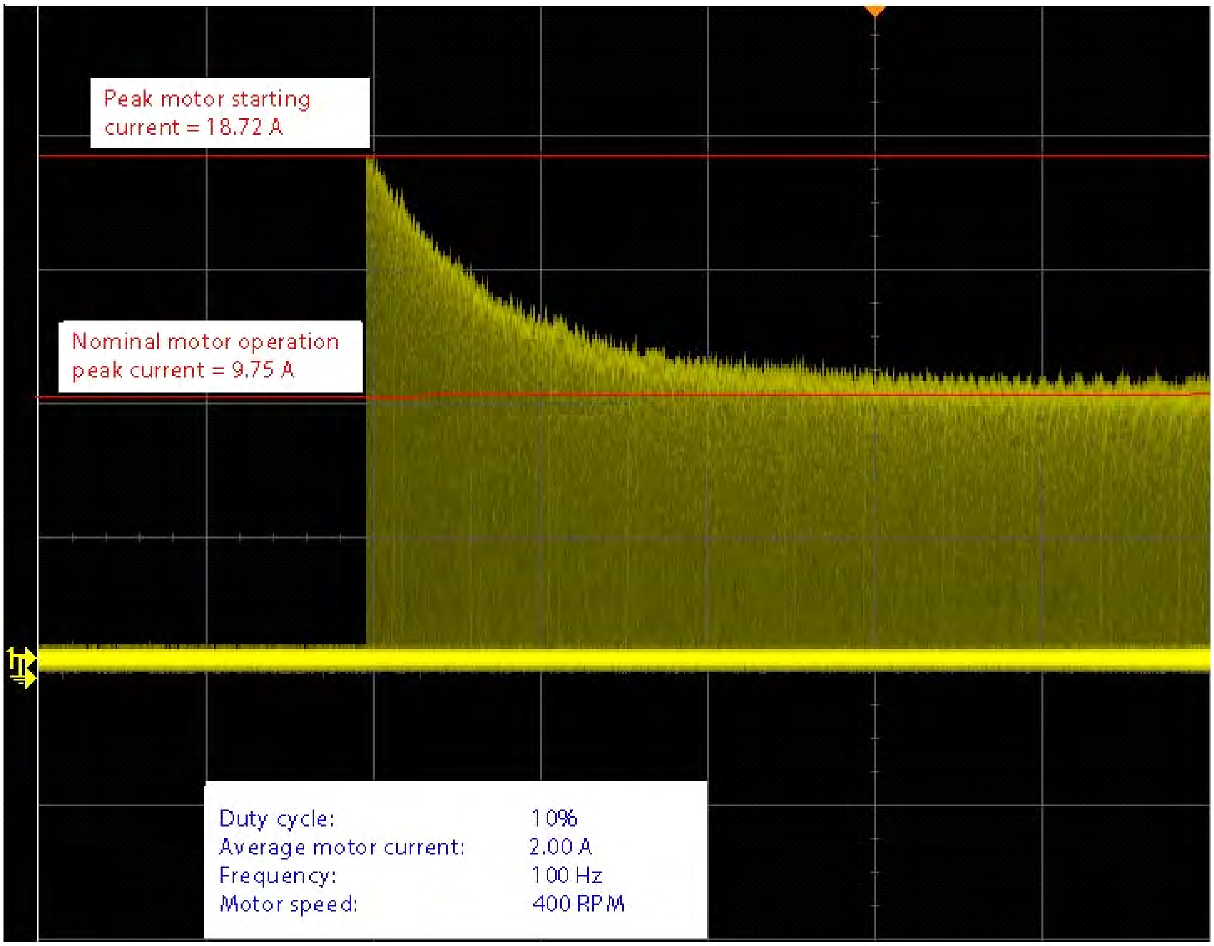

Figure 2. Starting and Operating Current of Motor

A load current of 5.6A is utilized when drilling an aluminum sheet that is 5mm thick.

LED D6 illuminates to indicate a low battery when the battery voltage is 13.8V or lower. The system shuts down when the battery voltage reaches 12V.

Test Results: Battery Charging

The results of testing for the battery charging operation are listed in Table 3.

Table 3. Battery Charging Test Results

Parameters	Value
Battery type	Nickel Cadmium
Battery voltage	14.4 V

Table 3. Battery Charging Test Results (Continued)

Parameters	Value
Ampere Hour rating	1500m AH
Charging type	Constant voltage
Charging current	800mA (initial, decreases with charging time)
Charging time	2 hours (approximately for completely discharged battery pack)
Charge termination	Negative voltage on battery terminals/constant time interval
Maximum battery voltage when charging completely discharged battery	18.2V
Trickle charging current	40mA
Voltage of the battery when completely discharged using motor load	12V

Summary

This application note describes the smooth speed control of a typical battery-operated hand-held drill with a built-in battery charger that employs Zilog's low-cost Z8 Encore! F0830 Series or F083A Series MCU. This design features two LEDs that indicate various conditions such as motor operation, motor overcurrent, battery charge, and low battery. This design also includes functions such as motor protection for overcurrent and short circuit events, and controlled NiCd battery charging operation.

The advantages of this design over existing cordless hand-held drills are two-fold:

- There is no need to plug the battery pack into a separate charger unit
- The smooth startup of the motor reduces the high starting current typical of most hand-held drill motors

References

The following documents describe functional specifications and/or otherwise support this application note. Each is available for download from the Zilog website.

- Z8 Encore! F0830 Series Product Specification (PS0251)
- Z8 Encore!-Based AA-Type NiMH and NiCd Battery Charger Reference Design (AN0229)
- Z8 Encore! XP-Based NiCd Battery Charger Application Note (AN0221)

Appendix A. Schematics

Figure 3 displays the schematic diagram that supports this Cordless Drill Motor and Battery Charging Control application.

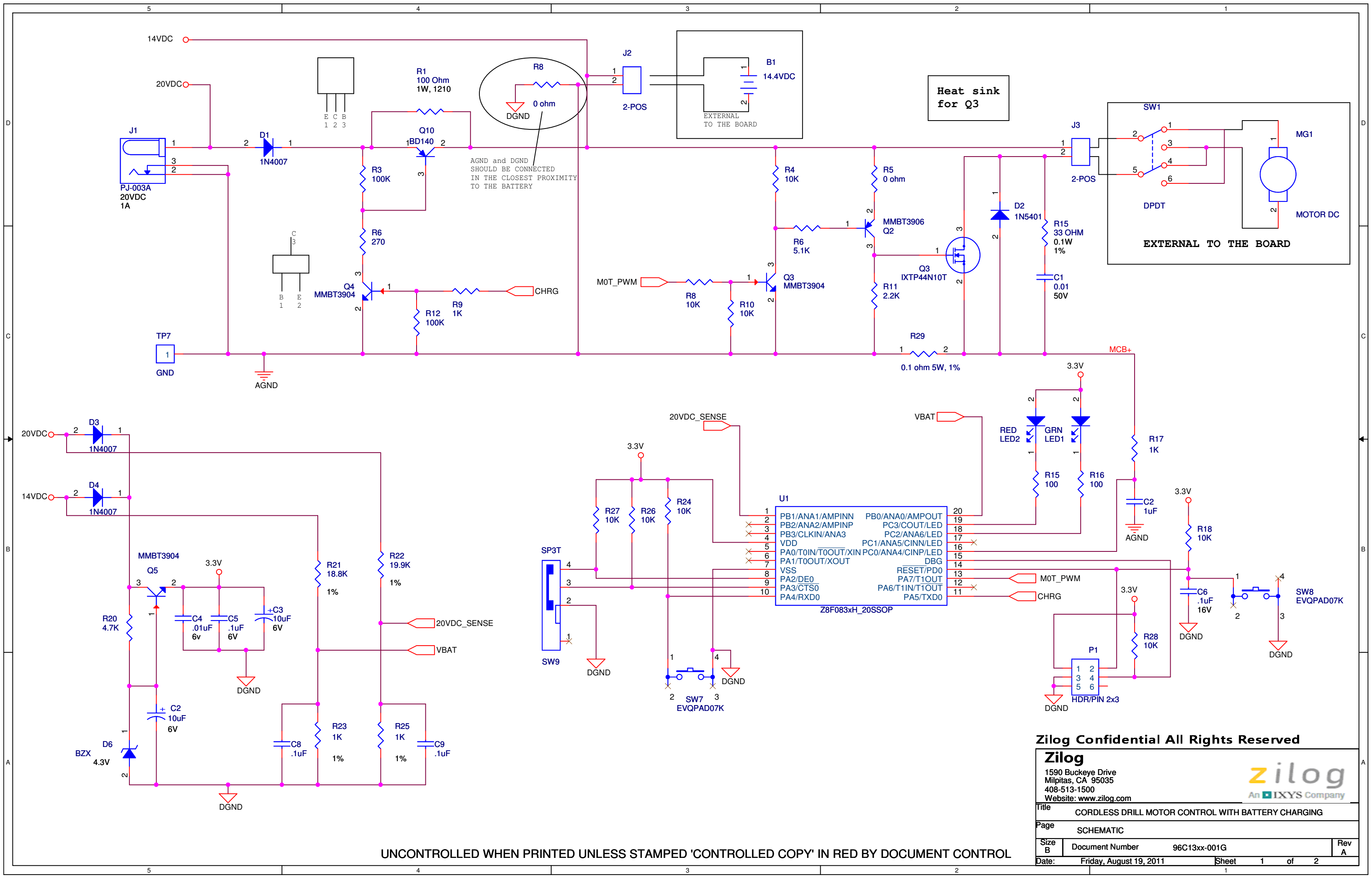

Figure 3. Cordless Drill Motor Control with Battery Charging Schematic Diagram

Appendix B. Flowcharts

Figures 4 through 8 chart the flow of the main motor control and battery-charging functions plus all interrupts that support this application.

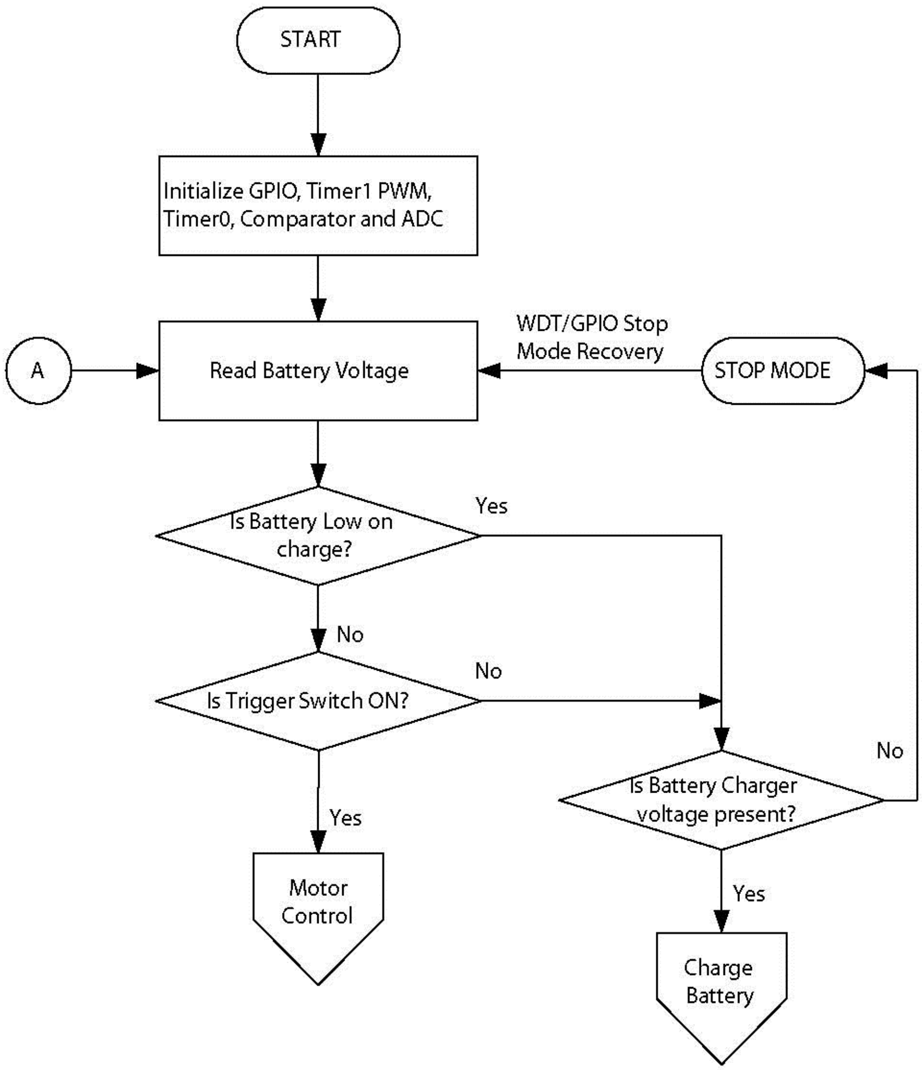

Figure 4. Flow of the Main Function

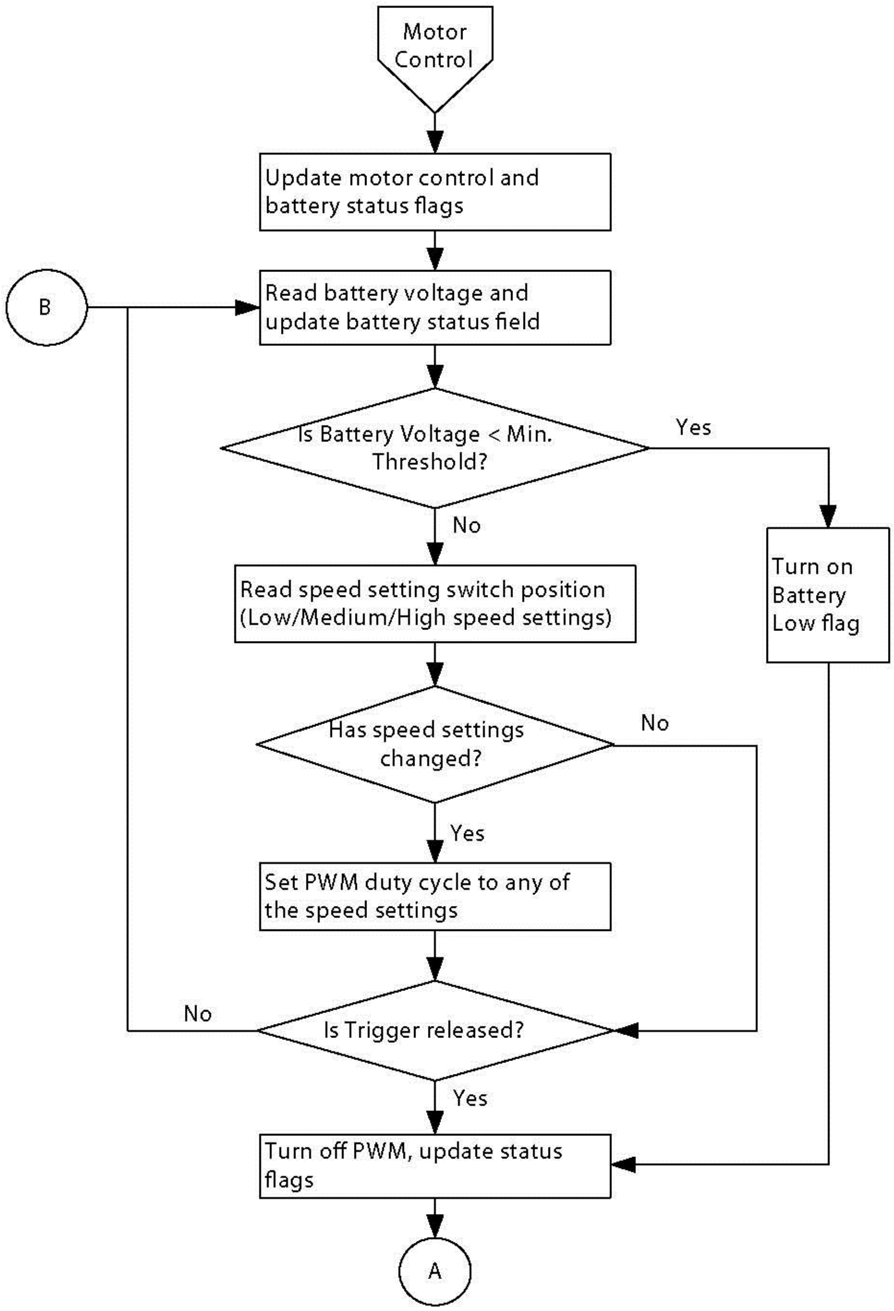

Figure 5. Motor Control Algorithm

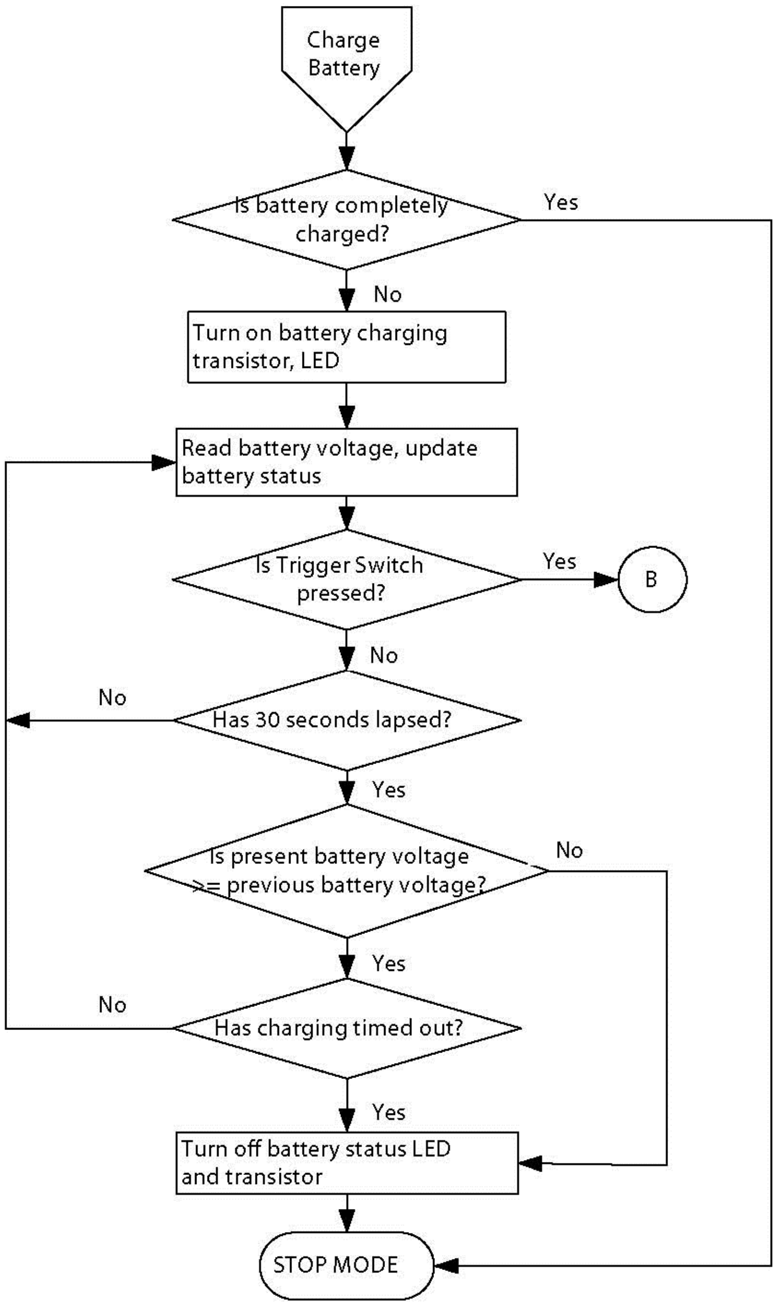

Figure 6. Battery Charging Algorithm

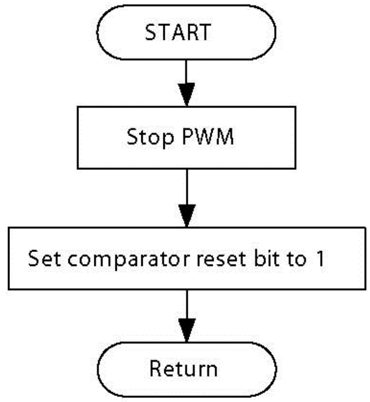

Figure 7. flow of the Comparators Interrupt

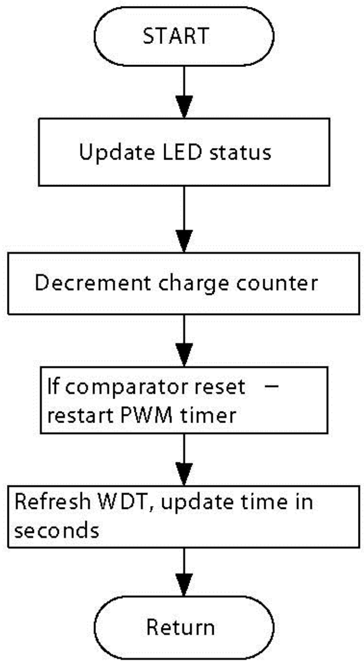

Figure 8. Flow of the Timer0 Interrupt

Appendix C. Battery Technology

The four popular battery types, NiCd, NiMH, SLA and Li-Ion, display different charging and discharging characteristics. The battery life and performance of each of these battery types primarily depends upon the battery charging mechanism used in the design. Because overcharging of the battery can invariably result in poor performance (and can also damage the battery), and because the design must be tailored appropriately to the application, charging must be terminated when the battery is completely charged. Because different batteries behave differently when approaching a fully-charged state, different charge termination techniques are required. While charging, batteries exhibit a marked rise in voltage above their rated voltages. The NiCd and NiMH rechargeable battery types used in this application are briefly discussed in this appendix.

Nickel Cadmium

Nickel Cadmium (NiCd) batteries are used in a vast array of portable consumer equipment. The single-cell voltage for NiCd batteries is 1.2V. These types of batteries are charged using the *constant current* charging method. While charging, as the voltage crosses the full charge point, the voltage gradually drops. This voltage drop is approximately 15mV per cell in the battery, and is recognized as a *full charge condition* that results in the termination of the charge. This termination mechanism is known as *–dv/dt termination*. The battery voltage rises to 1.65V per cell during charging. The main disadvantage of the NiCd battery is that it must be discharged periodically to protect its performance; this phenomenon is known as *memory effect*.

Nickel Metal Hydride

Nickel Metal Hydride (NiMH) batteries exhibit high power density compared to NiCd batteries. The per-cell voltage of the NiMH battery type is 1.2V, which is similar to that of NiCd batteries. NiMH batteries are charged using the *constant current* charging method. While charging, the voltage drop is not as low when compared to NiCd batteries.

Therefore, –dv/dt charge termination is not recommended for NiMH batteries. Instead of a drop in cell voltage, these types of batteries tend to stabilize after a small drop. This *flat region* indicates a full battery charge; the termination mechanism is known as *zero dv/dt termination*. As compared to NiCd batteries, NiMH batteries do not suffer from *memory effect*. As a result, they perform better than NiCd batteries in devices such as cell phones. The higher price typical of NiMH batteries is justified by their reduced weight and the absence of the memory effect.

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