## *Design Guide: TIDA-010030*

# *Accurate gauging and 50-µA standby current, 13S, 48-V Li-Ion battery pack reference design*

## Description

This reference design is a low standby and ship mode current consumption and high SOC gauging accuracy 13S, 48-V Li-ion battery pack design. It monitors each cell voltage, pack current and temperature with high accuracy and protects the Li-ion battery pack against overvoltage, undervoltage, over temperature and over current situations. The SOC gauging, based on bq34z100-g1, takes advantage of an impedance tracking algorithm and achieves as high as 2% accuracy at room temperature. Through a well-designed auxiliary power supply strategy and high efficiency, low quiescent current DC-DC converter LM5164, this design achieves 50-µA stand-by and 5-µA ship mode consumption, saving more energy and allowing longer shipping time and idle time. This reference design was implemented for a 2-layer PCB. Also, this design supports a well running firmware, which helps to decrease product research time.

## Resources

| | |
|---|---|
| TIDA-010030 | Design Folder |
| BQ34Z100-G1, BQ76940, BQ76200, BQ7718 | Product Folder |
| MSP430FR2155 | Product Folder |
| LM5164 | Product Folder |
| SN6501 | Product Folder |
| THVD1500 | Product Folder |
| ISO1042 | Product Folder |

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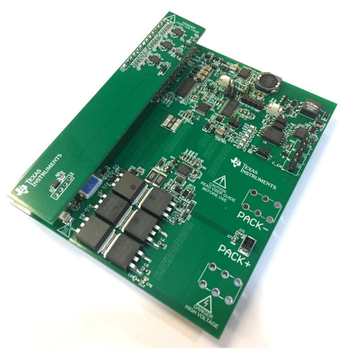
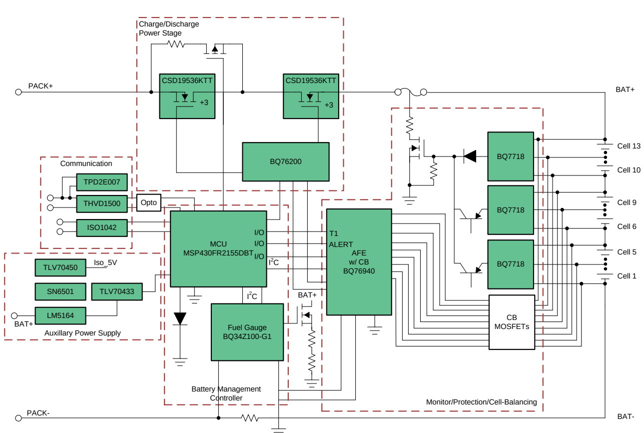
## Features

- 2% battery pack SOC accuracy at room temperature.
- 50-µA current consumption when in standby mode
- 5-µA current consumption when in shipping mode
- Robust and programmable protection, including: cell over voltage, cell under voltage, overcurrent discharge, short circuit, overtemperature and undertemperature
- Support 100-mA cell balancing
- High-side charging and discharging MOSFETs and support pre-discharge function

## Applications

- e-bike battery pack
- e-scooter battery pack
- Mowing robot battery pack
- UPS Li-Ion battery pack
- Other over 10S battery pack applications





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## 1 System Description

The e-bike market is growing rapidly. Because of the weight limited and longer endurance request, the battery cell chemistries of the battery pack is shifting to Li-ion, Li-polymer, or Li-iron phosphate types. These chemistries are good in both volumetric and gravimetric energy density. While these chemistries provide high energy density and thereby lower volume and weight as an advantage, they are associated with safety concerns and need more complicated monitoring and accuracy capacity gauging. Those concerns are undervoltage (UV) and overvoltage (OV), over temperature (OT), and overcurrent (OC), over discharge and charge current, all which contribute to the accelerating cell degradation and may lead to thermal runaway and explosion. Therefore the pack current, temperature and each cell voltages should be timely monitored in case of some unusual situations. And pack must be protected against all these situations. The capacity gauging is able to calculate how much capacity is still stored in the pack and predict the run-time and charge time, avoiding suddenly shutdown when ridding the e-bike. A good accuracy gauging design can also extend run-time because it allows users using all available battery capacity without damaging the battery cells. Another important feature is the current consumption when the e-bike is in ship mode or idle.

This design is mainly focus on e-bike battery pack applications and also suitable for other high cell applications, such as e-scooter battery pack, mowing robot battery pack, etc. It contains both primary and secondary protection to ensure safety use of the battery pack. The primary protection will protect the battery pack against all unusual situations, including: over voltage, under voltage, over discharge current, short circuit, over temperature and under temperature. The secondary protection which uses hardware over voltage protection is an add on board with is easily remove and added based on actual demands. This design utilizes Impedance Track™ gauging algorithm which helps to achieve very high SOC gauging accuracy even for old battery cells or at low or high temperature. Meanwhile, this design carefully designs the auxiliary power and firmware, which achieves quite low ship mode and standby mode current consumption (5–µA for ship mode and 50-µA for standby mode). Also, this design supports a well running firmware based on a low power consumption MSP430™ MCU MSP430FR2155. This will definitely give a lot help for customers' system design.

## 1.1 Key System Specifications

The most important there features are 50-µA standby current consumption, smooth SOC gauging at low temperature and 5-µA ship mode current consumption. Table 1 lists other features.

**Table 1. Key System Specifications**

| PARAMETER | Conditions | Spec Range | | | Unit |
|---|---|---|---|---|---|
| | | Minimum | Typical | Maximum | |
| Cell architecture | Li-ion Battery | | 13S | | |
| Stack Voltage | Li-ion Battery | 36 | 48 | 55 | V |
| Cell Balancing Current | Li-ion Battery | | | 100 | mA |
| SOC accuracy of fuel gauging | 25°C | | 2 | | % |
| Charge Current | | | 10 | | A |
| Discharge Current | | | 20 | 30 | A |
| Pre-discharge Current | | | 0.2 | | A |
| Primary OV protection | Threshold | | 4200 | | mV |
| | Delay | | 2 | | s |
| Secondary OV protection | Threshold | | 4300 | | mV |
| | Delay | | 4 | | s |
| UV protection | | | 2900 | | mV |
| OCD protection | | | 36 | | A |
| SCD protection | | | 56 | | A |
| Over Temperature Protection | Charge | | 55 | | °C |
| | Discharge | | 60 | | °C |
| Under Temperature Protection | Charge | | 0 | | °C |
| | Discharge | | –20 | | °C |
| Communication speed | RS-485 | | 9600 | 19200 | kbps |
| Standby mode current consumption | | | 50 | | µA |
| Shipping mode current consumption | | | 5 | | µA |

# 2 System Overview

## 2.1 Block Diagram

**Figure 1. TIDA-010030 Block Diagram**

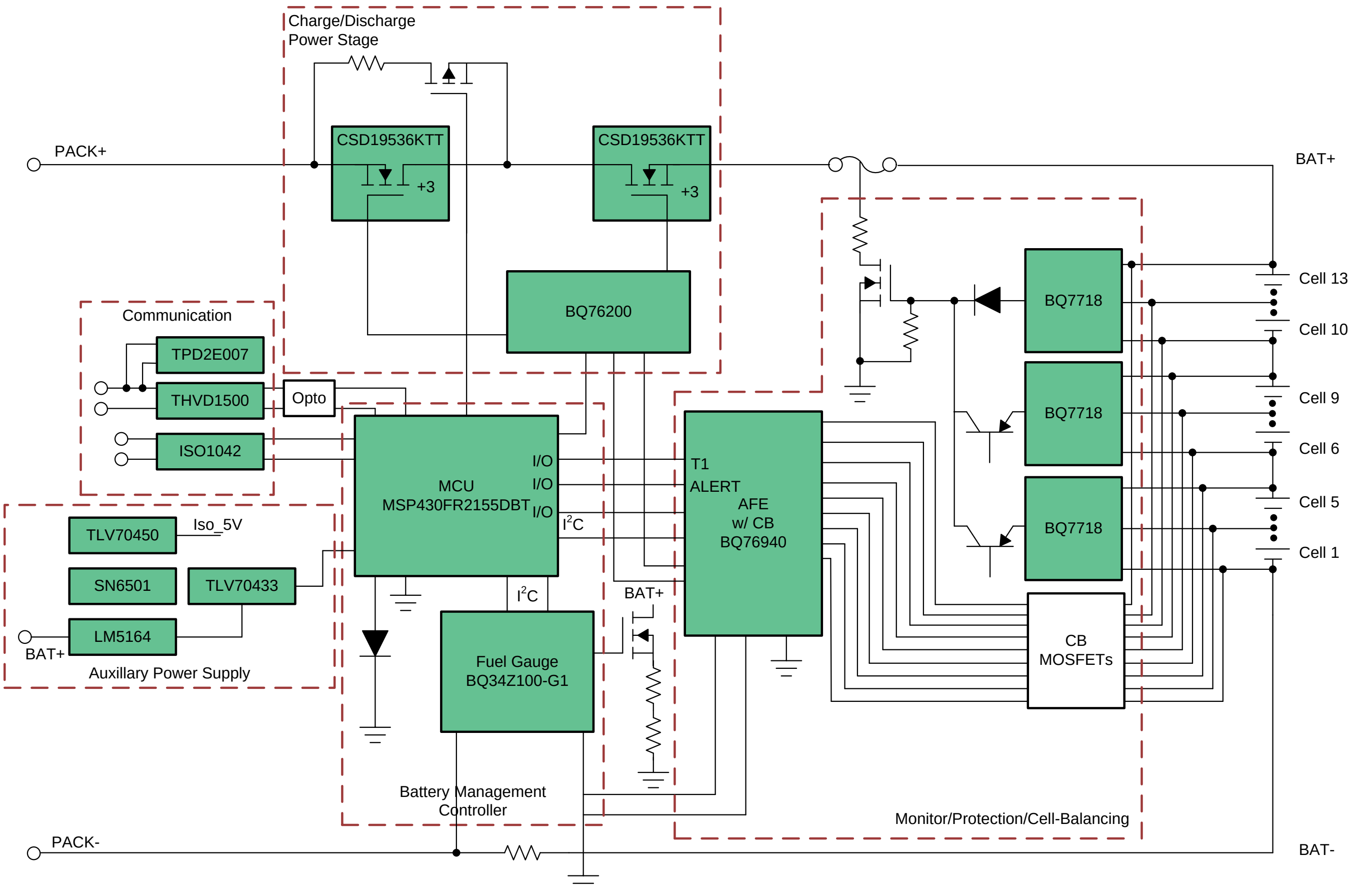



Figure 1 shows the system diagram containing several sub systems: monitor/protection/cell-balancing, battery management controller, auxiliary power supply, charge/discharge power stage, and communication. The battery cell monitoring and balancing uses TI 9-15S AFE bq76940 to monitoring each cell voltage and pack current and temperature, it also integrates over voltage and under voltage hardware protection, cell balancing and charge and discharge FET drivers. The battery gauging utilizes Impedance Track™ gauging algorithm based device bq34z100-g1 which can handle large cell packs. There is a lower power MSP430™ MCU MSP430FR2155 which will configure AFE, read data from AFE and gauge and upload all the requested information to system side. The design firmware is open framed which will give some help for customers' system design. The secondary protection is a add-on function, which is easily removed and added based customers' request.

## 2.2 Highlighted Products

### 2.2.1 BQ76940

The BQ76940 of robust AFE device serves as part of a complete pack monitoring and protection solution for next-generation high-power systems, such as light electric vehicles, power tools, and uninterruptible power supplies. The BQ76940 is designed with low power in mind: Sub-blocks within the IC may be enabled or disabled to control the overall chip current consumption, and a SHIP mode provides a simple way to put the pack into an ultra-low power state. The BQ76940 supports 9 cells to 15 cells providing measurement of individual cell voltages. This AFE can measure a variety of battery chemistries, including Li-ion, Li-iron phosphate, and more. A coulomb counter is provided for current measurement. Three thermistors are provided for temperature measurement. Hardware protection features are configured by registers set by the system controller and automatically switch off charge and discharge. Through I²C, a host controller can use the BQ76940 to implement many battery pack management functions such as monitoring (cell voltages, pack current, pack temperatures), protection (controlling charge or discharge FETs), and balancing. Integrated ADCs enable a purely digital readout of critical system parameters with calibration handled in TI's manufacturing process.

### 2.2.2 BQ34Z100-G1

The bq34z100-G1 device is an Impedance Track™ fuel gauge for Li-Ion, PbA, NiMH, and NiCd batteries, and works independently of battery series-cell configurations. Batteries from 3 V to 65 V can be easily supported through an external voltage translation circuit that is controlled automatically to reduce system power consumption. The bq34z100-G1 device provides several interface options, including an I²C slave, an HDQ slave, one or four direct LEDs, and an ALERT output pin. Additionally, the bq34z100-G1 provides support for an external port expander for more than four LEDs.

### 2.2.3 BQ76200

The bq76200 device is a low-power, high-side, N-Channel system. A high-side protection avoids ground disconnection in the system and also allows continuous communication between the battery pack and host system. The device has additional P-Channel FET control to allow low-current pre-charge to a deeply depleted battery or pre-discharge to a capacitive load, and a PACK+ voltage monitor control for the host to sense the PACK+ voltage. The independent enable inputs allow CHG and DSG FETs to be turned on and off separately, offering great implementation flexibility in battery systems. The bq76200 device can be used with a companion Analog Front End device such as the bq76920/30/40 family, a 3-series to 15-series Cell Analog Front End Monitoring, and a host microcontroller or dedicated state-of-charge (SOC) tracking gas gauge device.

### 2.2.4 MSP430FR2155

MSP430FR215x micro-controller (MCUs) is part of the MSP430™ MCU value line portfolio of ultra-low-power low-cost devices for sensing and measurement applications. The device includes a 12-channels 12-bit ADC and two comparators. The MSP430FR215x supports an extended temperature range from –40° up to 105°C, so higher temperature industrial applications can benefit from the FRAM data-logging capabilities of the device. The extended temperature range allows developers to meet requirements of applications such as smoke detectors, sensor transmitters, and circuit breakers. The MSP430FR215x features a powerful 16-bit RISC CPU, 16-bit registers, and a constant generator that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows the device to wake up from low-power modes to active mode typically in less than 10 µs. The MSP430 ultra-low-power (ULP) FRAM microcontroller platform combines uniquely embedded FRAM and a holistic ultra-low-power system architecture, allowing system designers to increase performance while lowering energy consumption. FRAM technology combines the low-energy fast writes, flexibility, and endurance of RAM with the nonvolatile behavior of flash. MSP430FR215x is supported by an extensive hardware and software ecosystem with reference designs and code examples to get your design started quickly.

### 2.2.5 LM5164

The LM5164 synchronous buck converter is designed to regulate over a wide input voltage range, minimizing the need for external surge suppression components. A minimum controllable on-time of 50 ns facilitates large step-down conversion ratios, enabling the direct step-down from a 48 V nominal input to low-voltage rails for reduced system complexity and solution cost. The LM5164 operates during input voltage dips as low as 6 V, at nearly 100% duty cycle if needed, making it an excellent choice for wide input supply range industrial and high cell count battery pack applications. With integrated high-side and low-side power MOSFETs, the LM5164 delivers up to 1 A of output current. A constant on-time (COT) control architecture provides nearly constant switching frequency with excellent load and line transient response. Additional features of the LM5164 include ultra-low IQ and diode emulation mode operation for high light-load efficiency, innovative peak and valley overcurrent protection, integrated VCC bias supply and bootstrap diode, precision enable and input UVLO, and thermal shutdown protection with automatic recovery. An open-drain PGOOD indicator provides sequencing, fault reporting, and output voltage monitoring. The LM5164 is available in a thermally-enhanced, 8- pin SO PowerPAD™ package. Its 1.27-mm pin pitch provides adequate spacing for high-voltage applications.

### 2.2.6 THVD1500

THVD1500 is a robust half-duplex RS-485 transceiver for industrial applications. The bus pins are immune to high levels of IEC Contact Discharge ESD events eliminating need of additional system level protection components. The device operates from a single 5-V supply. The wide common-mode voltage range and low input leakage on bus pins make THVD1500 suitable for multi-point applications over long cable runs. THVD1500 is available in industry standard 8-pin SOIC package for drop-in compatibility. The device is characterized from –40°C to 125°C.

### 2.2.7 ISO1042

The ISO1042 device is a galvanically-isolated controller area network (CAN) transceiver that meets the specifications of the ISO11898-2 (2016) standard. The ISO1042 device offers ±70-V DC bus fault protection and ±30-V common-mode voltage range. The device supports up to 5-Mbps data rate in CAN FD mode allowing much faster transfer of payload compared to classic CAN. This device uses a silicon dioxide (SiO2 ) insulation barrier with a withstand voltage of 5000 VRMS and a working voltage of 1060 VRMS. Electromagnetic compatibility has been significantly enhanced to enable system-level ESD, EFT, surge, and emissions compliance. Used in conjunction with isolated power supplies, the device protects against high voltage, and prevents noise currents from the bus from entering the local ground. The ISO1042 device is available for both basic and reinforced isolation (see Reinforced and Basic Isolation Options). The ISO1042 device supports a wide ambient temperature range of –40°C to +125°C. The device is available in the SOIC-16 (DW) package and a smaller SOIC-8 (DWV) package.

### 2.2.8 TLV704

The TLV704 series of low-dropout (LDO) regulators are ultralow quiescent current devices designed for extremely power-sensitive applications. Quiescent current is virtually constant over the complete load current and ambient temperature range. These devices are an ideal power-management attachment to low-power microcontrollers, such as the MSP430. The TLV704 operates over a wide operating input voltage of 2.5 V to 24 V. Thus, the device is an excellent choice for both battery-powered systems as well as industrial applications that undergo large line transients. The TLV704 is available in a 3-mm × 3-mm SOT23-5 package, which is ideal for cost-effective board manufacturing.

### 2.2.9 SN6501

The SN6501 is a monolithic oscillator/power-driver, specifically designed for small form factor, isolated power supplies in isolated interface applications. The device drives a low-profile, center-tapped transformer primary from a 3.3-V or 5-V DC power supply. The secondary can be wound to provide any isolated voltage based on transformer turns ratio. The SN6501 consists of an oscillator followed by a gate drive circuit that provides the complementary output signals to drive the ground referenced N-channel power switches. The internal logic ensures break-before-make action between the two switches. The SN6501 is available in a small SOT-23 (5) package, and is specified for operation at temperatures from –40°C to 125°C.

### 2.2.10 TPD2E007

This device is a transient voltage suppressor (TVS) based electrostatic discharge (ESD) protection device designed to offer system level ESD solutions for wide range of portable and industrial applications. The back-to-back diode array allows AC-coupled or negative-going data transmission (audio interface, LVDS, RS-485, RS-232, and so forth) without compromising signal integrity. This device exceeds the IEC 61000-4-2 (Level 4) ESD protection and is ideal for providing system level ESD protection for the internal ICs when placed near the connector. The TPD2E007 is offered in a 4-bump PicoStar and 3-pin SOT (DGK) packages. The PicoStar package (YFM), with only 0.15 mm (Max) package height, is recommended for ultra space saving application where the package height is a key concern. The PicoStar package can be used in either embedded PCB board applications or in surface mount applications. The industry standard SOT package offers straightforward board layout option in legacy designs.

## 2.3 System Design Theory

### 2.3.1 Auxiliary Power Supply Design

This auxiliary power circuit consists of a DC/DC BUCK converter, Isolated power supplies and several LDOs. The DC/DC BUCK converter is controlled by LM5164, a constant on-time (COT) control architecture device. The on-time is calculated with Equation 1. In CCM, the operating frequency is programmed by the $R_{RON}$ resister and can be calculated using Equation 2. Therefor the $R_{RON}$ can be determined using Equation 3.

$$t_{on}(\mu s) = \frac{R_{RON}(k\Omega)}{V_{IN}(V) \times 2.5} \tag{1}$$

$$F_{SW}(kHz) = \frac{V_{OUT}(V) \times 2500}{R_{RON}(k\Omega)} \tag{2}$$

$$R_{RON}(k\Omega) = \frac{V_{OUT}(V) \times 2500}{F_{SW}(kHz)} \tag{3}$$

To decrease the standby power consumption, the light load efficiency should be carefully designed. When at quite light load, the switching loss is the mainly loss and to decrease the switching loss, the switching frequency is designed at a low value. In this design, the CCM frequency is designed as 50 kHz. Therefore the $R_{RON}$ is 250 kΩ.

The BUCK inductor is calculated using Equation 4. where ΔI is the current decrease value when the main FET is off. In this design, the critical mode load is designed at 600 mA, therefore L is 68 µH.

$$L(H) = \frac{V_{OUT}(V) \times \left(1 - ton(ms) \times F_{SW}(kHz)\right)}{F_{SW}(kHz)} \tag{4}$$

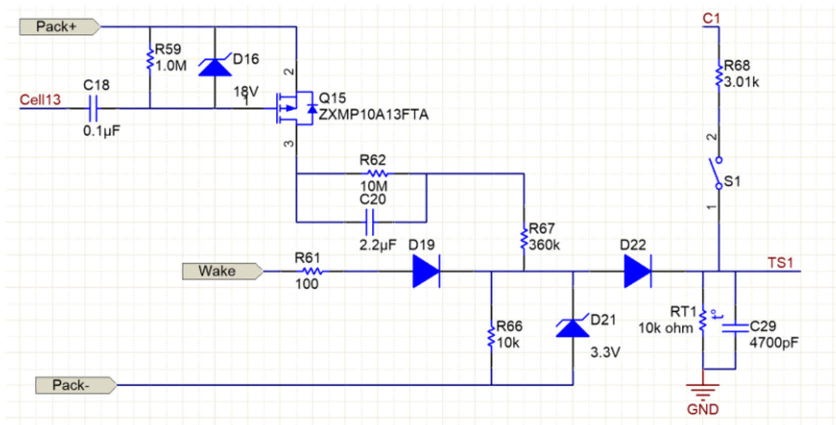
### 2.3.2 Pack Current Sensing Design

The pack current sensing is using a high accuracy resister. To ensure accurate current measurement, the input voltage generated across the current sense resistor should not exceed ±125 mV. For applications with a very high dynamic range, it is allowable to extend this range to absolute maximum of ±300 mV for overload conditions where a protector device will be taking independent protective action. In such an overloaded state, current reporting and gauging accuracy will not function correctly. The normal current is designed as 30 A and the OCD threshold is design as 60 A. Therefore the current sensing resister is designed less than 2.08 mΩ. A 2 mΩ with 50-ppm temperature coefficient and power rating of 5 W is used in this design.

### 2.3.3 Wake-up Circuit Design

When the battery pack is first time powered on or with quite low battery voltage, system will enter ship mode and the whole system except for BQ76940 is powered off to save power. In this mode, the BQ76940 device is monitoring the wake up command. This design gives two wake up method, the first method is through a button which will generate a wake up signal on TS1 pin. The second method is detecting if charger attached with circuit shown as Figure 2. When a right charge is attached, Q15 will be turned on and pull TS1 high, and because of C20 and C18, Q15 will be turned off, generating a wake up signal on TS1 pin. *Wake* signal is from the MCU and can wake up the BQ76940 from shutdown mode, also.

**Figure 2. Wake Up Circuit**



# 3 Hardware, Software, Testing Requirements, and Test Results

## 3.1 Required Hardware and Software

### 3.1.1 Hardware

The board is configured during assembly with a selection of components to be installed and there are no configuration jumpers or options prior to connection. Figure 3 shows the top side of the board.

**Figure 3. Board Top Side**

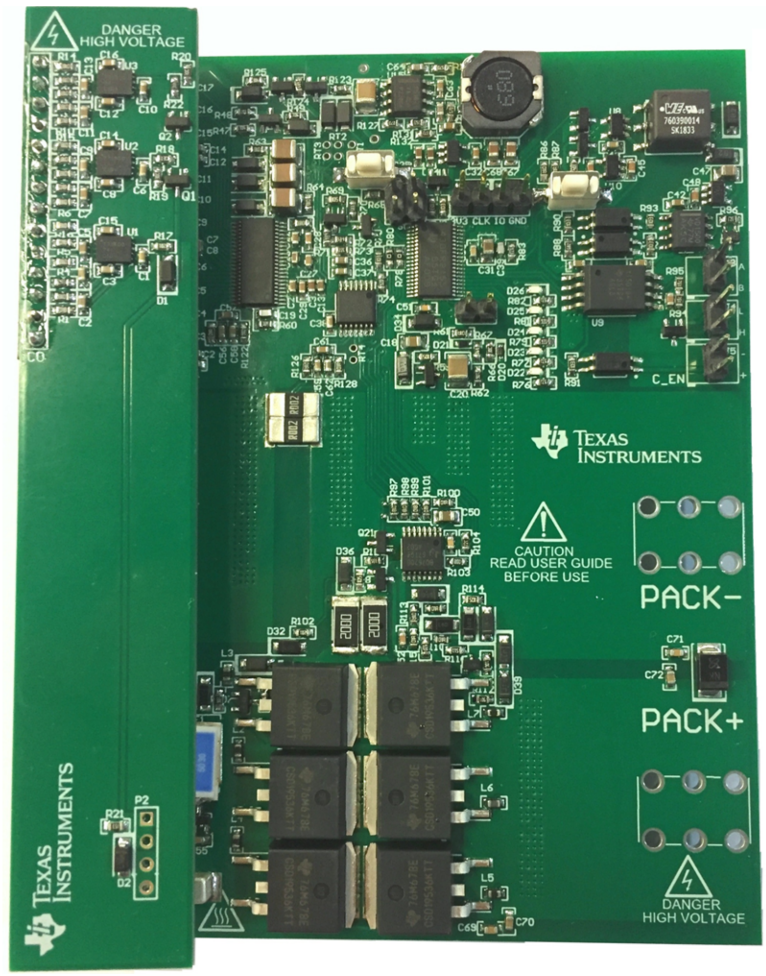



Table 2 describes the connections for the board.

**Table 2. Board Connections**

| CONNECTOR AND PIN ASSIGNMENTS | FUNCTION OR SCHEMATIC NET | NOTES |
|---|---|---|
| J1 | BAT- | Cell stack negative; this provides a reference for the electronics and the high current path from the cells |
| J2 | BAT+ | Cell stack positive; this provides power for the high-side driver and the high current path from the cells |
| | | |
| J3-1 | RS-485-B | RS485 BUS port, B |
| J3-2 | RS-485-A | RS485 BUS port, A |
| J4-1 | CAN-H | High-level CAN BUS |
| J4-2 | CAN-L | Low-level CAN BUS |

**Table 2. Board Connections (continued)**

| CONNECTOR AND PIN ASSIGNMENTS | FUNCTION OR SCHEMATIC NET | NOTES |
|---|---|---|
| J5-1 | Commu_EN | Communication control from system side |
| J5-2 | SGND | Isolated ground |
| J6 | PACK+ | Charger positive or load positive |
| J7 | PACK- | Charger negative or load negative |
| P1-1 | SDA | I2C communication SDA from bq34z100-g1 and bq76940 |
| P1-2 | SDA_MCU | I2C communication SDA from MCU |
| P1-3 | SCL | I2C communication SCL from bq34z100-g1 and bq76940 |
| P1-4 | SCL_MCU | I2C communication SCL from MCU |
| P2-1 | 3V3 | SBW program connector 3.3 V |
| P2-2 | SBCLK | SBW program connector SBCLK |
| P2-3 | SBIO | SBW program connector SBIO |
| P2-4 | GND | SBW program connector ground |
| P3-1 | Fuse_G | Secondary protection output signal |
| P3-2 | Fuse_G | Secondary protection output signal |
| P3-3 | GND | Secondary protection output reference |
| P3-4 | GND | Secondary protection output reference |
| P4, P5 | Cn | (n = 0 to 13) Cell monitor, balance, and electronics power connections. P4 is the connector with battery cells. P3 and P5 are the connectors with Secondary protection board |
| P6-1 | PRES | Detect system load attached |
| P6-2 | GND | Ground |

### 3.1.2 Software

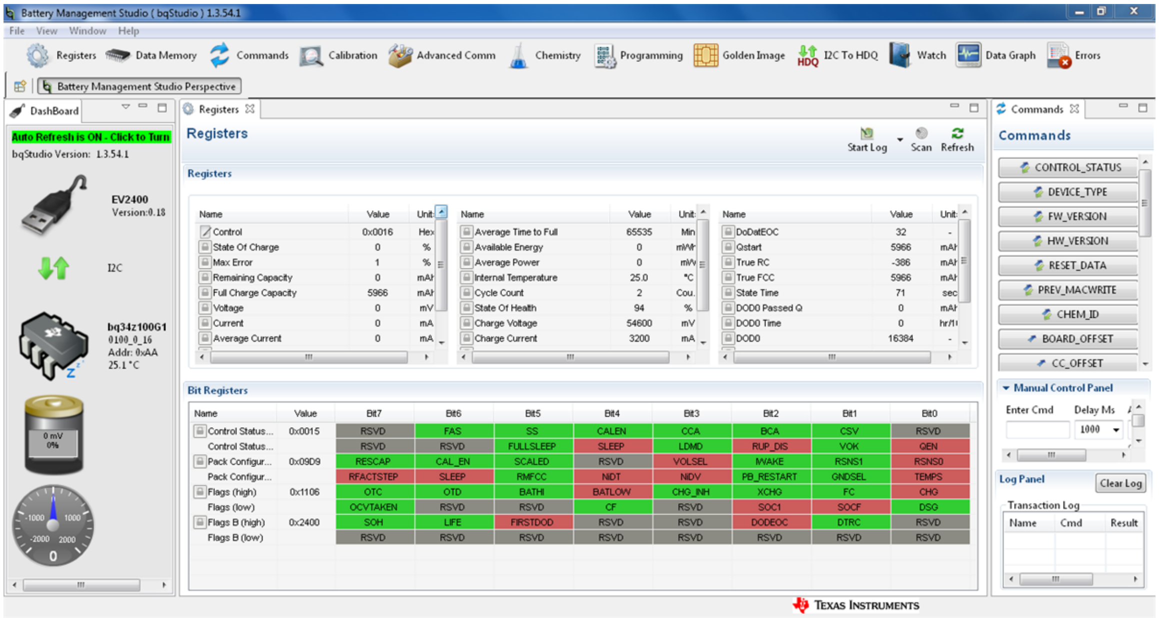
#### *3.1.2.1 Using the bq769X0 Eval Software*

Download the bq769X0 Eval Software from ti.com. It can act as a host controller to read voltage, current and temperature data from bq76940. See the *bq76930 and bq76940 Evaluation Module* user's guide to learn how to use this tool.

#### *3.1.2.2 Using bqStudio*

The bqStudio software can be started from the desktop icon or the Start → Texas Instruments → Battery Management Studio menu or equivalent for supported operating systems. When bqStudio is started while connected to a working gauge, the software detects the gauge and open its display similar to Figure 4. The dashboard section on the left side of the display shows the connected interface and part and the voltage and current of the part. The dashboard refreshes periodically but can be turned off if desired. The registers tab is displayed in the middle pane, which shows a snapshot of when the tool started or from the last refresh. The tab can be refreshed by clicking the Refresh button in the upper-right corner of the tab or by selecting the scan button for periodic update. The Start Log button starts a log of the data, which is useful for recording the gauge data over time. Across the top of the bqStudio window and below the File menu are other tools which typically open in the center tab area of the display. On the right side of the display is a Command window which the user can scrolled through to display various commands that can be selected as a button. Below the Commands window is the Log Panel, which shows the command and its result. Status messages display in the bottom border of the bqStudio window.

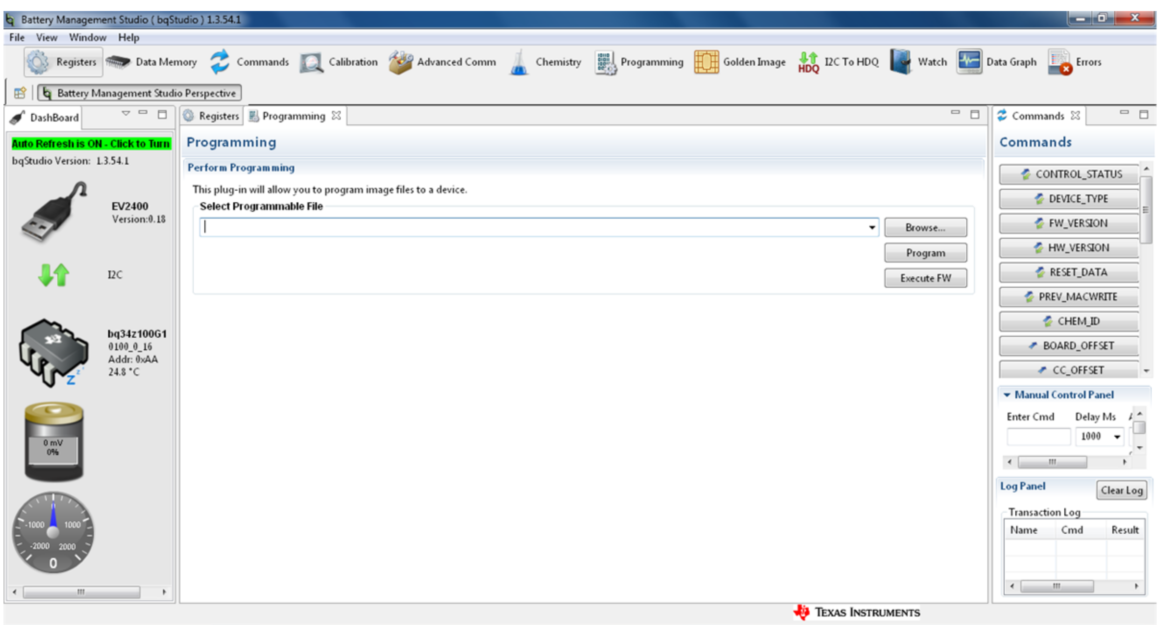
**Figure 4. bqStudio Register Display**




### 3.1.2.2.1 *Programming*

Before configure bq34z100-g1, it is recommend to program the device. Select the Programing Update window, the Program screen is shown as Figure 5. This window allows the user to program the device to a new version of firmware.

**Figure 5. Programing Screen**

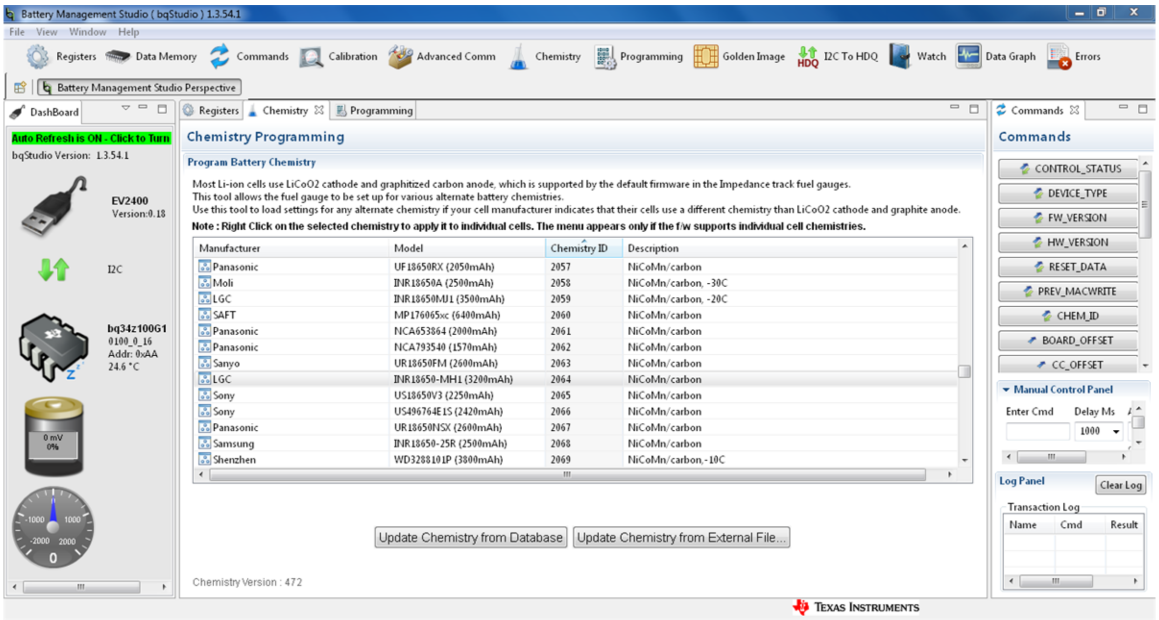



- Search for the bq34z100_G1_v0_16_build_17.srec file using the Browse button.
- Press the Program button and wait for the download to complete.
- Press the Execute FW button after the download has completed.
- Select File | Restart to initialize bqStudio to the new firmware.

#### *3.1.2.2.2 Chemistry*

The chemistry file contains parameters that the simulations use to model the cell and its operating profile. It is critical to program a Chemistry ID that matches the cell into the device. Some of these parameters can be viewed in the Data Flash section of the Battery Management Studio. Press the Chemistry button to select the Chemistry window, see Figure 6.

**Figure 6. Chemistry Screen**

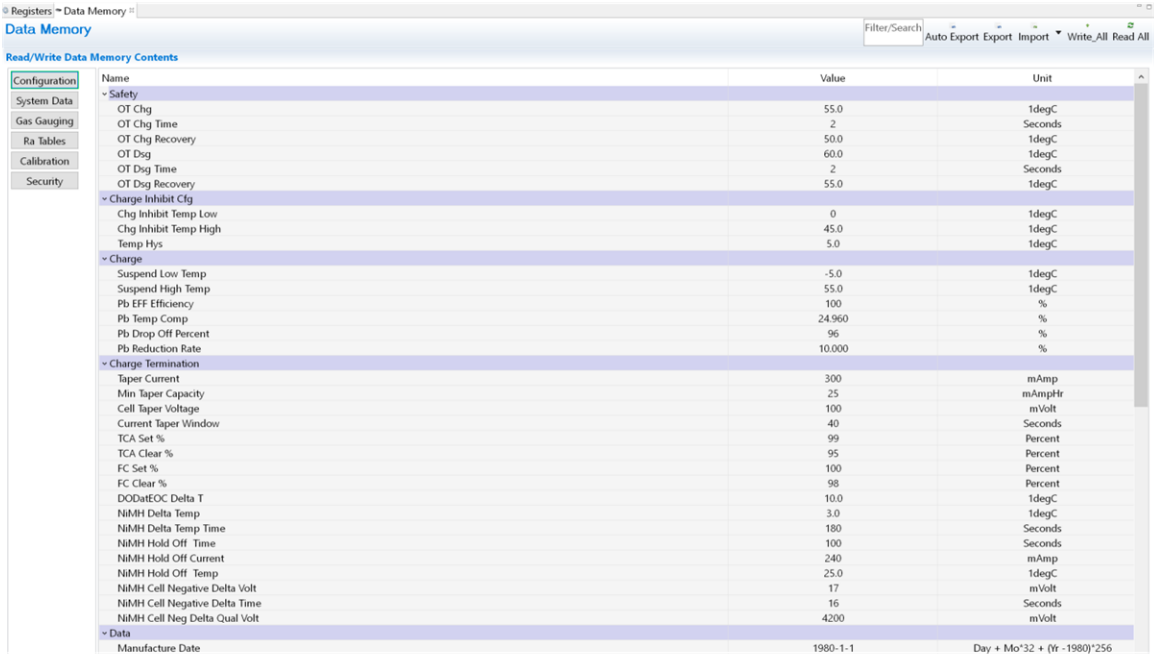



- Select the ChemID that matches your cell from the table.
- Press the Update chemistry in the data flash button to update the chemistry in the device.

#### *3.1.2.2.3 Configuration*

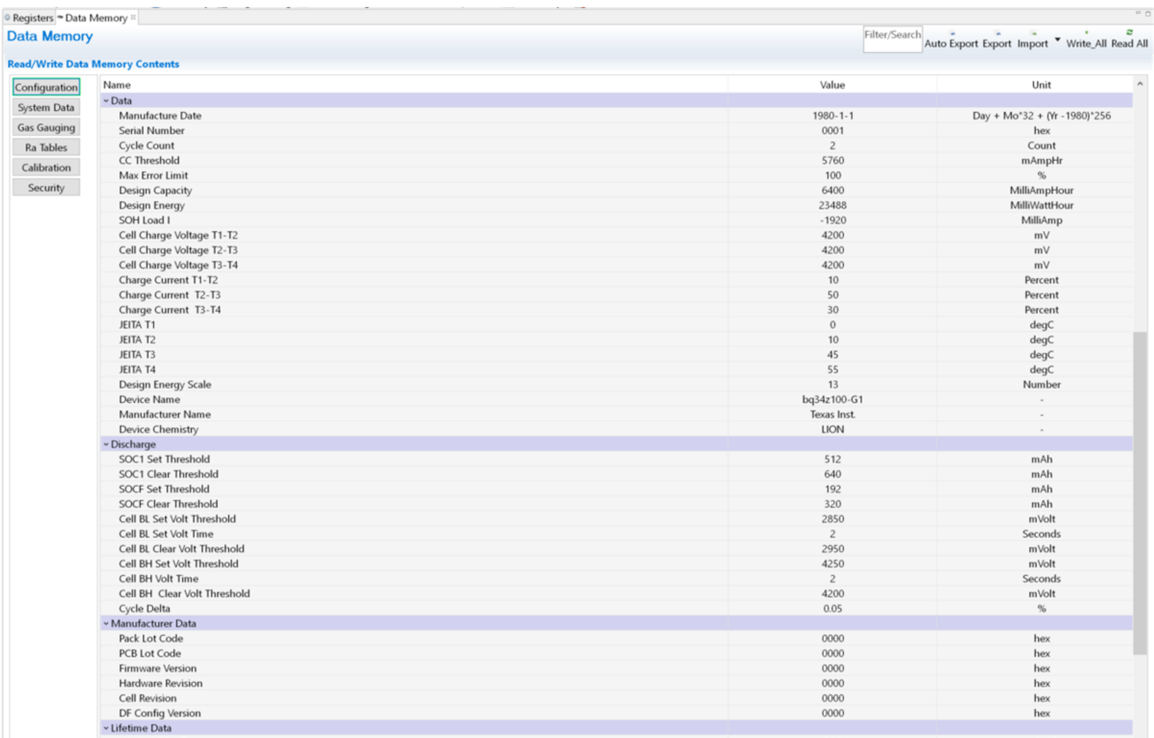
The bq34z100-g1 gauge is configured primarily using the Data Memory tab. Different sections are displayed by selecting the button for the section on the left side of the pane. The selection is written by clicking the Write To Data Memory button at the bottom of the popup. The popup must be closed with the X button in the top-left corner. All the registers configurations below Configuration of this design is shown as Figure 7, Figure 8, and Figure 9.

**Figure 7. Configuration-1**



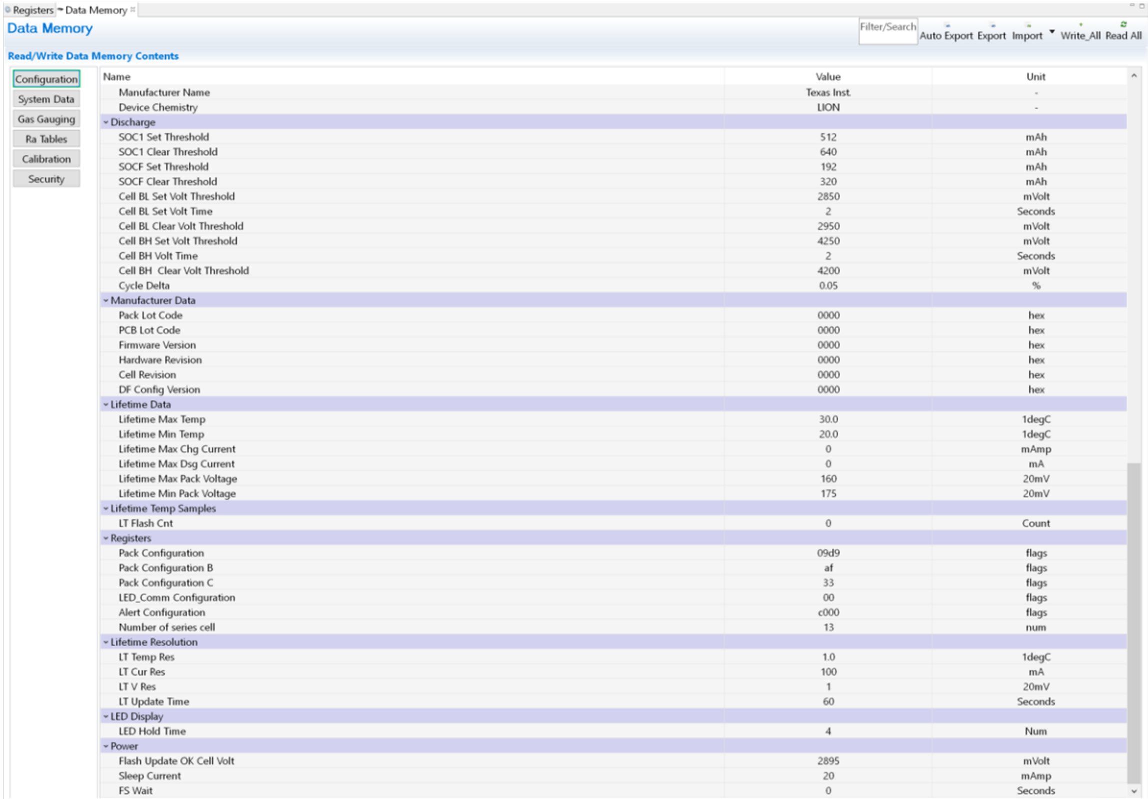

| Name | Value | Unit |
|---|---|---|
| Safety | | |
| OT Chg | 55.0 | 1degC |
| OT Chg Time | 2 | Seconds |
| OT Chg Recovery | 50.0 | 1degC |
| OT Dsg | 60.0 | 1degC |
| OT Dsg Time | 2 | Seconds |
| OT Dsg Recovery | 55.0 | 1degC |
| Charge Inhibit Cfg | | |
| Chg Inhibit Temp Low | 0 | 1degC |
| Chg Inhibit Temp High | 45.0 | 1degC |
| Temp Hys | 5.0 | 1degC |
| Charge | | |
| Suspend Low Temp | -5.0 | 1degC |
| Suspend High Temp | 55.0 | 1degC |
| Pb EFF Efficiency | 100 | % |
| Pb Temp Comp | 24.960 | % |
| Pb Drop Off Percent | 96 | % |
| Pb Reduction Rate | 10.000 | % |
| Charge Termination | | |
| Taper Current | 300 | mAmp |
| Min Taper Capacity | 25 | mAmpHr |
| Cell Taper Voltage | 100 | mVolt |
| Current Taper Window | 40 | Seconds |
| TCA Set % | 99 | Percent |
| TCA Clear % | 95 | Percent |
| FC Set % | 100 | Percent |
| FC Clear % | 98 | Percent |
| DODatEOC Delta T | 10.0 | 1degC |
| NiMH Delta Temp | 3.0 | 1degC |
| NiMH Delta Temp Time | 180 | Seconds |
| NiMH Hold Off Time | 100 | Seconds |
| NiMH Hold Off Current | 240 | mAmp |
| NiMH Hold Off Temp | 25.0 | 1degC |
| NiMH Cell Negative Delta Volt | 17 | mVolt |
| NiMH Cell Negative Delta Time | 16 | Seconds |
| NiMH Cell Neg Delta Qual Volt | 4200 | mVolt |
| Data | | |
| Manufacture Date | 1980-1-1 | Day + Mo*32 + (Yr -1980)*256 |

**Figure 8. Configuration-2**




| Name | Value | Unit |
|---|---|---|
| Data | | |
| Manufacture Date | 1980-1-1 | Day + Mo*32 + (Yr -1980)*256 |
| Serial Number | 0001 | hex |
| Cycle Count | 2 | Count |
| CC Threshold | 5760 | mAmpHr |
| Max Error Limit | 100 | % |
| Design Capacity | 6400 | MilliAmpHour |
| Design Energy | 23488 | MilliWattHour |
| SOH Load I | -1920 | MilliAmp |
| Cell Charge Voltage T1-T2 | 4200 | mV |
| Cell Charge Voltage T2-T3 | 4200 | mV |
| Cell Charge Voltage T3-T4 | 4200 | mV |
| Charge Current T1-T2 | 10 | Percent |
| Charge Current T2-T3 | 50 | Percent |
| Charge Current T3-T4 | 30 | Percent |
| JEITA T1 | 0 | degC |
| JEITA T2 | 10 | degC |
| JEITA T3 | 45 | degC |
| JEITA T4 | 55 | degC |
| Design Energy Scale | 13 | Number |
| Device Name | bq34z100-G1 | - |
| Manufacturer Name | Texas Inst. | - |
| Device Chemistry | LION | - |
| Discharge | | |
| SOC1 Set Threshold | 512 | mAh |
| SOC1 Clear Threshold | 640 | mAh |
| SOCF Set Threshold | 192 | mAh |
| SOCF Clear Threshold | 320 | mAh |
| Cell BL Set Volt Threshold | 2850 | mVolt |
| Cell BL Set Volt Time | 2 | Seconds |
| Cell BL Clear Volt Threshold | 2950 | mVolt |
| Cell BH Set Volt Threshold | 4250 | mVolt |
| Cell BH Volt Time | 2 | Seconds |
| Cell BH Clear Volt Threshold | 4200 | mVolt |
| Cycle Delta | 0.05 | % |
| Manufacturer Data | | |
| Pack Lot Code | 0000 | hex |
| PCB Lot Code | 0000 | hex |
| Firmware Version | 0000 | hex |
| Hardware Revision | 0000 | hex |
| Cell Revision | 0000 | hex |
| DF Config Version | 0000 | hex |
| Lifetime Data | | |
| Lifetime Max Temp | 30.0 | 1degC |

**Figure 9. Configuration-3**



Registers | Data Memory

Data Memory

Filter/Search | Auto Export | Export | Import | Write_All | Read All

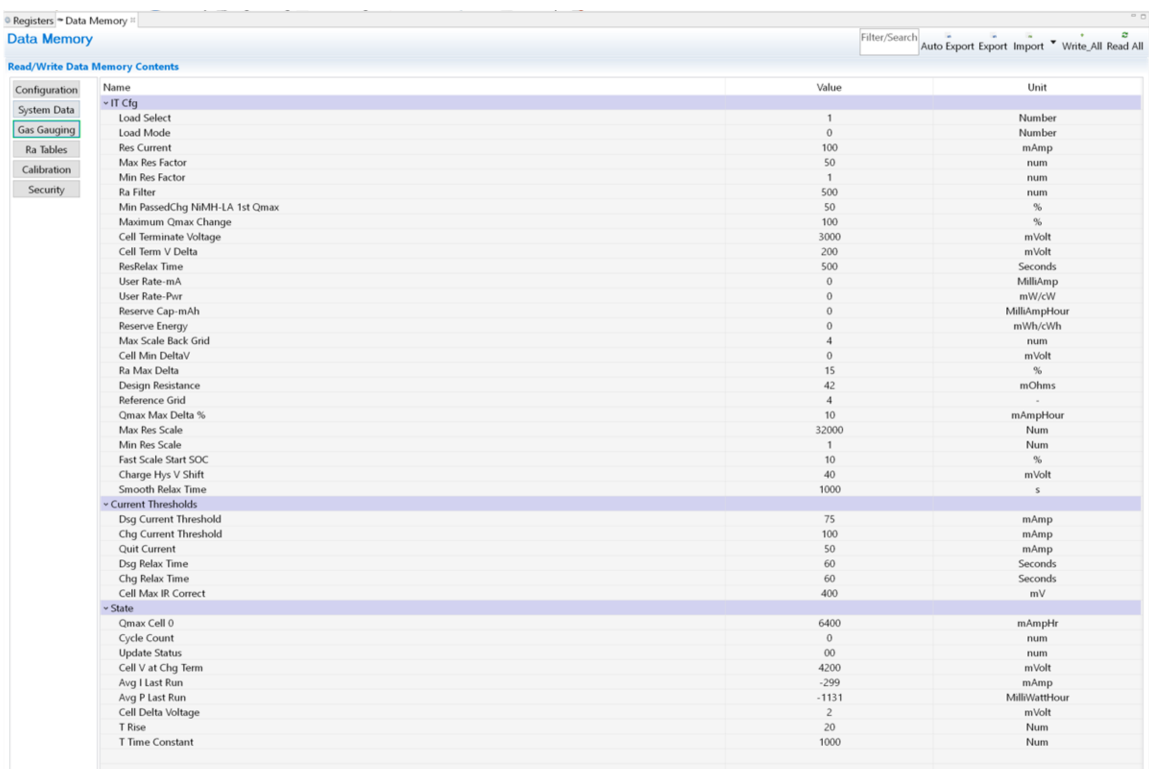
Read/Write Data Memory Contents

Configuration | System Data | Gas Gauging | Ra Tables | Calibration | Security

| Name | Value | Unit |
|---|---|---|
| Manufacturer Name | Texas Inst. | - |
| Device Chemistry | LION | - |
| Discharge | | |
| SOC1 Set Threshold | 512 | mAh |
| SOC1 Clear Threshold | 640 | mAh |
| SOCF Set Threshold | 192 | mAh |
| SOCF Clear Threshold | 320 | mAh |
| Cell BL Set Volt Threshold | 2850 | mVolt |
| Cell BL Set Volt Time | 2 | Seconds |
| Cell BL Clear Volt Threshold | 2950 | mVolt |
| Cell BH Set Volt Threshold | 4250 | mVolt |
| Cell BH Volt Time | 2 | Seconds |
| Cell BH Clear Volt Threshold | 4200 | mVolt |
| Cycle Delta | 0.05 | % |
| Manufacturer Data | | |
| Pack Lot Code | 0000 | hex |
| PCB Lot Code | 0000 | hex |
| Firmware Version | 0000 | hex |
| Hardware Revision | 0000 | hex |
| Cell Revision | 0000 | hex |
| DF Config Version | 0000 | hex |
| Lifetime Data | | |
| Lifetime Max Temp | 30.0 | 1degC |
| Lifetime Min Temp | 20.0 | 1degC |
| Lifetime Max Chg Current | 0 | mAmp |
| Lifetime Max Dsg Current | 0 | mA |
| Lifetime Max Pack Voltage | 160 | 20mV |
| Lifetime Min Pack Voltage | 175 | 20mV |
| Lifetime Temp Samples | | |
| LT Flash Cnt | 0 | Count |
| Registers | | |
| Pack Configuration | 09d9 | flags |
| Pack Configuration B | af | flags |
| Pack Configuration C | 33 | flags |
| LED_Comm Configuration | 00 | flags |
| Alert Configuration | c000 | flags |
| Number of series cell | 13 | num |
| Lifetime Resolution | | |
| LT Temp Res | 1.0 | 1degC |
| LT Cur Res | 100 | mA |
| LT V Res | 1 | 20mV |
| LT Update Time | 60 | Seconds |
| LED Display | | |
| LED Hold Time | 4 | Num |
| Power | | |
| Flash Update OK Cell Volt | 2895 | mVolt |
| Sleep Current | 20 | mAmp |
| FS Wait | 0 | Seconds |

All the registers configurations below Gas Gauging of this design is shown as Figure 10.

**Figure 10. Gas Gauging Screen**



Registers | Data Memory

Data Memory

Filter/Search | Auto Export | Export | Import | Write_All | Read All

Read/Write Data Memory Contents

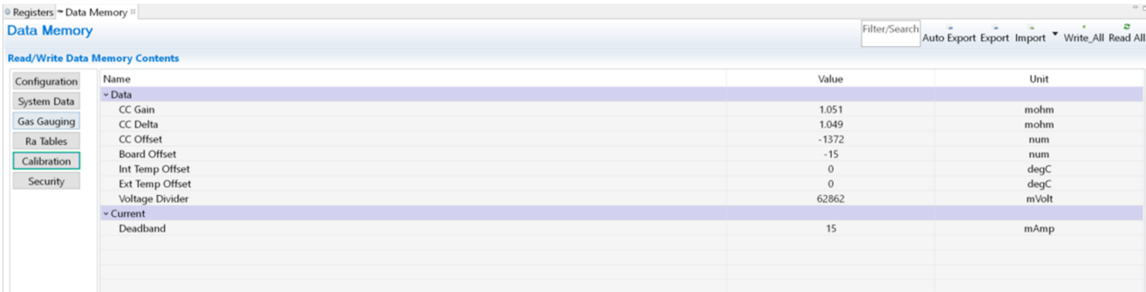
Configuration | System Data | Gas Gauging | Ra Tables | Calibration | Security

| Name | Value | Unit |
|---|---|---|
| IT Cfg | | |
| Load Select | 1 | Number |
| Load Mode | 0 | Number |
| Res Current | 100 | mAmp |
| Max Res Factor | 50 | num |
| Min Res Factor | 1 | num |
| Ra Filter | 500 | num |
| Min PassedChg NiMH-LA 1st Qmax | 50 | % |
| Maximum Qmax Change | 100 | % |
| Cell Terminate Voltage | 3000 | mVolt |
| Cell Term V Delta | 200 | mVolt |
| ResRelax Time | 500 | Seconds |
| User Rate-mA | 0 | MilliAmp |
| User Rate-Pwr | 0 | mW/cW |
| Reserve Cap-mAh | 0 | MilliAmpHour |
| Reserve Energy | 0 | mWh/cWh |
| Max Scale Back Grid | 4 | num |
| Cell Min DeltaV | 0 | mVolt |
| Ra Max Delta | 15 | % |
| Design Resistance | 42 | mOhms |
| Reference Grid | 4 | - |
| Qmax Max Delta % | 10 | mAmpHour |
| Max Res Scale | 32000 | Num |
| Min Res Scale | 1 | Num |
| Fast Scale Start SOC | 10 | % |
| Charge Hys V Shift | 40 | mVolt |
| Smooth Relax Time | 1000 | s |
| Current Thresholds | | |
| Dsg Current Threshold | 75 | mAmp |
| Chg Current Threshold | 100 | mAmp |
| Quit Current | 50 | mAmp |
| Dsg Relax Time | 60 | Seconds |
| Chg Relax Time | 60 | Seconds |
| Cell Max IR Correct | 400 | mV |
| State | | |
| Qmax Cell 0 | 6400 | mAmpHr |
| Cycle Count | 0 | num |
| Update Status | 00 | num |
| Cell V at Chg Term | 4200 | mVolt |
| Avg I Last Run | -299 | mAmp |
| Avg P Last Run | -1131 | MilliWattHour |
| Cell Delta Voltage | 2 | mVolt |
| T Rise | 20 | Num |
| T Time Constant | 1000 | Num |

#### *3.1.2.2.4 Calibration*

The Calibration of this design is shown as Figure 11. The voltage and current must be calibrated before normal operation.

**Figure 11. Calibration Screen**




Voltage Calibration

- Measure the voltage from BAT+ to BAT– and enter this value in the Applied Voltage field and select the Calibrate Voltage box.
- Press the Calibrate Gas Gauge button to calibrate the voltage measurement system.
- Deselect the Calibrate Voltage boxes after voltage calibration has completed.

If this doesn't work, users can also manually input the Voltage Divider value to do the voltage calibration.

Temperature Calibration

- Enter the room temperature in the Applied Temperature field and select the Calibrate Temperature box and select the thermistor to be calibrated. The temperature value must be entered in degrees Celsius.
- Press the Calibrate Gas Gauge button to calibrate the temperature measurement system.
- Deselect the Calibrate Temperature box after temperature calibration has completed.

Current Calibration

- Select the Calibrate CC Offset and Calibrate Board Offset boxes and insure that there is no current flow.
- Press the Calibrate Gas Gauge button to calibrate.
- Deselect the Calibrate CC Offset and Calibrate Board Offset boxes after current calibration has completed.
- Connect and measure a 2-A load from PACK- and BAT– to calibrate the current gain.
- Enter –2000 in the Applied Current field and select the Calibrate Current box.
- Press the Calibrate Gas Gauge button to calibrate.
- Deselect the Calibrate Current box after current calibration has completed.

### *3.1.2.3 MSP430 MCU™ Firmware*

To achieve quite low standby current consumption, the MSP430 MCU™ firmware has to be carefully designed. This design gives an example of the firmware. The program flow chart is shown in Figure 12, Figure 13, and Figure 14. Figure 15 shows the faults handling.

**Figure 12. MSP430 MCU™ Firmware Program Flow Chart**

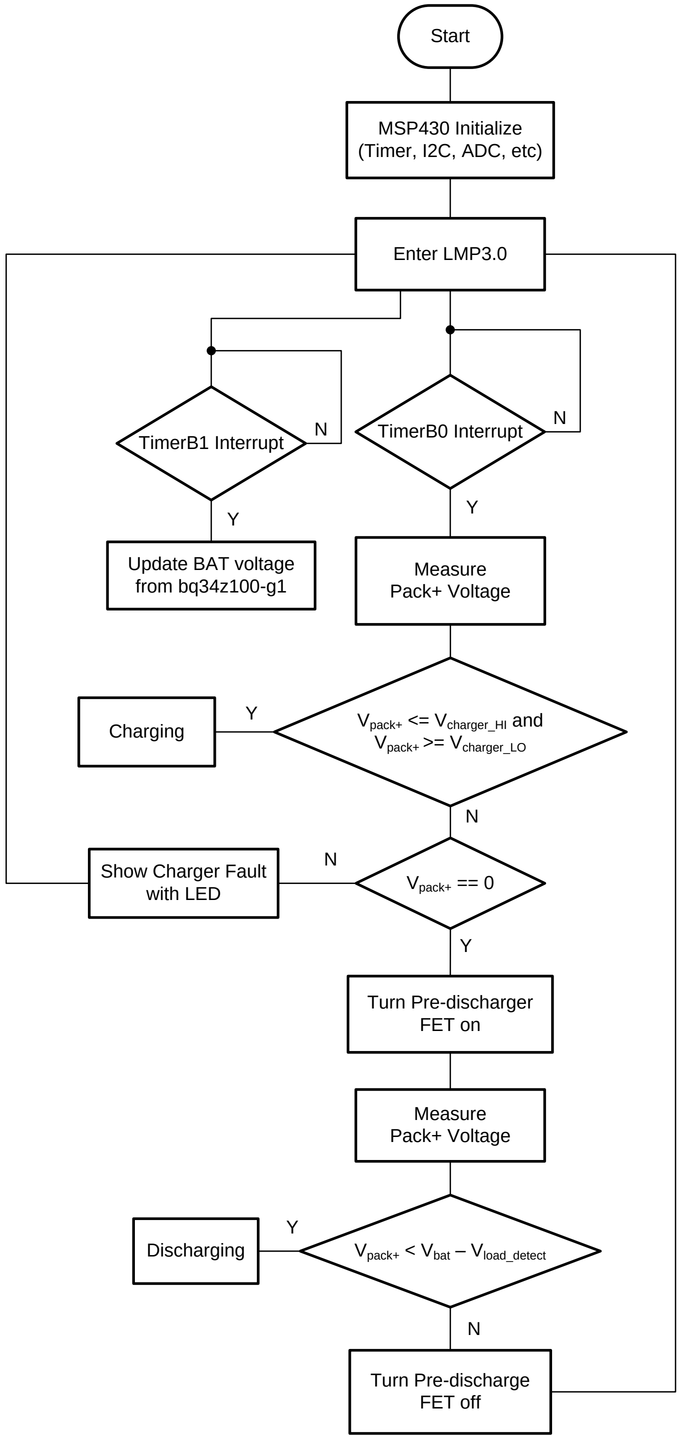


**Figure 13. Charging Firmware Program Flow Chart**

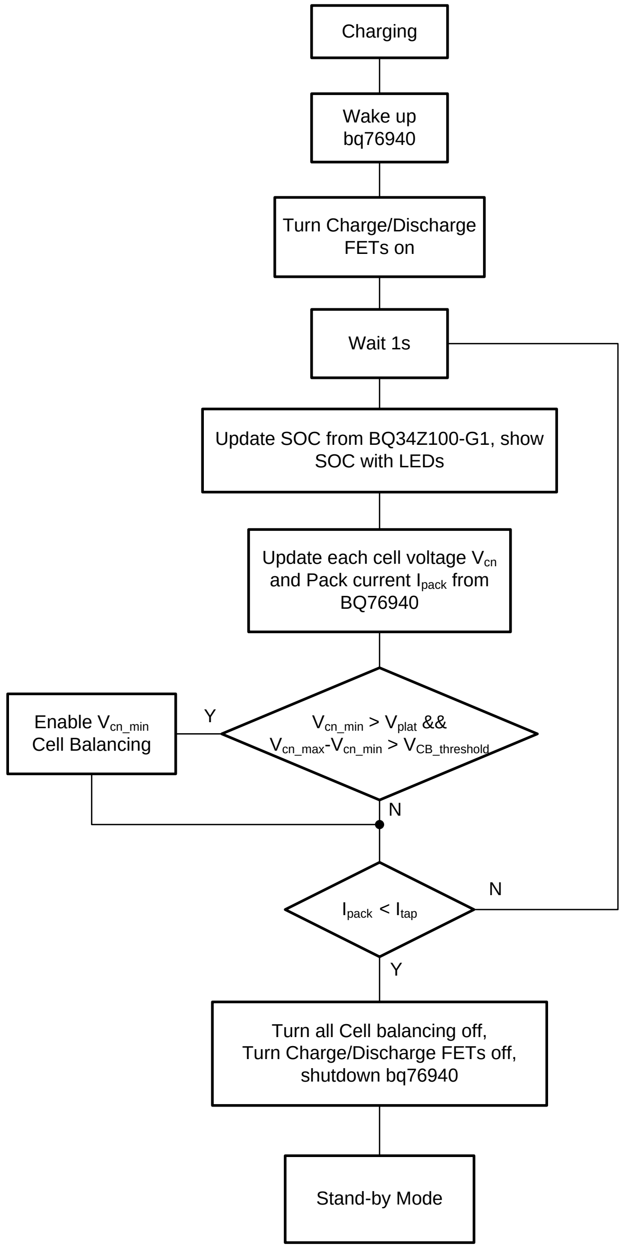


**Figure 14. Discharging Firmware Program Flow Chart**

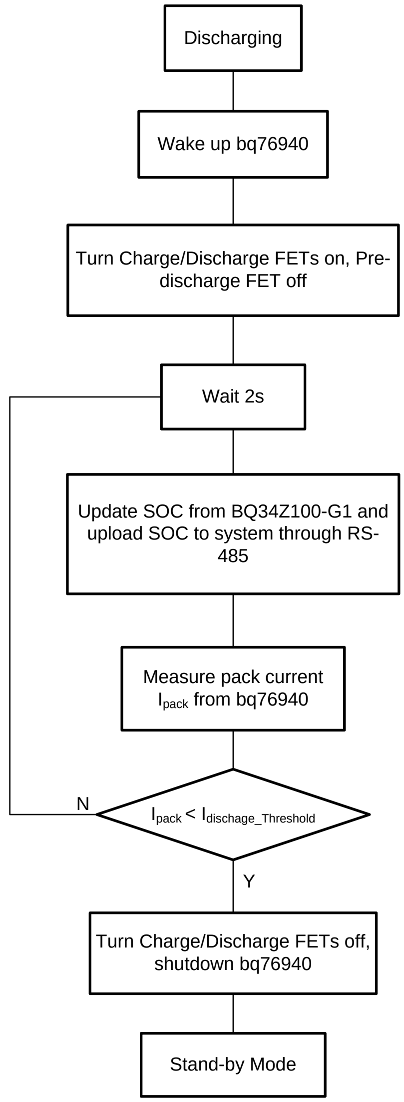
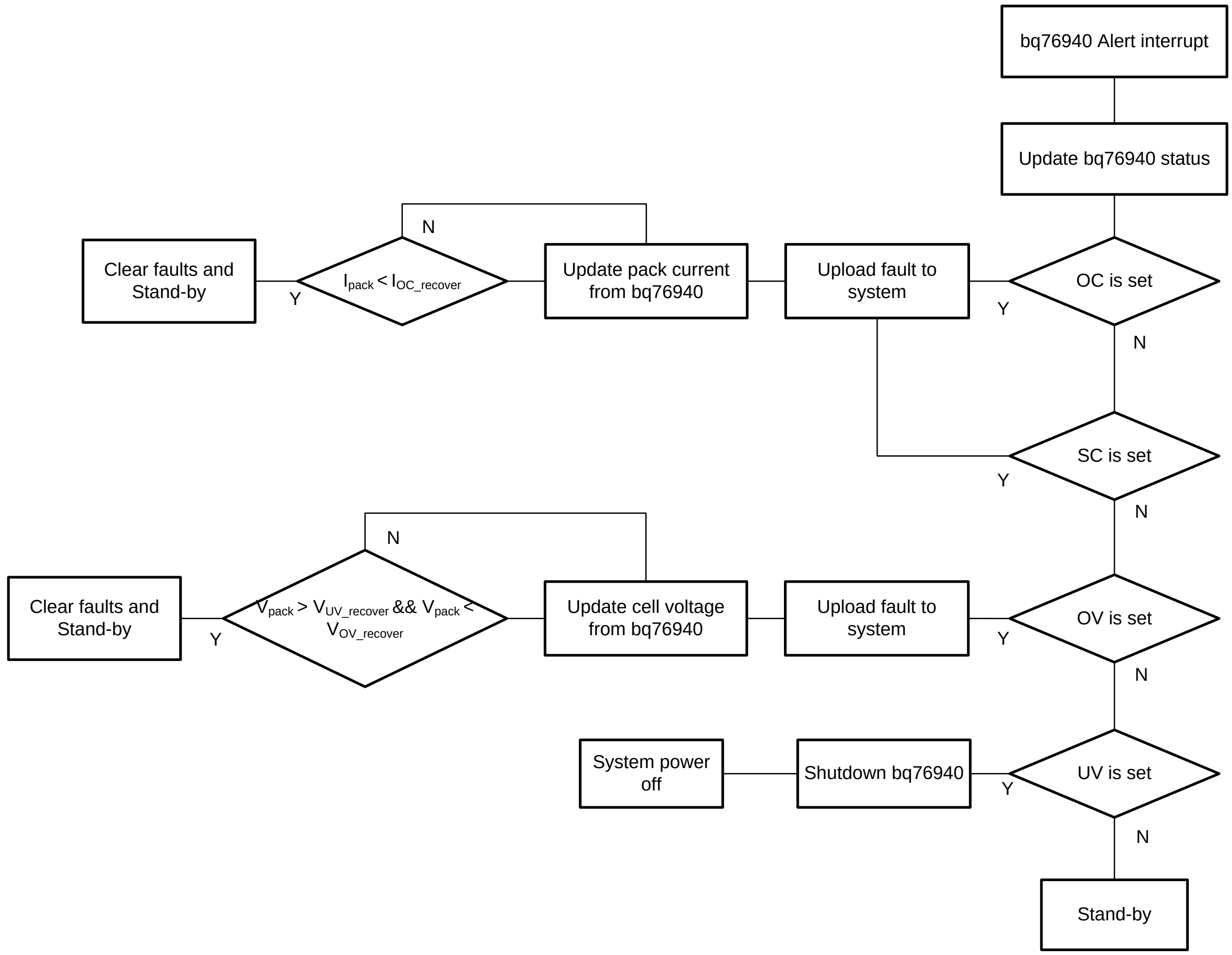


**Figure 15. Faults Handling**



## 3.2 Testing and Results

### 3.2.1 Test Setup

The following procedures should be followed before running this design board. The design was constructed with 13S pack configurations and tested using both equipment and battery cells. Board calibration was performed using simulated cells powered by a DC power supply. Learning cycle and normal testing was performed using a 13S2P cell assembly. Table 3 summarizes the equipment used for testing.

**Table 3. Test Equipment Summary**

| EQUIPMENT | MODEL OR DESCRIPTION |
|---|---|
| Oscilloscope | Tektronix DPO 3054 |
| DC Power supply | Chroma 62050P-100-100 |
| Electronic load | Chroma 63106 |
| Multimeter | Agilent 34401A |
| Communication adapter | Texas Instruments EV2300 or EV2400 |
| MSP430 programmer | MSP430 LaunchPad™ |
| Battery cell | INR18650 MH1 3200 mAh |

#### 3.2.1.1 Calibration Setup

The board voltage and current calibration was performed using DC power supply. Figure 16 shows the voltage calibration setup example, Figure 17 shows the current calibration setup example. After setup the board, press S1 button to wake up the system, then open bqStudio software and follow Section 3.1.2.2.4 to finish voltage and current calibration.

**Figure 16. Voltage Calibration Setup**

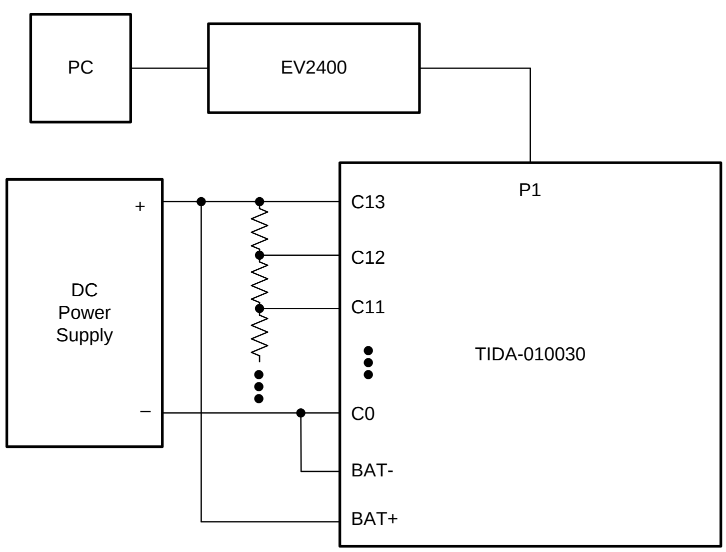
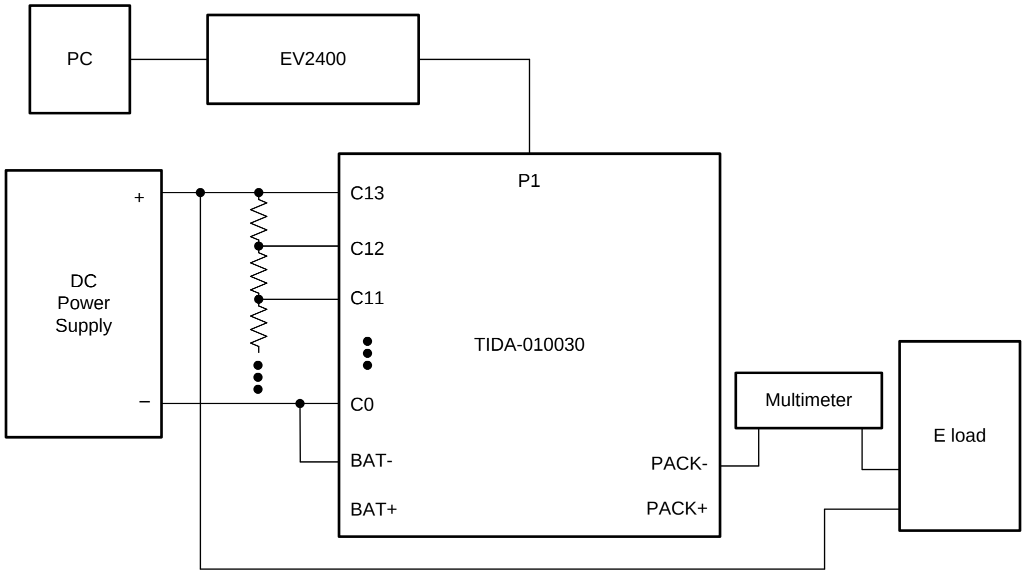


**Figure 17. Current Calibration Setup**

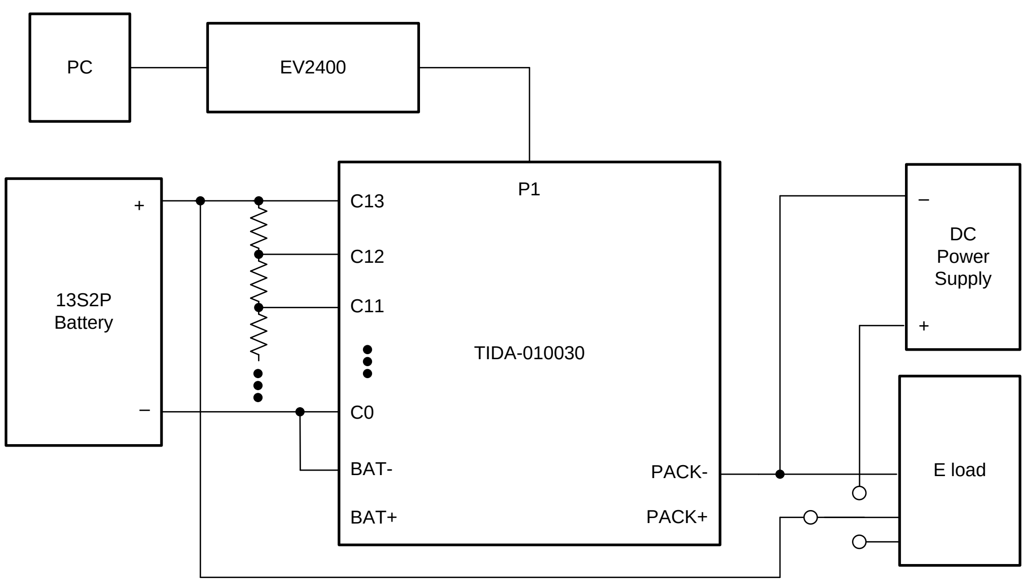



### 3.2.1.2 Learning Cycle

After the board calibration and configuration, a learning cycle should be finished with battery cells. The matched Chemistry ID much be programmed to the device before doing learning cycle (See Section 3.1.2.2.2). Figure 18 shows the example setup for learning cycle. Follow below process to finish a learning cycle.

- Discharge the battery until the voltage reaches the term voltage
- Relax for at least 5 hours
- Use IT_ENABLE command to set the QEN in Control Status register
- Charge the battery to full with 0.2C
- Relax at least 2 hours until VOK is clear
- Discharge the battery until the voltage reaches the Term Voltage with 0.2C
- Relax at least 5 hours

**Figure 18. Learning Cycle Setup**



After a successful learning cycle, the board is ready for testing. Figure 19 shows the normal charging setup. Figure 20 shows the normal discharging setup.

**Figure 19. Normal Charging Setup**

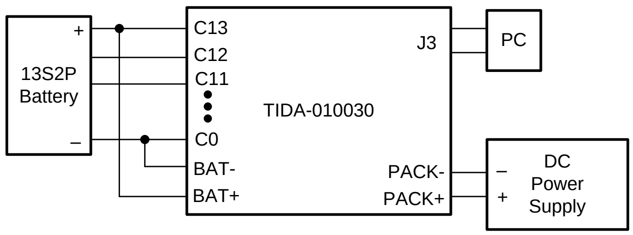
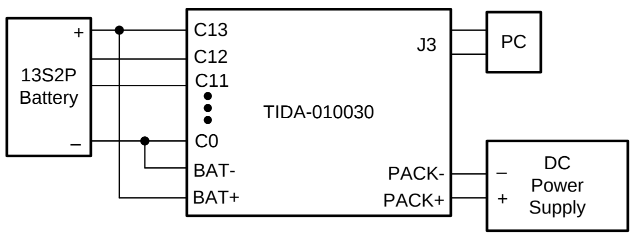



**Figure 20. Normal Discharging Setup**




### 3.2.2 Test Results

#### *3.2.2.1 Boot*

The 3.3-V MCU is powered by the DC/DC converter, LM5164, and the input of the LM5164 is controlled by two signals: REGOUT from the BQ76940 and SYS from the MCU. Either of them is high will enable the input of the LM5164 and therefore enable the MCU power supply. When the board is powered on for the first time, the board is in ship mode. The whole system, except for the BQ76940, is not powered on. Choose either of the following methods to wake the system up. The first method is through pressing button S1. Figure 21 shows BQ76940 TS1 PIN and REGOUT PIN voltage waveform. The REGOUT PIN is set high after 1-ms delay from when the S1 button is pressed. The second method to wake the board is to attach a charger. When the battery pack has low battery voltage, the board will also enter ship mode. When at this mode, wake the board up by attaching a charger. Figure 22 shows the test result. Both methods will generate a rising edge on TS1 PIN. Then set REGOUT high to enable the MCU power supply. When the MCU is powered on, it will set SYS high. The whole system has stable power supply regardless of if the BQ76940 is in shutdown or normal mode.

**Figure 21. Wake up With Button**

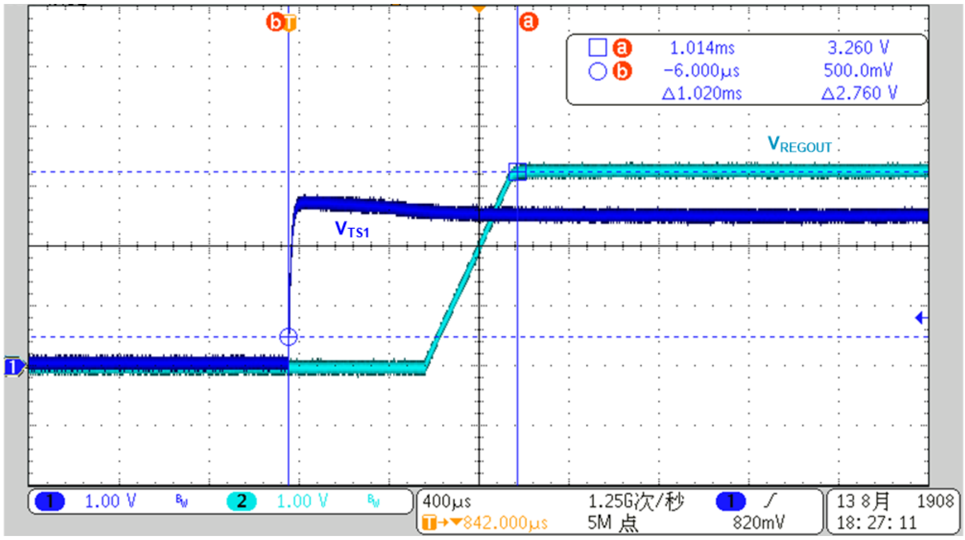
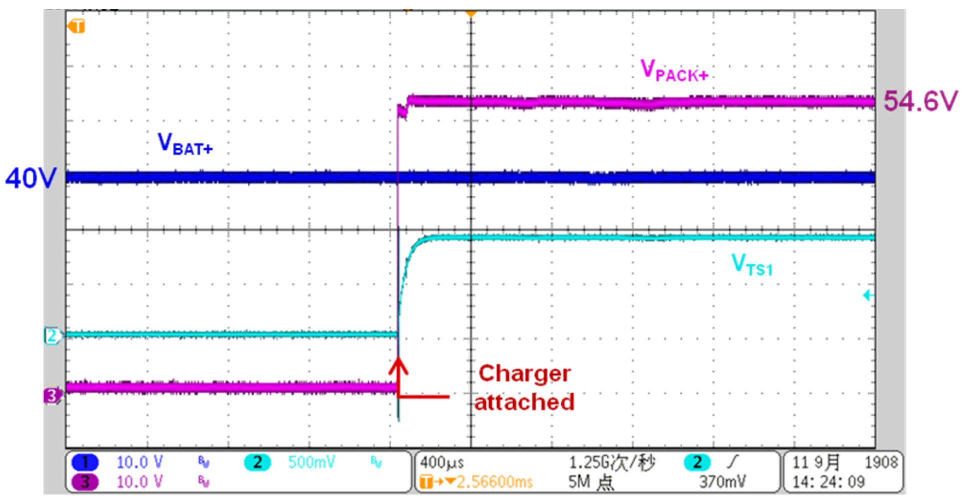


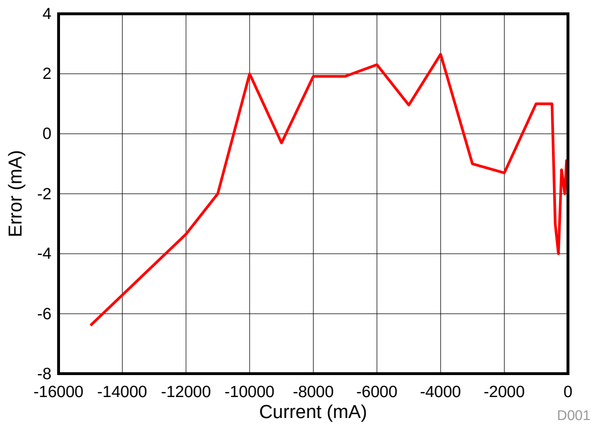

**Figure 22. Wake up With Charger**




### 3.2.2.2 *Voltage & Current Accuracy*

Before normal using, the board needs to be calibrated. After calibration, the voltage and current measurement should have good accuracy. Figure 23 shows the BQ76940 cell voltage measurement accuracy. The voltage error is typically below ±10 mV. Figure 24 shows BQ34z100-g1 voltage measurement accuracy. The voltage error is typically below ±20 mV. Figure 25 shows BQ34z100-g1 current measurement accuracy where the error is below ±10 mA. The BQ76940 measures the voltage across the current sensing resister and sends the voltage data out through $I^2C$. The firmware should do the calculation and gets the current information. There is no BQ76940 current measurement accuracy test result. The information can be attained from the firmware.

**Figure 23. bq76940 Cell Voltage Accuracy**




D001_TIDA-010030.grf

**Figure 24. bq34z100-g1 Voltage Accuracy**

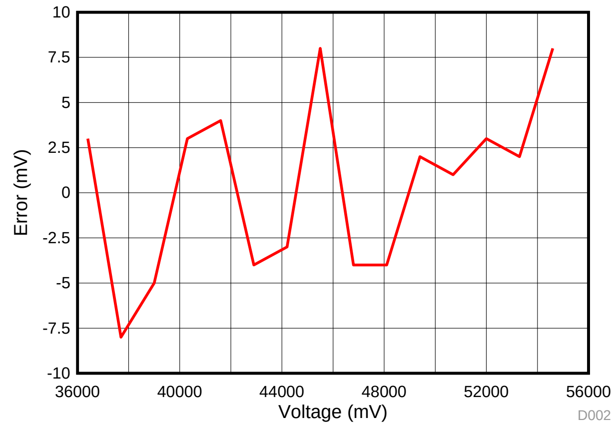
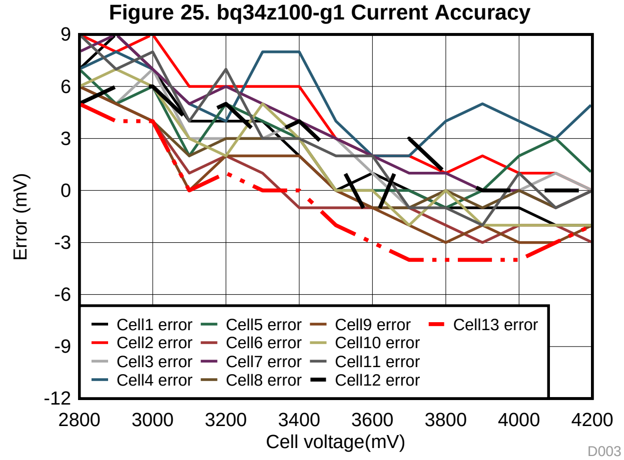


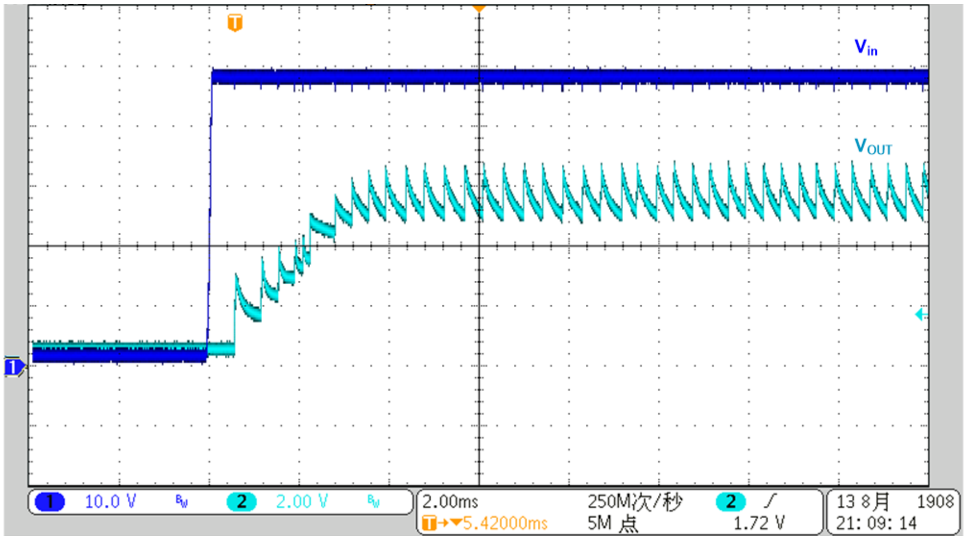

**Figure 25. bq34z100-g1 Current Accuracy**



### 3.2.2.3 DC/DC BUCK

This design is powered by a BUCK converter. To decrease light load consumption, LM5164 will enter DCM and decrease switching frequency. Figure 26 shows the BUCK converter start-up waveform.

**Figure 26. BUCK Start up**




### 3.2.2.4 Standby Mode

In this design, standby mode refers to two kind of scenarios: when the battery pack is outside of the e-bike and when the battery pack is put inside of the e-bike but not running. Because this design is for using the same charge and discharge port, the charger is only attached in the first scenario. The battery pack in the first scenario should be able to detect if the charger is attached or if the battery pack is put inside of the e-bike. The battery pack in the second scenario should be able to detect if load is on or if the battery pack is plugged in outside of the e-bike. Figure 27 shows the standby test waveforms in the first scenario. The dark blue curve is the pre-discharge MOSFET drive voltage and the green curve is PMON of the BQ76200, which controls a switch to measure PACK side voltage. The light blue curve is the PACK side voltage. The first pulse of PMON is to measure PACK voltage with pre-discharge MOSFET off. If the charger is attached, the voltage should be equal to 54.6 V. If not, the pre-discharge will be turned on. After a short time delay, the PACK voltage will be measured again. If the battery pack is put in the e-bike, a large capacitor will be connected between PACK+ and PACK-, therefore, the measured voltage is lower than the battery voltage. Otherwise, the PACK voltage is equal to the battery voltage. The detection sequence happens every 200 ms, which will not cause obvious delay. In the second scenario, the pre-discharge MOSFET is mostly on. If load is on, there will be a voltage drop across the resister series with the pre-discharge MOSFET, therefore, the measured voltage is lower than the battery voltage. If not, the pre-discharge will turn off. After a some time delay, the PACK voltage is measured. If the battery pack is plugged outside of the e-bike, the output capacitor is much smaller, which will cause a larger voltage drop. The waveforms are shown in Figure 28.

**Figure 27. Standby Scenario 1 Test Waveforms**

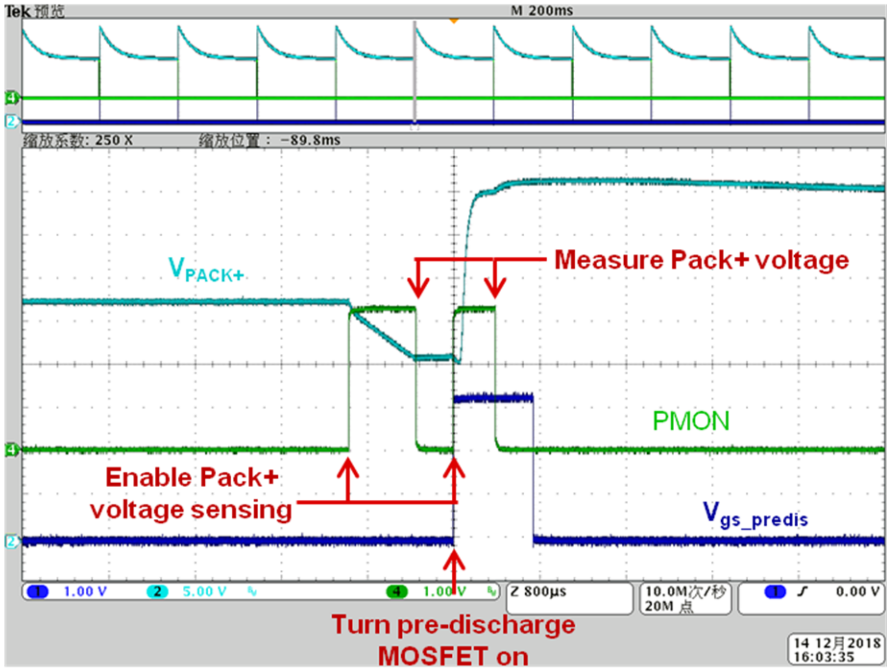
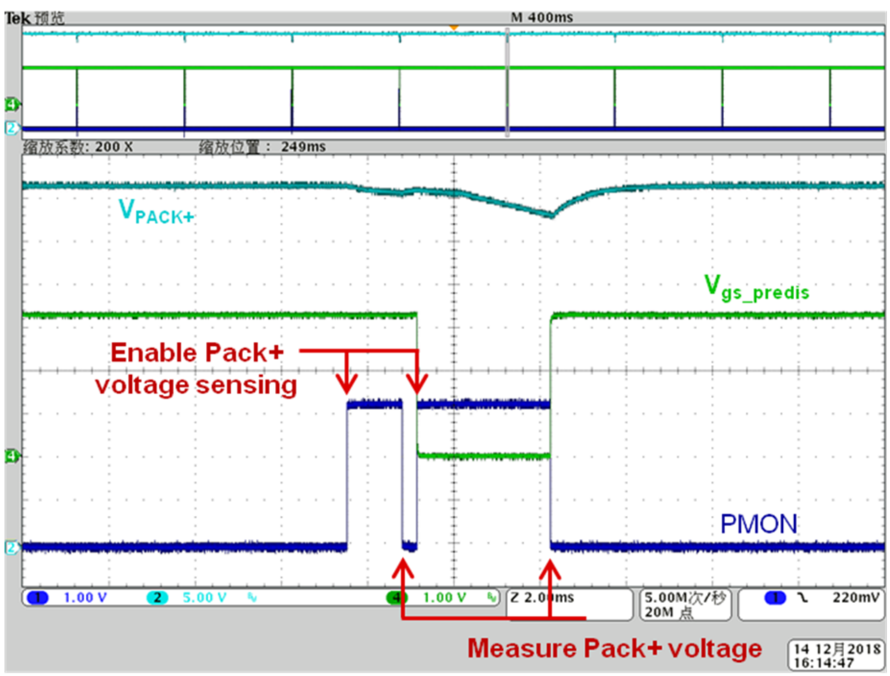



**Figure 28. Standby Scenario 2 Test Waveforms**




When in standby mode in the second scenario and when the load is turned on, the pre-discharge MOSFET will allow a small current to power the system. The charge and discharge MOSFETs are turned on after some delay. Figure 29 shows the test waveforms. The purple curve is the discharge MOSFET drive voltage, the blue curve is the PACK side voltage, and the green curve is the discharge load. Figure 30 shows the test waveforms when the load is off and when the system enters standby mode in the second scenario.

**Figure 29. Standby Scenario 2 Detect Load**

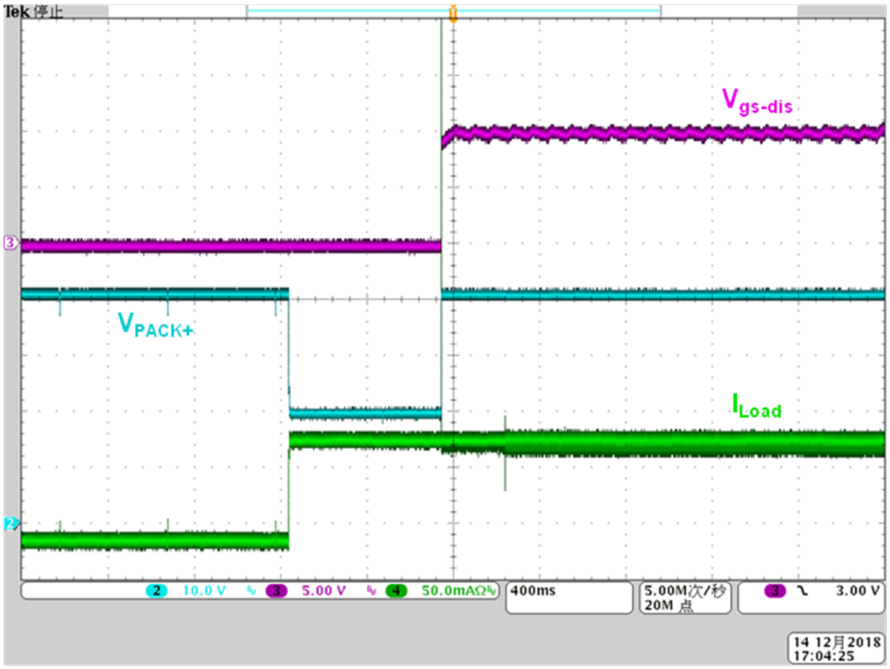
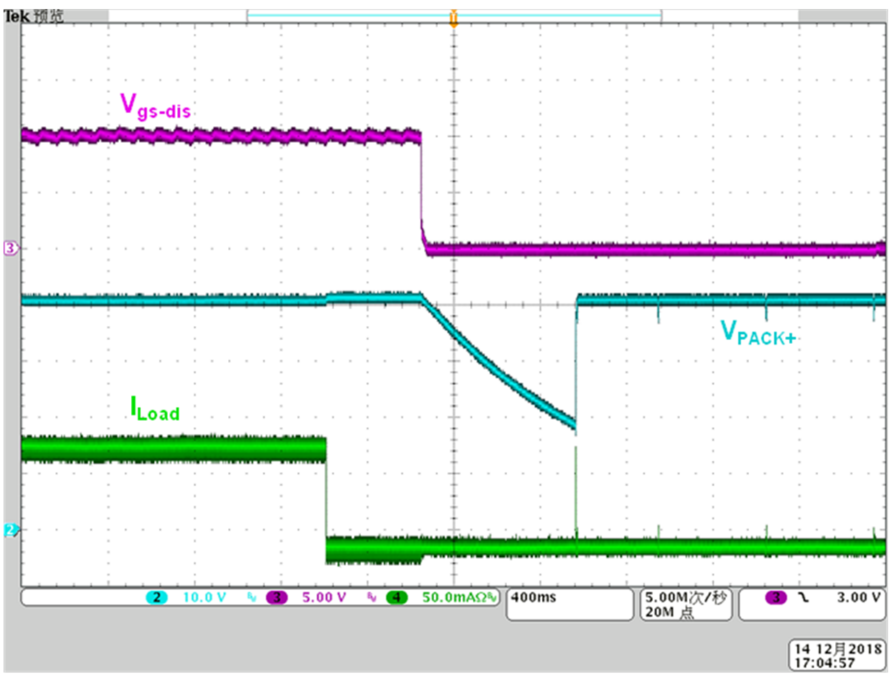



**Figure 30. Load Off to Standby Scenario 2**




When in standby mode in the first scenario and and the charger is attached, Figure 31 shows the resulting test waveforms. The purple curve is the charge MOSFET drive voltage, the light blue curve is the PACK side voltage, the dark blue curve is the battery voltage, and the green curve is the discharge load. When the charger MOSFET is turned on, the PACK side voltage is clamped to the battery voltage. Figure 32 shows the test waveforms when the charger is removed and the system enters standby mode in the first scenario.

**Figure 31. Standby Scenario 1 Detect Charger**

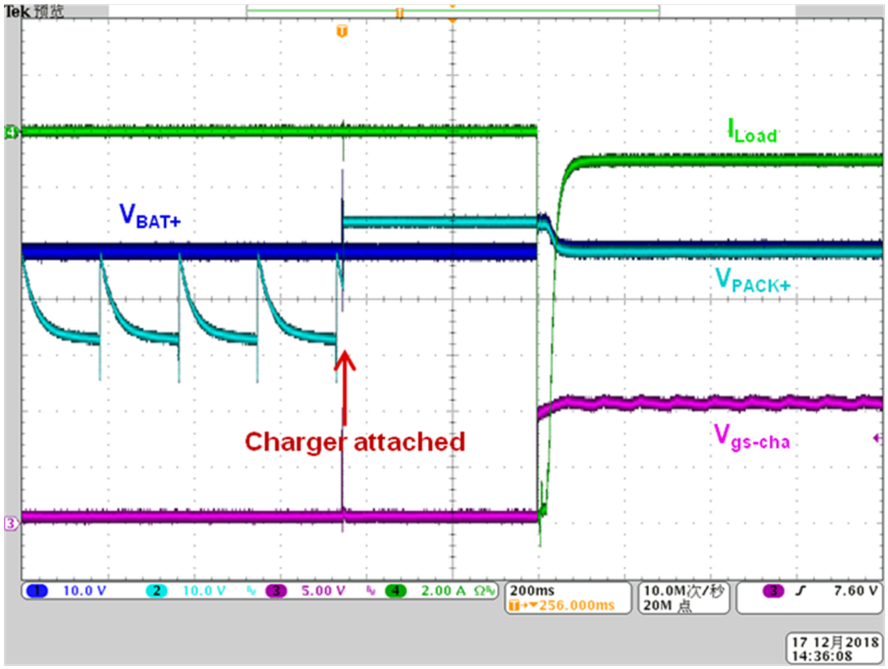
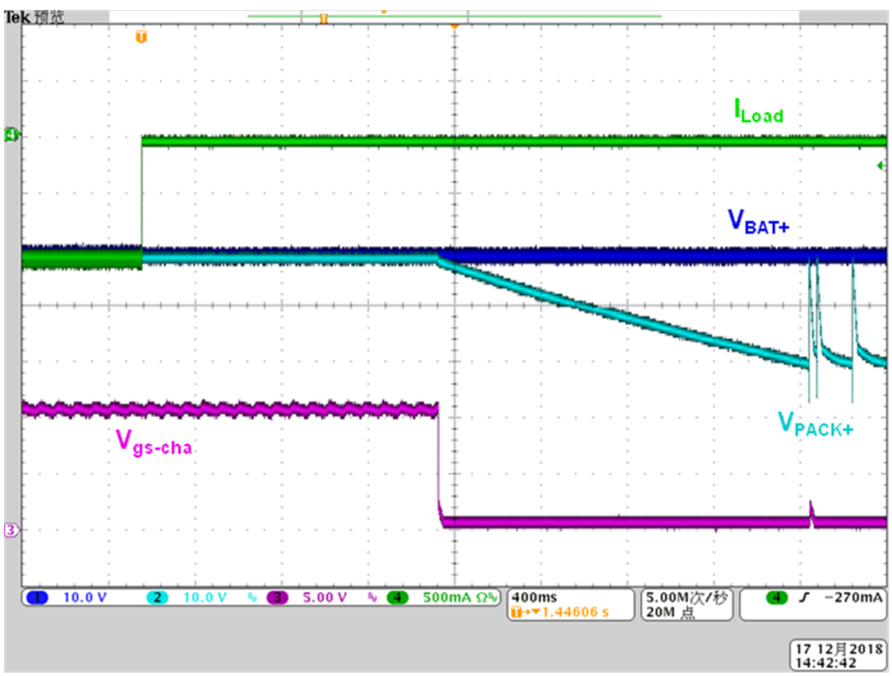


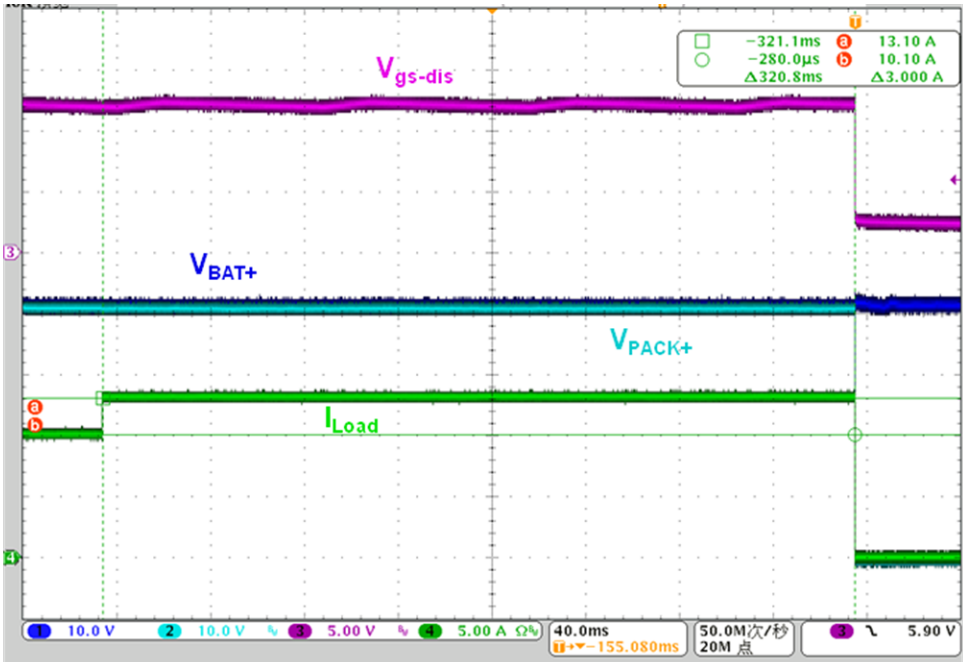

**Figure 32. Charger Removed to Standby Scenario 1**



### 3.2.2.5 Protections

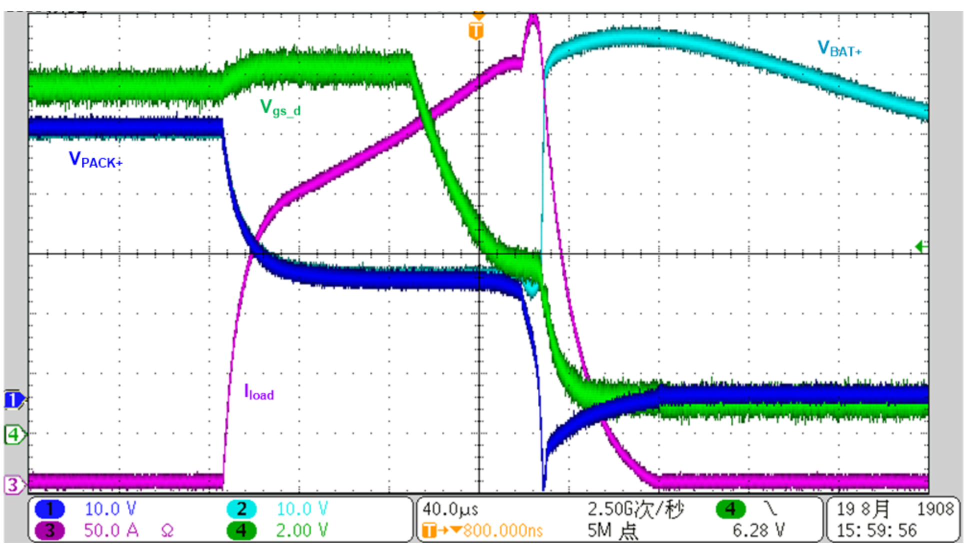
The firmware configures the OCD threshold at 11 mV which turns out about 11-A discharge current with the delay is set at 320 ms. Figure 33 shows the waveform. The green curve is discharge current, the dark blue curve is the battery voltage, the light blue is the PACK side voltage, and the purple curve is the discharge MOSFET drive voltage. When the discharge current is switched from 10.1 A to 13.1 A after a 320-ms delay, the discharge MOSFET is turned off to stop the discharging.

**Figure 33. Overcurrent Discharge Protection**




To test the design's short circuit protection feature, a switch is used to short PACK+ to PACK–. Figure 34 illustrates the SCD triggered. The purple curve is the discharge load, the dark blue curve is the PACK side voltage, the light blue curve is the battery voltage, and the green curve is the discharge MOSFET drive voltage. When the switch shorts PACK+ and PACK-, the current increases quickly to the SCD threshold, 22 A. Meanwhile, the PACK side voltage is pulled to a low value. After a delay of about 70 µs, the discharge MOSFET is turned off and stops the discharging.

**Figure 34. Short-Circuit Discharge Protection**



### 3.2.2.6 SOC Gauging

The SOC gauging accuracy is tested at room temperature. The SOC result is shown in Figure 36. There are 3 stages of discharging: 1.28-A discharge, 1-A discharge, and 1.28-A discharge. Figure 35 shows the SOC error. The maximum error is less than 2%.

**Figure 35. SOC Result**

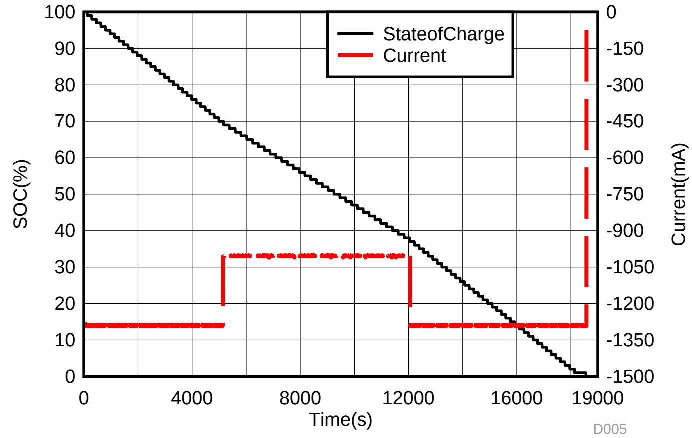
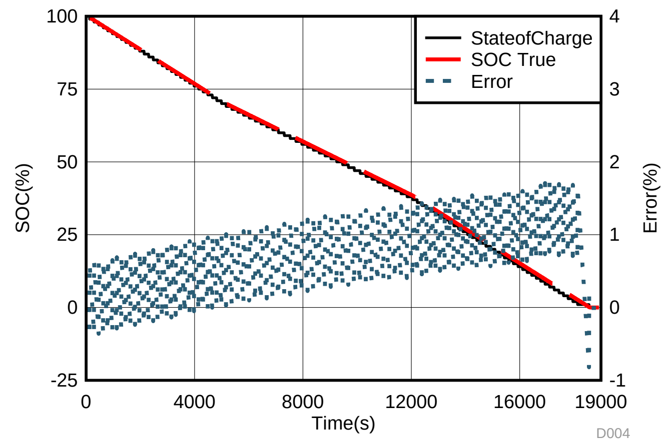



**Figure 36. SOC Error**



# 4 Design Files

## 4.1 Schematics

To download the schematics, see the design files at TIDA-010030.

## 4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-010030.

## 4.3 PCB Layout Recommendations

### 4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-010030.

## 4.4 Altium Project

To download the Altium Designer® project files, see the design files at TIDA-010030.

## 4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-010030.

## 4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-010030.

# 5 Software Files

To download the software files, see the design files at TIDA-010030.

# 6 Related Documentation

1. Texas Instruments, *bq34z100EVM wide range impedance track™ enabled battery fuel gauge solution user's guide*
2. Texas Instruments, *bq34z100-G1 wide range fuel gauge with impedance track™ technology data sheet*
3. Texas Instruments, *bq76930 and bq76940 evaluation module user's guide*
4. Texas Instruments, *bq769x0 3-series to 15-series cell battery monitor family for Li-Ion and phosphate applications data sheet*
5. Texas Instruments, *LM5164 100-V input, 1-A synchronous buck DC/DC converter with ultra-low $I_Q$ data sheet*

## 6.1 Trademarks

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Altium Designer is a registered trademark of Altium LLC or its affiliated companies.
All other trademarks are the property of their respective owners.

## Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

| Changes from A Revision (February 2019) to B Revision | Page |
|---|---|
| • Added *This reference design was implemented for a 2-layer PCB.* | 1 |

| Changes from Original (December 2018) to A Revision | Page |
|---|---|
| • Changed LM5164-Q1 to LM5164 | 1 |
| • Changed 15-µA to 5-µA throughout document | 1 |
| • Added information regarding *Wake* signal to Section 2.3.3 | 7 |
| • Added information to Section 3.2.2 | 22 |
| • Added content to Section 6 | 31 |