Single-Cell Impedance Track™ Gas Gauge for Novices

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ABSTRACT

This application report introduces the bq27350 Impedance Track™ gas gauge solution.

1 Introduction

This application report provides an introductory overview of the following bq27350 Impedance Track™ gas gauge topics:

- The Basics
  - The bq27350 Impedance Track™ Gas Gauge Overview
  - Impedance Track™ Technology Operation Principle
  - Gas Gauge Hardware
  - bq27350EVM-001 Evaluation Module
  - bqEVSW Software for Use with bq27350
- Next Steps
  - Developing a PCB for bq27350
  - Solution Development Process
  - Mass Production Setup
- Glossary
- Appendix – Reference Schematic

2 The Basics

2.1 *bq27350 Impedance Track™ Gas Gauge Overview*

2.1.1 Key Features:

- Patented Impedance Track™ technology accurately measures available charge in Li-ion and Li-polymer batteries.
- Better than 1% capacity estimate error over the lifetime of the battery
- Instant capacity estimate accuracy – no learning cycle required
- Based on a powerful low-power reduced instruction-set (RISC) CPU core with high-performance peripherals
- Integrated, field-programmable FLASH memory eliminates the need for external configuration memory
- Measures charge flow using a high-resolution, 16-bit integrating delta-sigma converter
- Uses 16-bit delta-sigma converter for accurate voltage and temperature measurements
- Extensive data reporting options for improved system interaction

The bq27350 is an advanced, feature-rich battery gas gauge IC, designed for accurate reporting of available charge of Li-ion or Li-polymer batteries in single-cell applications. The bq27350 incorporates the patented Impedance Track™ technology, whose unique algorithm allows for real-time tracking of battery capacity change, battery impedance, voltage, current, temperature, and other critical information of the battery pack. Unlike the *current integration*- or *voltage correlation*-based gas gauge algorithms, the Impedance Track™ algorithm takes full advantage of battery response to electronic and thermal stimuli and therefore maintains the best capacity estimate accuracy over the lifetime of the battery. The bq27350 automatically accounts for charge and discharge rate, self-discharge, and cell aging, resulting in excellent gas-gauging accuracy even when the battery ages. The IC also provides a variety of battery performance parameters to a system host over a standard serial communication bus (I^2C).

The heart of the bq27350 programmable battery management IC is a high-performance, low-power, RISC CPU, which offers powerful information processing capability that is crucial to battery management functional calculation and decision-making. The IC also integrates plenty of program and data flash memory and an array of peripheral and communication ports, facilitating rapid development of custom implementations and eliminating the need for external configuration memory.

The bq27350 is equipped with two high-resolution, analog-to-digital converters (ADC) dedicated for accurate coulomb counting and voltage/temperature measurements. These low-power analog peripherals improve accuracy beyond discrete implementations.

The bq27350 measures cell voltage, temperature, current, and integrated passed charge using the two delta-sigma ADCs of the bq27350.

2.2 *Impedance Track™ Technology Operation Principle*

What makes the Impedance Track™ technology unique and much more accurate than existing solutions is a self-learning mechanism that accounts for the change of (1) battery impedance and (2) the no-load chemical full capacity (Qmax) due to battery aging. A fact that is often ignored is that battery impedance increases when the battery ages. As an example, typical Li-ion batteries double the impedance after approximately 100 cycles of discharge. Furthermore, battery impedance also varies significantly between cells and at different usage conditions, such as temperature and state-of-charge. Therefore, to achieve sufficient accuracy, a large, multidimension impedance matrix must be maintained in the IC flash memory, making the implementation difficult. Acquiring such a database is also time-consuming. The Impedance Track™ technology significantly simplifies gas-gauging implementation by continuously updating the battery impedance during the usage lifetime of the battery, and thus only needs a simple, initial impedance data base. Temperature and load effects are automatically accounted for when calculating the full-charge capacity (FCC) and the remaining capacity (RM). On the other hand, the Qmax is calculated also and updated during the usage of the battery — only in more strict conditions as mentioned later in this section.

The full-fledged monitoring mechanisms of the bq27350 allow for accurate measurement of the following key properties:

- OCV: Open-circuit voltage of a battery, usually assuming the battery is already in relaxation mode
- Battery impedance: $\frac{\text{OCV} - \text{BatteryVoltageUnder Load}}{\text{AverageLoad Current}}$
- PassedCharge: Coulomb counter integrated charge during battery charge or discharge
- SOC: State-of-charge at any moment, defined as SOC=Q/Qmax, where Q is the PassedCharge from the full-charge state
- DOD: Depth of discharge; DOD= 1-SOC
- DOD_0: Last DOD reading before charge or discharge
- DODcharge: DOD for a fully charged pack
- Qstart: Charge that would have passed to make DOD = DOD_0
- Qmax: Maximum battery chemical capacity
- RM: Remaining capacity
- FCC: Full-charge capacity, the amount of charge passed from the fully charged state to the terminate voltage

Figure 1 illustrates charge, discharge, and relaxation modes of the battery. The times and current thresholds that are noted in the graph are values that are programmed by the user in Flash memory. As seen in Figure 1, relaxation starts after *Chg Relax Time* or *Dsg Relax Time* has elapsed after the pack current measured by the ADC is within ±*Quit Current*. The relaxation ends after *Quit Relax Time* elapses following a pack current detected that exceeds either *Charge Current Threshold* or *Discharge Current Threshold*.

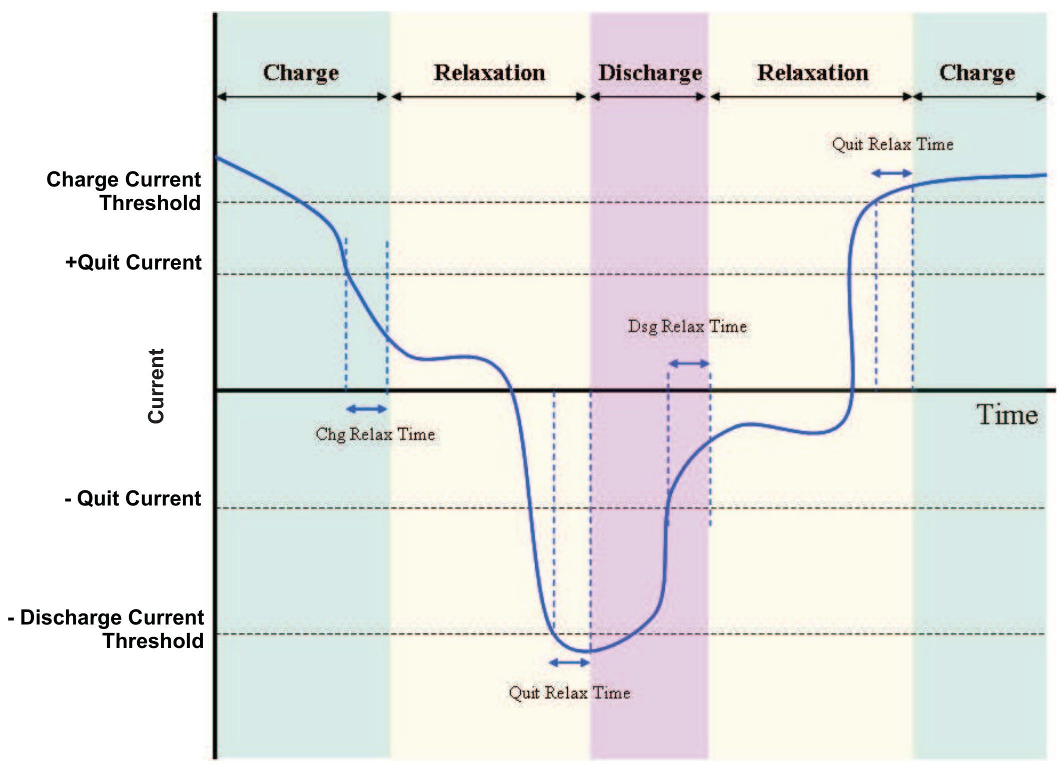


Figure 1. Algorithm Operation Mode Changes With Varying Battery Current

The SOC is estimated based on the OCV of the battery because of a strong correlation of SOC to OCV for a particular battery chemistry, shown in Figure 2 as an example. In the relaxation mode, where no load current is present and the current is below a user-chosen *quit current* level, the SOC is determined using the measured cell voltage (must meet certain voltage settling criteria; see the *Fuel Gauging* section in the bq27350 data sheet, SLUS754, for details) and the predefined OCV versus SOC relationship.

During charging and discharging, the SOC is continuously calculated using the relationship of present Qmax to the integrated passed charge measured by the coulomb counter ADC:

$$Q_{max} = \frac{Passedcharge}{|SOC1 - SOC2|} \quad (1)$$

The derivation of this equation is discussed in the following paragraphs. Figure 3 graphically illustrates some of the Impedance Track™ terminology.

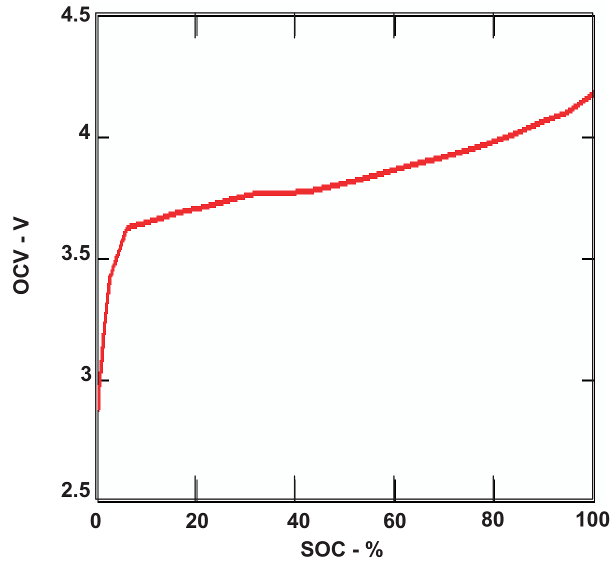


Figure 2. SOC Dependency on OCV

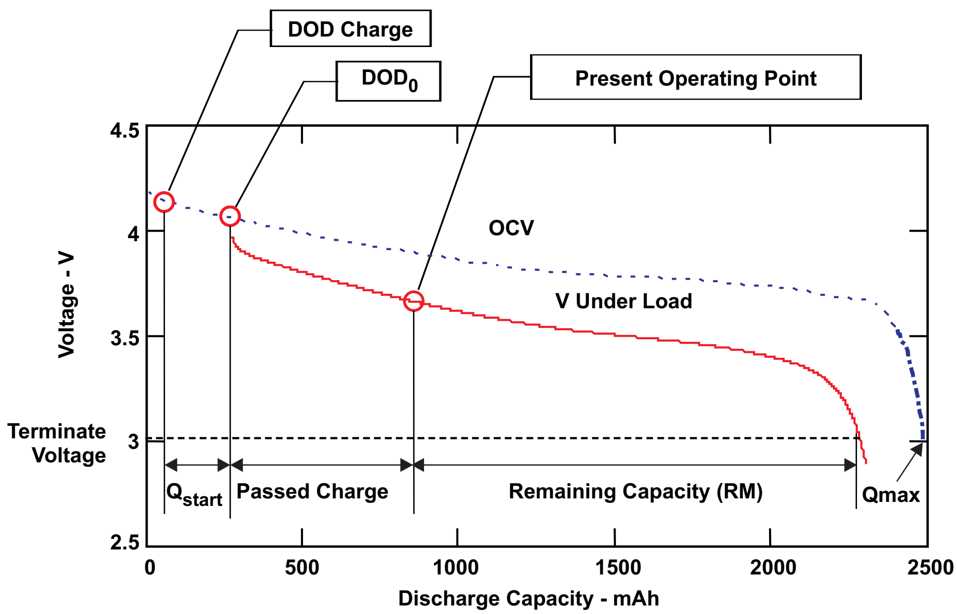


Figure 3. OCV Characteristics (Dotted Curve) and Battery Discharge Curve Under Load (Solid Curve)

Qmax is calculated with two OCV readings (leading to calculation of two SOC values, SOC1 and SOC2) taken at fully relaxed state (dV/dt < 4 µV/s) before and after charge or discharge activity and when the passed charge is more than 37% of battery design capacity, using Equation 2:

$$SOC1 = \frac{Q1}{Qmax}, \; SOC2 = \frac{Q2}{Qmax} \quad (2)$$

subtracting these two equations yields

$$Q_{max} = \frac{\text{Passedcharge}}{|\text{SOC1} - \text{SOC2}|},\ \text{where Passedcharge} = |\text{Q1} - \text{Q2}|. \tag{3}$$

This equation demonstrates that it is unnecessary to have a complete discharge cycle to learn the battery chemical capacity.

When an external load is applied, the impedance of the cell is measured by finding the difference between the measured voltage under load and the open-circuit voltage (OCV) specific to the cell chemistry at the present state-of-charge (SOC). This difference, divided by the applied load current, yields the impedance. In addition, the impedance is correlated with the temperature at time of measurement to fit in a model that accounts for temperature effects.

With the impedance information, the remaining capacity (RM) can be calculated using a voltage simulation method implemented in the firmware. The simulation starts from the present DOD, i.e., DOD_{start} and calculates a future voltage profile under the same load with a 4% DOD increment consecutively:

$$V(DOD_I,T) = OCV\ (DOD_I,T) + I \times R(DOD_I,T),$$

where $DOD_I = DOD_{start} + I \times 4\%$ and I represents the number of increments, and $R(DOD_I,T)$ is the battery impedance under DOD_I and temperature T. Once the future voltage profile is calculated, the Impedance Track™ algorithm predicts the value of DOD that corresponds to the system termination voltage and captures this as DOD_{final}. The remaining capacity then is calculated using:

$$RM = (DOD_{final} - DOD_{start}) \times Q_{max}$$

FCC (Full-charge capacity) is the amount of charge passed from the fully charged state to the termination voltage, and can be calculated using:

$$FCC = Qstart + PassedCharge + RM$$

The following section presents a more detailed description of the gas gauge hardware.

2.3 Gas Gauge Hardware

To perform the Impedance Track algorithm the gas gauge must be able to obtain cell voltage, temperature and pack current measurements. This section briefly discusses the hardware blocks that make the necessary measurements.

2.3.1 TPS77025 LDO Regulator

The TPS77025 serves an important role for the bq27350 1-cell lithium-ion battery pack gas gauge chipset solution. The TPS77025 powers the bq27350 directly from its 2.5-V, 50-mA low-dropout (LDO) regulating output, which is powered by the battery voltage. This LDO has an enable low pin that is used such that if the Dsg FET from the protector circuit opens and the bq27350 enters SHUTDOWN mode (see bq27350 datasheet) then the LDO is shut off to prevent any loading to the cell from the LDO and gas gauge.

2.3.2 Cell Voltage Measurement

The maximum input voltage for the CELL+ pin is 1 V. Given that a cell under normal conditions can have a voltage as high as 4.2 V, there's a voltage divider network (R5 and R7) that is configured to translate the cell voltage into ground-referenced voltage, which can be measured by the bq27350 gas gauge IC. The voltage divider is only active enough time to allow the signal at the CELL+ pin to stabilize and for the ADC to take several samples to determine a battery voltage measurement.

2.3.3 Temperature Measurement

The ADC that is used for the battery voltage measurement is shared with the temperature measurement function. The TS pin is the input used when measuring the voltage across a thermistor to determine temperature. The reference design demonstrates the necessary components needed along with an NTC103AT thermistor so that the bq27350 can correlate the voltage at TS pin with a temperature reported in °C. The bq27350 has the option to use either the external or internal temperature sensing. This is selected with the [TEMPS] bit in *Pack Configuration* flash register.

2.3.4 Pack Current Measurement

The SRP and SRN pins are the high impedance inputs to the integrating ADC (coulomb counter). A very low value sense resistor is placed in series with the cell on the ground side to convert the pack current to a voltage that the ADC can measure. The ADC differential input is limited to ±200 mV. The low-pass filter that feeds the sense resistor voltage to the bq27350 SRP and SRN inputs filters out system noise and does not affect the coulometric measurement accuracy, because the low-pass filter does not change the integrated value of the waveform.

2.4 Additional Pack Circuit Components

2.4.1 R5402-Series Pack Protector IC

All Li-ion battery packs should include safety provisions due to the danger present of allowing the cells to operate in extreme conditions such as overcharging. Some IC circuits are dedicated to monitor the voltage and current of a battery pack exclusively to control the flow of current into or out of the Li-ion cell that makes up the pack. The reference design used in this document shows the R5402-series protector IC manufactured by Ricoh. This device independently controls two N-channel MOSFETs which are dedicated to restrict charge or discharge paths.

The pin that controls the discharge MOSFET turns off if the voltage detected by the IC's VDD is under a specific voltage threshold (typically 2.3 V) that is defined within the IC, or if the voltage detected at the high input impedance V-pin is greater than the discharge overcurrent threshold (typically 100 mV). The voltage at the V-pin is a representation of current measurement due to voltage drop across MOSFETs. To recover from an undervoltage condition the Protection IC must detect a voltage above the discharge recovery threshold (typically 3 V).

The charge MOSFET is turned off if the voltage detected at the VDD pin is greater than an overcharge threshold (typically 4.275 V) or if the V- pin detects a voltage less than the charge overcurrent threshold (typically -100 mV). To recover from this condition, it is expected that the cell is discharged until it reaches a recovery threshold which is typically 200 mV less than the overcharge threshold.

Many IC manufacturers can provide products similar to the R5402 series. It is up to designers to select which protector IC to include in their pack circuit design.

2.4.2 bq26100 Authentication IC

Many counterfeit batteries are being manufactured and lack the necessary safety features so that cost can be reduced. Many OEMs are opting to add some means of authentication to their authorized battery packs to ensure that they are not liable for any accidents that could occur due to the use of these unauthorized packs.

The bq26100 IC provides a method to allow a microcontroller that is embedded in the main system to query the IC that is contained in the authorized pack and to verify that it responds with an expected result based on a challenge and a secret key. The bq26100 uses the well-known SHA-1 algorithm to process the challenge given by the system and return a digest that the system considers valid or unacceptable.

The reference design presented in this document uses the bq26100 with the bq27350. The system accesses the bq26100 through I^2C commands given to the bq27350. The bq27350 handles the SDQ communication with the bq26100 and then retrieves the response so that the system can read it from the bq27350.

2.5 bq27350EVM-001 Evaluation Module

The bq27350EVM-001 evaluation module (EVM) is a complete evaluation system for the bq27350 battery pack electronics system. The EVM includes:

1. One bq27350 circuit module
2. A current sense resistor
3. An NTC103AT thermistor
4. An EV2300 PC interface board for gas gauge interface
5. A PC USB cable
6. Windows™-based PC software

The circuit module includes one bq27350 IC, one TPS77025 IC, and all other onboard components necessary to monitor and predict capacity, in single-cell Li-ion or Li-polymer battery packs. The circuit module connects directly across the cell in a battery. With the EV2300 interface board and software, the user can read the bq27350 data registers, program the chipset for different pack configurations, log cycling data for further evaluation, and evaluate the overall functionality of the bq27350 solution under different charge and discharge conditions.

The bq27350 EVM is simpler than the reference design presented in this document. The EVM board does not include a pack protector circuit and an optional shutdown circuit. The purpose for the EVM is for customers to evaluate specifically the gas gauge operation.

2.6 bqEVSW Software for Use With bq27350

The bqEVSW is a Windows™-based evaluation software program provided by TI for functional evaluation of the bq27350/TPS77025 chipset. On opening the software, it automatically detects the presence of EV2300 USB module and the chipset. Once the device type and version of firmware are identified, the software displays the I^2C interface. The users may also toggle between DataRAM, Data Flash, I2C Pro, Calibrate, and Auth screens for a variety of information about the battery pack and the chipset settings. The bqEVSW can also be used for battery cycle data logging. See the bq27350EVM user's guide and application reports for more information.

3 Next Steps

3.1 Developing a PCB for bq27350 and TPS77025 Chipset

Using the 1-cell reference design schematic in the Appendix as a guide, a battery pack schematic should be designed to meet the individual requirements. A single-cell protector circuit IC must be selected by the pack module designer. The one used in this reference design is similar in functionality to many pack protector IC from other manufacturers. The pack protector IC controls a pair of FETs that are opened in case of overvoltage, undervoltage, overcurrent and short-circuit conditions.

Next, the current-sense resistor should be selected. As a general guideline, 20 mΩ is appropriate for a single (1P) 18650 cell, whereas 10 mΩ is recommended for a 2P pack.

Printed-circuit board layout requires careful consideration when developing a smart battery application. The high currents developed during a battery short-circuit event can be incompatible with the micropower design of the semiconductor devices. It is important to realize that battery transients can be capacitively or magnetically coupled into low-level circuits resulting in unwanted behavior. Success with a first-pass design can depend on realizing that parallel circuit board traces are indeed small capacitors and current transformers. The ideal board layout would have the entire high-current path physically located away from the low-current electronics. Because this is not often possible, the coupling principle must be taken into account. Short-circuit, ESD, and EMI testing should be part of the initial checkout of a new design.

With regard to component placement, several components surrounding the bq27350 need special attention. Most important are the power-supply decoupling capacitor C11 and the low pass filters for the differential input of the coulomb counter ADC (C7, C8, R9, and R10). The C11 capacitor must be close to the gas gauge device and have low-resistance / low-inductance connections that do not form large loops. The low pass filter components should be as close as possible to the SRP and SRN pins. Components of lesser priority but still a concern are the master reset network C9, R11. These should all be placed in the general vicinity of the IC.

Proper sensing of voltage and current requires the use of Kelvin connections at the sense resistor and at the top and bottom battery terminals. If top and bottom connections to the cells allow too much voltage drop, then the resulting error in cell voltage measurement has an effect on the measurement accuracy of battery capacity and therefore the remaining run time.

It Is important to have correct grounding. There should be high and low current ground paths. These should be kept separate, only joining together at the sense resistor.

3.2 Solution Development Process

Browsing the data flash screens of the bq27350 evaluation software can be a challenging experience. However, the default value for most of them can be easily used. The first step is to set up the data flash value for the coulomb capacity for a specific application (*Design Capacity*).

With different types of cells and number of parallel cells, capacity settings are different. To determine the values for *Qmax Cell 0*, *Qmax Pack*, *and Design Capacity* multiply the corresponding value for a single cell by the number of cells in parallel.

With the preceding changes in place, the evaluation module should function normally with the target cell configuration. The next step is to review all of the selectable features in the *Pack Configuration* register . Use the data sheet to review each configuration bit in this register and configure them for a specific application. See the EVM user's guide (SLUU253) schematic for implementation details.

3.3 Mass Production Setup

One of the main benefits of Impedance Track™ technology is the significant reduction in the complexity of battery pack mass production. Because many data flash values are adaptively derived with use, it is possible to simply transfer the knowledge gained from a single *golden* pack to each individual pack as it leaves the assembly line. Charging and discharging each pack in order to force it to learn its capacity is unnecessary.

A good strategy for production is a 7-step process flow:

1. Write the data flash image to each device. This image was read from a *golden* pack
2. Calibrate the device.
3. Update any individual flash locations, such as serial number, lot code, and date that could be entered in *Manufacturer Info* registers.
4. Perform any desired protection tests.
5. Connect the cell.
6. Initiate the Impedance Track™ algorithm.
7. Seal the pack.

The TI application report *Data Flash Programming and Calibrating the bq27350 Gas Gauge* (SLUA415) discusses the first two steps in detail. Description of steps 6 and 7 can be found in the bq27350 data sheet (SLUS754). Calibration is presented as sample VB6 code for those who wish to develop their own calibrator. However, Texas Instruments has higher-level support for high-speed programming and calibration steps. A single channel test and calibration program is available, with open-source code. Also, a multistation test system is available.

For additional application reports covering various aspect of bq27350 Impedance Track solution, see the Texas Instruments bq27350 online product folder.

4 Glossary

- OCV: Open-circuit voltage of a battery
- Passed Charge: Coulomb counter integrated charge during battery discharge or battery charge
- Qmax: Maximum battery chemical capacity
- Design Capacity: Cell chemical capacity specified by cell manufacturer times number of paralleled cells
- SOC: State-of-charge at any moment, defined as SOC=Q/Qmax (usually in %), where Q is the Passed Charge from full charge state
- DOD: Depth of discharge; DOD= 1-SOC (usually in %)
- DOD_0: Last DOD reading before charge or discharge
- DODcharge: DOD for a fully charged pack
- Qstart: Charge that would have passed from fully charged state to make DOD = DOD_0
- RM: Remaining capacity, in mAh or mWh
- FCC: Full-charge capacity, the amount of charge passed from the fully charged state to the terminate voltage, in mAh or mWh
- Quit current: user-defined current levels for both charge and discharge, usually about ~10 mA
- Relaxation mode: the state of the battery when the current is below user-defined *quit current* levels and after a user-defined minimum charge relax time (see Figure 1)

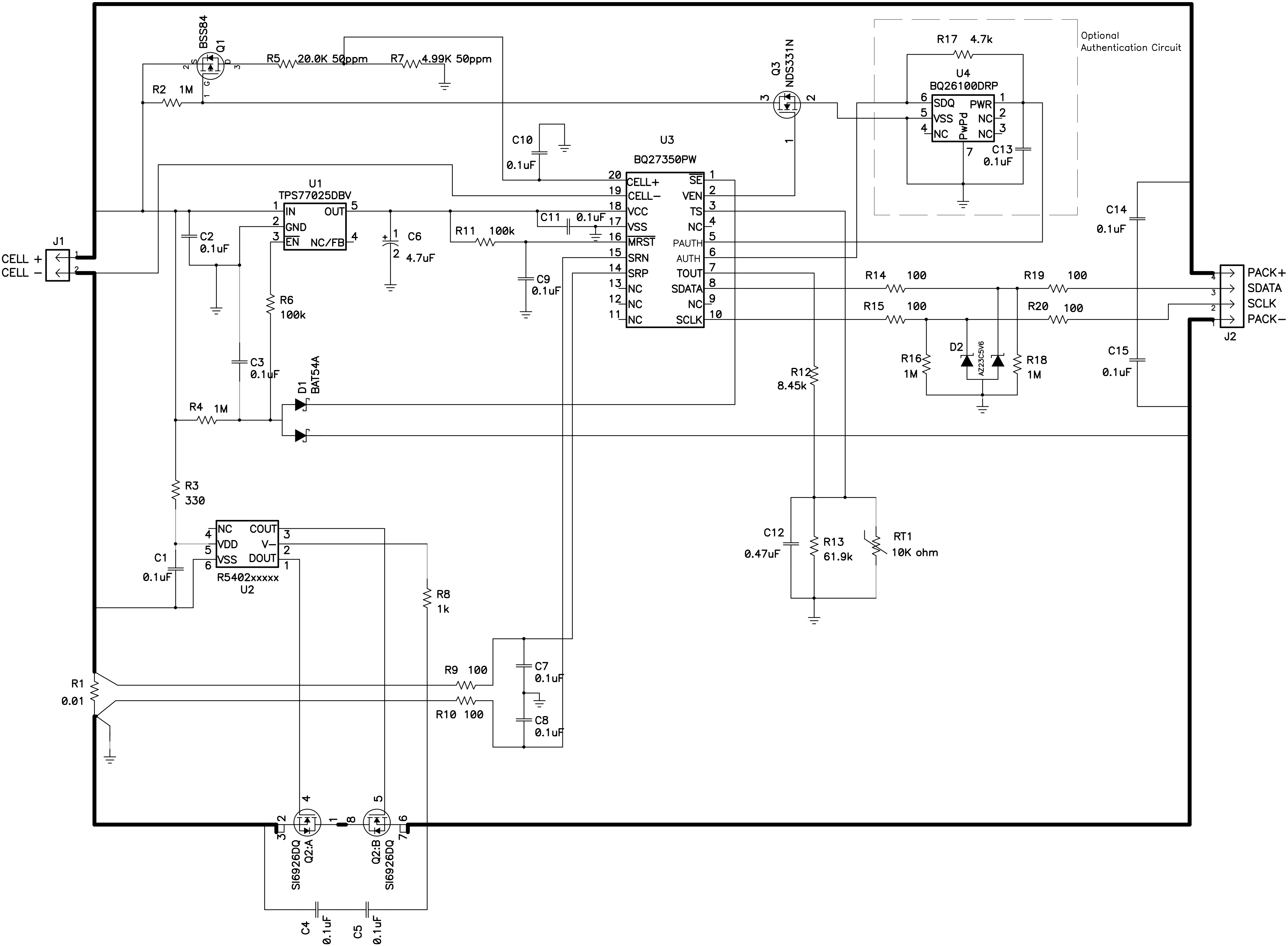
4.1 Reference Documents

The following documents should also serve as reference when researching the bq27350 and Single Cell Impedance Track products:

- *bq27350, Single Cell Li-Ion Battery Manager With Impedance Track Fuel Gauge Technology* data sheet (SLUS754)
- *bq27350EVM Single Cell Impedance Track Technology Evaluation Module* user's guide (SLUU253)
- *Configuring the bq27350 Data Flash* application report (SLUA419)
- *Data Flash Programming and Calibrating the bq27350 Gas Gauge* application report (SLUA415)

4.2 Reference Design Schematic

The reference design schematic is affixed to this page.



CELL +
CELL −
J1
BSS84
Q1
R5 20.0K 50ppm
R7 4.99K 50ppm
R2 1M
Q3
NDS331N
Optional
Authentication Circuit
R17 4.7k
U4
BQ26100DRP
SDQ
VSS
NC
PWR
NC
NC
PwPd
C13
0.1uF
C10
0.1uF
U3
BQ27350PW
CELL+
CELL−
VCC
VSS
MRST
SRN
SRP
NC
NC
NC
SE
VEN
TS
NC
PAUTH
AUTH
TOUT
SDATA
NC
SCLK
U1
TPS77025DBV
IN
GND
EN
OUT
NC/FB
C2
0.1uF
C6
4.7uF
C11 0.1uF
R11 100k
C9
0.1uF
R6
100k
C3
0.1uF
D1
BAT54A
R4 1M
R3
330
C1
0.1uF
NC
VDD
VSS
COUT
V−
DOUT
R5402xxxxx
U2
R8
1k
R9 100
R10 100
C7
0.1uF
C8
0.1uF
R1
0.01
SI6926DQ
Q2:A
Q2:B
SI6926DQ
C4
0.1uF
C5
0.1uF
R14 100
R19 100
R15 100
R20 100
D2
AZ23C5V6
R16
1M
R18
1M
R12
8.45k
C12
0.47uF
R13
61.9k
RT1
10K ohm
C14
0.1uF
C15
0.1uF
PACK+
SDATA
SCLK
PACK−
J2

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